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Resource Allocation and Power Control to Maximize the Overall System Survival Time for Mobile Cells with a D2D Underlay

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***Abstract*—The limited battery life of user equipment (UE) is always one of the key concerns of mobile users and a critical factor that could limit device-to-device (D2D) communications. In this work, considering that UEs may have different residual battery energy levels, we define the overall system survival time as the minimal expected battery lifetime of all transmitting UEs in a cell. We then propose to maximize the overall system survival time by jointly optimizing the resource allocation and power control (RAPC) D2D links as well as conventional cellular (CC) links. Subject to the transmission rate requirement of each link, the joint optimization problem is formulated as a mixed integer non-linear programming (MINLP) problem, which is solved by a game theory based distributed approach. Simulation results demonstrate that our game theory based RAPC approach can enormously prolong the overall system survival time as compared with existing RAPC approaches.**

***Index Terms*—D2D communication, resource allocation, power control, residual energy, overall system survival time.**

I. Introduction

Device-to-device (D2D) communications as an underlay to cellular networks has been considered in 5G cellular networks to enhance the spectral efficiency, offload traffic from base stations (BSs), and reduce the transmission delay to user equipment (UE) [1].

One of the critical problems of D2D underlaying cellular networks is the mutual interference between D2D and conventional cellular (CC) links, as they share radio resources. Without a proper resource allocation and power control (RAPC) mechanism, such mutual interference may become so severe that it will aggravate both D2D and CC links. In [2]-[4], the authors proposed centralised, semi-distributed, and distributed RAPC mechanisms for D2D underlaying CC communications, respectively, to enhance the system performance in terms of throughput or spectrum efficiency. However, none of these works has considered the energy consumption of UEs, which are typically with limited battery capacity and may be quickly out of service if the energy consumption is not managed properly.

Considering that UEs may have different values of residual battery energy and power consumption, we define the overall system survival time as the minimal expected battery lifetime of all transmitting UEs in a cell. There have been some initial efforts in developing energy-efficient RAPC solutions for D2D communication [5]-[8]. An RAPC scheme based on non-cooperative game theory was proposed in [5], where each D2D pair minimises its own transmission power according to the strategies of other UEs. In [6]-[8], the RAPC schemes aim to either minimize the sum transmission power of both D2D and CC transmitters or maximize the system energy efficiency. Nevertheless, none of these works has studied energy saving for UEs with low residual energy to prolong the overall survival time of the cellular network. The success of D2D assisted or enabled applications, such as multihop D2D communications, D2D content sharing, and personal hotspot, relies on the sufficiently long survival of all cooperative devices.

In this letter, we propose to maximize the overall system survival time by jointly optimizing the RAPC for D2D communications underlaying a cellular network. More specifically, we formulate the RAPC problem subject to the available subchannels and transmission rate requirement of each link into a mixed integer non-linear programming (MINLP) problem, which is NP-hard. In view of this, we propose a game theory based distributed approach to solve the RAPC problem, where the D2D and CC links are considered as non-cooperative players with the overall system survival time as their utility function. We prove the existence of the Nash equilibrium and propose a low complexity algorithm to calculate each player's best response. Performance of the proposed game theory based RAPC approach is evaluated through simulation in comparison with relevant existing schemes.

II. System Model and Problem Formulation

We consider a single cell system with one BS located at the center of the cell and multiple UEs distributed in the cell coverage area randomly. The system supports D2D communications underlaying CC communications, where the interference from other cells is controlled via inter-cell interference coordination and the D2D links can reuse both the uplink (UL) and downlink (DL) radio resources [9]. The system consists of K orthogonal frequency division multiple access (OFDMA) subchannels, $K/2$ for UL CC links and $K/2$ for DL CC links, respectively. Each subchannel has the same bandwidth of B. We assume that a D2D or CC link transmits in only one subchannel. One or more D2D links may share the same subchannel with a CC link, while each subchannel can be allocated to at most one CC link.

This work considers the RAPC for given sets of D2D links, Γ, UL CC links, Λ_{UL} ($|\Lambda_{UL}| \leq K/2$), and DL CC links, Λ_{DL}

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($|\Lambda_{DL}| \leq K/2$). D2D link $i \in \Gamma$ consists of a transmitter UE and a receiver UE, which are located close enough to each other. CC link j in Λ_{UL} (or Λ_{DL}) has one CC UE acting as the transmitter (or the receiver). Specially, any UE in the cell belongs to at most one link. The mode selection and D2D peer discovery are out of scope of this work.

Following [5], the energy consumption of each transmitting UE includes two parts: the circuit power and the transmission power. The expected battery lifetime of the ith transmitting UE ($i \in \Gamma \cup \Lambda_{UL}$) is given by:

$$L_i = \frac{Q_i}{P_{i,c} + p_i},\ i \in \Gamma \cup \Lambda_{UL} \tag{1}$$

where Q_i, $P_{i,c}$, and p_i are the residual energy, circuit power, and transmission power of the ith transmitting UE, respectively. For DL CC links in Λ_{DL}, we assume that the BS has sufficient amounts of energy and lifetime. Thus, the overall system survival time, OST_{sys}, is defined by:

$$OST_{sys} = \min_i\ L_i,\ i \in \Gamma \cup \Lambda_{UL} \tag{2}$$

We use variable δ_{i_k} =1 to indicate that link i is allocated in subchannel k, δ_{i_k}=0 otherwise. With the objective of maximizing the overall system survival time, the optimization problem is formulated as follows:

OPT:

$$\underset{\delta_{i\_k},\ p_i,\ i \in \Gamma \cup \Lambda_{UL} \cup \Lambda_{DL},\ k=1,\ldots,K}{arg} \max\ OST_{sys} \tag{3}$$

s.t.:

$$\sum_{k=1}^{K} B \cdot \log_2\Big(1 + \frac{\delta_{i\_k} \cdot p_i \cdot g_{ii}}{N_0 + \sum\limits_{(j \in \Gamma \cup \Lambda_{UL} \cup \Lambda_{DL}) \cap (j \neq i)} \delta_{j\_k} \cdot p_j \cdot g_{ji}}\Big) \geq b_i,\ \forall i \in \Gamma \cup \Lambda_{UL} \cup \Lambda_{DL} \tag{4}$$

$$\sum_{k=1}^{K} \delta_{i\_k} = 1,\ \forall i \in \Gamma \cup \Lambda_{UL} \cup \Lambda_{DL} \tag{5}$$

$$\delta_{i\_k} \in (0,1),\ \forall k \in \{1,\ 2,\ ...,\ K\},\ \forall i \in \Gamma \cup \Lambda_{UL} \cup \Lambda_{DL} \tag{6}$$

$$\begin{aligned} &\delta_{i\_k} + \delta_{j\_k} \leq 1, \\ &\forall k \in \{1,\ 2,\ ...,\ K\},\ \forall i,\ j \in \Lambda_{UL} \cup \Lambda_{DL},\ i \neq j \end{aligned} \tag{7}$$

$$p_i \geq 0,\ \forall i \in \Gamma \cup \Lambda_{UL} \cup \Lambda_{DL}. \tag{8}$$

where b_i and g_{ii} are the transmission rate requirement and channel power gain of link i, respectively, g_{ji} represents the interference channel power gain from the transmitter of link j to the receiver of link i, and N_0 is the additive noise power. We consider a slow fading channel model. In each scheduling period, the channel power gain and interference channel power gain for links in $\Gamma \cup \Lambda_{DL}$ are calculated as $d^{-2} \cdot |h|^2$. d is the distance between the transmitter and the receiver, h is a complex Gaussian channel coefficient which satisfies $h \sim CN(0,1)$. While for links in Λ_{DL}, the channel power gain and interference channel power gain are calculated as $d^{-2} \cdot |h|^2 \cdot G_{BS}$, where G_{BS} is a constant and represents the signal receiving gain of the BS.

Constraint (4) is the transmission rate constraint. According to Shannon's theory, signal to interference plus noise ratio (SINR) at the receiver in the allocated subchannel for each link should exceed a certain value to guarantee the transmission rate requirement. Constraints (5) and (6) imply that each link will transmit in one and only one subchannel. Constraint (7) represents different CC links must occupy different subchannels. Finally, constraint (8) identifies the transmission power of each link should be non-negative.

III. Game Theory Based Approach

A. The RAPC Game

The optimization problem in (3) is an MINLP problem, which is NP-hard. To solve it, we develop a game theory based approach in this section. Considering the CC links and D2D links as non-cooperative players, we define vector $\boldsymbol{s_{i^*}} = (\delta_{i^*\_1}, \delta_{i^*\_2}, ..., \delta_{i^*\_K})$ as the strategy player i^*. Given other players' strategies, $\boldsymbol{s_{-i^*}}$, player i^* tries to maximize the OST_{sys} by adjusting its own strategy. Transparently, $(\boldsymbol{s_{i^*}}, \boldsymbol{s_{-i^*}})$ should satisfy the constraints in (5)-(7). Thus, player i^*'s utility function, $u_{i^*}(\boldsymbol{s_{i^*}}, \boldsymbol{s_{-i^*}})$, is defined as the optimal solution of the following optimization problem:

$$u_{i^*}(\boldsymbol{s_{i^*}}, \boldsymbol{s_{-i^*}}) = \max_{p_i,\ i \in \Gamma \cup \Lambda_{UL} \cup \Lambda_{DL}} OST_{sys} \tag{9}$$

s.t.:

$$(4),\ (8) \tag{10}$$

$$\delta_{i\_k}\ is\ given\ by\ (\boldsymbol{s_{i^*}}, \boldsymbol{s_{-i^*}}),\ i \in \Gamma \cup \Lambda_{UL} \cup \Lambda_{DL}, k = 1,..,K \tag{11}$$

Definition 1: A set of strategies $\boldsymbol{s}$ for all the players participating in the RAPC game is a **Nash equilibrium** if no player can improve its utility function by unilaterally changing its own strategy, i. e.,

$$u_i(\boldsymbol{s_i}, \boldsymbol{s_{-i}}) \geq u_i(\boldsymbol{s_i'}, \boldsymbol{s_{-i}}),\ for\ \forall \boldsymbol{s_i'} \neq \boldsymbol{s_i},\ \forall i \in \Gamma \cup \Lambda_{UL} \cup \Lambda_{DL} \tag{12}$$

The Nash equilibrium offers a stable outcome of a non-cooperative game where multiple players adjust their own strategies through self-optimization and reach a condition from which no player wishes to deviate. Also, we can prove **Proposition 1**:

Proposition 1: Nash equilibrium exists in the constructed RAPC game. Moreover, the values of δ_{i_k}, ($i \in \Gamma \cup \Lambda_{UL} \cup \Lambda_{DL},\ k = 1, ..., K$) in the optimal solution of ***OPT*** in (3) is a Nash equilibrium.

Proof. See Appendix A. □

B. Best Response of Each Individual Player

From constraint (4), we can obtain that the transmission power needed of each link is influenced by all the other links allocated in the same subchannel. Assuming the links in set C_k are transmitted in subchannel k ($\delta_{i\_k} = 1,\ \delta_{i\_k'} = 0,\ \forall k' \neq k,\ \forall i \in C_k$), we can prove the following **Proposition**.

Proposition 2: For an arbitrary link $i^{\#}$ in C_k, under the transmission rate constraint (4), its minimum feasible transmission power, $p_{i^{\#},min}$, can be achieved only when all the inequalities relevant to the links in C_k in constraint (4) become equality at the same time, i. e.,

$$B \cdot \log_2\Big(1 + \frac{p_i \cdot g_{ii}}{N_0 + \sum\limits_{(j \in C_k) \cap (j \neq i)} p_j \cdot g_{ji}}\Big) = b_i,\ \forall i \in C_k \tag{13}$$

Proof. See Appendix B. □

Algorithm 1 : Best response for a single player, i^*

1: input the strategies of other players, $\boldsymbol{s_{-i^*}}$;
2: generate K sets, $C_1, ..., C_K$, to respectively record the links allocated to the K subchannels based on $\boldsymbol{s_{-i^*}}$;
3: for each k, calculate the minimum feasible transmission power of all the links in C_k by solving (14);
4: generate a vector $OST = zeros(1, K)$;
5: **for** $k = 1, ..., K$ **do**
6:   **if** $i^* \in \Lambda_{UL}$ and k is a DL subchannel **or** $i^* \in \Lambda_{DL}$ and k is an UL subchannel **or** $i^* \in \Lambda_{UL} \cup \Lambda_{DL}$ and there is another CC link in C_k **then**
7:     set $OST(k) = 0$;
8:   **else**
9:     put link i^* into C_k, calculate the new minimum feasible transmission power of the links in C_k by solving (14);
10:     with the results in lines 3 and 9, calculate the expected battery lifetime of each transmitting UE using (1), and calculate the achieved OST_{sys} using (2);
11:     put this OST_{sys} in $OST(k)$;
12:   **end if**
13: **end for**
14: assign link i^* in subchannel k^* which offers the maximum $OST(k)$ (if there are more than one, then randomly select one), calculate $p_{i^*,min}$;

Through equivalent transformation, (13) can be transformed into the following linear equations:

$$g_{ii} \cdot p_i + \sum_{(j \in C_k) \cap (j \neq i)} (1 - 2^{b_i/B}) g_{ji} \cdot p_j = (2^{b_i/B} - 1), \quad \forall i \in C_k \tag{14}$$

According to **Proposition 2**, we conclude that when transmission subchannels of the other links in $\Gamma \cup \Lambda_{UL} \cup \Lambda_{DL}$ are fixed ($\boldsymbol{s_{-i^*}}$ are given), the minimum feasible transmission power $p_{i,min}$ of each link i in $\Gamma \cup \Lambda_{UL} \cup \Lambda_{DL}$ is determined by which links are transmitted in its subchannel, and then determined by player i^*'s strategy, $\boldsymbol{s_{i^*}}$. In order to achieve player i^*'s best response given $\boldsymbol{s_{-i^*}}$, the proposed algorithm will test every feasible strategy for player i^*. In each testing, the algorithm first calculates the minimum feasible transmission power $p_{i,min}$ of each link i in $\Gamma \cup \Lambda_{UL} \cup \Lambda_{DL}$ if player i^* choose this strategy. Then the algorithm calculates the expected battery lifetime of each transmitting UE and the overall system survival time, OST_{sys}, using (1) and (2), respectively. After all the testings, the proposed algorithm will finally acquire the strategy for player i^* with the largest OST_{sys}. The proposed algorithm is given in **Algorithm 1**.

IV. Simulation Results

We evaluate the performance of the proposed game theory based approach through Monte Carlo simulations and all results are averaged over 1000 random tests. We compare our approach with another game theory based approach aiming at minimizing the total transmission power of the links [5], and a centralized random allocation RAPC algorithm, which allocates subchannels to the links randomly. The cellular UEs and D2D pairs are randomly distributed in the cell.

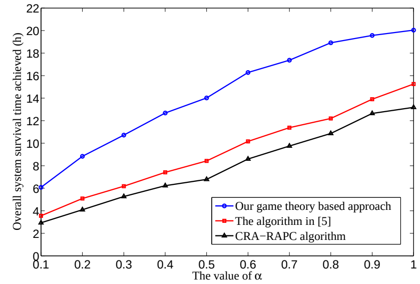

Fig. 1. OST_{sys} versus α, α reflects how different the residual energy levels of the transmitting UEs will be.

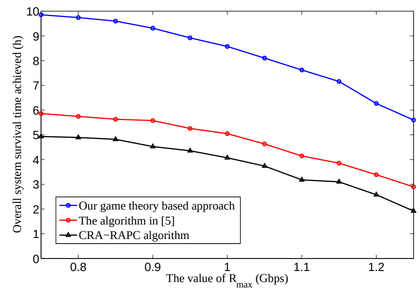

Fig. 2. OST_{sys} versus the maximum possible transmission rate requirement of the links, R_{max}.

The residual energy of each transmitting UE is uniformly distributed in $[Q_m \cdot \alpha, \ Q_m]$, and the residual energy of the BS is set to be infinite. α reflects how different the residual energy of transmitting UEs will be. Transmission rate requirements of the D2D and CC links are assumed to be randomly distributed in $[0, R_{max}]$. In the simulations, cell radius is set to be 300m, subchannel number K is set to be 20, numbers of D2D, UL CC, and DL CC links are set to be 20, 10, and 10, respectively, Q_m is set to be $0.8J$, additive noise power and circuit power of each transmitting UE are set to be 1e-5W and 0.01W, respectively. BS's signal receiving gain, G_{BS} is set to be 1000. The game theory based approaches will keep running until they reach a Nash equilibrium or their iteration numbers exceed a threshold (10 in this work).

Fig. 1 shows the OST_{sys} achieved by the three approaches under different values of α when $R_{max} = 1Gbps$. From Fig. 1, we can find that the performance of the three algorithms increase as α augments. The proposed game theory based approach always achieves the longest OST_{sys}. This is because our approach focuses on prolonging the battery lifetime for transmitting UEs with little residual energy. As α is small, transmitting UEs in the cell have greater residual energy variance and the advantage of our approach becomes more significant. When $\alpha = 0.1$, our approach outperforms the RAPC approach in [5] by 105% and the centralized random allocation algorithm by 290%.

Fig. 2 plots OST_{sys} versus R_{max} with α equals 0.2. From Fig. 2, we can see the OST_{sys} achieved by the three approaches decreases rapidly when R_{max} increases. This is because the average transmission rate requirement of the links grows as R_{max} rises, and these links must adopt larger transmission power to achieve higher SINR at their receivers according to Shannon's theory. This, in turn, will introduce greater interference to other links and force them to increase their transmission power. Similar with Fig. 1, results in Fig. 2 also indicate that our approach always achieves the best OST_{sys}

among the three approaches. When $R_{max} = 1.25Gbps$, our approach can prolong the OST_{sys} by 130% and 425%, respectively, if it is compared with the RAPC approach in [5] and the centralized random allocation algorithm.

V. Conclusion

This letter has investigated the RAPC problem for D2D communications underlaying a cellular network with the goal of optimizing the overall system survival time. For given D2D and CC links, an MINLP formulation as well as a game theory based approach are presented. We prove the existence of Nash equilibrium in our RAPC game and propose a low complexity algorithm to calculate each individual player's best response given the strategies of other players. We also demonstrate that, if the transmitting UEs in a cell have quite different values of residual battery energy, our approach can prolong the overall system survival time by about 105%-425% with comparison to existing RAPC approaches.

Appendix A
Proof of Proposition 1

Assume the optimal solution of **OPT** in (3) is $(\delta_{i\_k,opt},\ p_{i,opt})$ for $\forall i \in \Gamma \cup \Lambda_{UL} \cup \Lambda_{DL}$ and $k = 1,\ ...,\ K$, the optimal value of **OPT** is $OST_{sys,opt}$. We first prove the set of strategies, $\boldsymbol{s_{i,opt}} = (\delta_{i\_1,opt},\ ...,\ \delta_{i\_K,opt},)$ ($\forall i \in \Gamma \cup \Lambda_{UL} \cup \Lambda_{DL}$), is a Nash equilibrium of the constructed RAPC game.

We adopt the method of reduction to absurdity. If each player i in $\Gamma \cup \Lambda_{UL} \cup \Lambda_{DL}$ has the strategy of $\boldsymbol{s_{i,opt}}$ and there is a player i^* wanting to unilaterally adjust its strategy from $\boldsymbol{s_{i^*,opt}}$ to $\boldsymbol{s_{i^*,opt'}}$, then we have:

$$\boldsymbol{s_{i^*,opt'}} \neq \boldsymbol{s_{i^*,opt}} \tag{A–1}$$

$$u_{i^*}(\boldsymbol{s_{i^*,opt'}}, \boldsymbol{s_{-i^*,opt}}) > u_{i^*}(\boldsymbol{r_{i^*,opt}}, \boldsymbol{r_{-i^*,opt}}) \neq OST_{sys,opt}, \tag{A–2}$$

according to the definition of a player's utility function in (9). Also, when players i^*'s strategy equals $\boldsymbol{s_{i^*,opt'}}$, we assume the solution of (9) which achieves $u_{i^*}(\boldsymbol{s_{i^*,opt'}}, \boldsymbol{s_{-i^*,opt}})$ is $p_{i,opt'}$ for $\forall i \in \Gamma \cup \Lambda_{UL} \cup \Lambda_{DL}$. Obviously, $(p_{i,opt'},\ \boldsymbol{s_{i^*,opt'}},\ \boldsymbol{s_{-i^*,opt}})$ is a feasible solution of **OPT** in (3) and its corresponding value of the objective function is larger than $OST_{sys,opt}$. This contradicts the assumption that $(\delta_{i\_k,opt},\ p_{i,opt})$ is the optimal solution of **OPT**.

Moreover, as each variable of p_i for $\forall i \in \Gamma \cup \Lambda_{UL} \cup \Lambda_{DL}$ has lower limit, **OPT** in (3) at least has one optimal solution. Thus, we can arrive at **Proposition 1**.

Appendix B
Proof of Proposition 2

We also adopt the method of reduction to absurdity. We note the total number of links belonging to set C_k as N. For an arbitrary link $i^{\#}$ in C_k, we assume the optimal solution of the following optimization problem:

$$min\ p_{i^{\#}} \tag{B–1}$$

s.t.:

$$B \cdot \log_2(1 + \frac{p_i \cdot g_{ii}}{N_0 + \sum\limits_{(j \in C_k) \cap (j \neq i)} p_j \cdot g_{ji}}) \geq b_i,\ \forall i \in C_k \tag{B–2}$$

$$p_i \geq 0,\ \forall i \in C_k \tag{B–3}$$

is $p_{i^{\#},min}$. When $p_{i^{\#}}$ achieves $p_{i^{\#},min}$, amounts of the variables, p_i, $\forall i \in C_k$, are expressed as $(p_{1,min},\ ...,\ p_{i^{\#},min},\ ...,\ p_{N,min})$. If:

$$B \cdot \log_2(1 + \frac{p_{i^{\#},min} \cdot g_{i^{\#}i^{\#}}}{N_0 + \sum\limits_{(j \in C_k) \cap (j \neq i^{\#})} p_{j,min} \cdot g_{ji^{\#}}}) > b_{i^{\#}}, \tag{B–4}$$

we set $p_{i^{\#},min'} = (2^{b_{i^{\#}}/B} - 1) \cdot (N_0 + \sum\limits_{(j \in C_k) \cap (j \neq i^{\#})} g_{ji^{\#}} \cdot p_{j,min}) / g_{i^{\#}i^{\#}}$. Obviously, $p_{i^{\#},min'} < p_{i^{\#},min}$ and $(p_{1,min},\ ...,\ p_{i^{\#},min'},\ ...,\ p_{N,min})$ is also a feasible solution of the optimization problem in (B–1). This contradicts with the assumption that $p_{i^{\#},min}$ is the optimal solution. If:

$$B \cdot \log_2(1 + \frac{p_{i^{\#},min} \cdot g_{i^{\#}i^{\#}}}{N_0 + \sum\limits_{(j \in C_k) \cap (j \neq i^{\#})} p_{j,min} \cdot g_{ji^{\#}}}) = b_{i^{\#}}, \tag{B–5}$$

and there is a link $i^{\dagger} \neq i^{\#}$ in set C_k that satisfies the following inequality:

$$B \cdot \log_2(1 + \frac{p_{i^{\dagger},min} \cdot g_{i^{\dagger}i^{\dagger}}}{N_0 + \sum\limits_{(j \in C_k) \cap (j \neq i^{\dagger})} p_{j,min} \cdot g_{ji^{\dagger}}}) > b_{i^{\dagger}}, \tag{B–6}$$

we set $p_{i^{\dagger},min'} = (2^{b_{i^{\dagger}}/B} - 1) \cdot (N_0 + \sum\limits_{(j \in C_k) \cap (j \neq i^{\dagger})} g_{ji^{\dagger}} \cdot p_{j,min}) / g_{i^{\dagger}i^{\dagger}}$ and $p_{i^{\#},min'} = (2^{b_{i^{\#}}/B} - 1) \cdot (N_0 + g_{i^{\dagger}i^{\#}} \cdot p_{i^{\dagger},min'} + \sum\limits_{(j \in C_k) \cap (j \neq i^{\#}) \cap (j \neq i^{\dagger})} g_{ji^{\#}} \cdot p_{j,min}) / g_{i^{\#}i^{\#}}$. Similarly, we can get $p_{i^{\#},min'} < p_{i^{\#},min}$ and $(p_{1,min},\ ...,\ p_{i^{\dagger},min'},\ ...,\ p_{i^{\#},min'},\ ...,\ p_{N,min})$ is also a feasible solution of the optimization problem in (B–1). This contradicts with the assumption that $p_{i^{\#},min}$ is the optimal solution.

Thus, we arrive at **Proposition 2**.

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