Cooperative Peer-to-Peer Information Exchange via Wireless Network Coding

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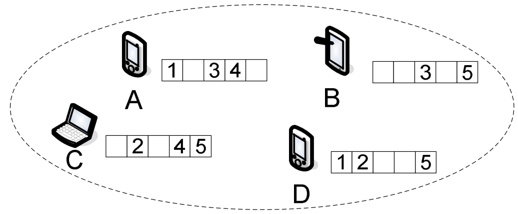
Abstract — **Network coding has been widely recognized as a promising information dissemination approach for wireless networks. However, in practical wireless networks enabled with network coding, different peer sending sequences make significant impact on overall network throughput and transmission delay. In this paper, we study the peer scheduling problem, which is defined as how to intelligently schedule the sending sequence among a group of peers to maximize the wireless coding gain. By conducting an in-depth investigation on the peer scheduling principles in wireless network coding, we propose a cooperative Peer-to-peer Information Exchange (PIE) scheme with an efficient and light-weight peer scheduling algorithm. The PIE scheme can not only fully exploit the broadcast nature of wireless channels, but also utilize the advantage of cooperative peer-to-peer information exchange. Finally, the effectiveness and efficiency of the PIE scheme are demonstrated through qualitative analysis and extensive simulations.**

Keywords* — *Cooperative, peer-to-peer, wireless network coding, scheduling

I. Introduction

Network coding has been widely recognized as a promising information dissemination approach to improving network performance [1]-[3] by allowing and encouraging coding operations at intermediate network forwarders. Primary applications of network coding include file distribution [4] and multimedia streaming [5] in peer-to-peer (P2P) overlay networks, data persistence in sensor networks [6], and information delivery in wireless networks [7]. Incorporation of network coding into the above applications brings benefits such as throughput improvement [8], energy efficiency [9], and delay minimization [10]. In addition, network coding also eases the block scheduling problem [4] and thus improves the efficiency of content distribution.

In wireless networks, network coding was further brought from theory to practice by embracing the wireless broadcast nature and opportunistic coding [7], which greatly promotes the application of network coding into wireless networks. In addition, the block scheduling problem is also settled through opportunistically snooping neighbor states and intelligently XOR-ing (mixing) packets. However, due to the shared wireless channel and the de facto half-duplex transmission feature, different sending sequences or scheduling policies will have a direct impact on the overall network throughput. In some cases, the gap between the optimal and the worst is huge. Thus, the information exchange among a group of peers still faces another scheduling problem, which is different from the block 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. We illustrate this problem using the following simple example.



Peer Scheduling Sequence	
Non-Optimal	Optimal
1). A: <1, 3, 4> 2). C: <2, 4, 5> 3). B: <3, 5> 4). A: <1, 3, 4>	1). A: <1, 3, 4> 2). C: <2, 4, 5> 3). D: <1, 2, 5>

Fig. 1. Cooperative Peer-to-Peer Information Exchange in Wireless Networks

As shown in Fig. 1, a wireless network consists of four peers, nodes *A*, *B*, *C*, and *D*, which can communicate through a shared wireless channel. These peers intend to exchange with each other a piece of information, which is comprised of five blocks. Currently, peer *A* holds block 1, 3, and 4; peer *B* holds block 3 and 5; peer *C* holds block 2, 4, and 5; peer *D* holds block 1, 2, and 5. The objective of the information exchange is to make each peer hold all the five blocks and we are expecting to achieve this objective with minimum number of transmissions through scheduling the sending sequence. In this simple example, we can proof through our summarized principles that a peer sending sequence of <*A*, *C*, *B*, *A*> is a solution but not optimal, while the sequence <*A*, *C*, *D*> is an optimal solution in terms of transmission efficiency under the assumptions of no packet loss and a peer always sending out a full-degree coded packet of all blocks it has. Such an optimal sequence can im-

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prove the transmission efficiency by 33% against the non-optimal sequence in the above example.

Notice that the peer scheduling problem is different from the problem examined in the COPE scheme [7] which emphasizes on how to opportunistically snooping neighbor states and intelligently XOR-ing these blocks from the viewpoint of a single peer, while the peer scheduling problem is how to intelligently schedule the sending sequence of peers to maximize the wireless coding gain from the viewpoint of all peers in a wireless network as a whole. According to [11], a peer scheduling problem in traditional networks is proven to be NP-hard; with network coding, a peer scheduling problem in wireless networks becomes more complicated due to the coded packets and is also deemed as NP-hard.

Most current research attentions are on block scheduling problems. Besides opportunistic snooping neighbor states, the COPE scheme [7] successfully handles the block scheduling problem by intelligently XOR-ing packets. A multi-partner scheduling scheme is also proposed for P2P-based Media-on-Demand streaming service in [13], which employs the Deadline-aware Network Coding (DNC) technique to adjust the coding window for each node and thus to meet the time sensitive requirement of media streaming services. In wireless ad hoc networks, the problem of efficient broadcasting, which is closely related to information exchange, is studied in [9] in terms of energy efficiency. Rarest First and Choke algorithms are advocated through real experiments from being replaced with source or network coding in the context of peer-to-peer file replication in the Internet [14]. The rarest first idea may not conflict with peer scheduling and can also be employed for wireless network coding. However, as shown in Fig. 1, directly applying this idea to peer scheduling is not necessarily optimal.

Furthermore, different from wireline channels, wireless transmissions are broadcast in nature, providing the opportunity to fully exploit the potential of network coding. However, the opportunity to fully utilizing wireless broadcast channels via network coding does not benefit in a natural way, which actually leaves us a generally open problem: the aforementioned peer scheduling problem. A similar problem, called the cooperative peer-to-peer repair (CPR), is introduced in traditional packet-forwarding networks [11] and also discussed in network coding enabled wireless ad hoc networks [15], where a centralized and a distributed CPR algorithms are proposed based on the observed four heuristics. The algorithms are demonstrated to be effective only if the undetermined four parameters (C1, C2, C3, and C4) are chosen appropriately, which on the other hand leaves another open problem: how to tune the four undetermined parameters to adapt the peer scheduling algorithm. Such aforesaid deficiencies motivate us to explore a more efficient scheme to achieve the maximal peer scheduling gain.

The contributions of this paper can be summarized as follows. We first identify a novel peer scheduling problem in the context of network coding enabled wireless networks [7], which arises from the employment of network coding for fully exploiting the broadcast nature of wireless channels. Then, based on the summarized principles on the peer scheduling problem in wireless network coding, we propose a cooperative Peer-to-peer Information Exchange scheme (PIE) with an efficient light-weight peer scheduling algorithm. The PIE scheme can not only fully exploit the broadcast nature of wireless channels, but also utilize the advantage of cooperative peer-to-peer information exchange. Qualitative analysis and extensive simulations are also given to demonstrate the effectiveness and efficiency of the PIE scheme.

The remainder of the paper is organized as follows. In Section II, the network model and assumptions of the PIE scheme are given. In Section III, we present the principles on the peer scheduling problem in network coding enabled wireless networks. In Section IV, the PIE scheme is proposed. The performance of the PIE scheme is evaluated in terms of transmission efficiency and computational overhead through extensive simulations in Section V, followed by the conclusions in Section VI.

II. Network Model and Assumptions

A. Network Model

In this paper, we consider a peer-to-peer network model comprised of several wireless nodes which are also called peers. These peers share a common wireless channel and can communicate with each other directly. Thus, all peers can only communicate in actually a half-duplex mode. In other words, if two peers are transmitting at the same time, their signals will interfere with each other and no peer can correctly receive the transmitted signal. On the other hand, due to the broadcast nature of wireless channels, in our network model, every other peer can receive the wireless signal and recover the frames correctly when one and only one is transmitting.

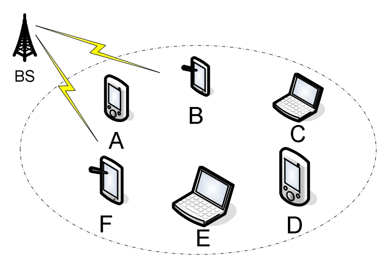

Fig. 2. Wireless Network Model

As for a practical application, we indicate the following scenario as shown in Fig. 2. A remote Base Station (BS) broadcasts a bunch of packets (blocks)[1] to the nodes. Due to the fading and dynamics of wireless channels, each peer receives some (maybe all or none) of these blocks. In order to mitigate the congestion of downlink channels from the BS to those nodes and release the bottleneck of the BS as a network gateway, we propose that the peers share their received blocks with each other through the local wireless network. A similar application scenario is examined in [11] [15] for the support of the Multimedia Broadcast/Multicast Services (MBMS) [12] over 3G cellular networks.

[1] The terms packet and block are used interchangeably in this paper.

B. Assumptions

Since the network model is enabled with network coding and a full-degree coded packet can help to achieve the most extensive wireless coding gain, we assume that a peer always sends out a full-degree coded packet of all the blocks it owns. Without loss of generality, we also assume randomly combined packets sent out by a peer are linearly independent to each other since they are linearly dependent with a very low probability [16] when the number of combined packets is no larger than the number of blocks the peer has. Similarly, the combined packets sent out from different peers are also linearly independent to each other even the peers may hold the same set of original blocks.

C. Notations and Definitions

TABLE I
LIST OF NOTATIONS

Notation	Definition
SB_i	a Single Benefit of Peer i
SB_{ij}	the Single Benefit of Peer i at the j-th transmission
TRN_i	the Total Receiving Number of Peer i
DD_i	the Deficiency Degree of Peer i
TSN_i	the Total Sending Number of Peer i
NUB_i	the Number of Unique Blocks of Peer i
D_{ij}	the Difference between Peer i and Peer j
Max_D_i	the Maximum Difference of Peer i against other peers
NAP	the Number of All Peers
BDM (BDV)	a Block Distribution Matrix (Vector)
BRM	a Block Rareness Matrix
PDM	a Peer Difference Matrix
PFV	a Peer Freshness Matrix
BAP_j	the Benefit of All Peers from the j-th sending operation

III. INVESTIGATIONS ON INFORMATION EXCHANGE PRINCIPLES IN WIRELESS NETWORK CODING

In this section, we investigate the *peer scheduling* problem in the aforementioned wireless network scenario. Since a specific solution to the peer scheduling problem in wireless networks mainly depends on the original status of the block distribution among the peers, we represent the status as a Block Distribution Matrix (BDM). A BDM is a (0,1)-matrix, also known as a binary matrix, in which each element is either zero or one. Row numbers and column numbers of a BDM represent peer indexes and block indexes, respectively. In other words, BDM(i, j) = 0 means that peer i does not have block j and BDM(i, j) = 1 means that peer i has block j.

In this way, a row of the BDM represents the block distribution information of a peer, which is also called a Block Distribution Vector (BDV). Thus, the block distribution information of peer i can be written as BDV_i. Based on a BDM, we can make the following definitions and, based on these definitions, we investigate the network coding enabled information exchange in our wireless network model and summarize the following principles, which constitute the theoretic bases of the PIE scheme. The correlations between the summarized principles and the PIE scheme are discussed in Subsection IV.B.

Definition 1: A single benefit of peer i (SB_i) is defined as the benefit degree peer i received from a single transmission. SB_{ij} denotes the benefit peer i received from the j-th transmission.

Principle 1. *SB_i or SB_{ij} is either 0 or 1, i.e., SB_i (SB_{ij}) = 0 or 1.*

When a peer sends out a coded packet, all other peers can receive it and benefit from it. It is well known that, say for peer i, if the received packet is linearly dependent on all the packets it has, the peer can not benefit from this newly arrived packet. In other words, such a non-innovative packet should be discarded. At this time, the benefit of peer i from this single transmission is 0, i.e., $SB_i = 0$. Otherwise, if the received packet is linearly independent on all packets that peer i has, the single benefit of peer i is 1, i.e., $SB_i = 1$.

Definition 2: The deficiency degree of peer i (DD_i) is defined as the number of packets peer i fails to receive from the BS, i.e., the number of innovative packets that peer i needs to recover the whole information.

Definition 3: The total receiving number of peer i (TRN_i) is defined as the number of packets required for peer i to receive from other peers before achieving the objective of information exchange.

Principle 2. TRN_i is no less than DD_i ($TRN_i \geq DD_i$).

TRN_i is no less than DD_i because Eq. (1) holds.

$$DD_i = \sum_{j=1}^{TRN_i} SB_{ij} \tag{1}$$

where SB_{ij} denotes the single benefit of peer i at the j-th round of transmission. Due to *Principle 1*, $SB_{ij} \leq 1$, we can derive that $TRN_i \geq DD_i$.

Definition 4: The total sending number of peer i (TSN_i) is defined as the number of coded packets peer i is required to send out for the completion of information exchange.

Definition 5: The number of unique blocks of peer i (NUB_i) is defined as the number of the blocks which are uniquely owned by peer i, i.e., no other peer has the unique block except peer i.

Principle 3. TSN_i is no less than NUB_i ($TSN_i \geq NUB_i$).

TSN_i is no less than NUB_i because if peer i sends out less than NUB_i coded packets, no other peers can recover all of the unique packets peer i uniquely owns.

Definition 6: The difference between peer i and peer j (D_{ij}) is defined as:

$$\begin{aligned} D_{ij} &= BDV_i - BDV_j \\ &= \sum_{k=1}^{TBN} 1_{\{BDV_{ik} > BDV_{jk}\}} \end{aligned} \tag{2}$$

where BDV_i denotes the block distribution vector of peer i, which is the i-th row vector of block distribution matrix (BDM) and so does BDV_j.

The calculation of D_{ij} can be performed according to the accompanying line, where the total block number (TBN) is also the total column number of BDM, and the calculating function is defined as:

$$1_{\{BDV_{ik} > BDV_{jk}\}} = \begin{cases} 1 & if \;\; BDV_{ik} > BDV_{jk} \\ 0 & Otherwirse \end{cases} . \tag{3}$$

BDV_{ik} is the k-th element of the vector BDV_i, which is the i-th row vector of BDM. Thus, BDV_{ik} can also be written as BDM_{ik}. Due to the fact that the elements of BDM may take the value of either 1 or 0, the condition $BDV_{ik} > BDV_{jk}$ is equivalent to that $BDV_{ik} = 1$ and $BDV_{jk} = 0$.

Definition 7: The total sending number is defined as the total number of sending operations required for all peers as a whole before the completion of the information exchange. Thus, TSN can be also calculated as the sum of all TSN_i:

$$TSN = \sum_i TSN_i \; . \tag{4}$$

Proposition I. From the viewpoint of peers, a lower bound of TSN is the maximum value among all the sums of DD_i and NUB_i, i.e.,

$$TSN \geq \max_i \{DD_i + NUB_i\} \; . \tag{5}$$

Proof: From the viewpoint of a peer i, the total sending number (TSN) of all peers is equal to the sum of TRN_i and TSN_i, i.e., $TSN = TRN_i + TSN_i$. According to *Principle 2* and *Principle 3*, we know $TRN_i \geq DD_i$ and $TSN_i \geq NUB_i$, respectively. Thus, we have $TSN \geq DD_i + NUB_i$. Because the inequality is true for all peers, we have the Eq. (5). ■

Proposition II. From the viewpoint of blocks, a lower bound of TSN is the ceiling value of the quotient of the sum of all DD_i's and the remainder of the number of all peers (NAP) minus 1, i.e.,

$$TSN \geq \left\lceil \left(\sum_{i=1}^{NAP} DD_i \right) \Big/ (NAP - 1) \right\rceil . \tag{6}$$

Proof: For a j-th sending operation, the benefit of all peers (BAP_j) is given by the following equation:

$$BAP_j = \sum_{k=1}^{NAP} SB_{kj} \; . \tag{7}$$

If peer i is the sender, $SB_{ij} = 0$ since peer i can not benefit from its own sending operation. Thus, according to *Principle 1*, $BAP_j \leq NAP - 1$. On the other hand, each peer has all blocks after the completion of sharing. Therefore, from the viewpoint of blocks, we have:

$$\sum_{j=1}^{TSN} BAP_j = \sum_{i=1}^{NAP} DD_i \; . \tag{8}$$

Thus, we have Eq. (6). ■

Corollary I. As a summary of ***Proposition I*** and ***Proposition II***, a lower bound of TSN is determined as follows:

$$\max \left\{ \left\lceil \left(\sum_{i=1}^{NAP} DD_i \right) \Big/ (NAP - 1) \right\rceil, \; \max_i \{DD_i + NUB_i\} \right\} . \tag{9}$$

IV. The Proposed PIE Scheme

Generally, the peer scheduling problem is NP-hard [11]. Therefore, it is non-trivial to propose an optimal peer scheduling scheme for information exchange. Based on the summarized principles on the peer scheduling issues in Section III, in this section, we propose a quasi-optimal but efficient and light-weight cooperative Peer-to-peer Information Exchange scheme (PIE). We also explore the inner-relations between the summarized principles and the PIE scheme in Subsection IV.B.

A. The Proposed PIE Scheme

The basic idea of the PIE scheme is to take the freshness of peers into considerations in addition to the rarest first principle on blocks. The basic concept of freshness is a kind of measurement on how much innovation a peer has against all other peers. In this paper, the freshness of a peer is defined as the sum of all differences between it and all other peers, which are defined in Eq. (2).

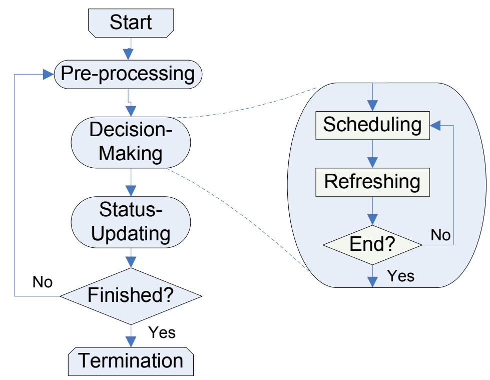

Fig. 3. Flow Chart of the PIE Scheme

The PIE scheme consists of four stages: pre-processing, decision-making, status-updating, and termination. The flow chart of the four stages is shown in Fig. 3. In the decision-making stage, two modules which respectively contain a key algorithm are also shown. The details of these stages and modules are depicted as follows.

Pre-processing: In the PIE scheme, immediately after the start of the block sharing process, peers first share block distribution vectors (BDVs) with each other, which can be performed by each peer directly broadcasting the BDVs to each other through the shared wireless channel. After that, each peer has the block distribution information of all other peers, which forms a BDM.

Then, based on the BDM, each peer can calculate the rareness of blocks and the freshness of peers, which are represented by a block rareness matrix (BRM) and a peer freshness vector (PFV), respectively. The BRM is calculated in this way: with the BDM, we first calculate the rareness of each block; the rareness of a block denotes the number of peers which have this block; the less the value of the rareness of a block, the rarer the block; the block rareness information is reorganized and saved into the BRM, where the row number denotes the rareness, the column number denotes the peer number, and the element value denotes the number of blocks of the rareness a peer has. For example, BRM(i, j) = 3 means that peer j has 3 blocks of the rareness i.

The peer freshness vector (PFV) is calculated from the peer difference matrix (PDM), whose element is defined in Eq. (2). An element of the PFV is the sum of all the elements in the corresponding row of the PDM, i.e., the i-th element of the

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PFV is the sum of all the elements in the *i*-th row of the PDM. Another data structure is the deficiency degrees (*DD*) of all peers, which is defined in *Definition 2* and used as the termination condition of the decision-making stage.

Decision-Making: After pre-processing, each peer can start the decision-making stage, which contains two modules. Each module is comprised of an important algorithm and the two algorithms are the scheduling algorithm and the refreshing algorithm, respectively.

Algorithm 1: Peer Scheduling Algorithm

```
Input: BRM, PFV
Output: next_sender
RBPS ← peers having the rarest blocks in BRM
MRPS ← peers having the most blocks in RBPS
if |MRPS| = 1
   next_sender ← the unique member of MRPS
else
   next_sender ← the peer in MRPS with largest freshness
endif
return next_sender
```

The peer scheduling algorithm is depicted in Algorithm 1. We first choose peers which own those rarest blocks and put them into a peer set with rarest blocks (RBPS). Then, those peers with most blocks in the RBPS are chosen to be put into a peer set with the most blocks which are rarest (MRPS). The next scheduled sender is the unique peer in the MRPS if it contains only one member; otherwise, the peer in the MRPS with the largest freshness is chosen as the next sender. If more than one peer has the same largest freshness, the algorithm just chooses the one with the minimum identity number. The freshness values of peers are taken from the PFV.

Algorithm 2: Status Refreshing Algorithm

```
Input: BRM, PDM, PFV, DD, next_sender
Output: BRM, PDM, PFV, DD
v_obj ← a rarest block of the next_sender
rare ← the rareness of the block v_obj
APS ← peers having the block v_obj
foreach peer in APS
   BRM(rare, peer) – –
endfor
foreach peer in all peers
   if PDM(next_sender, peer) > 0
      foreach member in all peers
         if PDM(next_sender, member) = 0
            PDM(member, peer) – –
            PFV(member) – –
         endif
      endfor
      DD(peer) – –
   endif
endfor
return BRM, PDM, PFV, DD
```

The status refreshing algorithm plays an important role in the PIE scheme because the updated status will influence the next round of peer scheduling, as shown in Algorithm 1. In algorithm 2, *BRM*, *PDM*, *PFV*, and *DD* represent the status of the block distribution information from different aspects. The *BRM* and the *PFV* are used for the next round of peer scheduling; the *PDM* is used to assist the refreshing of the *PFV*; and the *DD* is used for the termination of the decision-making stage, where the condition is that the *DD* equals all-zero.

Notice that many data structures are used instead of a single BDM. The reason is that for network coding based information exchange, peers send out coded packets, which make it difficult to keep tracking the status of block distribution information using a single BDM. Finally, in the decision-making stage, the PIE scheme gives out a peer scheduling sequence, which is produced by several rounds of peer scheduling and status refreshing based on the shared BDM.

Status-Updating: According to the peer scheduling sequence given in the previous decision-making stage, in this stage, peers send out one coded packet at a time without acknowledgement. Peers keep updating their own block distribution information with the reception of newly arrived coded packets. If no coded packets are lost, each peer can recover all of the original blocks in almost all situations, as shown in section V.

Termination: When each peer recovers all the original blocks, the whole information exchange process is finished. If the peers have more information for exchange, they can continue to repeat the above process; otherwise, the allocated resources such as wireless channels and temporary cache should be freed and peers are disassociated from each other.

B. *Discussions*

The PIE scheme is in line with our summarized principles in many aspects. According to *Principle 2*, the total receiving number of a peer is no less than its deficiency degree. From the proposed Algorithm 2, we can see that the *DD* does never equal all-zero before $TRN_i \geq DD_i$ since DD_i is decreased by at most one in each round of scheduling and refreshing. In addition, according to *Principle 3*, the total sending number of a peer (TSN_i) should be no less than NUB_i. In the PIE scheme, it is impossible to end the decision-making stage before peer i sends NUB_i packets since each unique block will make peer i stay in the peer set with rarest blocks (RBPS), resulting in that the sending chance will never be scheduled to other peers with only larger-rareness blocks, and the total sending number of all peers (*TSN*) can not be less than the total number of unique blocks in all peers. In other words, from the viewpoint of blocks, before all peers which have unique blocks sends, *DD* will never equal all-zero since the following equation holds:

$$\sum_{j=1}^{|NUB|} BAP_j = \sum_{j=1}^{|NUB|} (NAP-1) \leq |DD| \tag{10}$$

where $|NUB|$ and $|DD|$ are the sums of all NUB_i's and all DD_i's, respectively. In this way, the PIE scheme is naturally in accordance with the *Proposition I*. Moreover, according to Algorithm 2, we can see that the BAP_j is no larger than $NAP - 1$, which makes the PIE scheme conform to the *Proposition II*. Finally, following *Proposition I* and *Proposition II*, the *Corollary I* naturally holds.

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V. PERFORMANCE EVALUATION

To verify the effectiveness and efficiency of the PIE scheme, we conduct extensive simulations for performance evaluation. In our simulation scenarios, each peer can successfully receive the original blocks from a BS with a prescribed probability, which translates to the sparsity degree of the original blocks in the BDM. We evaluate the performance of the PIE scheme in terms of transmission efficiency against the changes of the number of peers, the number of blocks, as well as the sparsity degree and compare the transmission efficiency and computational overhead of the PIE scheme with those of the rarest first algorithm simply transferred from block scheduling to peer scheduling.

Notice that we use the theoretical lower bound of the *TSN* obtained in *Corollary I* as the benchmark for the evaluation of transmission efficiency, which is defined as:

$$E_t = \frac{TTA/TSN}{TTA/LB} = \frac{LB}{TSN} \tag{11}$$

where E_t is the transmission efficiency, *TTA* is the total transmission amount of information exchange, *TSN* is the result of our simulations, and *LB* is the theoretical lower bound of the total sending number, as defined by Eq. (9).

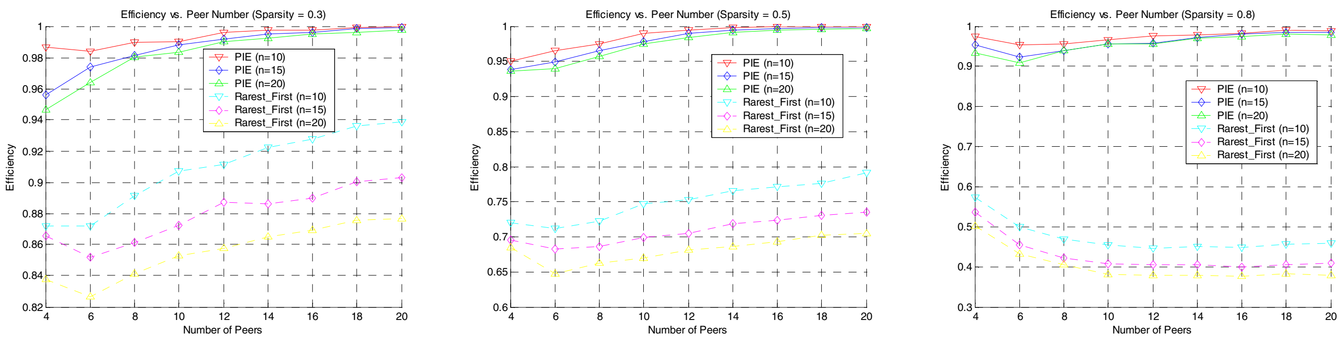

Fig. 4. Efficiency vs. The Number of Peers (Sparsity = 0.3, 0.5, and 0.8, respectively)

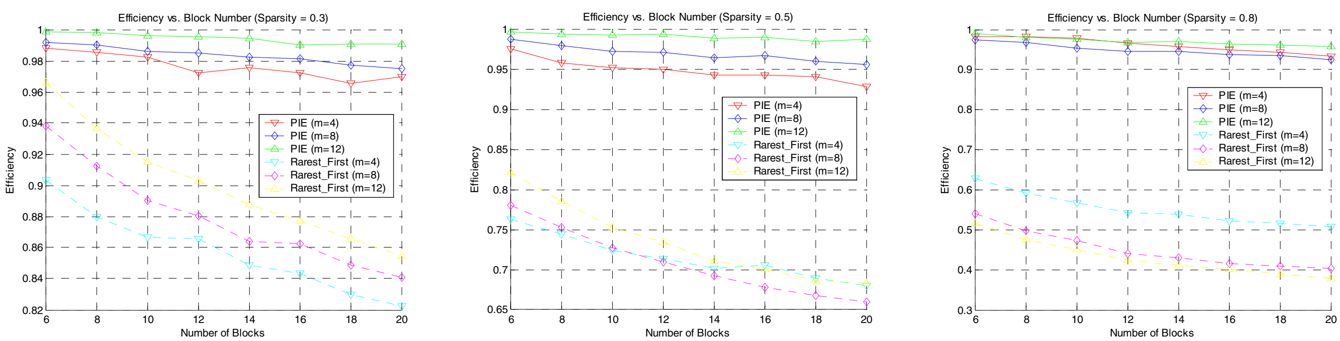

Fig. 5. Efficiency vs. The Number of Blocks (Sparsity = 0.3, 0.5, and 0.8, respectively)

A. Transmission Efficiency

Fig. 4 shows the transmission efficiency versus the number of peers. The simulation results of scenarios with different sparsity degrees are also shown. From Fig. 4, we can see that the transmission efficiency of the PIE scheme is much higher, about 30% on average, than that of the rarest first algorithm. With the increase of the number of peers, the transmission efficiencies of both schemes increase; while PIE almost reaches the optimal transmission efficiency. Simulation scenarios with different numbers of blocks, which are denoted by n = 10, 15, and 20, are also shown in the figures for the purpose of comparison and extensive verification.

The transmission efficiency versus the number of blocks (packets) is shown in Fig. 5. From Fig. 5, we can also see that the transmission efficiency of PIE is much higher than that of the rarest first algorithm. With the increasing of the number of blocks, the transmission efficiencies of both schemes decrease in some degrees, while PIE maintains a high transmission efficiency of more than 95% in almost all situations. Simulation scenarios with different numbers of peers, m = 4, 8, and 12, are also shown in the figures for the purpose of comparison and extensive verification.

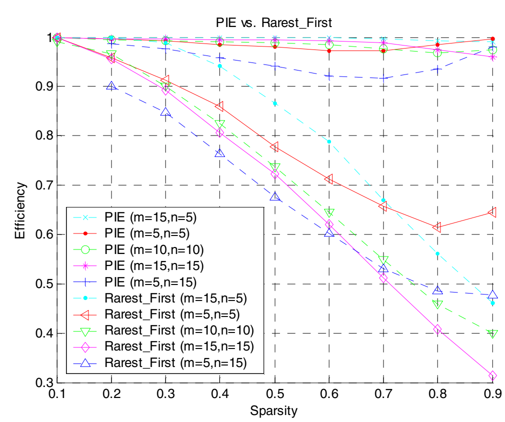

Fig. 6. PIE vs. Rarest First

For a specific investigation on the transmission efficiency versus the sparsity degree, we plot in Fig. 6 the changing relations between them in diverse situations with different numbers of peers (m = 5, 10, and 15) and different numbers of blocks (n = 5, 10, and 15). From Fig. 6, it can be clearly seen that the transmission efficiency of PIE is higher than 95% in almost all situations except the situations where the number of peers is small (m = 5) and the number of blocks is high (n = 15). On the other hand, both schemes have almost the same changing trend, while PIE outperforms the rarest first algorithm in terms of transmission efficiency in diverse situations with extensive sparsity degrees.

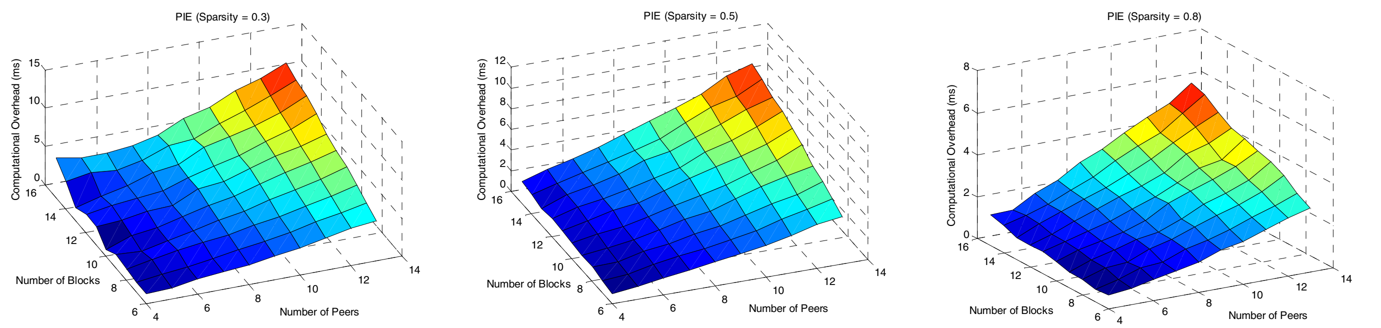

Fig. 7. Computational Complexity (Sparsity = 0.3, 0.5, and 0.8, respectively)

B. *Computational Overhead*

The computational overheads of PIE in scenarios with different sparsity degrees are plotted in Fig. 7, where all the values of computational overheads are collected from a laptop platform with a CPU of Intel Pentium M 1.8GHz and a RAM of 512MB. As shown in Fig. 7, the computational overhead of PIE increases with the increase of the number of peers and/or the number of blocks, and its increasing rate also increases with the decrease of the sparsity degree. In addition, the computational overhead of PIE is less than 10 ms in almost all situations, which is pretty light-weight and practical for deploying PIE into reality.

VI. CONCLUSIONS

In this paper, we first identified the peer scheduling problem, which arises from the employment of network coding for fully exploiting the broadcast nature of wireless channels. Then, several principles were summarized through an in-depth investigation on the information exchange in network coding enabled wireless networks. Based on these principles, we proposed a cooperative peer-to-peer information exchange (PIE) scheme with a simple, efficient, and light-weight peer scheduling algorithm. The PIE scheme can not only fully exploit the broadcast nature of wireless channels, but also utilize the advantage of cooperative peer-to-peer information exchange. Finally, the effectiveness and efficiency of the PIE scheme are demonstrated through qualitative analysis and extensive simulations. Our future work is to develop efficient peer scheduling schemes for multi-hop wireless networks.

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