Network Coding Approach: Intra-Cluster Information Exchange in Sensor Networks

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***Abstract*— In this paper, we focus on the intra-cluster information exchange problem and proposed some novel solutions. Firstly, a cluster model is presented and some algorithms based on it are proposed, such as routing, flooding, cluster head relay and network coding algorithm. The theoretical analysis and simulation comparison of these algorithms are shown subsequently. We find that network coding algorithm allows to realize significant energy and time savings, when each node of the cluster is a source that wants to transmit information to all other cluster member nodes. Energy efficiency directly affects battery life and delay time is a very important network performance thus both are critical design parameters in wireless ad hoc sensor networks. Further more, the network coding algorithm we proposed are efficient and implementable. We analyze theoretical cases in detail, and use the packet level simulation.**

I. Introduction

The concept of network coding was introduced in a seminal paper by Ahlswede et. al. [1] and immediately attracted increasing interests. Li, Yeung, and Cai [2] showed that it is sufficient for the encoding functions at the interior nodes to be linear, i.e., a code in which each packet sent over the network is a linear combination of the original packets. In a subsequent work, Koetter and Médard [3] developed an algebraic framework for network coding and investigated linear network codes for directed graphs with cycles. This framework was used by Ho et al. [4] to show that linear network codes can be efficiently constructed by employing a randomized algorithm. Jaggi et al. [5] proposed a deterministic polynomial-time algorithm for finding a feasible network code for a given multicast network.

The basic idea in Network Coding is that intermediate nodes in the network not only forward but also process the incoming information flows, which results in significant benefits. In fact, wireless ad-hoc and sensor networks are the most natural setting for Network Coding because the very characteristics of wireless links that complicate routing, namely, their unreliability and broadcast nature, are the very characteristics for which coding is a natural solution. What's more, the wireless environments offer more freedom in terms of protocol design choices.

Comparing to the traditional routing method, network coding may offer throughput benefits. As shown in Figure 1, S_1 and S_2 multicast to both R_1 and R_2. All links have capacity 1. With network coding (by xoring the data on link CD), the achievable rates are 2 for each source, the same as if every destination were using the network for its sole use. Without network coding, the achievable rates are less (for example if both rates are equal, the maximum rate is 1.5).

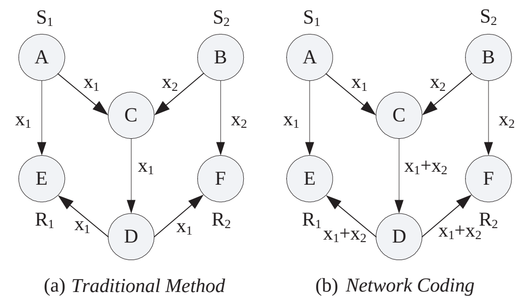

Fig. 1. Network Coding vs Traditional Routing

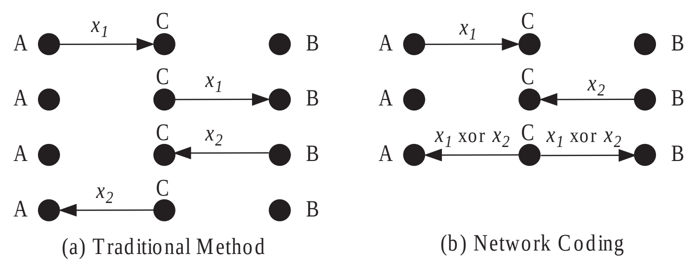

Fig. 2. Information Exchange in Wireless Networks

Network coding may offer benefits not only for multicast flows, but also for other traffic patterns, such as information exchange [6]. Information exchange is the mutual exchange of independent information between two nodes in networks. An explicit example of information exchange in wireless networks using Network Coding is shown in Figure 2. Fig.2(a) shows that node A and B send information to each other via intermediate node C. Node C just plays a store-and-forward role. While in Fig.2(b), after receiving the information from A and B, node C broadcasts $x_1 \oplus x_2$ (modulo 2 addition) instead of x_1 and x_2 in sequence. Thus, both A and B can recover the information of interest, while the number of transmissions is reduced. Consequently, the transmission energy cost and time consumption are reduced.

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In this paper, we focus on intra-cluster information exchange in wireless ad hoc sensor networks by using Network Coding. Consider this kind of scenario that each node is a source that transmits information to all other nodes in the cluster. As energy efficiency is very critical to wireless ad hoc sensor networks, we are interested in the minimum amount of energy required to transmit one unit of information from all the sources to all receivers. Such all-to-all communication is traditionally used during routing discovery and routing update phases. Exchange of congestion control information and synchronization in distributed computation environments may require that some information from all the nodes be broadcast to all other nodes of the network. This kind of information exchange in a network is called all-to-all broadcast or gossiping [7]. Another important applications where information exchange is used are in the situation awareness problem [8][9] and personalized exchange [10]. More recently, it has been described as a key mechanism for application layer communication in intermittently connected ad-hoc networks [11].

The main contributions of this paper can be summarized as follows:

- So far as we know, it is the first time to consider the application of Network Coding in clustered wireless ad hoc sensor networks.
- we propose some approaches to achieve information exchange in cluster, which are easy to apply in practical networks.
- The network coding algorithm we proposed is novel and efficient for information exchange. Comparing to other methods, our algorithm significantly reduces the transmission number and so as to the energy and time cost.

The rest of the paper is organized as follows. In section 2, we will show cluster model for wireless ad hoc sensor network. Section 3 describes the algorithms for information exchange: the traditional way and Network Coding approaches. The simulation description and results are given in section 4. At last we will conclude the paper in section 5.

II. Cluster Model

In this paper, we do not care about how the clusters are formed, but focus on how efficient the information are exchanged. We will formulate the intra-cluster information exchange problem by an ideal topology as shown in Figure 3. We consider this kind of scenario: node $A_i(1 \leq i \leq 6)$ wants to broadcast its information(a sequence of packets $\{X_i(n)\}$) to node $A_j(1 \leq j \leq 6, i \neq j)$, and node $A_j(1 \leq j \leq 6)$ wants to broadcast a sequence of packets $\{X_j(n)\}$ with the same length of $X_i(n)$ to node $A_i(1 \leq j \leq 6, i \neq j)$, i.e., all the nodes in the cluster broadcast information to all the other nodes in the same cluster.

We assume that each node A_i can successfully broadcast one unit of information to all neighbors $N(A_i)$ within a given transmission range, through physical layer broadcast. The transmission range is the same for all nodes, and cluster head can reach every node in cluster by only one hop. And for

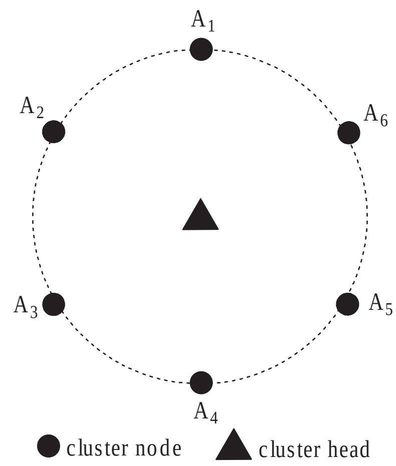

Fig. 3. Cluster Model for Intra-cluster Information Exchange

each node, there exists at least one node, and the transmission range of the two nodes can cover the whole cluster. Thus, minimizing the energy is equivalent to minimizing the number of transmissions required to convey a unit of information from all sources to all receivers. More precisely, let T denote the total number of transmissions required to finish one unit of intra-cluster information exchange process, and let n denote the number of common nodes (cluster head is not included) in the cluster.

III. Algorithms

To solve the intra-cluster information exchange problem, There are many methods: flooding, routing and network coding. These algorithms are described in this section and the transmission numbers are compared to evaluate the algorithm efficiency.

A. Flooding

Flooding is an old technique [12] that can also be used for routing in wireless ad hoc sensor networks. In flooding, each node receiving a data or management packet repeats it by broadcasting, unless a maximum number of hops for the packet are reached or the destination of the packet is the node itself. Flooding is a reactive technique, and it does not require costly topology maintenance and complex route discovery algorithms. On the other hand, the main disadvantage of the flooding algorithm is high energy consumption levels, which is an extremely important factor in ad hoc sensor networks.

The flooding algorithm for intra-cluster information exchange is shown in Fig.4. The algorithm is explicit and we can analyze the transmission number T_{flood} refer to Figure 3. Assume node A_1 broadcasts its information firstly, after rebroadcasting by node A_2, A_6, A_3 and A_5, the packet arrives node A_4. Though node A_4 is the last node receiving the packet, A_4 still needs to rebroadcast it. Because without global topology and schedule knowledge, the last node in flooding process still needs to broadcast one extra time. Then we can make out that to spread the information of node A_1,

```
if (it's time to deliver packet) {
    broadcast own information;
}

if (receiving packets) {
    if (not cluster head) {
        if (packet has not been received/generated) {
            if (TTL > 0) {
                broadcast it;
            }
        }
    }
}
```

Fig. 4. Flooding Algorithm for Intra-cluster Information Exchange

the 6 times broadcasts are needed. And now we can come to a conclusion that the transmission number of intra-cluster information exchange by flooding is n^2, i.e.,

$$T_{flood} = n^2. \tag{1}$$

B. Random Routing

As assumed above, each node does not know the global information about the cluster and can only communicate with its neighbors. Take the Fig.3 for example, assume node A_1 wants to send information to node A_5, it does not know $A_1 \rightarrow A_6 \rightarrow A_5$ is the shortest path, and maybe it chooses the path: $A_1 \rightarrow A_2 \rightarrow A_3 \rightarrow A_4 \rightarrow A_5$. Without loss of generality, we assume the probability which path is chosen is 0.5. Thus the average transmission number for node A_1 to deliver its information to any node in cluster is $(n-1)/2$. Consequently, the transmission number of one node to spread its information to all the others is $n(n-1)/2$ and the transmission number of the whole information exchange is $n^2(n-1)/2$, i.e.,

$$T_{routing} = n^2(n-1)/2. \tag{2}$$

For simplicity, we just consider the transmission number of information deliver and do not take the routing discovery into account, which is complicated in such circular network. Thus, we get $T_{routing} > n^2(n-1)/2$.

C. Cluster Head Relay

There is another explicit but efficient algorithm for intra-cluster information exchange: relay information by cluster head. Every node sends information to the cluster head who broadcasts the packet to all the nodes in the cluster. Thus, the total transmission number is

$$T_{relay} = 2n. \tag{3}$$

This cluster head relay algorithm is very simple and effective. Each node just sends own information directly to the head without knowing any other information such as topology, geography, etc. The cluster head is responsible to exchange information between the cluster members. But the drawback of this algorithm is that the network traffics are not well balanced because the transmission number of cluster head is at least n, half of the total transmission number, which cause cluster head easy to die or to be rotated frequently.

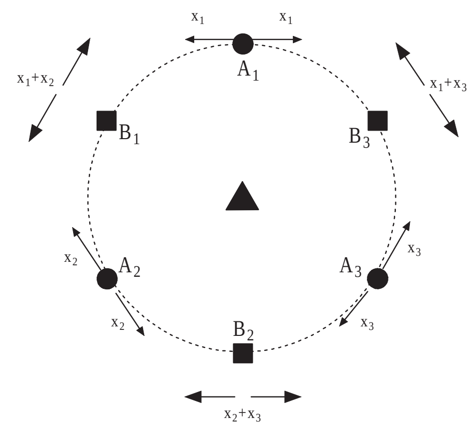

Fig. 5. Network Coding Algorithm 1 for Intra-cluster Information Exchange

D. Network Coding Algorithm 1

An energy efficient broadcasting algorithm for circular network is proposed in [13], which can be used in intra-cluster information exchange. The authors assume that node number n in circular network is an even number(in our example, $n = 6$). And partition the n nodes in two sets $A = \{a_1, \ldots, a_{n/2}\}$ and $B = \{b_1, \ldots, b_{n/2}\}$ of size $n/2$ each, such that every node in A has as nearest neighbors two nodes in B. In other words, the nodes in A and B are interlaced on the circle. For example, in Fig.5, n = 6, and the nodes in set A are depicted as circles while the nodes in set B are depicted as squares.

Each step in the algorithm consists of two phases. In phase 1, the nodes in set A transmit their information to their neighbors. Thus each node in B receives two messages, one from each of its nearest neighbors in A. For example, in Fig.5, node B_1 receives x_1 and x_2. In general, node B_i receives x_i and x_{i+1}. In phase 2, the nodes in set B simply add (modulo 2 addition) the information symbols they receive and broadcast it. For example, node A_1 receives $x_1 + x_2$ from node B_1 and $x_1 + x_3$ from node B_3. Thus, node A_1 has the information units from sources A_2 and A_3. Moreover, at each step, each transmission brings two new information units to two receivers. Note that in the last step, second phase, fewer transmissions are required, but this will not affect the order of the result. Each step involves n transmissions. This scheme transmits $n/2$ information units in $n\frac{n}{4}$ transmissions. To exchange information between n nodes, we have the transmission number:

$$T_{NC1} = n^2/2. \tag{4}$$

E. Network Coding Algorithm 2

In this section, we propose a novel network coding algorithm for intra-cluster information exchange. In our algorithm, each step consists of two phases, which are described in Fig.6. In the first phase nodes transmit and cluster head receives. In the second, cluster head broadcasts and cluster nodes receive. The scheme operates as follows.

Algorithm NC2:
Step 1:

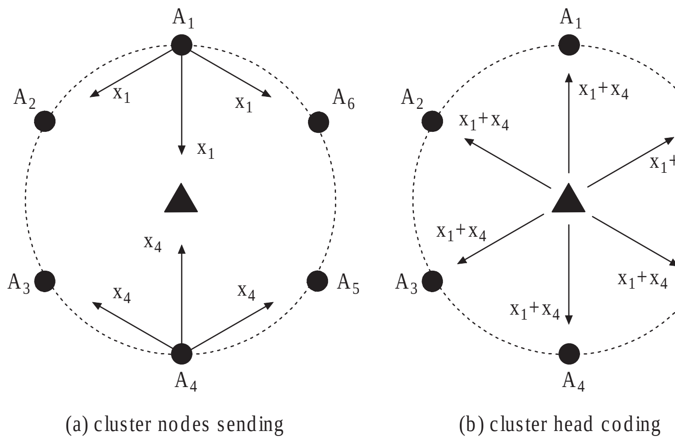

Fig. 6. Network Coding Algorithm 2 for Intra-cluster Information Exchange

- Phase 1: Two cluster nodes broadcast their information to their nearest neighbors, and the information will be heard by cluster head. To focus on the network coding algorithm and transmission number, we assume that the intra-cluster communication is scheduled well and conflict free. For example, in Fig.6(a), node A_1 and A_4 broadcast x_1 and x_4 respectively. And the cluster nodes, receive either x_1 or x_2, as assumed in *Cluster Model*, while the cluster head receives both.
- Phase 2: The cluster head simply adds (modulo 2 addition) the two packets and broadcasts it. Take the Fig.6(b) for example, after receiving x_1 from node A_1 and x_4 from A_4, cluster head broadcasts $x_1 \oplus x_4$ to the whole cluster. Thus, each node in cluster can obtain x_1 and x_4.

Step $k, k > 1$:

- Phase 1: If there are cluster nodes having not broadcasted their information, then step $k-1$, otherwise go to phase 2.
- Phase 2: End the algorithm.

From the algorithm, we can see that every node in the cluster needs to broadcast its information only once and the cluster head just need broadcasts the $\frac{n}{2}$ coded packets. Thus, the transmission number of our network coding algorithm can be made out:

$$T_{NC2} = n + \frac{n}{2} = \frac{3}{2}n. \tag{5}$$

In section 2, we assume that for each node, there exists at least one node, and the transmission range of the two nodes can cover the whole cluster. But sometimes the condition can not be satisfied, and in our algorithm the cluster head will broadcast extra $\frac{n}{2}$ packets in case that some nodes have not sufficient information to decode the packets. For example, in Fig. 6, if node A_6 is out of the transmission range of node A_1 and A_4, consequently A_6 will not obtain x_1 and x_4, but only receive $x_1 \oplus x_4$ from cluster head. Therefore, node A_6 cannot decode the information by itself. Thus the cluster head has to broadcast x_1 or x_4 to those nodes which have not efficient information to decode the incoming information. And the number of the extra packets needed to broadcast by cluster head is at most $\frac{n}{2}$. So, we can get:

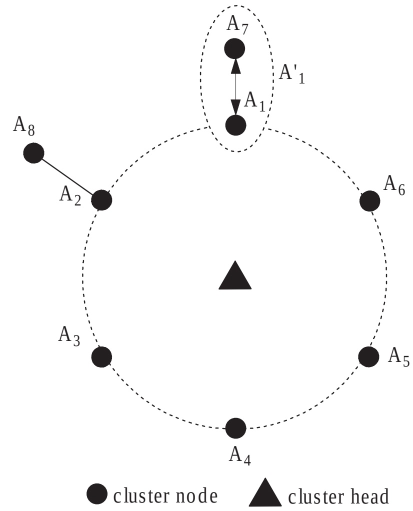

Fig. 7. Intra-cluster Information Exchange using Virtual Nodes

$$\frac{3}{2}n \leq T_{NC2} \leq 2n = T_{relay}. \tag{6}$$

We can see from the inequation (6) that the upbound of the transmission number of our algorithm is equal to the *Cluster Head Relay Algorithm*.

Let us consider if there are cluster member nodes which are out of the transmission range of the cluster head, i.e., the nodes transfer packets to the cluster head by more than one hops, which is shown in Fig.7. In the figure 7, node A_7 is two-hop away from cluster head and we take node A_7 and A_1 as one virtual node A_1'. That means the node A_1' will exchange information of node A_1 and A_7 with other cluster nodes, and node A_1 will exchange information it obtained from other nodes with node A_7 inside the virtual node A_1'.

IV. SIMULATION

A. Environment setup and Performance metrics

We evaluate Information Exchange algorithms via simulation using NS2 [14] and compare the *network coding algorithm 2* to the flooding algorithm, random routing scheme and cluster head relay mechanism. In order to evaluate the performance, we compare the four algorithms with respects to the following metrics: residual energy and average time consumed in the information exchange process.

In our simulation environment, sensor nodes are distributed over a $200m \times 200m$ area, and the transmission range of each node is set to be $50m$. Without loss of generality, the cluster head (node 0) is located at the center of the simulation area. Two kinds of topology scenarios are simulated: one is the circular networks as shown in Fig.3, and the other is random topology, i.e., cluster nodes are uniformly random distributed in the area. Each sensor has the same maximum battery energy capacity and for simplicity, the cluster head has the same maximum battery capacity as other sensors. In the simulation, all nodes exchange their data packets to each other, as described in section 1. Each data packet is set to

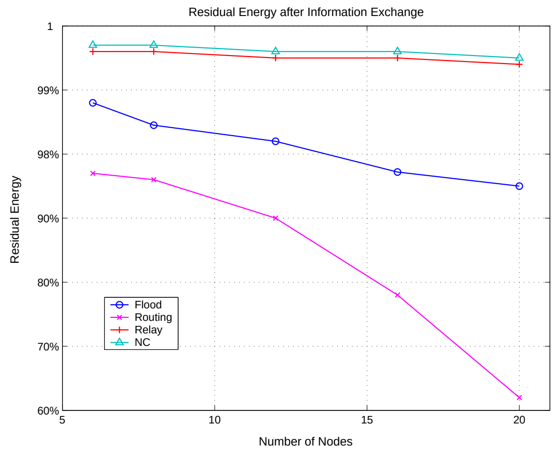

Fig. 8. The Comparison of Energy Consumption after Information Exchange (Circular Networks)

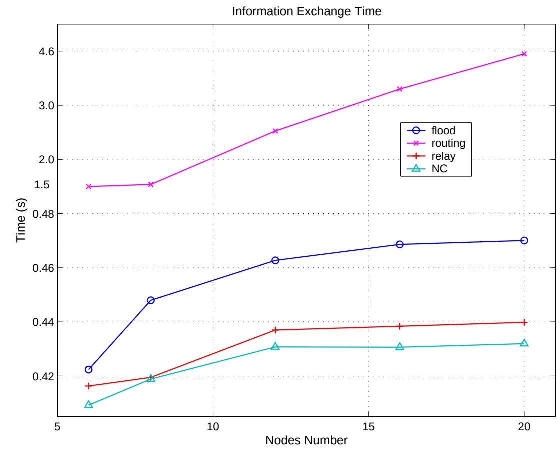

Fig. 10. The Comparison of Time Consumption after Information Exchange (Circular Networks)

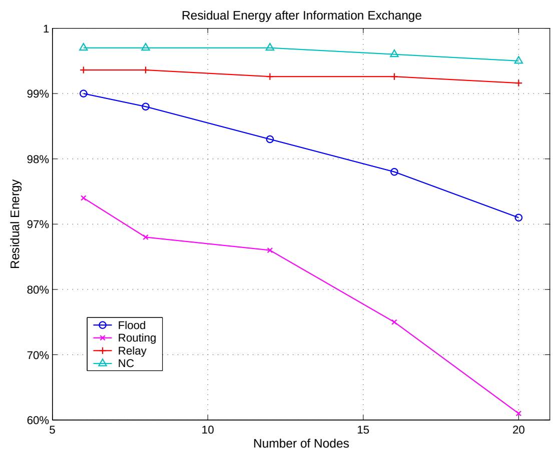

Fig. 9. The Comparison of Energy Consumption after Information Exchange (Random Topology)

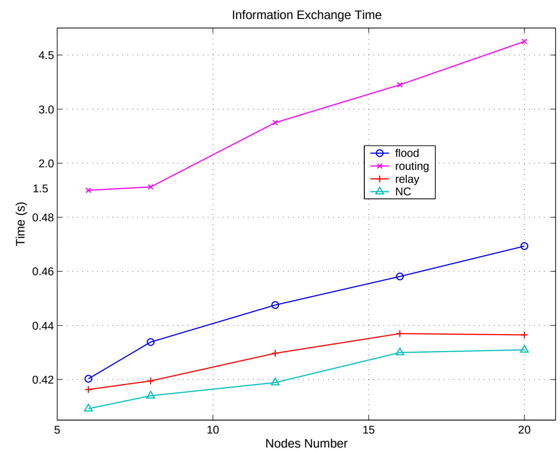

Fig. 11. The Comparison of Time Consumption after Information Exchange (Random Topology)

the fixed length (64 bytes) and a clear channel is assumed. In each kind of simulated networks, five different numbers of deploying nodes, 6 nodes, 8, 12, 16 and 20 nodes are simulated to evaluate the performances under different densities. And totally, there are 20 different scenes (different topologies and packets generating sequences) in each of these five cases.

B. Simulation results

Fig.8 and Fig.9 show the residual energy after information exchange in circular network and random network respectively. We can see from the two figures that in both circular and random networks, network coding algorithm, cluster head relay and flood approach cost much less energy than routing scheme. It is because routing is a kind of unicast communication, i.e., each source node must generate single packet for each destination node. Among network coding, cluster head relay and flood algorithms, network coding costs the least energy, which accords with the equations (1)-(5). Also we can know from the graphs that the residual energy of the four algorithms reduces as the node number increases.

The other performance metric we focus on in this paper is the information exchange time. It is shown in Fig.10 and Fig.11 that network coding costs the least time in both circular and random networks while random routing costs most, which accords with the theoretical analysis in section 3. Although the performance of cluster head relay is better than flood and routing, it is still not as good as network coding. And the load-balancing in cluster head relay approach is not optimal, for the traffic load of cluster head is half of the total traffic, as analyzed in section 3.

We also compare the information exchange time of those four algorithms between circular network and random topology. The results are shown in Fig.12-15. In the legends of the figures, *C* denotes for *Circular Networks* and consequently, *R* denotes for *Random Topology*. From the graphs, we can see that the information exchange time of *Flood*, *Relay* and *Network Coding* is less in random topology than in circular network. It is because that in random topology, the distances between nodes in cluster, especially the distance between cluster member nodes and cluster head, are not as large as in the circular network, which is convenient for those algorithms. To the random routing algorithm, the time consumed in information exchange process in random topology is almost equal to in circular networks. This is because in random

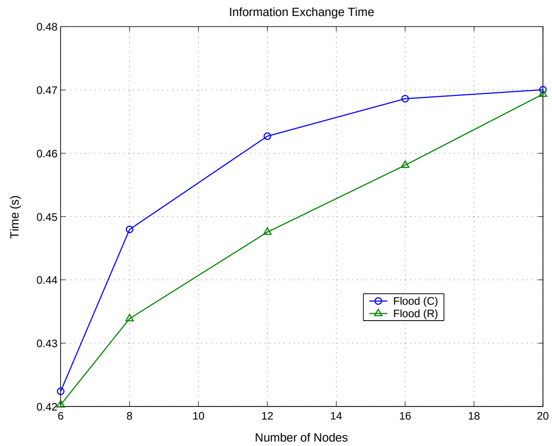

Fig. 12. Time Consumption of Flood after Information Exchange (Between Circular Network and Random Topology)

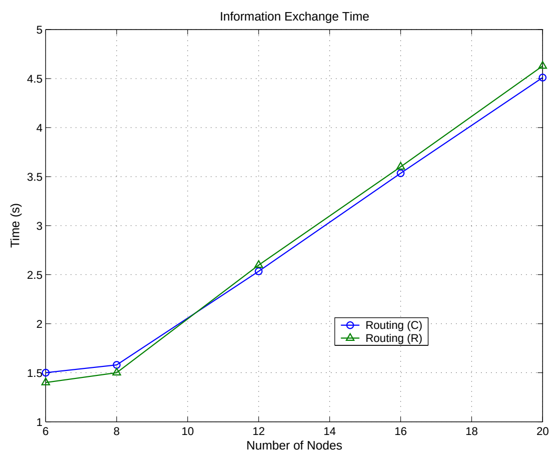

Fig. 13. Time Consumption of Routing after Information Exchange (Between Circular Network and Random Topology)

routing algorithm, packets are forwarded among those cluster member nodes, thus the time consumed in circular network has not much difference to the time cost in random topology. Further more, we can find from the figures that proper numbers of nodes, such as numbers from 8 to 16, are more suitable for using network coding in random topology.

V. Conclusions

In this paper, we identify intra-cluster information exchange in wireless ad hoc sensor networks as a new application scenario, and propose some novel solutions. After the theoretical analysis and simulations, we come to a conclusion that the cluster head relay approach and network coding algorithms perform much better than conventional solutions, such as routing and flooding, both in energy consumption and time cost. Further more, network coding algorithm performs best and can offer unique advantages. It is because Network coding algorithm, together with physical layer broadcast property offered by the wireless medium, can improve the efficiency in using resources. And the network coding algorithm we proposed is simple to implement and our simulation work indicates that there is a potential for significant benefits, when

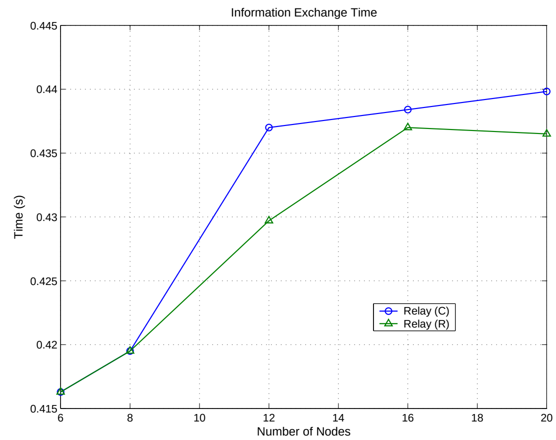

Fig. 14. Time Consumption of Cluster Head Relay after Information Exchange (Between Circular Network and Random Topology)

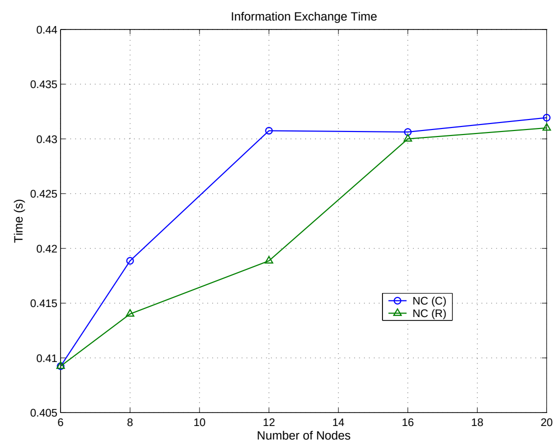

Fig. 15. Time Consumption of Network Coding after Information Exchange (Between Circular Network and Random Topology)

deploying network coding over a practical wireless environment. In the future, we will focus on MAC layer modification to develop more efficient network coding algorithms for intra-cluster information exchange.

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