Peer-to-Peer Information Exchange in Wireless Network using Network Coding

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Abstract –
In this paper, we study how information exchange is scheduled among peers to achieve high network throughput and lower transmission delay in wireless network using network coding. Based on the study of these scheduling principles, we propose a peer-to-peer information exchange (PIE) scheme with an efficient and light weight scheduling algorithm, which helps in the throughput improvement, energy efficiency and delay minimization of the network.

Keywords: peer-to-peer, wireless network, network coding, scheduling.

I. INTRODUCTION

Network coding has been widely recognized as a promising information dissemination approach to improving network performance [1] by allowing and encouraging coding operations at intermediate network forwarders. Network coding, in contrast, allows each node in a network to perform some computation. Therefore, in network coding, each message sent on a node's output link can be some function or "mixture" of messages that arrived earlier on the node's input links.

Primary applications of network coding include file distribution [2] and multimedia streaming [3] in peer-to-peer P2P) overlay networks, data persistence in sensor networks [4], and information delivery in wireless networks [5]. Incorporation of network coding into these applications brings many benefits such as throughput improvement [6], energy efficiency [7], and delay minimization [8]. Network coding can minimize the amount of energy required per packet (or other unit) of information multicast in a wireless network and can also minimize the delay, as measured, by the maximum number of hops for a packet to reach a receiver. With network coding, each generated block is a combination of all the blocks available to the transmitter and thus if any of them is useful downstream then the generated block will also be useful.

Current research focuses on block scheduling problems. Besides opportunistic snooping neighbor states, COPE [5] successfully handles the block scheduling problem by intelligently XOR-ing packets. A multi-partner scheduling scheme [10] employs the Deadline-aware Network Coding technique to adjust the coding window for meeting the time sensitive requirement of media streaming service. An energy efficient NBgossip scheme [11] utilizes network coding for neighborhood gossip in sensor ad hoc networks. The Rarest First algorithm is advocated through real experiments from being replaced with source or network coding in the Internet [12]. The rarest first idea can be employed in wireless network coding. However, directly applying this idea to peer scheduling is not necessarily optimal.

The recent advances in peer-to-peer, mobile ad hoc and wireless sensor networks have triggered the design of robust, simple, scalable and energy efficient information exchange algorithms. The use of gossip algorithms to solve this problem was first proposed by Demers *et al.* They used the idea for lazy update of data objects in replicated databases across many sites. In particular, they decomposed the update procedure into two steps. At first, every site chooses another site at random and the two sites exchange with each other their complete database contents. After this, once a site receives new updates, it becomes a "hot rumor" and periodically updates other sites randomly. Since then, gossip algorithm has been an interesting topic for many researchers. Using this algorithm reduces the time and energy consumption required to disseminate all information in the energy constrained networks. In NB gossip [11] nodes do not simply forward messages received, instead the linear combinations are sent out.

In this paper, we redefine a *peer scheduling* problem in network coding enabled wireless networks [9]. Based on the summarized peer scheduling principles, we propose a cooperative Peer-to-peer Information Exchange (PIE) scheme with an efficient light-weight peer scheduling algorithm. In addition to the rarest first principle on blocks, we take into consideration the freshness of peers, which is a measurement on how much innovation a peer has against other peers. PIE can not only fully exploit the broadcast nature of wireless channels, but also take advantage of cooperative peer-to-peer information exchange. Qualitative analysis and extensive simulations demonstrate its effectiveness and efficiency.

II. LITERATURE SURVEY

Sensor networks are especially useful in catastrophic or emergency scenarios such as floods, fires, terrorist attacks or earthquakes, where human participation may be too dangerous. The sensor nodes are used to collect and communicate data and will send it to the server. These sensor nodes may themselves fail suddenly and unpredictably, resulting in the loss of valuable data. Generally the existing routing schemes like virtual routing take the decisions based on the load imposed on every network link. When a particular link, or an area, becomes congested, some of the routes are modified. Alternate routes are found for every source-destination pair and the load is distributed between them, so memory burden is on all nodes. It does not guarantee full utilization of the network resources under high traffic loads. In this, only one or two routes are usually established between every two routers. Therefore, it is not possible to react to changes in the traffic pattern. The source can find only one or two paths and cannot choose the optimal path. To overcome this problem we use a technique called "Network Coding". With network coding, it may be possible to increase throughput [6] by pushing both streams through the bottleneck link at the same time. The method is simple. Using network coding, the node can mix the two streams together by taking their exclusive-OR (XOR) bit-by-bit and sending the mixed stream through the link.

In this case, XOR [5] is the function computed at the node. This increases the throughput of the network if the two streams can be disentangled before they reach their final destinations. This can be done using side information if it is available downstream. Network coding can be employed to solve the Cooperative Peer-to-peer Repair (CPR) problem [9], where centralized and distributed CPR algorithms are proposed based on observed heuristics. Cooperative Peer-to-Peer Repair (CPR) has been proposed to recover from packet losses incurred during 3G broadcast. With network coding, each node of the distribution network is able to generate and transmit encoded blocks of information. The randomization introduced by the coding process **eases** the scheduling of block propagation, and, thus**,** makes the distribution more efficient. This is particularly important in large unstructured overlay networks, where the nodes need to make block forwarding decisions based on local information only. The main advantage of using network coding for distributing large files is that the schedule of the content propagation in the overlay network is much easier.

Table1 gives the notations used in this paper

Table 1 LIST OF NOTATIONS

Notation	*Description*
TRNi	Total Receiving Number of Peer i
DD_i	Deficiency Degree of Peer i
TSNi	Total Sending Number of Peer i
NUBi	Number of Unique Blocks of Peer i
BDM(BDV)	Block Distribution Matrix i
BRM	Block Rareness Matrix
PDM	Peer Difference Matrix
PFV	Peer Freshness Vector
BAPj	Benefit of All Peers from the j-th sending operation

III. INFORMATION EXCHANGE PRINCIPLES

Since a specific solution to the peer scheduling problem 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 one or zero. Row numbers and column numbers of a *BDM* represent peer indexes and block indexes, respectively. In other words, *BDM* (,) = 0 means that peer does not have block and *BDM* (,) = 1 means that peer has block . Based on a *BDM*, we summarize the

following principles. The correlations between the principles and PIE are discussed in Subsection IV-B.

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 the information exchange.

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

$$TSN \geq max \{DD + NUB \}, \qquad (1)$$

Where *DD* is the number of innovative packets that peer needs to recover the whole original information, and *NUB* denotes the number of the blocks which are uniquely owned by peer .

Proof: From the viewpoint of peer , the *TSN* for all peers is equal to the sum of *TRN* and *TSN* , i.e., *TSN* = *TRN* + *TSN* , where *TRN* and *TSN* are the numbers of packets that peer receives and sends before the completion of information exchange, respectively. Obviously, we have $TRN \geq DD$ and $TSN \geq NUB$. Thus, we have $TSN \geq DD + NUB$. Because the inequality is true for all peers, we have Eq. (1).

Proposition 2: From the viewpoint of blocks, a lower bound of *TSN* can be given as follows:

$$TSN \geq [(\textstyle\sum^{N}_{i=1} DD_i)/(N\text{-}1)] \qquad (2)$$

where *N* is the number of peers (≥ 2).

Proof: For the -th sending operation, the benefit of all peers (*BAP*) is defined as a cumulative value of the benefits received by all peers. Thus, we have $BAP \leq \; - 1$. On the other hand, each peer has all blocks after the completion of information sharing. Therefore, we have:

$$\sum_{=1}^{TSN} BAP = \sum_{i=1}^{N} DD_i \qquad (3)$$

Thus, we have Eq. (2).

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

$$Max \{[(\textstyle\sum^{N}_{i=1} DD_i)/(N\text{-}1)],\ \max_i \{ DD_i + NUB_i\}\} \qquad (4)$$

Lemma 1: In the above network model, for any peer , incoming packets have no innovation to other

peers, thus peer has no necessity to code incoming packets into its future outgoing packets.

Proof: Without loss of generality, let an incoming packet be from peer . In the above network model, all other peers can receive this packet, which thus has no innovation to those peers any more. In addition, it is peer that codes this packet, which is a linear combination of all packets peer has and thus has no innovation to peer . Therefore, for any peer , the incoming packet has no innovation to any other peers including peer and thus peer has no necessity to include the incoming packet into its future outgoing packets.

Proposition 3: In the above network model, sending sequences are order-independent.

Proof: According to Lemma 1, for a given peer sending sequence, switching the orders of any two peers does not change the outcome. In other words, sending sequences are order-independent in the above network model.

IV. PROPOSED SCHEME

Based on the peer scheduling principles, in this section, we propose a quasi-optimal but efficient and light-weight cooperative Peer-to-peer Information Exchange (PIE) scheme.

A. The PIE Scheme

The main idea of PIE is to take the freshness of peers into consideration in addition to the rarest first principle on blocks. The basic concept of freshness is a measurement on how much innovation a peer has against all other peers, which can be represented as follows:

$$PVF = \sum_j PDM_{ij} = \sum_j \sum_k 1_{\{BDVik > BDVjk\}} \qquad (5)$$

where *PFV* denotes the freshness of peer , *PDM* denotes the difference of peer against peer , *BDV* is the block distribution vector of peer , which is the -th row vector of block distribution matrix (*BDM*) and so does *BDV* . The indicator function is defined as follows:

$$1_{\{BDVik > BDVjk\}} = 1, \text{ if } BDVik > BDVjk$$
$$= 0, \text{ otherwise} \qquad (6)$$

where *BDV* is the -th element of the vector *BDV* .

From Eq. (5), it can be seen that freshness is a cumulative difference of a peer against other peers. Thus, the concept of freshness represents a measurement of possible innovation a peer has against other peers. This definition captures the essence of network coding based information

exchange in terms of innovative information, thus assisting to maximize the wireless coding gain.

As shown in Fig.1, PIE consists of four stages: preprocessing, decision-making, status-updating, and termination. The decision-making stage contains two modules with an algorithm in each module. The details of these stages and modules are depicted as follows.

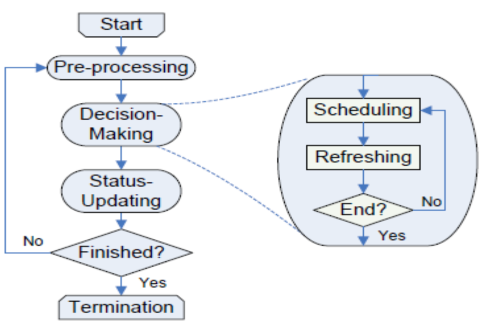

Figure 1 Flow chart of PIE

Pre-processing: In PIE, peers first share *BDVs* with each other. The sharing of *BDVs* can be performed by each peer directly broadcasting *BDVs* to others through the shared side channel. Finally, each peer has the block distribution information of all other peers, which forms a *BDM*.

With the *BDM*, each peer can calculate the rareness of blocks and the freshness of peers, which are represented in a Block Rareness Matrix (*BRM*) and a Peer Freshness Vector (*PFV*), respectively. A *BRM* can be calculated as follows. We first calculate the rareness of each block; the rareness of a block denotes the number of peers that have this block; the less the value of the rareness of a block, the rarer the block. The block rareness information is reorganized and put 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 that a peer has. For example, *BRM* (,) = 3 means that peer has 3 blocks of the rareness . *PFV* is calculated from *PDM*, as defined in Eq. (5). Another data structure is the deficiency degrees (*DD*) of all peers, which is used as the termination condition of the decision-making stage.

Decision-Making: After pre-processing, each peer can start the decision-making stage, which consists of two modules; one is comprised of the peer scheduling algorithm, and the other the status refreshing algorithm. The peer scheduling algorithm is described in Algorithm 1. First, we choose peers that

own the rarest blocks and put them into a peer set with rarest blocks (*RBPS*). Then, peers with most blocks are chosen from the *RBPS* and put into another peer set (*MRPS*). The next sender is the unique peer in *MRPS* if it contains only one member; otherwise, the peer with the largest freshness is chosen as the next sender. The freshness values of peers are taken from *PFV*.

The status refreshing algorithm plays a crucial role in PIE since the refreshed status will affect the next round of peer scheduling. In Algorithm 2, *BRM*, *PDM*, *PFV*, and *DD* represent the information of system status from different aspects. *BRM* and *PFV* are for the next round of peer scheduling; *PDM* is for status refreshing; and *DD* is for the termination of the decision-making stage, where the termination condition is that *DD* equals a zero vector.

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, PIE gives a peer scheduling sequence, which is generated through several rounds of peer scheduling and status refreshing based on the initially shared *BDM*.

Algorithm 1: Peer Scheduling Algorithm

```
Data: BRM, PFV
Result: next_sender
begin
    RBPS ← peers having the rarest blocks in BRM
    MRPS ← peers having the most blocks in RBPS
    if |MRPS| = 1 then
        next_sender ← the unique member of MRPS
    else
        next_sender ← the peer in MRPS with largest freshness
    end
    return next_sender
end
```

Status-Updating: According to the peer scheduling sequence given in the decision-making stage, in this stage, peers send out one coded packet at each time without acknowledgement. Peers keep updating their own block distribution information with the reception of new packets. If a packet is lost, a retransmission from the same peer is required to complete information exchange.

Algorithm 2: Status Refreshing Algorithm

```
Data: BRM, PDM, PFV, DD, next_sender
Result: BRM, PDM, PFV, DD
begin
    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 do
        BRM(rare, peer)−−
    end
    foreach peer in all peers do
        if PDM(next_sender, peer) > 0 then
            foreach member in all peers do
                if PDM(next_sender, member) = 0 then
                    PDM(member, peer)−−
                    PFV(member)−−
                end
            end
            DD(peer)−−
        end
    end
    return BRM, PDM, PFV, DD
end
```

Termination: When each peer recovers all original blocks, the whole process is completed. If those peers have more information for exchange, they can repeat the above process.

B. Discussions

PIE is in line with our summarized principles. For the proof of Proposition 1, we have $TRN \geq DD$ and $TSN \geq NUB$. The former principle is observed by PIE, since DD is decreased by at most one in each round of scheduling and refreshing in Algorithm 2. The latter is also observed by PIE, since each unique block will make peer stay in *RBPS*, resulting in that the transmission opportunities will never be scheduled to other peers with only larger-rareness blocks. In other words, from the viewpoint of blocks, before all peers which have unique blocks sends, DD will never equal a zero vector since the following equation holds:

$$\sum_{j=1}^{|NUB|} BAP_j = \sum_{j=1}^{|NUB|} (N-1) \leq |DD \qquad (7)$$

where $|NUB|$ and $|DD|$ are the sums of all NUB's and all DD's, respectively. Thus, PIE is naturally in accordance with the Proposition 1. Moreover, according to Algorithm 2, we can see that the BAP is no larger than -1, making PIE conforms to the Proposition 2. Finally, following Proposition 1 and Proposition 2, the Corollary 1 naturally holds.

V. CONCLUSION

In this paper, we have proposed a cooperative Peer-to-peer Information Exchange (PIE) scheme with a peer scheduling algorithm for wireless networks using network coding. Network Coding allows intermediate nodes to combine packets by taking their exclusive-OR (XOR) bit-by-bit to reduce number of transmissions, which reduces energy utilization and helps in throughput improvement. Sending maximum number of hops for a packet to reach a receiver helps in delay minimization. It also increases transmission efficiency and decreases computational overhead.

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