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NCPIE: network-coding-based cooperative peer-to-peer information exchange in wireless communications

***Abstract**. In this paper, we propose a network-coding-based cooperative peer-to-peer information exchange (NCPIE) algorithm to solve peer scheduling problem in wireless communications. NCPIE can achieve lower transmission delay and higher network throughput by studying the issue of scheduling transmission opportunities among peers in wireless communications. Experimental results demonstrate the effectiveness of NCPIE is best than that of rarest first algorithm and peer-to-peer information exchange algorithm.*

***Streszczenie.** W artykule zaproponowano algorytm NCPIE wymiany informacji w bezprzewodowych sieciach P2P. Można osiągnąć mniejsze opóźnienia transmisji i większą przepływność przez stosowanie odpowiednich harmonogramów wymiany. (**NCPIE – algorytm wymiany informacji w bezprzewodowych sieciach P2P**)*

Keywords: Network Coding, Peer Scheduling, Transmission Efficiency
Słowa kluczowe: sieci bezprzewodowe, seici P2P.

1 Introduction

Network coding [1] has recently emerged as a promising approach to improving the capacity of a network by allowing mixing of various traffic flows via algebraic operations. Primary applications of network coding include data dissemination and streaming service [2] in peer-to-peer overlay networks, topology design [3], security and the information delivery in wireless networks [4]. Incorporation of network coding into the above applications brings benefits such as energy efficiency [5], throughput improvement [6], delay minimization [7], and security improvement [8].

In recent years, peer-to-peer (P2P) file sharing has become the most popular application in the Internet. In wireless networks, how to effectively achieve peer-to-peer file sharing is still an active field of research. Many P2P algorithms have been proposed by studying how to utilize the contributed resources of each peer. However, due to the shared wireless channel and the half-duplex transmission feature, different sending sequences or scheduling algorithms will have a direct impact on the overall network throughput. In some cases, the gap between the optimal and the worst throughputs is huge. Thus, the information exchange among a set of peers still faces scheduling problem. In this paper, we define such a problem of determining peer sending sequences as the peer scheduling problem. In other words, the peer scheduling problem is how to determine the scheduling policy among a group of potential senders to achieve the maximal utilization of limited wireless resources. And according to [9], a general peer scheduling problem in traditional networks is proven to be NP-hard. Although the rarest first algorithm [10] was introduced to solve the peer scheduling problem, it can't achieve the optimal state in general conditions.

Then cooperative peer-to-peer information exchange (PIE) algorithm is proposed in [11], where network coding is used to solve the peer scheduling problem. Although the performance of the PIE is better than that of rarest first algorithm, the performance of the PIE is not ideal when the number of packets is more than the number of peers. To solve the problem and design more efficient algorithm, we propose a network-coding-based cooperative peer-to-peer information exchange (NCPIE) algorithm. Compared with rarest first algorithm, which only takes into consideration the rarest of packets, and PIE, which takes into consideration the freshness of peers, we take into consideration the benefits of peers, which is a measurement on how many peers can receive novel packets from one transmission of a peer, the number of non-encoded packets contained by peers, and the number of encoded packets contained by peers. Qualitative analysis and extensive simulations demonstrate its effectiveness.

The rest of this paper is organized as follows. Section II describes network model and the problem definition. In Section III, we present the principles on the peer scheduling problem in wireless networks. NCPIE is depicted in Section IV. In Section V, the performance of NCPIE is evaluated in terms of transmission efficiency and computational overhead through extensive simulations, while we conclude our work in section VI.

2 Network model and problem definition

We consider a wireless network formed by N wireless peers and a server. A wireless peer is represented as p_i ($1 \le i \le N$), and the distance between p_i and p_j is represented as d_{ij} . Meanwhile, for each p_i , the communication range and interference range are defined as c_i and r_i ($c_i \le r_i$), respectively. The set of wireless peers is defined as G . The edge sets ℓ and ℓ' are defined as below:

(1) $$\ell = \left\{(i,j) \middle| p_i \in G, p_j \in G, d_{ij} \le c_i \right\}$$

(2) $$\ell' = \left\{(i,j) \middle| p_i \in G, p_j \in G, d_{ij} \le r_i \right\}$$

$(i,j) \in \ell$ denotes that p_j is with the communication range of p_i . Likewise, $(i,j) \in \ell'$ denotes that p_j is within the interference range of p_i . In this paper, we assume that c_i is large enough so that all peers can communicate with each other directly. Therefore, if a transmission from p_i to p_j is successful, three conditions must be satisfied: (1) $(i,j) \in \ell$ and $(j,i) \in \ell$, (2) all peers $\{p_l \in G | l \ne i, (l,j) \in \ell'\}$ are not sending, and (3) all peers $\{p_l \in G | l \ne i, (l,i) \in \ell'\}$ are not sending. The first condition ensures that p_i and p_j are within the communication range of each other. The remaining conditions ensure that no interference occurs during the transmission.

We suppose that all peers are interested in a file, which only exists in the server, and the file is divided into

M packets, $\Gamma = \{d_1, d_2, \cdots, d_M\}, M \geq 1$. Due to unreliability of the wireless channel, a peer p_i receives a subset $\Re_i \subseteq \Gamma$. Meanwhile, to mitigate the burden of the server for retransmission, the peers can share their received packets with each other. The aim is to make sure that all peers can recover the file. A $N \times M$ Packet Received Matrix (PRM) records the information of each packet d_i on each peer, i.e., $PRM_{ik} = 1$ if $d_k \in \Re_i$, and 0, otherwise, where $PRM_{ik} = 2$ means that p_i receives a coded packet including d_k, but p_i can't recover d_k from the coded packets. To denote the updated PRM after the r^{th} transmission time, a superscript r is added to PRM. PRM^0 denotes the initial PRM while PRM^E denotes the PRM after eventually reaching the end of the repair process, where $PRM^E_{ik} = 1$, $\forall (i,k) \mid n_i \in G, d_k \in \Gamma$. Meanwhile, a Number of Received packet Matrix (NRM) is used to record the number of received independent packets of each peer.

t_r is defined as the scheduling method at the r^{th} transmission round. t_r is a $1 \times N$ matrix, i.e., $t_{ri} = 1$ if p_i is selected to transmit packet at transmission round r, and 0, otherwise. Consequently, we can get a series of scheduling methods $T_E = (t_1, t_2, \cdots, t_E)$, which can complete the transmission $PRM^0 \overset{t_1}{\Rightarrow} PRM^1 \overset{t_2}{\Rightarrow} \cdots \overset{t_E}{\Rightarrow} PRM^E$ in E transmission rounds. Our aim is to find a T_E that minimizes E. Therefore, the problem can be mathematically defined as:

(3) $$\min_{T_E} E$$

Subject to:

(4) $$t_{ri} = 1 \Rightarrow t_{rj} = 0,\ \forall (i,j) \in \ell'$$

(5) $$PRM^r_{jk} = PRM^{r-1}_{jk},\quad \forall j \in G \,\big|\, \nexists \big((i,j) \in \ell \text{ and } t_{ri} = 1\big)$$

(6) $$PRM^r_{jk} = PRM^{r-1}_{jk},\quad \forall j \in G \,\big|\, \exists \big((h,j),(i,j) \in \ell', h \neq j, t_{rh} = 1 \text{ and } t_{ri} = 1\big)$$

(7) $$PRM^E_{jk} = 1,\ \forall j \in G$$

(8) $$PRM^r_{jk} \in \{0,1,2\}, \forall j \in G$$

(9) $$E \in Z^+$$

Eq. (4) ensures that if the peer is within the interference range of the sender, then the other peers don't transmit. Eq. (5) stipulates that in order to receive a packet, a peer must be within the transmission range of the sender. Eq. (6) ascertains that if the peer is within the interference range of multiple senders, it can't successfully decode a packet. Eq. (7) means that all peers receive the whole M independent packets at stage E, while Eq. (8) and (9) are integrality constraints.

Without loss of generality, we suppose that a peer always transmits a coded packet of all the packets owned by it. Meanwhile, we suppose randomly combined packets transmitted by a peer are linearly independent of each other. Table 1 shows the notations used in this paper.

Table 1 List of notations

Notations	Description
PRM	Packet Received Matrix
PRV_i	The i-th row vector of PRM
SGM_{ij}	System gains if peer i sending at the j-th transmission
TSN_i	Total Sending Number of peer i
TRN_i	Total Receiving Number of peer i
NPN_i	Number of Packets Needed by peer i
NUP_i	Number of Unique Packets of peer i
BAP_j	Benefit of All Peers from the j-th sending operation
NRM	Number of Received packets matrix
NRV_i	The i-th row vector of NRM

3 Investigations on information exchange principles

Because a specific solution to the peer scheduling problem depends on the initial status of PRM and NRM, we deduce the following principles based on PRM and NRM.

Definition 1: the total sending number (TSN) is defined as the total number of sending operations performed by all peers as a whole for the completion of information exchange. In other words, $TSN = E$.

Proposition 1: From the viewpoint of peers, a lower bound of TSN is the maximum value among all the sums of NPN_i and NUP_i, i.e.,

(10) $$TSN \geq \max_i \{NPN_i + NUP_i\}$$

where NPN_i is the number of independent packets which peers i needs to recover the file, and NUP_i represents the number of packets which are uniquely owned by peer i.

Proof: From the viewpoint of peer i, the TSN for all peers is equal to the sum of TSN_i and TRN_i, i.e., $TSN = TSN_i + TRN_i$, where TSN_i and TRN_i are the numbers of packets that peer i receives and sends before the completion of information exchange, respectively. Obviously, we have $TRN_i \geq NPN_i$ and $TSN_i \geq NUP_i$. Thus, we have $TSN \geq NPN_i + NUP_i$. Because the inequality is true for all peers, we have Eq. (10).

Proposition 2: From the viewpoint of packets, a lower bound of TSN can be given as follow:

(11) $$TSN \geq \left\lceil \frac{\sum_{i=1}^{N} NPN_i}{N-1} \right\rceil$$

where N is the number of peers ($N \geq 2$).

Proof: For the j-th sending operation, the benefit of all peer (BAP_j) is defined as a cumulative value of the benefits received by all peers. Thus, we have $BAP_j \leq N-1$. On the other hand, each peer has all packets after the completion of information exchange. Therefore, we have $\sum_{j=1}^{TSN} BAP_j = \sum_{i=1}^{N} NPN_i \Rightarrow \sum_{i=1}^{N} NPN_i = \sum_{j=1}^{TSN} BAP_j \leq TSN(N-1)$. Thus, we have Eq. (11).

Corollary 1: As a summary of proposition 1 and 2, a lower bound of TSN is :

(12) $$\max\left\{\left\lceil\frac{\sum_{i=1}^{N} NPN_i}{N-1}\right\rceil, \max_i\left\{NPN_i + NUP_i\right\}\right\}$$

3 NCPIE algorithm

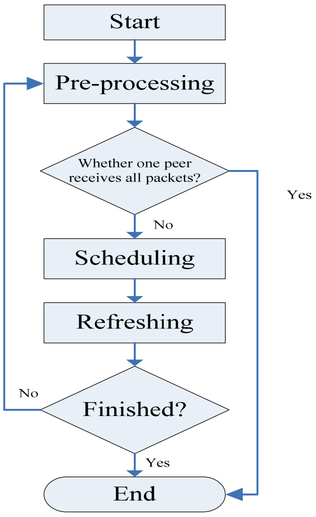

Fig1. Flow chart of NCPIE

Although the peer scheduling problem is NP-hard, a quasi-optimal but efficient NCPIE algorithm is depicted in this section, which is shown in Fig. 1. NCPIE consists of four parts: pre-processing, scheduling, refreshing, end. The details of these parts are described as follows.

Pre-processing: In NCPIE, peers first collect the other part of PRM and NRM, which can be realized by each peer directly broadcasting PRV and NRV to others through the shared channel. With the PRM and NRM, each peer can calculate system gains of peers, which are represented in a System Gain Matrix (SGM). A SGM can be calculated as follows.

(13) $$SGM_{ij} = \sum_k 1_{\{PRV_i > PRV_k\}}$$

where SGM_{ij} denotes how many peers can derive benefit from the transmission of peer i at the j-th sending operation. PRV_i is the i-th row vector of PRM. The indicator function is defined as follows:

(14) $$1_{\{PRV_i > PRV_k\}} = \begin{cases} 1, & (\sum_m 1_{\{PRV_{im} > PRV_{km}\}}) > 0 \\ 0, & \text{Otherwise} \end{cases}$$
$$1_{\{PRV_{im} > PRV_{km}\}} = \begin{cases} 1, & PRV_{im} > PRV_{km}, PRV_{km} \neq 1 \\ 0, & \text{Otherwise} \end{cases}$$

where PRV_{im} is the m-th element of the vector PRV_i. For example, $SGM_{ij} = 3$ means that if peer i sends packets at the j-th sending operation, 3 peers can get useful information from the transmission of peer i.

And then we judge whether there are peers, which receive all M independent packets. If existing, one of them p_n will be selected as the sending peer until all peers receive the M independent packets. And we can see that if p_n is chosen as sending peer, all peers will get useful information except peers which have received all M independent packets, every sending operation. In other words, Compared with other algorithms, BAP_j is maximum every transmission in NCPIE. Therefore, TSN is closer to the lower bound.

Algorithm 1: Scheduling Algorithm

```
Input : PRM, NRM, SGM
Output : sending_peer
begin
    PSHSG ← peers having the highest system gain in SGM
    if |PSHSG| = 1 then
        sending_peer ← the unique member of PSHSG
    else
        PSMUP ← the peers in PSHSG with the most uncoded packets
        if |PSMUP| = 1 then
            sending_peer ← the unique memeber of PSMUP
        else
            PSMP ← the peers in PSMUP with the most packets
            if |PSMP| = 1 then
                sending_peer ← the unique memeber of PSMP
            else
                PSMEP ← the peers in PSMP with the most encoded packets
                sending_peer ← the first member of PSMEP
            end
        end
    end
end
```

Scheduling: The scheduling algorithm is depicted in Algorithm 1. Firstly, the peers with the highest system gain are chosen from SGM and put into a peer set with highest system gain ($PSHSG$). The sending peer is the unique peer in $PSHSG$ if it contains only one member. Otherwise, the peers with the most uncoded packets are collected from $PSHSG$ and put into a peer set with most uncoded packets ($PSMUP$). The number of uncoded packets of peer i is equal to the sum of elements which are equal to one in PRV_i. If there is only one member in $PSMUP$, the sending peer is the unique peer in it. Otherwise, the peers with the most packets are selected from $PSMUP$ to form a peer set with most packets ($PSMP$). The number of packets of peer i is equal to NRM_i, i.e., $NRM_i = 3$ means that peer i receives 3 independent packets. If there is only one member in $PSMP$, the sending peer is the unique peer in it. Otherwise, the peers with the most encoded packets are selected from $PSMP$ to form a peer set with most encoded packets ($PSMEP$). The number of encoded packets of peer i is equal to NRM_i minus the sum of elements which are equal to one in PRV_i. And then the first member of $PSMEP$ is chosen as the sending peer.

Algorithm 2: Refreshing Algorithm

```
Input : sending_peer, PRM, NRM
Output:PRM, NRM
begin
    send_packet ← a coded block of the sending_peer
    for i=1:N do
        if send_packet is novel for peer i
            NRM_i = NRM_i + 1;
            PRM(i,:)--
        end
    end
end
```

Refreshing: According to the peer scheduling sequence given in the scheduling stage, in this stage, the sending peer sends out a coded packet, and we assume that other peers can correctly receive the coded packet. Then peers update correlative variables. If the coded packet contains the information needed by peer i, $NRM_i = NRM_i + 1$. If $PDM(i, j) \in \{0, 2\}$ and peer i can decode packet j from the coded packet, $PRM(i,j)=1$. Otherwise, if the coded packet contain the information of packet j and peer i can't decode packet j, $PRM(i,j)=2$.

End: When all peers receive the whole file, the process is completed. If those peers have other information for exchange, they can repeat the above process.

4 Simulation results

1. Transmission Efficiency

To verify the effectiveness and efficiency of NCPIE, we conduct extensive simulations for performance evaluation. In our simulations, each peer can successfully receive the original packets from a server with prescribed probability, which is defined as the sparsity of the original file. The performance of NCPIE is evaluated and also compared with PIE and rarest first algorithm in terms of transmission efficiency and computational overhead.

The theoretical lower bound of TSN in Corollary 1 is used as the benchmark for evaluation of transmission efficiency, which is depicted as:

$$E_t = \frac{LB}{TSN} \tag{15}$$

Where E_t is transmission efficiency, TSN is our simulation result, and LB is the theoretical lower bound of the total sending number.

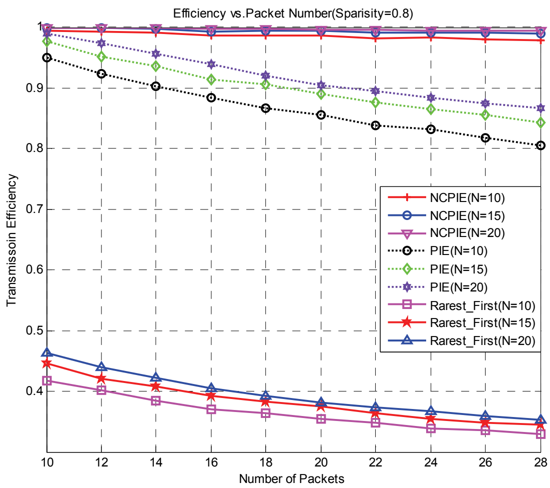

Fig. 2 Transmission Efficiency vs. The Number of Packets

The transmission efficiency versus the number of packets is shown in Fig. 2. The simulation results of scenarios with different sparsity are shown. From Fig. 2, we can see that transmission efficiency of NCPIE outperforms that of PIE and rarest first algorithm. With the increase of the number of packets, the transmission efficiencies of all algorithms become worse. However, NCPIE still maintains more than 95% transmission efficiency in all scenarios. And the transmission efficiency of NCPIE descends most slowly than that of two other algorithms.

Compared with PIE, NCPIE needs to search the optimal sending peer every transmission. However, for PIE, once a sending peer is chosen, the sending peer may sends encoded packets many times. In other words, NCPIE tries to search the optimal sending peer every transmission, however, PIE can't. Therefore, the performance of NCPIE is better than that of PIE. And when one peer, which receives all M independent packets, takes charge of the transmission, the system gain is maximum every transmission. The probability of peers, receiving all M independent packets, is $(sparsity)^M \times N$ before peers sharing information. With the increase of M, the probability becomes small. Therefore, the trend of curves in Fig. 2 is degressive.

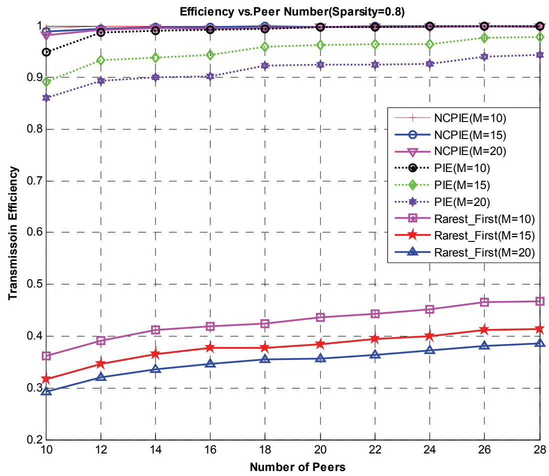

Fig.3 Transmission Efficiency vs. The Number of Peers

The transmission efficiency versus the number of peers is shown in Fig. 3. From Fig. 3, we can see that the transmission efficiency of NCPIE is highest than that of the rarest first algorithm and PIE. With the increase of the number of peers, the transmission efficiencies of all algorithms ascend in some degree. It's because that with the increase of N, the probability of peers receiving all M packets become large. Besides, NCPIE maintains a high transmission efficiency of more than 97% in all situations.

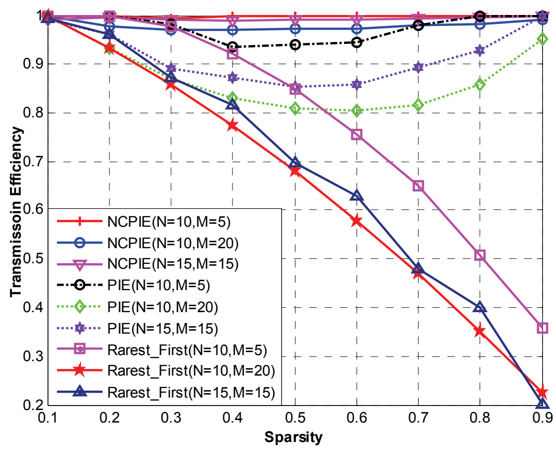

Fig.4 Transmission Efficiency vs. Sparsity

For a specific investigation on the transmission efficiency versus the sparsity, in Fig. 4 we plot the changing relations between them in diverse situation with different numbers of peers (N=10 and 15) and different numbers of packets (M=5, 15 and 20). From Fig. 4, it can be seen that the transmission efficiency of NCPIE is higher than 97% in all situations. And the transmission efficiency of NPCIE outperforms that of PIE and rarest first algorithm.

2. Computational Overhead

The computational overheads of three algorithms in scenarios with different number of packets, different number of peers and different sparsity are shown in Fig. 5 (a), (b) and (c) respectively. All the values of computational overheads are collected from a desktop computer with a CPU of Intel Core 2 2.66GHz and a RAM of 2GB. From Fig. 5, the computational overhead of NCPIE is largest. That is because NCPIE needs to search the optimal sending peer, however, it isn't necessary for PIE. Moreover, the computational overhead of NCPIE is less than 25 ms, which is pretty light-weight and practical for deploying NCPIE into reality.

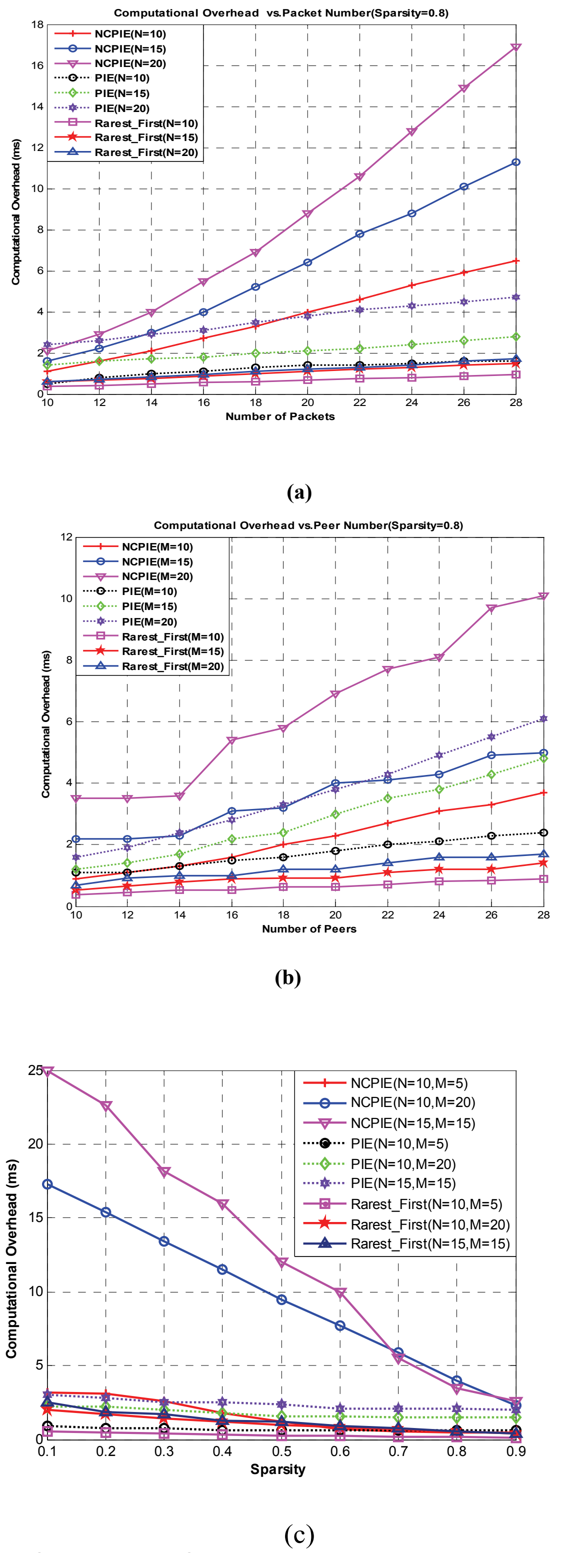

Fig. 5 Computational Complexity

4. Conclusions

In this paper, we define the peer scheduling problem as a minimum optimization problem. To solve the problem, a network-coding-based cooperative peer-to-peer information exchange (NCPIE) algorithm is proposed. NCPIE supplies a gap of PIE, whose problem is that the transmission efficiency is not ideal, when the number of packets is larger than the number of peers. And NCPIE can't only fully take the advantage of the broadcast nature of wireless channels, but also exploit the cooperative peer-to-peer information exchange. Besides, simulations have verified the effectiveness of NCPIE. Our future research will consider how to reduce the computational overhead of NCPIE, when the sparsity is small, and designing efficient peer scheduling algorithm for multi-hop wireless networks.

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