

## Network Coding based Reliable Multi-path Routing in Wireless Sensor Network

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### Abstract

*This thesis proposes a network coding based and easily-realizable composite network topologic model. It is composed of disjoint multi-path routing (DMR) and braided multi-path routing (BMR) in wireless sensor network, and network coding technology is also employed in our multi-path routing. With the use of the Node Coding technology and the multi-path technology, NC-RMR (Network Coding based Reliable disjoint and braided Multipath Routing) strengthens the network reliability, and meanwhile reduces the number of desired sub paths and helps to balance the network loads. Finally, its theoretic correctness and performance superiority was verified in the simulation.*

**Keywords:** wireless sensor network, network coding, disjoint multi-path, braided multi-path

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### 1. Introduction

The primary mission of the sensor network is to collect relevant data from the monitoring regions and then transmit it to the sink nodes through a self-organized network, which will monitor the events based on the information collected from one or more source nodes. Large amount of nodes are randomly deployed in the sensor network, and in order to save energy, the nodes generally enjoy weak wireless communicating capacities, which directly influences the judgments of events within the monitoring regions. Therefore, it is necessary to build a reliable communicating mechanism in the wireless sensor network to insure the stability of data transmission. At present, there are some reliable transmitting technologies in wireless sensor network as follows: traditional forward error correcting technology [1], message response retransmitting technology [2], multi-path routing technology [3] and some other new technologies, for example, the network coding technology [4], which is to be discussed later in this thesis.

Among all these technologies, the multi-path routing technology is a typical method for strengthening data transmitting reliability using redundant nodes. Sun Liming, Li Jianzhong [5] et al. proposed an algorithm for establishing DMR (Disjoint Multi-path Routing) and BMR (Braided Multi-path Routing), both of which could insure connectivity of the network topology. However, data transmission along the links will still suffer a low success rate when the signal channel quality is universally poor or the links encounter lots of hops in the network. Thus, another reliable transmitting routing--Reliable Information Forwarding using Multiple Paths (ReInForM), was proposed in Literature [6], this routing gives first consideration to such elements as the demand for stability, channel quality and also the number of hops from the sensor nodes to the sink node, and then calculates the number of links needed to meet the requirements of stability, thus building multiple paths, and achieving reliable transmission with data transmitted simultaneously in multiple paths.

Seeing from the above analysis, the multipath technology serves to insure reliable transmission by adding massive redundant links, which will consume great amount of energy and fail to meet the requirements of low power consumption by the sensor network. Here, Network coding just presents a brand new mode of data transmission, which will avoid transmitting failure caused by data disorders or packet losses, saving energy in data delivering at nodes and making up for deficiency in traditional multipath routing transmission.

Accordingly, the thesis first proposes the NC-RMR (Network Coding based Reliable disjoint and braided Multipath Routing), then analysis it's performance. In the end, it comes to a summary of all what have been practiced throughout the whole thesis.

## 2. Related Work

The NC-RMR protocol introduced in the thesis borrows the path calculating method in the RelInform protocol. However, there are still big differences between them. Firstly, NC-RMR protocol applied network coding technology to avoid data redundancy; And secondly, it merged the DMR with BMR, which increases data transmitting reliability; Lastly, NC-RMR realized balance of network loads and selection of the next-hop optimal node that does not exist in the RelInform protocol.

The deficiency of traditional multi-path routing lies in that its expanded network traffic will result in an increased rate of packet loss. Stefan dolman [7] et al. proposed to split raw packets into more smaller ones, and then send them into each path respectively, in which case, even if some of the packets get lost, the raw packets can still be recovered at the receiving end. However, despite its similarity to network coding, NC-RMR remains an idea based on the storage-transmitting mechanism. NC-RMR works on data coding and decoding, and would insure that lost parts of the packets will not influence restoration of the raw packets.

Recent studies have shown that in WSN, fusion of network coding with multi-path routing protocols can better lower the routing request frequency, data wait delay and energy consumption, etc., as well as improving transmission reliability. Hunter TE [8] et al. elaborated on how network coding works in improving network throughput, saving transmitting energy and increasing safety levels in collaborative communication. Yang Lin [9] et al. applied this technology to multipath data transmission on low-orbit satellites, and proved that network coding would improve the success rate in multipath transmission. Qian Xiao et al. [10] propose an efficient algorithm called DGNC for this scenario using inter-session network coding and opportunistic routing. In the scenario of up links from users to cooperating nodes are not reliable, Zheng Lv et al. [11] construct a wireless channel model and introduce channel coding and network coding into cooperative communication system and propose a cooperating scheme based on joint channel-network coding.

Main contributions of the NC-RMR protocol discussed in this thesis include: firstly, it is a NC-based and reliable multi-path routing protocol, and it merged the DMR and BMR technology together, which further improves network operability and reduces energy consumption. Secondly, compared with other multipath protocols, it emphasizes more on the process of establishing multiple paths. In the end, we simulate the NC-RMR model to verify the correctness of description in this thesis as well as the performance superiority of the model.

## 3. NC-RMR Routing Model

This thesis adopted two indicators, Successful Delivery Ratio (SDR) [12, 13] and Normalized Redundancy (NR) [12], to evaluate the model in this thesis.

SDR: Probability of the sink nodes successfully receiving data packets sent from the source node at a time, it reflects reliability of the network.

NR: Ratio of the data length delivered in total to the data packet length received in the network after the sink node receives a data packet successfully. It reflects traffic volume of data redundancy.

### 3.1. Idea of Design

NC-RMR combines DMR with BMR. As seen from its network topology in Figure 1, there is no jointing nodes between the sub-paths, and each hop within the sub-paths is a braid multi-path consisting of two intertwined nodes. This is mainly serves to bring the NC technology into the sensor network, so as to reach relatively high SDR while taking care of such factors as energy consumption, degree of congestion, loads balancing and network time delay.

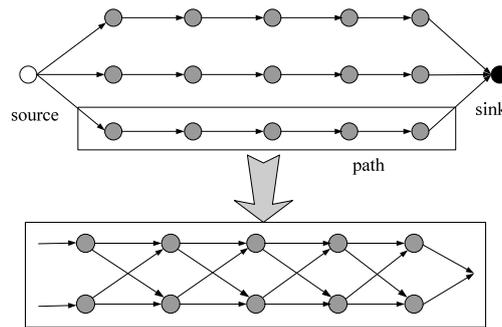


Figure 1. Network Topology of the NC-RMR Model

### 3.2. Model Establishment Process

The process of establishing the routing model can be divided into 4 phases: a, obtaining path hop counts; b, calculating the number of sub-paths; c, establishing the paths actively; d, the sink nodes feeding back path establishing messages.

#### 3.2.1. Obtaining Path Hop Counts

The sink node broadcasts route updates periodically and directionally. After receiving the updates, the node broadcasts them with hop counts plus 1. Thus each node gets its minimal hop counts reaching the sink node as well as the hop counts reaching sink node through different paths. To make it simpler, we take the mean value of these hop counts as the estimated path hop count  $N$ .

#### 3.2.2. Calculating the Number of Sub-paths

Before delivering data, the source node will create an expected value for accuracy of data packets being successfully received at the sink nodes. As can be known from Literature [14], data transmission enjoys the highest rate of success when the number of data packets after coding equals that of the path hops. Therefore, the number of data packets  $n'$  on each sub-path after coding is equal to the hop counts  $H$  going through each sub-path.

The source node will make out the number of sub-paths desired based on the expected SDR, signal channel bit error rate and the data packet length. Assume that the length of data packets delivered from the source node is  $L$  bit, and suppose that  $m$  is the number of split data packets before coding. Select the coding parameter for network coding after splitting from F2, and then the length of the coding parameter is one byte. Besides, after splitting the data packets, add a packet header with a length of  $L_{head}$  to the data packets, and in this model, express the data packet length after linear network coding as LNC-BMR with bit as the unit. Then the length of data packets encoded can be determined by Eq.1, where the data packet length as  $L$  bit.

$$L_{NC-BMR} = L/m + L_{head} \times 8 + m \times 8 \quad (1)$$

Thus  $p$  can be expressed as Equation (2), where the bit error rate of packet transmission in the signal channels is expressed as  $p_b$ .

$$p = (1 - p_b)^{L_{NC-BMR}} \quad (2)$$

$p_c$  means the probability of each packet being correctly delivered by each sub-path to the target node. And express the probability of the sink node successfully receiving  $k$  data packets as  $a_k$ . Meanwhile suppose that the source node has delivered  $n$  data packets in total, the probability of the sink node to receive  $k$  data packets correctly submit to the Bernoulli Distribution of  $(p_c, n)$ . Then  $a_k$  can be expressed as Equation (3).

$$a_k = C_n^k \times p_c^k \times (1 - p_c)^{(n-k)} \quad (3)$$

As long as the sink node receives m or more data packets, then the probability is that of data successfully transmitted. Thus SDR can be expressed as the following Equation:

$$SDR = 1 - \sum_{k=0}^{m-1} a_k \tag{4}$$

As we can see from the above analysis, once constraining the desired SDR, we will be able to back-deduce the total number n of the data packets after network coding. As each sub-path transmits H coded data packets, we then get the number of desired sub-paths, which is equal to n/H. The length of data packets in the model is determined by m, which will directly determines the probability of successfully transmitting data packets at each hop. Therefore, the value of m is of prime importance in the model.

**3.2.3. Establishing the Paths Actively**

Seeing from analysis in the previous section, we can work out the desired number of sub-paths at a given SDR, expressed as  $N_{bp}$ . The calculated value of  $N_{bp}$  may be quite large, which will make establishment work very complicated, hence we will build relatively less paths actually.

1) Procedures of building paths at the Source Nodes

The source node selects one node from the neighboring nodes as the next-hop node and delivers a path request data packet in the following formats (Table 1):

Table 1. Formats of Request Data Packets

$ID_t$	$ID_s$	$ID_n$	$ID_y$	$N_{hop}$	SDR	$N_m$
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Table 2. Meaning of the fields

$ID_t$	Type of data packet
$ID_s$	Address of the source node
$ID_n$	Address of the current node
$ID_y$	Sequence number of the sub-path, with the original value being 1
$N_{hop}$	Hop counts of nodes in paths
SDR	Desired SDR
$N_m$	Number of Data Packets after Coding.

In Figure 2, the desired SDR value of the source node X is  $p_{sdr}$ . X delivers in proper sequence the path request data packets to  $N_y$  nodes. Upon completion of each delivery, 1 is added to the  $ID_y$  until  $ID_y > N_y$  when delivery process is over.

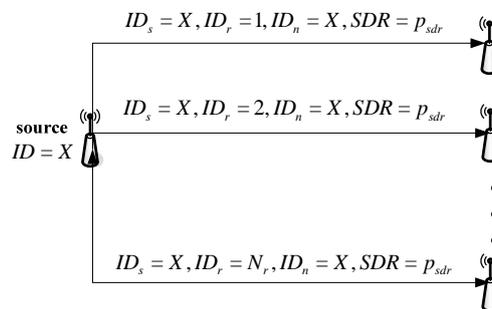


Figure 2. Source Node Actively Building the Path

2) Intermediate Node Routing Workflow

Following is the processing flow when a node receives the path request data packet:

A. Check the local storage of the node, and evaluate whether the node has been in a certain path. If it is, go to C and if not, continue with B;

B. Save IDs, IDn, IDy,  $N_{hop}$  and Nm of the request data packets in the cache of the node and set IDn as the address for the current node. Add 1 to  $N_{hop}$  and go on transmitting downwards to look for new paths;

C. Change the data type IDt from request identity into negative identity, and then return the data packets to nodes with address IDn;

D. After receiving the negative data packets, the previous hop will select other target nodes for delivery and meanwhile save the addresses of those nodes until no negative data packet is returned.

### 3) Establishing Workflow of Corresponding Binding Nodes

Following is the flow for each intermediate node looking for binding nodes:

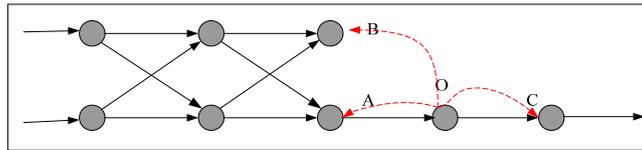


Figure 3. Finding Binding nodes

A. The intermediate node O delivers request data packets for neighboring nodes successively to Nodes A and B in the previous hop (the node in the previous hop of the first intermediate node is the source node and other nodes own two previous-hop nodes) and Node C in the next hop, as shown in Figure 3;

B. After Nodes A, B and C receive request data packets from neighboring nodes, they would deliver the unused neighboring nodes to the request Node O.

C. After Node O receives the returned data packets and obtains three idle neighboring node addresses, it will figure out the intersection sets and selects a node as the destination to deliver corresponding request data packets;

D. After the node receives the request data packets from the corresponding nodes, it views the cache and checks whether they are already in a certain path. If it is the case, go to E, otherwise, go to F;

E. Constrain IDt as a negative identity and forward it to Node O, which, upon receiving, continues to select other nodes inside the intersection, set as destinations for delivery;

F. Save  $N_{hop}$  and the addresses of O, A, B, C in the node cache and deliver path-building request data packets to Nodes A, B and C;

### 3.2.4. Feedback from Sink Nodes

Sometimes, when nodes in the network are unevenly or sparsely distributed, hop counts of the sub-paths may deviate from the estimated value. At this time, the sink node needs to re-calculate the number of logic sub-paths needed so as to achieve the expected effect.

We shall infer the hop counts necessary for  $N_{bp}$  logic sub-paths to deliver data packets based on Field  $N_{hop}$  in the path request data packets received at the sink nodes, then number the logic sub-path with  $i$  and constrain  $N_{hopi}$  as the hop counts each logic sub-path has gone through. As we can know from Step 2, the number of original data packets after coding equals the hop counts of sub-paths. Therefore, we can infer the rate of success rate  $p_{bi}$  of each logic sub-path in delivering data packets.

So if we express the probability of successfully delivering  $k$  data packets on Sub-path  $i$  as  $a_{k,i}$ , then we shall infer from the Bernoulli Formula that.

$$a_{k,i} = C_{N_{hopi}}^k \times p_{b,i}^k \times (1 - p_{b,i})^{(N_{hopi} - k)} \quad (5)$$

Probability  $b_w$  of the total quantity  $w$  of data packets being received successfully at the sink node can be inferred from different combinations of summation of the numbers of data packets successfully received by different sub paths.

$$b_w = \sum_{k=0,1,\dots,N_{hopj}, s.t(\sum_{i=1}^{N_{hop}} k=w)} \prod_{i=1}^{N_{hop}} a_{k,i} \tag{6}$$

SDR' of the newly-established model can be expressed as the Equation below:

$$SDR' = 1 - \prod_{w=0}^{m-1} a_w b_w \tag{7}$$

With SDR' determined, now we can make a comparison with the desired SDR:

A. If  $SDR' > SDR$ , then the model-building is a success, and the sink node will return a feedback data packet to the source node in the format as shown in Table 3.

Table 3. Formats of Feedback Data Packets

ID <sub>x</sub>	ID <sub>s</sub>	ID <sub>bp</sub>	N <sub>y</sub>	N <sub>num</sub>	N <sub>hop</sub>
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Table 4. Meaning of the Fields

ID <sub>x</sub>	ID of data packets
ID <sub>s</sub>	Address of the source node
ID <sub>bp</sub>	Number of sub paths
N <sub>y</sub>	Sub-path hop counts
N <sub>num</sub>	Times of paths needing to be used repeatedly
N <sub>hop</sub>	Hop counts which paths travel through

B. If  $SDR' < SDR$ , then it means the model fails to meet the requirements and thus we need to adjust the Nnum value of sub paths so as to increase the number of logic sub paths and meet the requirements.

#### 4. Performance Analysis

In this section, we will make comparison and analysis of the SDR and NR indicators for the newly-built model and NC-BMR model under the same topological environment, with the same parameters to be given as well.

Figure 4 is the network topology of the newly-built model. The length of the data packet delivered is 512bit. Hop counts H is 5. The number of nodes in each cluster N=2. The pre-coding data packets are split into K=3, and the after-coding data packets K'=5.

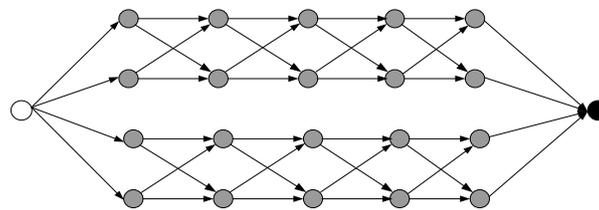


Figure 4. Network Topology for the Newly-built Model

Make comparison of the two kinds of models respectively with the number of data packet split as  $m=1,3,5,7$  respectively. SDR and NR are shown separately in Figure 5 and Figure 6.

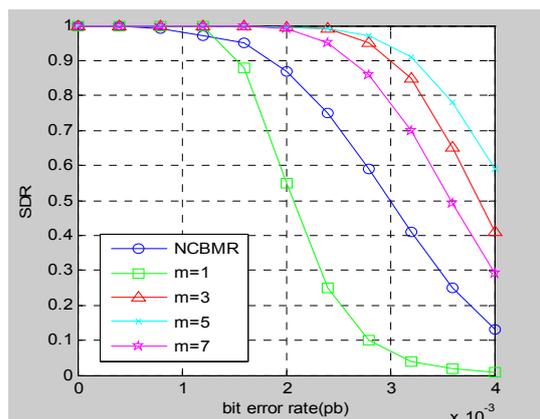


Figure 5. SDR of the Two Models

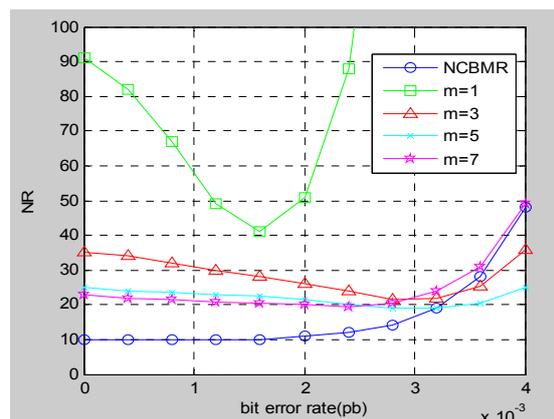


Figure 6. NR of the Two Models

Here, we come to the conclusions from the above figure as follows:  $m$  Value exerts direct influences upon the SDR of the newly-built model. As seen from the figure, the relationship of these SDRs in time of an identical bit error rate is:  $SDR_{m=5} > SDR_{m=3} > SDR_{m=7} > SDR_{m=1}$ . It is not that the higher the  $m$  value is, the higher the SDR of the model will be. When the  $m$  value is too low and the data packet length is too large, the per-hop data transmission rate of success will drop. Even though fewer data packets received will make it possible to restore the original data, since of low probability for the data packets to be correctly delivered to the sink nodes, it will still lead to the drop of the model's SDR. When  $m$  is too large, it increases the data redundancy on one hand, leading to an over-short data packet length after coding and a coding coefficient occupies too high a proportion, while on the other, the sink node needs to receive more data packets before it can restore the original data and thus reduces the SDR of the model.

As we can see from Figure 6, when the bit error rate is low, the NR of the new model will be higher than that of the NC-BMR model as it transmits more data packets. With the increase of bit error rate, when the new model selects the proper  $m$  value, the NR will come down lower than that of the NC-BMR model because the data SDR of the new model decreases less. Besides, we can also get from the figure that the  $m$  value exerts great influences upon NR, whose quality stays basically at the same level with SDR.

## 5. Conclusion

With the use of the Node Coding technology and the multi-path technology, NC-RMR strengthens the network reliability, and meanwhile reduces the number of desired sub paths and helps to balance the network loads. Then introduce partial data redundancy through applying the random linear network coding technology of the finite field, in which case it will enable the sink nodes to restore the original data packets in time of packet disorders and partial data packets loss. All in all, NC-RMR will better display its superiority in networks of poor signal channel quality.

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