Energy Efficient Reliable Multi-path Routing Using Network Coding for Sensor Network

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Abstract：
With the advantage from network coding, the packets are encoded at source and intermediate nodes respectively, and the sink node obtains the data by decoding. Even if partial packets are lost, some nodes or links are failure, the original data can be recovered at the sink node. This paper presents an Energy Efficient Reliable Multi-path Routing Using Network Coding (NC-EERMR) routing protocol for sensor network. NC-EERMR employs hop-by-hop method to form multi-path, and each node only maintains the paths from local nodes to the next hop ones without establishment of end-to-end paths. During the next hop node election, the neighbor nodes are divided into groups, and the data is sent to the next hop node whose hop to sink node is fewer. Through theoretical and simulation results, NC-EERMR protocol reduces the required transmission path number and redundant data, ensures the reliability of transmission, and reduces node energy consumption.
Keyword: network coding, multi-path Routing, reliable transmission, wireless sensor networks

1. Introduction

The existing reliable transmission mechanism for wireless sensor network includes the traditional FEC(Forward Error Correction), ACK(Acknowledgement), multi-path transmission, and some new technology such as network coding.

Multi-path routing can establish more than one path in procedure of routing discovery, then reduce times of routing discovery. It can utilize link redundancy to enhance system delivery rate and reduce the control cost and end-to-end delay. It is typically proposed in order to increase the reliability of data transmission or provide load balance[1,2,3,4]. Reference [1] executes multi-path expansion for AODV(Ad hoc On-demand Distance Vector) routing, and proposes AOMDV(Ad hoc On-demand Multipath Distance Vector) routing as one kind of multi-path routing protocols. Reference [7] considers reliability , channel quality as well as the hop number from sensor nodes to sink node, decides necessary path number as well as next hop node number, and implements one kind of data transmission mechanism to satisfy certain reliable demand, which is called ReInForM.

The Directed Diffusion Protocol[5] adopts three-stage operation including diffusion, data spreading and path strengthen cyclically, which can adapt node failure, topological change. Multi-path Source Routing (MSR) protocol[6] is based on the routing establishment and routing maintenance of DSR （Dynamic Source Routing） to adapt the multi-path routing. It returns a number of paths during the routing establishment.

Although multi-path routing increases reliability of transmission, many paths increase data redundancy and energy consumption. On the one hand, Multi-path routing adopts parallel mechanism to transmit data, the different performance of paths leads to much difference in data transmission delay and chaotic data in the sink. On the other hand, the data loss increases duo to frequent network topology change and link error. Network coding technology brings new mechanism for error control.

In traditional networks, the intermediate nodes carry out path search and transmission mechanism, and the received information flow is transmitted directly to the next node (unicast),or transmitted to many nodes after duplication (multicast). Because network information is one kind of continuous bit flow, it should also be executed with some mathematical operation. Network coding may bring enhancement of throughput, multicast efficiency and robustness for the network.

Much research focuses on random distributed network coding and realization of network coding in actual environment [8] [9]. Leong[10] presents a random network coding algorithm, and compares this algorithm with Steiner tree generation algorithm and Dijkstra shortest path algorithm. Reference [11] presents an optimal algorithm combined distributed source coding with network coding whose purpose is to improve reliability and fault-tolerant of sensor network, meanwhile consider compression efficiency and robustness of distributed source coding.

Reference [12] presents detection strategy based on random network coding. All the raw data are transformed simply by the polynomial hash function, and the sink node can judge whether the data packets are revised through the decoding of received data and hash value.

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COPE[8] is the first study of the network coding implementation in real wireless environment. However, the protocol requires nodes to store data packets and encode them. If the network has congestion, it may cost more storage space of the nodes.

There are also some references [13,14,15,16,17,18] to investigate the robustness of network coding. Reference [15] investigates some basic attributes of network error correction algorithm and main sources of network error, defines the least rank of network error correction coding, which enhances the probability of error recovery distinctly. Reference [19] applies theory of network coding into the ReInForM(Reliable Information Forwarding using Multiple paths) , and analyzes quantitatively the performance of network coding. Path number of multi-path routing with network coding is computed, and comparison of paths with and without network coding is made, which demonstrates that multi-path routing with network coding has better redundancy control compared to traditional multi-path routing.

In this paper, we present an Energy Efficient Reliable Multi-path Routing Using Network Coding (NC-EERMR) routing protocol for sensor network in order to satisfy reliable transmission demand. In second section of this paper, some related work is introduced to demonstrate the main operation principle and some improvement of our protocol. In third section, network model and network coding parameters are described. In forth section, NC-EERMR routing protocol design is discussed in details. Analysis and simulation results are finished and compared in section five, which is followed by some conclusion in section six.

2. Related work

Reference[7] presents a reliable routing protocol based on the requirement of transmission reliability. From the source node, reliability and current status such as channel quality and hops to sink nodes are considered to determine the number of transmission paths, and the number of next hop nodes to meet the expected reliable data transmission. The protocol is based on the idea of multiple copies of one packet sent on some random selection paths. Not only the packet is copied in source nodes, but also it can be copied in intermediate nodes. This path number increasing mechanism guarantees the reliability of transmission, but it increases the network cost. It's not an ideal choice to wireless sensor networks with limited energy, and the protocol will reuse some paths, which is difficult to make network load balance.

NC-EERMR routing protocol in this paper fully considers the data transmission reliability and redundancy, adopts hop-by-hop multi-path mechanism, considers the transmission reliability for each hop, chooses the optimal next hop as the path beginning, and takes into account the distribution of other nodes. Encoding operation is implemented in the source node and intermediate nodes, and decoding data is carried out in sink nodes. The routing is suitable for wireless sensor network model with poor channel quality and higher reliability requirement.

In reference [13], the authors balance energy consumption and transmission reliability in wireless sensor networks, and present an algorithm combined multi-path routing with FEC. On the base of multi-path mechanism, disjoint and braid multi-path is introduced, and then packet is divided into a number of small data packets and data redundancy is added to the packets. The article analyzes the least path number required for the expected successful delivery rate. Reference [20] calculates path number after network coding. But it does not give special design for the network coding protocol, and the path estimation exits certain error with the real requirement. NC-EERMR routing protocol in this paper considers the adaptive adjustment of paths, and designs a network coding based multi-path routing protocol.

From the view of channel error rate, reference [21] analyzes quantitatively the multi-path routing with network coding. NC-EERMR employs and expands the multi-path network model and system performance parameters from reference [21].

Reference [22] analyzes linear network coding, selection of coding coefficient and complexity of coding algorithm, and further draws conclusion that network coding can improve the network throughput, enhance the fault-tolerant and robustness of network. In this paper, random network coding model from reference [23] is employed, it need not know the entire network topology, and it only chooses a suitable encoding vector in limited domain to ensure the effectiveness of encoding data.

3 Network Model and Network Coding Parameter

3.1 network model

Flooding multi-path routing model of single source and sink node pair is shown in Fig 3.1. Data is sent from source to sink node, and in order to ensure reliable transmission, flooding broadcast to the sink gradually is employed through many intermediate nodes. According to the hop from intermediate nodes to sink node, nodes are divides into N sets, which are represented from 1st layer to N th layer respectively. Assume that there is not any intersect between sets, and the node number contained in each set is represented with n_i , here $i = 1 \dots N$. Moreover the sink node is in the set N .

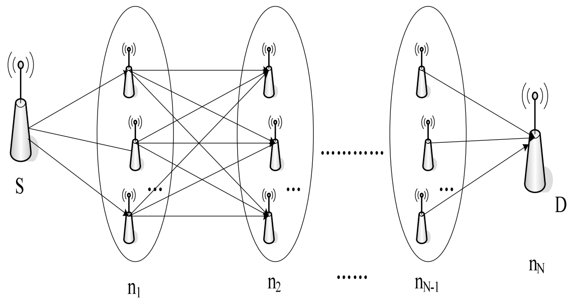

Fig 3.1 multi-path routing model with flooding

The source node encodes the original packets with network coding mechanism and broadcasts data packet to the next hop node set, in view of channel quality, there are parts or all nodes in the next hop node set to receive this packet, and these nodes encode the received packets again with proper coding coefficients and continue to broadcast packets to the next hop. Assume that data always transmit along sink node direction, then nodes in each node set judge the packet whether it is from the upwind node set after receiving data packet. If so, it judges whether it already received this packet, if it had already received, it just discards, if it has not, it encodes and continues to broadcast this packet to each node in the next node set until the data arrive at the sink node where the packets are decoded to recover the original data packets.

In this model, suppose each hop which makes a mistake is mutually independent, the error probability of each hop transmission is e, which is channel error rate. The probability of correct packets received by a node in the i th node set is a_i. $a_{i\ n}$ represents the probability of n nodes in the i th layer node set which receive a packet correctly.

3.2 parameters of network coding

In order to obtain better analysis of network coding based system, two parameters are defined. One is the reliability parameter r, which represents the probability of successful transmission from the data source to the sink node and is called reliability. The other is the redundancy p, which represents the average number of transmission packets for successful packet transmission. When the sink node achieves the same reliability, the smaller redundancy p has better transmission performance.

(1) finite field F_q of network coding

This paper adopts stochastic linear coding method. Under the stochastic coding strategy, for all nodes besides the sink node, the mapping from the input to the output link in sufficient finite field is selected stochastically. This finite field value range decides independency probability of coding coefficient, then affects the stochastic linear coding performance. If the field value is too small, even if the sink node receives sufficient coding packets, because the coding coefficient has high linear correlation, the original packets are unable to be recovered. If the value is oversized, encoding coefficient takes too many bytes which will cause memory storage cost. In reference [6], the authors point out that when finite field achieves 2^{16}, then for any group of the sink nodes, its probability of successfully decoding is 0.996, and the unsuccessful probability duo to the encoding vector linear correlation can be neglected.

(2) encoding coefficient l

In network coding, encoding coefficient l is the ratio of n packets after network coding with m original packets at the source node, then

$$l = \frac{n}{m} \qquad (3.1)$$

The bigger l is, the more encoding packets for the same original packets exist, the more packets received by sink node correspondingly comes up. The probability of linear uncorrelation can be increased, but some resource cost increases. If coefficient l is too small, then the number of encoding packets received by the sink node is possibly smaller than m. According to the decoding condition of the stochastic linear network coding, the sink node will be unable to decode the packets, and then can not recover the data.

4. NC-EERMR routing protocol design

This improved routing protocol aims to guarantee reliable transmission of wireless sensor network, and has enhancement in energy consumption, load balance and data redundancy.

Multi-path routing has small delay, load balance, large throughput, and can ensure high reliable data transmission, which is one of main reliable transmission mechanisms in wireless sensor network. In order to ensure end-to-end reliable transmission, ReInforM routing[7] considers channel quality and the hops from source to sink nodes to decide the needed transmission path number, as well as next hop node number and the corresponding node selection, realizes the expected successful data transmission. But this routing exists some disadvantages and NC-EERMR makes some progress described in section two. Following is the main design description of NC-EERMR routing protocol.

4.1 path number calculation

The source node encodes m original packets into n （$n \geq m$） packets whose size is the same. If m is too small, network coding superiority can not exert sufficiently. If m is too large, much storage space and other disadvantages will manifest for sensor network. Suppose that successful delivery of m original packets needs M paths. The formula of calculating M is as following.

Suppose that each node knows the channel quality of its neighbor nodes, which is represented by channel error rate e, and the channel quality of each node to its all neighbor nodes is the same. For the source node, each hop action is an independent event, and the successful delivery probability of each hop is （1-e）. Then after k hops, the successful delivery probability $p(k)$ of packets arrived at the sink node is:

$$p(k) = (1-e)^k \qquad (4.1)$$

According to decoding condition of linear network coding[13], if the sink node can correctly recover m original packets, then the sink node needs to receive m encoding packets at least. At least m paths in all M paths successfully are in operation to satisfy the expected reliability r, and such experiment satisfies Bernouli model expressed in formula 4.2.

$$r = 1 - \sum_{i=0}^{m} C_M^i (1-(1-e)^k)^{M-i} (1-e)^{ki} \qquad (4.2)$$

Sometimes it does not always exist M paths in which each path has k hops, therefore some parallel paths can be used to transmit packets. m original packets demand M paths in certain reliability, then reliable packet transmission needs M/m paths. In application, above formula is not convenient, so some estimation such as normal distribution is used to ensure certain accuracy.

Normal distribution $N(\mu,\sigma)$ is used to estimate Bernouli model. The average value μ and variance σ can be expressed as follows:

$$\sigma^2 = M(1-e)^k (1-(1-e)^k) \qquad (4.3)$$

$$\mu = E(n) = M(1-e)^k \qquad (4.4)$$

For standard normal distribution, any suppose r has $P(n \geq x_r) \geq r$, so the boundary x_r value can be obtained.

Then the path number M can be calculated by formula(4.5).

$$m = x_r \sigma + \mu = x_r \sqrt{M(1-e)^k (1-(1-e)^k)} + M(1-e)^k \qquad (4.5)$$

From the above formula, path number M may be obtained for m data packets in certain reliability transmission after adopting network coding. In the above estimation process, the value M which uses normal distribution will be larger than the ideal value obtained by (4.2). In order to be closer to ideal value, auto-adaptive adjustment is demanded. Because simulation value m is not very large in this paper, the error adjustment for M is as following:

$$M = \left\lfloor \frac{M+1}{m} \right\rfloor * m \qquad (4.6)$$

In the formula, hops k from the source node (or intermediate nodes) to the sink node can be obtained by the following mechanism: the sink node periodically broadcasts routing updating information to neighbor nodes, this information includes a field which contains hops to the sink node. After the neighbor node receives this, it updates local hops, and adds 1 into hops in the information which points to the sink node, then broadcasts this to neighbor nodes, and each node setting is updated, moreover the renewed nodes do not treat new information. Like this, each node can know its own hops to the sink node and the hops in its neighbor nodes to the sink node. Therefore, before the data starts transmission, the sink node must carry on reverse broadcast information in order to obtain hop information. The following explains the path establishment and transmission allocation process.

4.2 data transmission from the source node

NC-EERMR routing algorithm requests that the source node encodes data before transmitting data. According to the packet order, each m data packets are arranged to be a group, which is represented by $X_1, X_2, \cdots, X_m$. The group order increases from 0 to a upper limited value, and then returns back to 0. When the source node transmits the packets in this group, it selects m random number as encoding coefficient ($g_{i,1}, g_{i,2}, \cdots, g_{i,m}$) from the finite field Fq (here q=8). According to formula (4.7), encoding is made to become encoded packets Y_i, simultaneously encoding coefficient and group identification are added to the packets head.

$$Y_i = \sum_{j=1}^{m} g_{i,j} X_j, i = 1,2,\cdots,n \qquad (4.7)$$

After network coding, the packet format is shown at Fig.4.1. This packet head includes path number, hops to the sink node etc..

ID	Coding efficient	hops	Path number	Coding data

Fig4.1 packets format of NC-EERMR

If n encoded packets Y_i is produced, then the same encoding operation should be made n times. The value n affects redundancy, and optimal n transmitted from the source node should be larger than m.

If the needed path number is larger than neighbor number of source node, then in the scheduled time it allows some neighbor nodes to receive multiple data from source nodes. In order to ensure reliable transmission, it must select the next hop node according to certain rule.

4.3 next hop node selection and path number assignment

According to the number of hops from neighbor nodes of the source to sink nodes, the neighbor nodes are divided into three categories by the source node: the nodes that have the same hops to the sink node with the source node, the nodes whose hops are smaller to the sink node, and the nodes that are more than one hop. These three types of nodes were expressed by H^0 , H^- , H^+ respectively. In order to ensure that all the selected neighbor nodes can provide M paths to send data, assume that in the three types of nodes, K^0, K^-, K^+ nodes are selected respectively, and the number of paths are P^0, P^-, P^+ for the source node, which is represented as 4.8:

$$K^0\ P^0 + K^-\ P^- + K^+\ P^+ = M \quad (4.8)$$

P^0, P^-, P^+ are arranged as follows:

$$P^- = \frac{P^0}{1-e} = \frac{P^+}{(1-e)^2} \quad (4.9)$$

The process which source node chooses next nodes to transmit data is as following.

First, Taking into account that the hop number should be as little as possible, the source node first chooses the nodes in H^- as the next node. If the number of hops calculated is less than the nodes in H^-, then the nodes in H^- can meet the reliability requirements. Otherwise, additional nodes are needed, the number of the additional paths is:

$$N_l = M - K^- \quad (4.10)$$

Additional paths are first selected the nodes from H^0. Only when the value calculated according to formula 4.10 is greater than the number of nodes in H^0, then it is necessary to select the nodes from H^+. According to the formula 4.8 and 4.9, the paths that the next node creates for the source node can be calculated. The path number calculated is added as a parameter of the packet head, and transmitted to the next node with the encoding data.

If the expected path number is greater than the neighbor node number, some neighbors will receive multiple data from the source node within a certain time interval. Here the nodes in H^0 and H^+ are selected as next nodes in order to maintain the network load balance.

4.4 encoding and transmission of the next node

Suppose that the next node R receives the encoded packets $Y_1, Y_2, ...Y_b$ with the same group identification from the source node, the correspondent encoding coefficient is ($g_{i,1}, g_{i,2}, \cdots, g_{i,m}$) for each Y_i, here $i = 1,2,\cdots,b$. Y_l^r is taken as new encoded packets, $h_{i,l}$ is the encoding vector after encoding, and this node will create b new encoding packets according to the formula 4.11.

$$Y_l^r = \sum_{i=1}^{b} k_{i,l} Y_i = \sum_{j=1}^{m} h_{i,l} X_j , l = 1,2,\cdots b \quad (4.11)$$

$k_{i,l}$ is the new encoding vector in the limited domain F_q. According to the following formula 4.12, it can obtain new encoding vector in the data packets after re-encoding:

$$h_{j,l} = \sum_{i=1}^{b} k_{i,l} g_{i,j} \quad (4.12)$$

When the next node re-encodes the packets received, because each packet has the number of assigned paths, so in the new packets, the largest number in original packets is taken as the number of the assigned paths, and added into the head of new packets. After the next hop node creates the new packets, it continues to send forward to its own next hop node. Because of the difference of the channel quality and hops to the sink node, in order to ensure the reliability designated by the source node ,it is necessary to re-calculate the reliability demanded by this current node.

The probability of successful transmission from the next node to the sink node $p(k)$ is

$$p(k) = (1-e)^{k-1} \quad (4.13)$$

The path number distributed for this node is N, the probability that the N paths can not send data packets successful is:

$$p(N) = (1-(1-e)^{h-1})^N \quad (4.14)$$

The reliability that this node needs is

$$r_i = 1 - (1 - (1 - e)^{k-1})^N$$

(4.15)

The path number is calculated according to r_i, k, e. This node chooses its next node with the same method as the source node, and assigns the path. This process goes on until the data arrives to the sink node.

4.5 decoding and data recovery of sink node

When the sink node receives m (or more) encoded data, it can recover the original m packets with the method of matrix conversion.

Suppose that m data packets receive by sink node are $Y_1, Y_2, \cdots, Y_m$, then the sink node checks further the linearity correlation of encoding coefficient ($g_{i,1}, g_{i,2}, \cdots, g_{i,m}$) ($i = 1,2,\cdots,k$) of these m data packets. If this encoding coefficient satisfies the full rank matrix, it can recover m original packets by formula 4.16.

$$\begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_m \end{bmatrix} \begin{pmatrix} g_{1,1} & \cdots & g_{1,m} \\ \vdots & \ddots & \vdots \\ g_{m,1} & \cdots & g_{m,m} \end{pmatrix} \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_m \end{bmatrix} \Rightarrow \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_m \end{bmatrix} = \begin{pmatrix} g_{1,1} & \cdots & g_{1,m} \\ \vdots & \ddots & \vdots \\ g_{m,1} & \cdots & g_{m,m} \end{pmatrix}^{-1} \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_m \end{bmatrix} \quad (4.16)$$

When the encoding data that the sink node received are less than m, it can inform the previous node to re-encode and transmit the same group data in the memory buffer by the packet feedback mechanism, until the sink node can recover m original data packets.

NC-EERMR routing algorithm is an excessive number of paths that are not fixed, ensures that each hop has excessive paths to transmit the packets, and each step of transmission guarantees the expected reliability by the source node. Therefore, the entire transmission process can ensure the reliability. On the other hand this protocol does not repeat to choose some paths which is propitious to the network load balance. At the same time, NC-EERMR routing protocol employs network coding technology and the mechanism of random linear coding at the source node and intermediate nodes, and decoding in sink node makes sink nodes recover the original packets from the chaotic sequence and information loss.

5. Performance Analysis of NC-EERMR Routing Protocol

NC-EERMR routing protocol which considers the transmission reliability with hop-by-hop makes data transmit along excessive paths through coding operation, and obtains the data in the sink node. This protocol improves data transmission reliability and saves the energy consumption. The performance of reliability, redundancy and normalized energy consumption is analyzed by the simulation of NC-EERMR routing algorithm.

The network topology is a 100m*100m square region, and 200 nodes distribute randomly in this region. During simulation, the source node is at the most bottom-left of this region, the sink node is at the most top-right of this region, and channel bit error rate obeys normal distribution along with the mean value and variance. MAC layer of nodes runs IEEE802.11 protocol. The node transmission radius is 15m. Each packet is 100 bytes before being coded, the head has the 4 bytes coding vector after coding. The simulation time is 800s. Suppose that each node has enough buffer to store the received data, and the buffer is cleared automatically while each transmission has completed.

In order to make comparison, the path number calculation of ReInforM routing algorithm is made first. The source node in ReInforM routing decides path number to ensure the reliability by three parameters of reliability r, channel error e and hops k. According to reference [7] the path number N that one packet can transmit successfully from the source node is :

$$N = \frac{\log(1-r)}{\log(1-(1-e)^k)} \quad (5.1)$$

The path number that the source node demands to deliver m packets successfully is:

$$M' = mN \quad (5.2)$$

5.1 Reliability and redundancy

(1) relationship of reliability and path number

Let bit error rate be 0.7×10^{-3}, the hops from the source to sink nodes be 6, and 4 original packets form one group. Under this situation, performance influence of multi-path number on transmission reliability is studied.

Let NC-EERMR-Ana is the result of theoretical analysis, and NC-EERMR-Sim is the result of simulation from simulation tool. The result of ReInforM is the theoretical analysis from paper[7]. The result in figure 5.1 indicates that our theoretical analysis is consistent with the simulation method, and the data transmission reliability obviously enhances while path number increases, moreover the reliability of NC-EERMR routing algorithm increases more quickly, which is better than ReInforM at the same path number. Under a certain reliability situation, path number of system with network coding mechanism is fewer than that without network coding. At the situation that the path number is 16, NC-EERMR routing can guarantee 95% reliability, but ReInForM routing needs 24 paths to guarantee the similar reliability. Because NC-

EERMR routing algorithm need not guarantee that each data packet is received correctly, the sink node only need receive partial coded packets to recover the source data correctly, and it is also mutually independent among these coded packets, therefore, the higher the expected reliability is, the larger the difference of the path number under these two kind of mechanisms with or without network coding is. While the path number reduction of the NC-EERMR routing algorithm means that fewer data packets can be transmitted, then the energy consumption is also reduced. NC-EERMR routing algorithm may remarkably enhance the transmission reliability and successful delivery rate, and confirm the accuracy of the theoretical analysis, too.

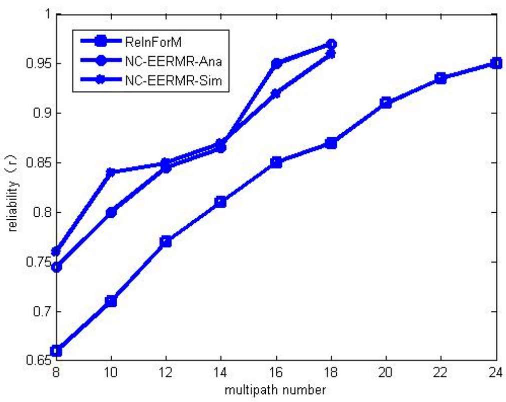

Fig.5.1 relationship between reliability and path number

(2) path number under different bit error rate and node hop

The path number reduction does not affect the reliability of NC-EERMR routing algorithm, because network coding technique is used in the algorithm to allow the partial information loss or partial link failure when the sink node decodes. Of course, there are many factors to affect path number, including channel error rate (bit error rate), network hop number, encoded packet number and so on.

Figure 5.2 stands for the influence of several parameters. In figure (1), the reliability is set to be 0.8, the hop number from the source to sink nodes is set to be 6, and one group has 4 original packets. From the figure, with the bit error rate increasing, the demanded path number also increases, and this tendency is especially obvious when the error rate is much higher. But under the same channel condition (or the same error rate), the path number which NC-EERMR routing algorithm need guarantee that certain reliability transmission is lower than that of ReInForM routing. When the error rate is higher, the difference of path number is bigger, and this means that NC-EERMR routing can manifest its superiority when the channel is bad.

If the bit error rate is set to be 0.7×10^{-3}, and other parameters are defined as that in the figure (1), figure (2) stands for change of path number caused by hops from the source to the sink nodes. Along with hop number increasing, the successful delivery rate of each path drops, thus path number of packet transmission increases. But path number of NC-EERMR routing algorithm increases smaller, and is less than that ReInForm under same the hop number. To some extent, the transmission energy reduces when path number decreases.

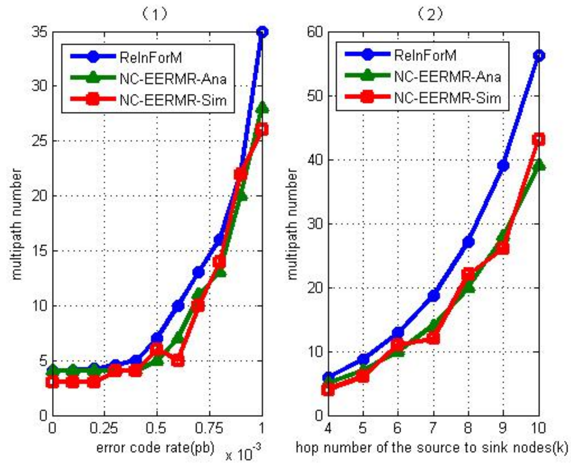

Fig.5.2 path number under different bit error rate and node hop

5.2 Normalized energy consumption

Figure 5.3 stands for the energy consumption of main components in wireless sensor networks. Here MCU is Micro Controller Unit. Network energy consumption is mainly from data sending and receiving.

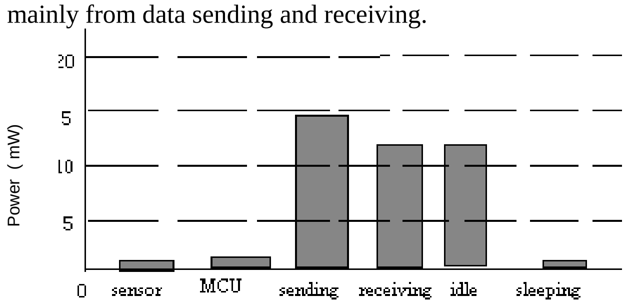

Figure 5.3 energy consumption of main node modules

According to communication theory, the energy transmitting 1 bit information per 100 m is probably equal to carrying out 3000 computation instruction. Therefore, some computation due to network coding such as operation of matrix is smaller relative to transmission, and this kind of computation consumption may be almost neglected.

Next, the energy consumed due to data transmission is studied, and normalized energy consumption is the change of energy quantified as transmission bytes.

ReInForM routing needs N transmission paths for expected reliability, and the energy consumption $O_{\mathrm{Re}\,InForM}$ for ReInForm routing protocol can be expressed as:

$$O_{\mathrm{Re}InForM} = N_s \sum_{i=0}^{k-1} (1-e)^i = \frac{(1-(1-e)^k)\log(1-r)}{e\log(1-(1-e)^k)} \qquad (5.3)$$

The path number is M for NC-EERMR route protocol, then the consumed energy $O_{NC-EERMR}$ is :

$$O_{NC-EERMR} = M \cdot \sum_{i=0}^{k-1} (1-e)^i = M \cdot \frac{(1-(1-e)^k)}{e} \qquad (5.4)$$

Assume that reliability is 0.7, hops from the source to the sink nodes is 7, and data packet size is 104bytes. Figure 5.4 presents the protocol energy consumption in the different channel error rate. From the figure, with the channel error rate increasing, the successful delivery byte number must also increase. Under the same channel condition, transmission bytes of NC-EERMR routing is less than that of ReInForM routing, particularly when the channel error rate is higher, this kind of superiority can manifest. Energy consumption of sensor networks are mainly from data transmission, which is quantified to be the bytes. Therefore network energy consumption reduces when the transmission byte number reduces.

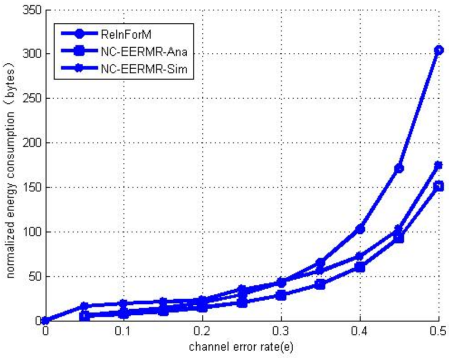

Fig.5.4 relationship of energy consumption and channel error rate

In NC-EERMR route protocol, network coding technique requires the node with certain operational capability. The random linear network coding carries out on the line operation to consume certain energy, and this protocol requires the coding vector in packets, and it need consume energy to transmit these vectors. These two kinds of energy consumption are called metadata consumption of network coding. Then the extra energy consumption of metadata has tremendous influence on the entire routing protocol. Figure 5.5 represents simulation results for this situation.

There are 4 packets in one group, the source node arrives at the sink node through 6 hops, each encoding vector takes 4 bytes, the total length of data packet is 104 bytes. When the channel error rate increases, the metadata consumption in NC-EERMR routing protocol goes up slowly around 50bytes,but that of ReInForM goes up faster. if the channel quality is quite good, the probability that each path makes a mistake is very small, the superiority of network coding cannot manifest. Therefore, network coding may improve network performance largely for the network with bad channel quality.

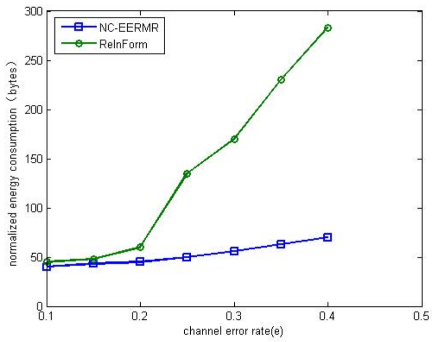

Figure 5.5 relationship of metadata energy consumption and channel error rate

6. Conclusion

From the simulation results, because of network coding and multipath, NC-EERMR routing protocol enhances the reliability of sensor network greatly, manifests directly the reduction of the transmission path number. This protocol obeys network coding rule, as long as the appropriate finite field space is selected, the sink node can recover the original packets from the packets which have chaotic order or partial information loss. When the channel quality is bad, the superiority of network coding manifests better. The path reduction and network fault tolerance cause energy consumption to decrease largely.

(1) This protocol is hop-by-hop multipath without end-to-end path establishment, each node only maintains local routing information to next hop nodes without broadcasting much routing information for the overall routing, and this mechanism reduces routing broadcast greatly, and reduces routing consumption.

(2)This protocol considers the link quality of wireless sensor network, and decides the next hop node according to paths assigned. During the next hop node election, the neighbor nodes are divided into groups, and the data is sent to the next hop node whose hop to sink node is fewer. This not only can use the most effective routing transmission, but also it is advantageous for network load balance.

(3) Another design for this protocol is to employ network coding technique. With appropriate coding coefficient, coding operation carries out at the source node and intermediate nodes, but only the sink node decode the packets to recovery the original data. The sink node need not receive all the packets transmitted from the source

node, only if the coding vector satisfies the decoding condition , the original packets can be decoded. Therefore, the path number and redundant data can be reduced, and the network fault tolerance is high.

(4)This protocol is high energy effective. Hop-by-hop can reduce the expenses of the routing broadcasting, and network coding can reduce the redundant data transmission. All of these can lead to the energy consumption reduction.

There are much research which is worth discussed in network coding for wireless sensor network on reliable transmission.

(1) The concrete implementation of the network coding in the actual network environment need consider some factors such as synchronization and coding coefficient choice.

(2) Complexity of network coding scheme should be reduced. How to implement one kind of minimum network coding without remarkable expense is very important.

(3) Unification technology of network coding with other network technology should be studied.

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