**SCIENCE CHINA**
Information Sciences

• RESEARCH PAPER •

December 2016, Vol. 59 122301:1–122301:15
doi: 10.1007/s11432-015-5468-6

# Efficient link scheduling with joint power control and successive interference cancellation in wireless networks

Xuan LI[1,2], Yan SHI[1*], Xijun WANG[1], Chao XU[1] & Min SHENG[1,2]

[1]*State Key Laboratory of Integrated Services Networks, Information Science Institute, Xidian University, Xi'an* 710071*, China;*
[2]*Science and Technology on Information Transmission and Dissemination in Communication Networks Laboratory, Shijiazhuang* 050081*, China*

Received August 25, 2015; accepted October 20, 2015; published online June 12, 2016

**Abstract** Existing works have addressed the interference mitigation by any two of the three approaches: link scheduling, power control, and successive interference cancellation (SIC). In this paper, we integrate the above approaches to further improve the spectral efficiency of the wireless networks and consider the max-min fairness to guarantee the transmission demand of the worst-case link. We formulate the link scheduling with joint power control and SIC (PCSIC) problem as a mixed-integer non-linear programming (MINLP), which has been proven to be NP-complete. Consequently, we propose an iterative algorithm to tackle the problem by decomposing it into a series of linear subproblems, and then the analysis shows that the algorithm has high complexity in the worst case. In order to reduce the computational complexity, we have further devised a two-stage algorithm with polynomial-time complexity. Numerical results show the performance improvements of our proposed algorithms in terms of the network throughput and power consumption compared with the link scheduling scheme only with SIC.

**Keywords** successive interference cancellation, power control, mathematical optimization, fairness, cross-layer link scheduling framework

**Citation** Li X, Shi Y, Wang X J, et al. Efficient link scheduling with joint power control and successive interference cancellation in wireless networks. Sci China Inf Sci, 2016, 59(12): 122301, doi: 10.1007/s11432-015-5468-6

## 1 Introduction

In wireless communication networks, how to efficiently utilize the channel resource has become a critical issue due to the scarcity of spectrum. Due to the broadcast nature of the wireless medium, when multiple wireless links occupy the same channel, the receivers may suffer from interference. A natural approach to combat the interference is adopting the scheduling mechanisms in the MAC layer, with which interference can be avoided by assigning independent resource units to conflict links, e.g., in the time or frequency domains [1–6]. However, such an interference avoidance scheme has limitation on spectrum utilization since there are only some particular links can utilize the same channel simultaneously, for

* Corresponding author (email: yshi@xidian.edu.cn)

 

instance, the links far away enough from each other [7]. In order to further improve the utilization of the channel resource, much attention has been paid to the cross-layer design by combining the physical layer techniques and the MAC layer scheduling schemes [8–19], which have the potential for improving the system performance significantly.

Since power control is an important physical layer technique to suppress the interference, it has been widely adopted by the cross-layer scheduling mechanisms [8–11]. With such a technique, the transmitter is allowed to adjust its transmit power to satisfy the signal-to-interference-plus-noise ratio (SINR) requirement at the intended receiver and hence, from the system perspective, more links can transmit simultaneously. In spite of that, when there are many nearby transmitting links, the channel resource cannot be efficiently utilized in practice due to the strong interference. Besides, when multiple desired signals arriving at a common receiver simultaneously, only one of them can be decoded by the receiver. Obviously, the spectral efficiency can be further improved if these two situations can be carefully handled.

Recently, successive interference cancellation (SIC) has been proposed as a novel approach of interference exploitation, which enables the receivers to decode multiple received signals in a sequential order. Particularly, the strongest signal is decoded first, then the next strongest, and so on [20–22]. From the theoretical aspect, authors in [23] have proved that the capacity region can be achieved by an SIC-based approach. On the other hand, the application of SIC has been discussed in [13, 22], which have demonstrated that it is very promising in alleviating the interference. Besides that, SIC has been introduced to the cross-layer link scheduling schemes in the wireless networks [12, 14–18, 24, 25].

However, there are several challenges to apply SIC in practice. More specifically, under SIC, the key issue for signals decoding is the sequential order of the interference cancellation. In order to guarantee the operation, the SINR of the strongest signal must be not less than the receiving threshold in each stage of cancellation. Once the requirement cannot be satisfied, the decoding procedure can hardly be carried out. On the other hand, the signals must be received with differing power levels, dependent on the order of decoding [12, 16, 18]. The larger the disparity among the received signal power levels, the easier the operation accomplish.

To well satisfy the above stringent requirements of SIC, we advocate to combine power control and SIC with link scheduling for mitigating the severe interference at the receivers. In this paper, we consider link scheduling in a time division multiple access (TDMA)-based wireless network, where each link will be assigned with a set of time slots for transmission. With the aim of utilizing the channel resource efficiently, SIC and power control are employed in the physical layer. Different from the traditional SIC-enabled link scheduling schemes, the dynamic power control for links is enabled to satisfy the sequential SINR requirements at the receivers.

Simply maximizing the throughput may lead to a severe bias on the resource allocation among the links. Consequently, we define a demand satisfaction factor (DSF) for each link to address fairness, which is the ratio between the amount of successfully transmitted traffic to the traffic demand [8]. In this paper, we maximize the DSF of the worst-case link and formulate the link scheduling with joint power control and SIC (PCSIC) problem as a mixed-integer non-linear programming (MINLP). In order to handle the nonlinear constrains and the mixed variables, we firstly transform the MINLP into a maximization problem and a series of minimization problems with linear constraints, which are presented as the integer linear programming (ILP) and the linear programming (LP), respectively. After that, the maximization problem and the minimization problems are solved in an iterative way. The analysis shows that the computational complexity of the iterative algorithm is exponential in the worse case. Therefore, we present a two-stage link scheduling algorithm, referred to as the fast PCSIC algorithm (FPA), to improve the DSF of the worst-case link with lower complexity. Under FPA, the network is regarded as a graph, where the maximum independent set of the graph will be chosen as the active links in each time slot. Finally, our numerical results show that the SIC-enabled schemes with power control can achieve significant performance gains than the pure SIC-enabled scheme.

The rest of this paper is organized as follows. In Section 2, the related work is discussed. Section 3 describes the system model and define the optimization problem. We present an iterative algorithm to decompose the PCSIC problem and solve it in Section 4. Section 5 illustrates the details of FPA.

Numerical results are given in Section 6. Finally, Section 7 concludes this paper.

## 2 Related work

As a conventional approach to combat interference in wireless networks, link scheduling has been extensively studied in decades (e.g., [1–3]). Authors in [1] have proposed two polynomial-time scheduling algorithms to satisfy the link demand and end-to-end demand, respectively. The link scheduling schemes for pursuing the network throughput improvement have been studied in [2, 3]. The RTS/CTS and the protocol interference model have been taken into account in [2] while the physical interference model has been considered in [3]. Nonetheless, it is spectrally inefficient for scheduling alone to handle all the conflicting links. To this end, the physical layer techniques have been introduced into the cross-layer link scheduling schemes.

In recent decades, much research effort has been paid to study the interaction between power control and link scheduling schemes for cross-layer design [8–11]. Authors in [10] have formulated the integrated link scheduling and power control problem as a mixed integer linear programming, which has been proven to be NP-complete. In order to get over the high computational complexity of the problem, many methods and strategies have been proposed, e.g., column generation and branch-and-bound in [9], monotonic optimization in [11]. To achieve the tradeoff between system throughput and user demands, the fair link scheduling with power control has been considered in [8].

With the pursuit of further improving the spectral efficiency, there is a growing interest in the study of joint SIC and link scheduling [12, 14–18, 24, 25]. In [24], the authors have proved the problem of link scheduling with SIC is NP-complete under the physical interference model and then developed an approximation algorithm. The SIC-enabled scheduling and topology control problems have been studied in [16, 25], respectively. Different from [16, 24, 25] focusing on minimizing the schedule length, authors in [12, 14, 15, 17] have concentrated on the throughput improvement in the network, which is also our major concern in this paper. A cross-layer scheme combine SIC and MAC scheduling protocol has been designed in [15]. Authors in [12] have advocated to joint SIC and interference avoidance, an optimization framework with formulation of physical, link, and network layers has been proposed. The optimal link activation problems with SIC for both uniform and non-uniform SINR threshold have been discussed in [18]. Rate control has been considered in [14] with the objective of maximizing the minimum flow throughput in the multihop wireless networks. Authors in [17] have quantified the throughput gains that can be obtained by SIC in the realistic-sized wireless networks. It is noted that in the aforementioned studies on SIC, the transmit power is assumed to be fixed.

As shown in our previous work [26], the link scheduling scheme with joint power control and SIC is promising in improving the spectral efficiency. Under the same formulations, we in this paper further present the analysis on the convergence and complexity of the proposed algorithm in [26]. Particularly, we also develop a two-stage algorithm with lower complexity.

## 3 System model and problem formulation

In this section, we will describe the system model and present the problem formulation for PCSIC in wireless networks.

### 3.1 System model

We consider a single-channel wireless network with a set of links $\mathcal{L}$ and a set of nodes $\mathcal{N}$. In this paper, we assume the nodes are stationary during the period of operation. Each node is equipped with an omni-directional antenna and its transmit power can be adjusted continuously in a given range $[0, P_{\max}]$. TDMA is adopted in the MAC layer as the multiple access scheme and in the time domain, a frame is divided into $T$ identical synchronized time slots with equal constant duration. Moveover, we assume each link $(i,j)$ is associated with a traffic demand $D_{ij}$ specifying the number of time slots required by the link

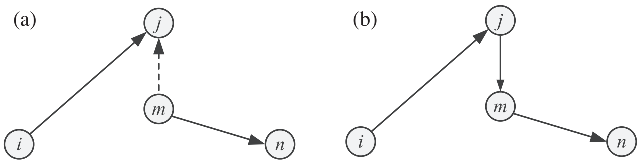


**Figure 1** Examples of network with three links. (a) Illustration of SIC; (b) illustration of fairness.

for its data transmission, which is determined by the mean packet arrival rate and transmission rate. In any given time slot, if the demand of a link has been met, we regard it as the satisfied link which will keep silence in the rest of time.

Firstly, we define a binary variable $X_{ij}^t$ for each link $(i,j)$ and time slot $t$:

$$X_{ij}^t = \begin{cases} 1, & \text{if link } (i,j) \text{ is active in time slot } t, \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

By "active", we mean that when $X_{ij}^t = 1$, the transmission from transmitter $i$ must be met the SINR requirements (the specific requirements will be presented later) at receiver $j$. Each node transmits at a constant rate $R$ when the corresponding link is active, note that the variation of the transmit power will not change the transmission rate.

In our model, a single transmission from a transmitter can only intend to one receiver at a time slot, i.e., unicast mechanism. Each node can only transmit or receive at one time, i.e., half-duplex operation. Under SIC, a receiver can detect at least one transmission simultaneously, in this paper, we refer to this reception constraint as the SIC-enabled receptivity. We use an $|\mathcal{L}| \times |\mathcal{L}|$ incidence matrix $\boldsymbol{Q}$ to describe the relationship between two links, where the element $q_{(i,j),(k,l)}$ of $\boldsymbol{Q}$ is

$$q_{(i,j),(k,l)} = \begin{cases} 0, & \text{if } (i,\ j),\ (k,\ l) \text{ have no nodein common or node } j = l, \\ 1, & \text{otherwise.} \end{cases} \tag{2}$$

It can be seen that the constraint

$$q_{(i,j),(k,l)} + X_{ij}^t + X_{kl}^t \leqslant 2, \quad \forall (i,j),(k,l) \in \mathcal{L}, \tag{3}$$

guarantees that the links do not share the common nodes or the links have the same receiver can be active in the same time slot. This feature simultaneously imposes unicasting, half-duplexing and SIC-enabled receptivity at each time slot.

We consider that interference occurs when a receiver detects more than one signals from other transmitters (including the intend and unintended transmitters) simultaneously. When link $(i,j)$ is active in time slot $t$, both Eqs. (4) and (5) must be satisfied at receiver $j$ [21]:

$$\frac{P_m^t G_{mj}}{\sum_{P_k^t G_{kj} < P_m^t G_{mj}} P_k^t G_{kj} + \sigma^2} \geqslant \beta, \ \ \forall P_m^t G_{mj} > P_i^t G_{ij}, \tag{4}$$

$$\frac{P_i^t G_{ij}}{\sum_{P_k^t G_{kj} < P_i^t G_{ij}} P_k^t G_{kj} + \sigma^2} \geqslant \beta, \tag{5}$$

where $P_i^t$ and $G_{ij}$ denote the transmit power of node $i$ in time slot $t$ and the channel gain from node $i$ to node $j$, respectively. In addition, $P_i^t G_{ij}$ is the receive power of the desired signal and $P_m^t G_{mj}$ is the interference power which is stronger than $P_i^t G_{ij}$. The noise power $\sigma^2$ is considered to be constant and the SINR threshold is denoted by $\beta$. The inequations present a sequential decoding order at the SIC-enabled receiver $j$. Eq. (4) means that the SINR of the stronger interference is required to be not less than the threshold $\beta$. Once the condition is satisfied, $P_m^t G_{mj}$ will be subtracted from the aggregated interference. On the other hand, in Eq. (5), the target signal will be decoded by regarding the remaining signals as interference, its SINR is also required not less than the threshold $\beta$. Taking an example in Figure 1(a), if link $(i,j)$ and $(m,n)$ are allowed to transmit in the same time slot, node $j$ has to firstly decode the stronger interference from node $m$ and then decode the target signal from node $i$ to guarantee the active transmission. In this paper, we assume the SIC-enabled receiver can decode two signals simultaneously as long as the SINR conditions are met, i.e., Eqs. (4) and (5).

To integrate the sequential SINR constraints with link scheduling, Eqs. (4) and (5) can be written as (9) and (10). In (9), $N$ is a sufficiently large constant (e.g. $N = P^t_m G_{mj} - \beta \sum_{(k,l)\in L}^{P^t_k G_{kj} < P^t_m G_{mj}} P^t_k G_{kj} X^t_{kl} - \beta\sigma^2$). When $X^t_{ij} X^t_{mn} = 1$, Eq. (9) becomes $P^t_m G_{mj} - \beta \sum_{(k,l)\in L}^{P^t_k G_{kj} < P^t_m G_{mj}} P^t_k G_{kj} X^t_{kl} - \beta\sigma^2 \geqslant 0$; when $X^t_{ij} X^t_{mn} = 0$, the associated constrain has a null effect. In (10), $N^*$ is a sufficiently large constant (e.g. $N^* = P^t_i G_{ij} - \beta \sum_{(k,l)\in\{L/(i,j)\}}^{P^t_k G_{kj} < P^t_i G_{ij}} P^t_k G_{kj} X^t_{kl} - \beta\sigma^2$).

In Figure 1(b), we assume link $(i,j)$ and $(m,n)$ can be active simultaneously via SIC if node $i$ and $m$ are assigned with the appropriate transmit power. As a result, we can obtain a system throughput which is $2R$. However, if we want to keep the higher system throughput, link $(j,m)$ has to stay silent all the time. It can be seen that the goal of throughput maximization may results discrimination on the resource allocation. Therefore, it is important to employ a fair allocation to meet the demands of the links in the networks with limited resource. To this end, we first define the DSF $\omega_{ij}$ for each link to indicates how much demand has been satisfied, where $\omega_{ij} \triangleq \sum_{t=1}^{T} X^t_{ij}/D_{ij}$. Then, we consider the max-min fairness to guarantee the transmission requirement of the worst-case link.

### 3.2 Problem formulation

To improve the DSF of the worst-case link and meanwhile satisfy the sequential SINR requirements, we jointly optimize link scheduling and power allocation to maximize the DSF of the worst-case link by the following optimization problem PCSIC:

$$\max \quad \min_{(i,j)\in\mathcal{L}} \sum_{t=1}^{T} X^t_{ij}/D_{ij} \tag{6}$$

$$\text{s.t.} \quad 0 \leqslant \sum_{t=1}^{T} X^t_{ij} \leqslant D_{ij}, \quad \forall (i,j)\in\mathcal{L},\ t\in[1,T], \tag{7}$$

$$q_{(i,j),(k,l)} + X^t_{ij} + X^t_{kl} \leqslant 2, \quad \forall (i,j),(k,l)\in\mathcal{L},\ t\in[1,T], \tag{8}$$

$$P^t_m G_{mj} - \beta \sum_{(k,l)\in\mathcal{L}}^{P^t_k G_{kj} < P^t_m G_{mj}} P^t_k G_{kj} X^t_{kl} - \beta\sigma^2 \geqslant \left(1 - X^t_{ij} X^t_{mn}\right) N, \quad \forall P^t_m G_{mj} > P^t_i G_{ij},\ t\in[1,T], \tag{9}$$

$$P^t_i G_{ij} - \beta \sum_{(k,l)\in\{\mathcal{L}/(i,j)\}}^{P^t_k G_{kj} < P^t_i G_{ij}} P^t_k G_{kj} X^t_{kl} - \beta\sigma^2 \geqslant \left(1 - X^t_{ij}\right) N^*, \quad \forall (i,j)\in\mathcal{L},\ t\in[1,T], \tag{10}$$

$$0 \leqslant P^t_i \leqslant P_{\max} X^t_{ij}, \quad \forall (i,j)\in\mathcal{L},\ t\in[1,T], \tag{11}$$

$$X^t_{ij} \in \{0,1\}, \quad \forall (i,j)\in\mathcal{L},\ t\in[1,T]. \tag{12}$$

Constraint (7) ensures that the time slots allocated to each link cannot be more than its traffic demand. Each transmission in the network should obey the specified rules (i.e., unicasting, half-duplexing and SIC-enabled receptivity), which is taken into account in constraint (8). Constraints (9) and (10) guarantee that the sequential SINR constraints can be satisfied for the desired signal. The range of transmit power is specified in constraint (11).

**Complexity of PCSIC**. By simplifying constraints (9) and (10) to $P^t_i G_{ij} - \beta \sum_{k\neq i}^{\mathcal{N}} P^t_k G_{kj} X^t_{kl} - \beta\sigma^2 \geqslant \left(1 - X^t_{ij}\right) \widetilde{N}$ where $\widetilde{N}$ is a sufficiently large constant, the sequential SINR constraints reduce to the conventional SINR constraint. That is a network has not employed SIC, so the PCSIC problem is the same as the link scheduling with power control problem in wireless network, which has been proved to be NP-complete in [10]. Therefore, PCSIC is also NP-complete. Hence, it is extremely hard to design an optimal scheme for the PCSIC problem. In the view of this, an efficiently algorithm is needed to obtain the acceptable solution.

## 4 An iterative algorithm for PCSIC

In the last section, the optimization formulation for the PCSIC problem is presented as an MINLP, the main difficultly for solving it is the high computational complexity caused by the nonlinear constrains and the mixed variables.

In order to linearize the constrains and separate the mixed variables, we propose an interative algorithm for the PCSIC problem. We first convert the MINLP into a maximization problem and a series of minimization problems, which are presented as ILP and LP optimizations, respectively. For the sake of clarity, we refer the maximization problem as link scheduling problem (LSP) which with the objective of maximizing the DSF of the worst link and the minimization problems as power control problems (PCPs) which with the objective of minimizing the total network power consumption. After the decomposition, the LSP and PCPs are solved in an iterative manner. In each iterative, the algorithm outputs a better set of active links only if the objective value of (6) can be further improved. In the following section, we will give the details of the decomposed problems and the iterative algorithm.

### 4.1 Link scheduling problem

In the LSP, all the nodes transmit with the fixed transmit power, which means the received power levels of the target signals and the aggregated interference are determined, $P_i^t$ is not a variable here and we only need to handle the scheduling variable $X_{ij}^t$. In addition, a new binary variable $\lambda_{im}^t$ is introduced to substitute $X_{ij}^t X_{mn}^t$ where $\lambda_{im}^t = 1$ if and only if $X_{ij}^t = 1$ and $X_{mn}^t = 1$. In consequence, Eq. (9) can be rewrite as

$$\lambda_{im}^t \in \{0,1\}, \quad \forall P_m^t G_{mj} > P_i^t G_{ij},\, t \in [1,\, T], \tag{13}$$

$$\lambda_{im}^t \geqslant X_{ij}^t + X_{mn}^t - 1, \quad \forall P_m^t G_{mj} > P_i^t G_{ij},\, t \in [1,\, T], \tag{14}$$

$$\lambda_{im}^t \leqslant X_{ij}^t, \quad \forall P_m^t G_{mj} > P_i^t G_{ij},\, t \in [1,\, T], \tag{15}$$

$$\lambda_{im}^t \leqslant X_{mn}^t, \quad \forall P_m^t G_{mj} > P_i^t G_{ij},\, t \in [1,\, T], \tag{16}$$

$$P_m^t G_{mj} - \beta \sum_{(k,l)\in\mathcal{L}}^{P_k^t G_{kj} < P_m^t G_{mj}} P_k^t G_{kj} X_{kl}^t - \beta\sigma^2 \geqslant \left(1 - \lambda_{im}^t\right) N, \quad \forall P_m^t G_{mj} > P_i^t G_{ij},\, t \in [1,\, T]. \tag{17}$$

Finally, we can obtain the LSP whose objective function is (6), scheduling constrains are (7), (8), (12) and SIC constrains are (10), (13)–(17).

### 4.2 Power control problem

With the scheduling index $X_{ij}^t$ given by LSP, we can adjust the transmit power of the active links. Accordingly, we obtained the following two kinds of PCPs. In PCP1, the stronger interference exists in the aggregate signal and the desired signal can be decoded only the constrains (19) and (20) are satisfied; in PCP2, no stronger interference exists so that the desired signal can be decoded once (23) is satisfied. The two kinds of PCPs present the decoding order of the transmissions at a SIC-enabled receiver. In PCP1, the receiver decodes the stronger interference firstly and then decodes the desired signal. In PCP2, the receiver decodes the the desired signal firstly.

**PCP1**:

$$\min \quad \sum_{i\in\mathcal{N}} P_i^t \tag{18}$$

$$\text{s.t.} \quad P_m^t G_{mj} - \beta \sum_{k\neq m}^{\mathcal{N}} P_k^t G_{kj} X_{kl}^t - \beta\sigma^2 \geqslant \left(1 - X_{ij}^t X_{mn}^t\right) N, \quad \forall\,(i,j) \in \{\mathcal{L} \setminus (m,n)\},\, t \in [1,\, T], \tag{19}$$

$$P_i^t G_{ij} - \beta \sum_{k\neq i,m}^{\mathcal{N}} P_k^t G_{kj} X_{kl}^t - \beta\sigma^2 \geqslant \left(1 - X_{ij}^t\right) N^*, \quad \forall (i,j) \in \mathcal{L},\, t \in [1,\, T], \tag{20}$$

**Algorithm 1** PCSIC Iterative Algorithm

1: **Initialization** $P_i^t = 0$ and $X_{ij}^t = 0$
2: Solve LSP by fixing all $P_i^t$ to be $P_{\max}$ , obtain the $X_{ij}^t$;
3: Solve PCPs with the $X_{ij}^t$ given by line2, get the corresponding $P_i^t$;
4: Solve LSP with the $P_i^t$, a new set of scheduling variables $X_{ij}^{t^*}$ can be reached;
5: **if** the the objective value of (6) can be improved **then**
6: GOTO line 10;
7: **else**
8: OUTPUT $X_{ij}^t$ and $P_i^t$;
9: **end if**
10: Solve PCPs with input $X_{ij}^{t^*}$;
11: **if** PCPs can return a feasible solution $P_i^{t^*}$ **then**
12: $(X_{ij}^t \leftarrow X_{ij}^{t^*}, P_i^t \leftarrow P_i^{t^*})$, GOTO line 4;
13: **else**
14: OUTPUT $X_{ij}^t$ and $P_i^t$;
15: **end if**

$$0 \leqslant P_i^t \leqslant P_{\max} X_{ij}^t, \quad \forall (i,j) \in \mathcal{L},\, t \in [1,\, T]. \tag{21}$$

**PCP2**:

$$\min \quad \sum_{i \in \mathcal{N}} P_i^t \tag{22}$$

$$\text{s.t.} \quad P_i^t G_{ij} - \beta \sum_{k \neq i}^{\mathcal{N}} P_k^t G_{kj} X_{kl}^t - \beta \sigma^2 \geqslant \left(1 - X_{ij}^t\right) N^*, \quad \forall (i,j) \in \mathcal{L},\, t \in [1,\, T], \tag{23}$$

$$0 \leqslant P_i^t \leqslant P_{\max} X_{ij}^t, \quad \forall (i,j) \in \mathcal{L},\, t \in [1,\, T]. \tag{24}$$

It is worth noting that when $X_{ij}^t$ is given, the value of (6) is fixed. In other words, we solve the PCPs to find the feasible transmit power levels under given the scheduling index, when there are more than one feasible transmit power levels, we choose the minimal power levels because reducing the total power consumption is conducive to reduce the interference in the network. Therefore, the objective function of the PCPs has been changed to minimize the transmit power of the nodes and hence, the active transmissions can be guaranteed with the minimal power levels. Keeping in mind that our ultimate goal is still increasing throughput subject to fairness and we will show it in the iterative algorithm.

As it can be seen, the nonlinear constraints of the PCSIC problem are all linearized. Next, the decomposed problems will be solved in an iterative way.

### 4.3 PCSIC iterative algorithm

In the PCSIC iterative algorithm, we first fix all the transmission power as $P_{\max}$, then the scheduling index $X_{ij}^t$ can be obtained by solving the LSP in line 2. In line 3, we use the $X_{ij}^t$ to get the new transmit power levels $P_i^t$. From line 4 to line 9, we use the $P_i^t$ to solve the LSP for seeking if there exists better scheduling result $X_{ij}^{t^*}$ with larger value of the objective function (6). The algorithm will check the feasibility of the $X_{ij}^{t^*}$ by solving the PCPs from line 10 to 15, the solutions of PCP1 and PCP2 will be compared and the one with better objective value will be chosen as $P_i^{t^*}$. After that, $P_i^{t^*}$ and $X_{ij}^{t^*}$ will substitute $P_i^t$ and $X_{ij}^t$ and start a new iteration in line 4. Finally, we will obtain the solution via the iteration of line 4 to line 15. If there are no feasible $P_i^{t^*}$ and $X_{ij}^{t^*}$ that can make improve the objective value of LSP, the iteration will stop and output the $P_i^t$ and $X_{ij}^t$.

**Theorem 1.** The convergence of the proposed PCSIC algorithm can be guaranteed.

*Proof.* From line 5 of the iterative algorithm, it can be observed that the objective value of PCSIC is improved after each iteration. Consequently, it always converges because the objective value of PCSIC is finite and monotonically increasing sequences with upper bounds converge [27].

It is clarified the PCSIC iterative algorithm can always converges, but seeking for the global optimal solution is not within its solution procedure. Even when it does, we cannot certify it theoretically. However, the iterative algorithm can linearize the constraints of the PCSIC and solve it with an acceptable computational complexity.

**Theorem 2.** The computation complexity of PCSIC iterative algorithm is $O(2^{\varepsilon+\zeta})$, where $\zeta$ is the number of links in the network, $\varepsilon$ is the number of the active links in each iteration.

*Proof.* The computation complexity of the iterative algorithm is decided by the LSP and PCPs. Note the LSP is an ILP, which can be solved by the branch-and-bound algorithm, costing $O(2^{\varepsilon})$ in the worst-case. The iterative algorithm solves a PCP2 and $O(2^{\varepsilon})$ PCP1s in each time slot. The computation complexity of solving the PCPs is $O(\varepsilon 2^{\varepsilon})$ since each problem with $\varepsilon$ variables. In addition, there are at most $T2^{\zeta}$ iterations between PCPs and LSP in $T$ time slots. As a result, the computation complexity of the PCSIC iterative algorithm is $O(2^{\varepsilon+\zeta})$.

It is obvious that the computation complexity is dominated by the computation complexity of solving ILP, the number of PCPs, and the iterations between PCPs and LSP. The computation complexity of solving ILP is determined by the number of the subproblems required to be solved during the execution of the branch-and-bound algorithm. Although it increases exponentially with the size of the problem in the worst case [28], the authors in [29] have shown the average complexity of the algorithm is much lower than the worst-case complexity in the moderate-sized networks. On the other hand, we find $\varepsilon$ is less than half of $\zeta$ in the scheduling procedure (it can be seen in the numerical results). Furthermore, in line 5 of the iterative algorithm, we set the termination condition to make the number of the iterations between PCPs and LSP manageable. Therefore, the iterative algorithm is efficient for the PCSIC problem in the moderate-sized networks.

## 5 A fast algorithm for PCSIC

Although the iterative algorithm can solve the PCSIC problem, its worst computational complexity increases exponentially with the number of links. In the view of this point, we propose an effective polynomial-time scheduling algorithm for the problem. In this section, we first introduce the detailed description of FPA and then present the analysis of FPA.

### 5.1 Algorithm description

In order to achieve a lower complexity, FPA is designed as a two-stage algorithm. In the first stage, we firstly built a conflict graph for the corresponding network, and then adjust the transmit power of the links with the same receiver to satisfy the SIC SINR requirements. After that, we update the conflict graph and choose the maximal independent set of the conflict graph as the active links in each time slot. The details are described below.

**Power adjustment stage**. According to the distribution of the nodes and the demands of the links in the network, we built a conflict graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ where $\mathcal{V}$ is the set of the vertexes and $\mathcal{E}$ is the set of the edges. The vertexes correspond to the links in the network and each vertex is considered to have a weight which represents the DSF of the corresponding link. $(i, j) \in \mathcal{E}$ is an undirected edge which implies that there exists conflict between vertex $i$ and $j$, their corresponding links cannot be active in the same time slot. Specifically, an undirected edge is placed by vertex $i$ and $j$ in $\mathcal{G}$ if the two corresponding links have a node in common. Taking an example in Figure 2, Figure 2(a) is the topology of a 4-links network, the corresponding conflict graph is shown in Figure 2(b). It can be seen that links (1,3) and (3,4), (3,4) and (5,4), (3,4) and (2,3), (1,3) and (2,3) have a node in common, so there exists an undirected edge between the corresponding vertexes in the conflict graph.

Compared to the case without SIC, the SIC-enabled receivers can decode multiple desired signals simultaneously. Therefore, after constructing the conflict graph, we find the links with the same receiver and adjust their transmit power to ensure the multiple desired signals with the common receiver can be decoded simultaneously. If the target has been reached, it means the conflict between the corresponding

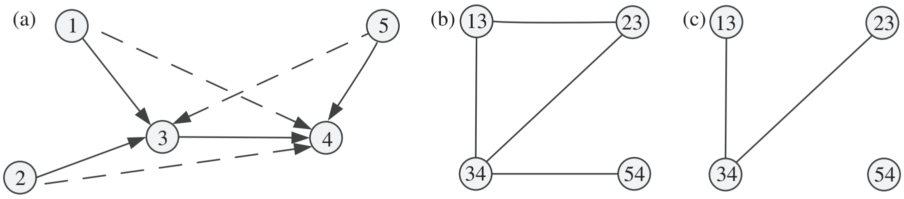


**Figure 2** A centralized scenario. (a) A network with 4 links, the target signals are described by solid lines and the interference by dotted lines; (b) conflict graph; (c) adjusted conflict graph.

vertexes can be canceled, so we can remove the undirected edges between them. If not, we will keep the undirected edge between the corresponding vertexes. After the adjustment, we update the information and obtain a new conflict graph $\mathcal{G}' = (\mathcal{V}', \mathcal{E}')$. We give Figure 2(b) and (c) to make a specific illustration. We assume that link (1,3) and link (2,3) can be active simultaneously after adjusting the transmit power of nodes 1 and 2, it can be seen that the undirected edge between their corresponding vertexes has been removed in Figure 2(c). Similarly, for link (1,3) and link (2,3), the undirected edge between their corresponding vertexes has been also removed in Figure 2(c).

It is noted that when we adjust the transmit power of the desired signals, the aggregated interference caused by the other concurrent transmission should be taken in account. For this point, we set a maximum aggregate interference $I_A(j)$ for each receiver $j$, which denotes the maximum allowable interference at receiver $j$. For instance, we assume the received power levels of all the possible signals arrived at receiver $j$ are: $P_1^tG_{1j} \geqslant P_2^tG_{2j} \geqslant \cdots \geqslant P_m^tG_{mj}$, where $P_1^tG_{1j}$ and $P_2^tG_{2j}$ are the received power of the desired signals and the others are the interference power. From Eqs. (4) and (5), we adjust $P_1^t$ and $P_2^t$ as the following equations: $P_1^t = \frac{P_2^tG_{2j}+I_A(j)+\sigma^2}{G_{1j}}$ and $P_2^t = \frac{I_A(j)+\sigma^2}{G_{2j}}$. It is apparently that the larger the value of $I_A(j)$ is, the more interference the receiver $j$ can tolerate. With the purpose of making $I_A(j)$ as large as possible, we calculate it by the following method. Firstly, we initialize $I_A(j)$ as a null set, then calculate the initial value of $P_1^t$ and $P_2^t$ with the above equations. If the initial value of $P_1^t$ or $P_2^t$ is lager than $P_{\max}$, it means the corresponding links cannot be active simultaneously. Otherwise, we sort the interference power (i.e., $P_3^tG_{3j}$ to $P_m^tG_{mj}$) in the non-descending order, then put the minimal interference power into $I_A(j)$ and calculate the value of $P_1^t$ and $P_2^t$. If $P_1^t$ and $P_2^t$ are not larger than $P_{\max}$, we continue putting the interference power into $I_A(j)$ in the non-descending order. If one of $P_1^t$ and $P_2^t$ is larger than $P_{\max}$, the adjustment process will stop and we choose $P_1^t$ and $P_2^t$ in the last round as the adjusted transmit power.

**Link scheduling stage**. With the given $\mathcal{G}' = (\mathcal{V}', \mathcal{E}')$, we adopt Algorithm 2 to choose the active links in each time slot. $\mathcal{S}$ denotes the set of active links in $T$ time slots, $\mathcal{S}^t$ denotes the set of active links in time slot $t$, $\mathcal{H}^t$ is the set of links that have not been scheduled in time slot $t$, $\mathcal{C}^t$ is the set of links that cannot be scheduled in time slot $t$.

As mentioned above, each vertex has a weight which represents the DSF of the corresponding link. Therefore, the vertex with the minimum weight indicates that its corresponding link is the worst-case link in the network. In line 4 of Algorithm 2, we choose the vertex with the minimum weight in $\mathcal{G}'$ and give the corresponding link a prior consideration in the scheduling of time slot $t$ to emphasize max-min fairness. From line 6 to 18, we adopt the minimum degree greedy algorithm to find the active links in each time slot, which has been proved to be the best among available independence set algorithms in [30]. The degree of the vertex indicates the number of the undirected edges associated to it in $\mathcal{G}'$. In other words, we choose the link with the weakest interference in each iteration with the purpose of allowing more links to coexist in $\mathcal{S}^t$. From line 8 to 17, we first check whether the transmit constrains of the chosen links can be satisfied (i.e. unicasting, half-duplexing and SIC-enabled receptivity), then check whether the sequential SINR requirements of the links can be satisfied. In line 12, $\mathcal{S}^t$ is a feasible link set where the sequential SINR requirements (i.e. Eqs. (4) and (5)) of all the links in $\mathcal{S}^t$ can be satisfied. When link $(m,n)$ has been put into $\mathcal{S}^t$, if $\mathcal{S}^{t^*} = \mathcal{S}^t \cup (m,n)$ is still a feasible link set, we say that link $(m,n)$ is feasible with $\mathcal{S}^t$. In line 20, when the weight of a vertex is 1, which means the demand of the corresponding link is satisfied, the link will keep silence in the rest of the scheduling time. Hence, the

**Algorithm 2** Independent set based scheduling

1: **Input** adjusted conflict graph $\mathcal{G}' = (\mathcal{V}', \mathcal{E}')$,
2: **repeat**
3: Set $\mathcal{S}^t = \varnothing$, $\mathcal{C}^t = \varnothing$ and $\mathcal{H}^t$ is the set of all vertexes in $\mathcal{G}'$;
4: Find the vertex $v$ with the minimal weight in $\mathcal{G}'$ and its corresponding link $(i,j)$;
5: $\mathcal{S}^t = \mathcal{S}^t \cup (i,j)$, $\mathcal{H}^t = \mathcal{H}^t / v$;
6: **while** $\mathcal{H}^t \neq \varnothing$ **do**
7: Find the vertex $u$ with minimal degree in $\mathcal{H}^t$;
8: **if** vertex $u$ has undirected edges relate to the corresponding vertexes of the links in $\mathcal{S}^t$ **then**
9: $\mathcal{H}^t = \mathcal{H}^t / u$, $\mathcal{C}^t = \mathcal{C}^t \cup u$;
10: **else**
11: Find its corresponding link $(m,n)$;
12: **if** link $(m,n)$ is feasible with $\mathcal{S}^t$ **then**
13: $\mathcal{S}^t = \mathcal{S}^t \cup (m,n)$, $\mathcal{H}^t = \mathcal{H}^t / u$ ;
14: **else**
15: $\mathcal{H}^t = \mathcal{H}^t / u$, $\mathcal{C}^t = \mathcal{C}^t \cup u$;
16: **end if**
17: **end if**
18: **end while**
19: $\mathcal{S} \leftarrow \mathcal{S} \cup \mathcal{S}^t$, update the weight of all vertexes in $\mathcal{G}'$;
20: **if** the weight of a vertex is 1 **then**
21: Remove it and all its incident undirected edges from $\mathcal{G}'$;
22: Recalculate the transmit power levels;
23: **end if**
24: Update $\mathcal{G}'$;
25: **until** running $T$ iterations
26: **Output** the scheduling result $\mathcal{S}$;

vertex and its related edges will be removed from the conflict graph $\mathcal{G}'$. In the meantime, the power adjustment stage will be carried out to recalculate the transmit power levels because the topology of the network has been changed.

### 5.2 Algorithm analysis

**Theorem 3.** The computation complexity of FPA is $O(\zeta^3 T)$, where $\zeta = |\mathcal{L}|$ denotes the number of links in the network, $T$ is the number of the time slots in the execution.

*Proof.* In the first stage, there are $\zeta$ links in the network, so it costs $O(\zeta^2)$ to built the conflict graph. Then, the computation complexity for each receiver to sort receiving signals in the descending order is $O(\zeta \log \zeta)$ and the computation complexity for each receiver to compute $I_A(j)$ is $O(\zeta)$. Moreover, the power adjustment stage can be carried at most $T$ times. Therefore, we can see that the computation complexity for the power adjustment is $O(\zeta^2 \log \zeta T)$. In the second stage, the computation complexity of Algorithm 2 is dominated by lines 6–18. Firstly, it costs $O(\zeta)$ to find the link with the minimal interference number. When we put the link into $\mathcal{S}^t$, the computation complexity is $O(\zeta^2)$ for us to check the feasible condition of the link by computing the sequential SINR of the receivers. There exists $\zeta$ links in the network, so it costs $O(\zeta^3)$ to find the independent set in a time slot. The over computation complexity of link scheduling stage is $O(\zeta^3 T)$, which is larger than the power adjustment stage. In consequence, the computation complexity of FPA is $O(\zeta^3 T)$.

## 6 Numerical results

### 6.1 Simulation setup

In our simulation, we consider the wireless multihop networks which located in a square $100 \times 100$ unit

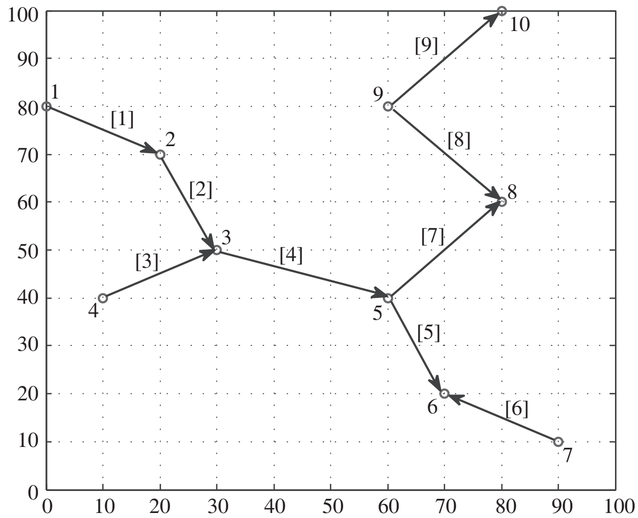


**Figure 3** The topology of a 9-link network.

region. For generality, the units for distance, transmission rate and transmit power are normalized appropriately. We asumme all the nodes have identical SINR threshold $\beta$ which is equal to 1. When a link is active in time slot $t$, the achieved transmission rate $R = 1$. The maximum transmit power $P_{\max} = 1$ and the noise power $\sigma^2 = 10^{-6}$. We simply consider the effect of path loss, the channel gain $G_{ij}$ is set to be $1/d_{ij}^3$ where $d_{ij}$ is the Euclidean distance between nodes $i$ and $j$. We adopt Jain's index [31] as our fairness metric to indicate how fair are the scheduling schemes. The formula for calculating Jain's index is presented as

$$J = \Bigg(\sum_{(i,j)\in\mathcal{L}} \omega_{ij}\Bigg)^2 \Bigg/ \Bigg(\zeta \cdot \sum_{(i,j)\in\mathcal{L}} \omega_{ij}^2\Bigg). \tag{25}$$

For the solution of the integer optimization problems in our formulation, we adopt an efficient off-the-shelf solver YALMIP, which is a modeling language relies on external optimization solvers.

### 6.2 A specific example

We compare four SIC-enabled schemes in this scenario. The main difference between them is whether power control is adopted or not. The one without power control refers to the max-min fairness scheme with a constant transmit power $P_{\max}$ (SIC-mm). The other three with power control correspond to the max-min fairness scheme (PCSIC-mm), the maximum throughput scheme which with the objective function of maximizing $\sum_{(i,j)\in L}\sum_{t=1}^{T} X_{ij}^t$ (PCSIC-mt) and FPA. In order to show the performance improvements of our schemes clearly, we present a specific example as follows. A 9-links wireless network is shown in Figure 3, each node and link has an unique ID. We fix the number of time slots $T$ to 10 and set the same traffic demand $D_{ij}$ for the scheduling schemes, which is (4,8,9,5,6,9,7,7,8).

Under the condition of that all the nodes transmit with the same power, when the transmitters with the same distance to a receiver transmit simultaneously, the multiple signals arriving at the receiver are with the same received power levels, neither of them can be decoded with SIC. From the topology of the given 9-links network in Figure 3, we see that links (2,3) and (4,3), (5,6) and (7,6), (5,8) and (9,8) cannot be active simultaneously, due to the same received power of the multiple target signals. Links (3,5) and (1,2), (5,8) and (7,6), (9,10) and (5,8) cannot be active simultaneously since the interference power is identical to the received power of the target signal.

Looking at the scheduling results in Table 1, it give the active links in each time slot, the network throughput (NT), power consumption (PC) and Jain's index. Since $R$ =1, the network throughput is equivalent to the number of the active links in the given time slots. The power consumption implies the total power consumption of the active links and the results are normalized by that of SIC-mm. Jain's index is adopted to measure the fairness, the closer its value is to 1, the more fairness the scheme is.

**Table 1** Active links in each time slot of the 9-link network

| Time slot | SIC-mm | FCA | PCSIC-mt | PCSIC-mm |
|---|---|---|---|---|
| 1 | 101001001 | 001011010 | 011001101 | 011001101 |
| 2 | 101010001 | 100101001 | 011001101 | 101011001 |
| 3 | 010000100 | 011001100 | 011001101 | 101011010 |
| 4 | 000101010 | 100011010 | 011001101 | 100101001 |
| 5 | 010001001 | 100101001 | 011001101 | 011011001 |
| 6 | 101010001 | 011001101 | 011001101 | 101001101 |
| 7 | 101000100 | 001011010 | 011001101 | 001011010 |
| 8 | 000101010 | 011001100 | 011011001 | 000101001 |
| 9 | 010001001 | 001011010 | 101011010 | 011001101 |
| 10 | 010000100 | 100010110 | 100010010 | 001000110 |
| NT | 31 | 41 | 48 | 44 |
| PC | 1 | 0.85 | 0.73 | 0.57 |
| Jain's index | 0.8658 | 0.8863 | 0.7865 | 0.8894 |

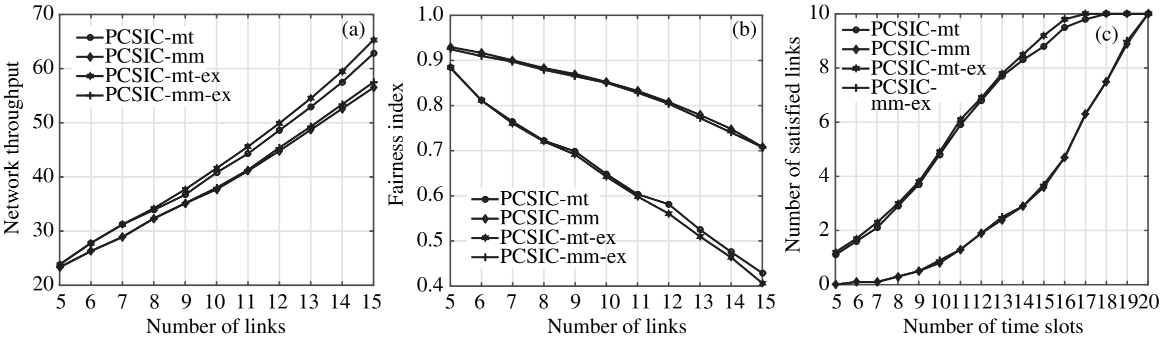


**Figure 4** System performance of four schemes in the networks with gird topologies. (a) Network throughput with $T=10$; (b) Jain's index with $T=10$; (c) number of satisfied links with $\zeta= 10$.

It can be seen that SIC-mm obtains the worst performance on network throughput since SIC alone can hardly handle the signals with the same received power. In the scheduling results of the schemes with power control, the fore-mentioned link pairs can coexist in the same time slot. Thereby, a significant increase on the network throughput is provided. We also notice that, unlike the other schemes, PCSIC-mt would not change the outputs unless the demand of one link is satisfied. Under PCSIC-mt, link (3,5) never gets chance to deliver its data in the given slots owing to the pursue of maximizing the throughput. Jain's index shows that simply maximizing the throughput in the resource-limited networks would lead to an extreme imbalance in resource allocation. Table 1 also gives the power consumption of the scheduling schemes, which indicates PCSIC-mt, PCSIC-mm, and FPA can provide noticeable throughput improvement over SIC-mm while the power consumption can be declined by 15%–43%.

### 6.3 Numerical results in general networks

Firstly, we consider a scenario where the square region is divided into a 6×6 grid and the nodes are located on the vertices of the grid. This kind of topologies can generate the signals with the same received power. Then, we consider a scenario where the nodes are placed randomly. Base on the node location, we randomly generate 5 to 15 links in the region where the length of the links is from 20 to 30 distance units. The demand of each link $D_{ij}$ is derived from $(1,T)$ randomly. The following results are presented by averaging 50 topologies to PCSIC-mt, PCSIC-mm, SIC-mm, and 1000 topologies to FPA.

The performance comparisons between the exhaustive method of the PCSIC problem (PCSIC-mt-ex and PCSIC-mm-ex), PCSIC-mt and PCSIC-mm are provided in Figure 4. For the PCSIC-mt-ex and PCSIC-mm-ex, we solve the problem in turn until all the scheduling variables $X_{ij}^t$ have been exhausted.

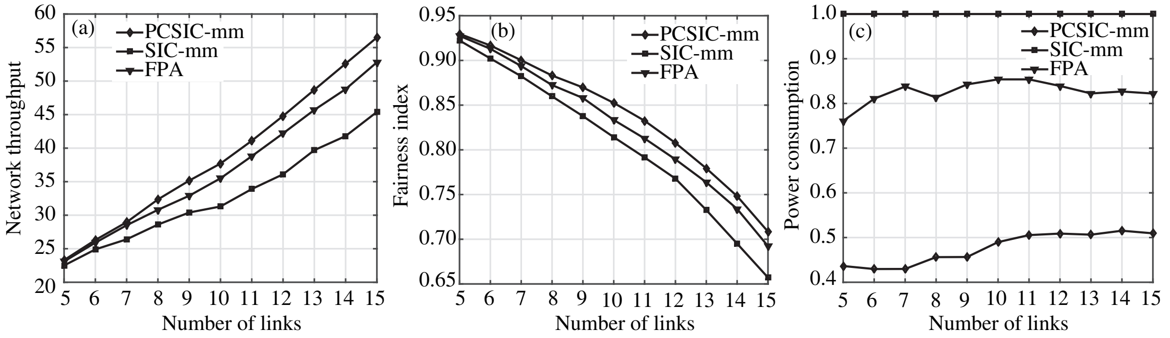


**Figure 5** System performance of three schemes in the networks with gird topologies, where $T = 10$. (a) Network throughput; (b) Jain's index; (c) power consumption.

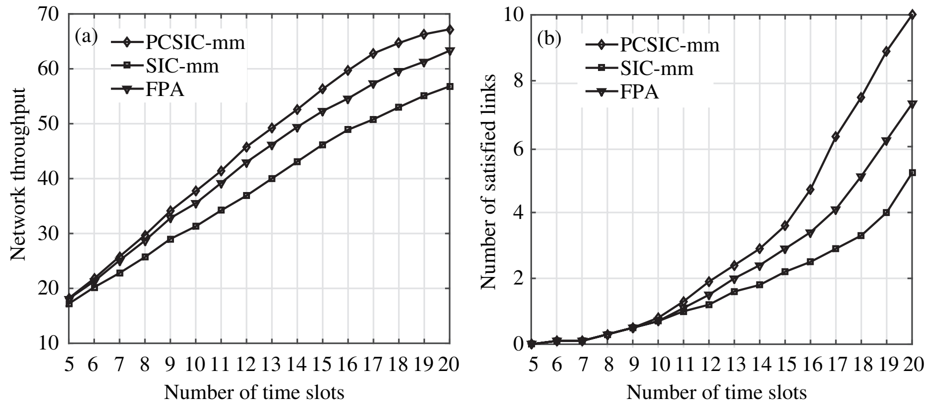


**Figure 6** System performance of three schemes in the networks with gird topologies, where $\zeta = 10$. (a) Network throughput; (b) number of satisfied links.

Figure 4(a) and (b) compare the network throughput and Jain's index among the schemes with $T = 10$, respectively. In Figure 4(a), it can be observed that the gap between the exhaustive method and our iterative algorithm is small. That implies the iterative algorithm is effectively in the moderate-sized networks. PCSIC-mt-ex and PCSIC-mt achieve a better performance on throughput while PCSIC-mm-ex and PCSIC-mm perform a reasonable reduction with the consideration of the worst-case link. In the meantime, we can observe from Figure 4(b) that PCSIC-mt-ex and PCSIC-mt have a seriously degrade on the performance of the fairness due to the throughput maximization. In order to show how the number of time slots affects the number of satisfied links, for a given link number $\zeta = 10$, we see that PCSIC-mm-ex and PCSIC-mm need more time slots to satisfy the demands of all links due to max-min fairness in Figure 4(c).

Figure 5 shows how the number of the links affects the performance of PCSIC-mm, FPA, and SIC-mm, where the number of time slots $T$ is fixed as 10. Figure 5(a) demonstrates that the SIC-enabled schemes with power control can utilize the channel resource more efficiently than SIC-mm. It is noticed that the throughput of SIC-mm is suppressed because it cannot deal with the signals with the same received power. On account of giving priority consideration to the worst-case link, we can see PFA can approximate to PCSIC-mm from Figure 5(b). Note that all the results in Figure 5(c) are normalized by that of SIC-mm. It is obvious that the power consumption of SIC-mm is the highest. This validates that more links can be active at a lower power cost by adopting our mechanisms. Different from FPA, PCSIC-mm can minimize the power consumption under the precondition of ensuring successful transmission.

Figure 6 illustrates how the number of the time slots affects the performance of the three schemes, where the number of links $\zeta$ is fixed to 10. Figure 6(a) directly shows that PCSIC-mm has the highest throughput so it can meet the demands of all the links with less time slots. In Figure 6(b), the number of satisfied links under the three schemes is given. It is seen that the demands are satisfied for only a few

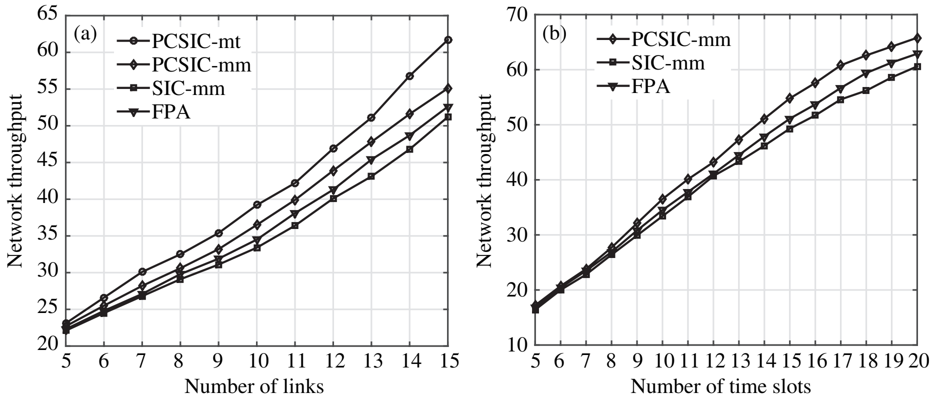


**Figure 7** Network throughput of the schemes in the networks with random topologies. (a) Network throughput with $T = 10$; (b) network throughput with $\zeta = 10$.

links at the beginning, and then for more links as the number of time slots increases. This is because the max-min fairness has been taken into account in the above schemes.

In Figure 7, we further compare the system performance among the schemes in the networks with random topologies. Figure 7(a) and (b) depict the network throughput of the scheduling schemes with $T = 10$ and $\zeta = 10$, respectively. Comparing with the performance in gird networks, PCSIC-mt, PCSIC-mm, and FPA perform little worse while SIC-mm achieves a better performance due to the random topologies. It can be seen that PCSIC-mt, PCSIC-mm, and FPA still have a higher throughput than SIC-mm, owing to power control can suppress the interference by adjusting the transmit power to an appropriate value. Therefore, it can be observed that the variation of topology has little influence on them.

## 7 Conclusion

In this paper, we have addressed the link scheduling with joint power control and SIC problem in wireless network to ensure the traffic requirements of the links by a formulated non-convex and mixed-integer programming, which integrates time slot assignment and power allocation. We have firstly proposed an effective algorithm to solve the PCSIC problem, which has been decomposed into a series of linear problems and solved in an iterative way. Then, by separating power allocation and time slot assignment, we have further devised a two-stage algorithm to reduce the computational cost. Simulation results have shown the performance improvements among the links in terms of network throughput and power dissipation, as well as provided extensive comparisons with the SIC-enabled scheme without power control.

**Acknowledgements** This work was supported by National Natural Science Foundation of China (Grant Nos. 61231008, 61172079, 61201141, 61301176, 91338114), Science and Technology on Information Transmission and Dissemination in Communication Networks Laboratory Fund Project, Programme of Introducing Talents of Discipline to Universities (Grant No. B08038), and National High Technology Research and Development Program of China (Grant No. 2014AA01A701).

**Conflict of interest** The authors declare that they have no conflict of interest.

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