symmetry

MDPI

Article

Reliability Improved Cooperative Communication over Wireless Sensor Networks

Zhuangbin Chen [1], Ming Ma [2], Xiao Liu [1], Anfeng Liu [1,*] and Ming Zhao [3]

1 School of Information Science and Engineering, Central South University, Changsha 410083, China; zhuangbinchen@csu.edu.cn (Z.C.); xiaoliu@csu.edu.cn (X.L.)
2 Department of Computer Science, Stony Brook University, New York, NY 11794, USA; minma@cs.stonybrook.edu
3 School of Software, Central South University, Changsha 410075, China; meanzhao@mail.csu.edu.cn
* Correspondence: afengliu@mail.csu.edu.cn; Tel.: +86-731-8887-9628

Received: 15 August 2017; Accepted: 22 September 2017; Published: 1 October 2017

Abstract: With the development of smart devices and connection technologies, Wireless Sensor Networks (WSNs) are becoming increasingly intelligent. New or special functions can be obtained by receiving new versions of program codes to upgrade their software systems, forming the so-called smart Internet of Things (IoT). Due to the lossy property of wireless channels, data collection in WSNs still suffers from a long delay, high energy consumption, and many retransmissions. Thanks to wireless software-defined networks (WSDNs), software in sensors can now be updated to help them transmit data cooperatively, thereby achieving more reliable communication. In this paper, a Reliability Improved Cooperative Communication (RICC) data collection scheme is proposed to improve the reliability of random-network-coding-based cooperative communications in multi-hop relay WSNs without reducing the network lifetime. In WSNs, sensors in different positions can have different numbers of packets to handle, resulting in the unbalanced energy consumption of the network. In particular, nodes in non-hotspot areas have up to 90% of their original energy remaining when the network dies. To efficiently use the residual energy, in RICC, high data transmission power is adopted in non-hotspot areas to achieve a higher reliability at the cost of large energy consumption, and relatively low transmission power is adopted in hotspot areas to maintain the long network lifetime. Therefore, high reliability and a long network lifetime can be obtained simultaneously. The simulation results show that compared with other scheme, RICC can reduce the end-to-end Message Fail delivering Ratio (MFR) by 59.4%–62.8% under the same lifetime with a more balanced energy utilization.

Keywords: wireless sensor networks; cooperative communications; adaptive transmitting power; message fail delivering ratio (MFR); network lifetime

1. Introduction

The Internet of Things (IoT) [1–4] uses smart equipment such as sensor-based devices [5–11], smartphones [12] and vehicle sensor devices [13] to gathering information and give a different method for carrying out complex data-sensing-based tasks to satisfy the significant demands of critical infrastructures [14–18], such as environmental and weather monitoring systems [19–23]. Wireless Sensor Networks (WSNs) has large numbers of sensor nodes, it has huge potential to solve military and civilian domains [24–29]. Portable devices usually operate on their own to solve a single or multiple signal processing tasks (such as communications) in a non-cooperative fashion. Having the ability to achieve superior performance without a dedicated and power-hungry central device, distributed and cooperative processing techniques over WSNs have received much attention [28,30,31]. Recently, multi-input-multi-output (MIMO) systems has higher promising to improve transmission reliability [25,28,32]; in WSNs, this feature can be obtained by receiving new versions of program codes that are disseminated from a sink node.

For data collection, some sensing applications have the strict requirement. The arrival ratio of data packet should be high [32]. Studies revealed that only the number of hop from source to the sink is 5, the end-to-end reliability is less than 73.51%, its reliability is less [32]. Due to the inherent characteristic of constrained resources, data packet is transmitted to the sink, the energy consumption in the area near to the sink is higher than other areas, the energy left of other nodes can be used to improve network performance [3,4,6,30–32].

In WSNs, the packet can be lost by malicious nodes. Liu et al. proposed a communication scheme named the Network Coding-based Cooperative Communications scheme (NCCC) as shown in Figure 1 [31], which achieves high reliability through the cooperation of multi-nodes, where the data transmission reliability can be evaluated by Message Fail delivering Ratio (MFR). Generally, increasing the data transmission power of a node is an effective method to improve the data reliability. However, this method will increase the energy consumption of the node, thereby shortening its lifetime [10]. Numerous studies have shown that there is a trade-off between energy efficiency and data reliability [25,28,30,32]. Determining how to guarantee the data transmission reliability while maintaining the lifetime of the node is a challenging issue. In this paper, based on a WSDN in which software inside the sensors can help them construct clusters to perform the data collection task, a data collection scheme named Reliability Improved Cooperative Communications (RICC) is proposed to increase the network reliability and energy utilization ratio without harming the network lifetime. The invitations are as follows:

(1) A Reliability Improved Cooperative Communications (RICC) with adjustable data transmission power [31] is proposed, in which the residual energy in non-hotspots is fully utilized to increase the transmission power of nodes to improve the data transmission reliability, whereas in hotspot areas, the transmission power is unchanged to maintain the previous network lifetime. For cooperative communications, the higher the transmission power of the nodes is, the shorter the lifetime of the nodes is. Thus, if the data transmission reliability is kept the same as before, the network lifetime is damaged. Due to different nodes load different amount of data, the energy consumption of different nodes is different, the non-hotspots area has much energy left. Therefore, in this paper, RICC adopts higher transmission power in non-hotspot regions, while using the same transmission power in hotspots areas as in previous schemes. Because most nodes are in non-hotspot areas, RICC can effectively improve the data transmission reliability. To the best of our knowledge, for coding-based cooperative communication WSNs, RICC is the first data collection strategy that enhances the reliability without harming the lifetime.

(2) The effectiveness of RICC is evaluated in this paper, and compared with Network Coding-based Cooperative Communications (NCCC), RICC has following features: (a) the network energy utilization ratio is enhanced by as much as 50% on average; and (b) it significantly improves the reliability of data collection, and specifically, under the same lifetime, RICC can reduce the weighted end-to-end MFR by approximately 59.4% to 62.8%.

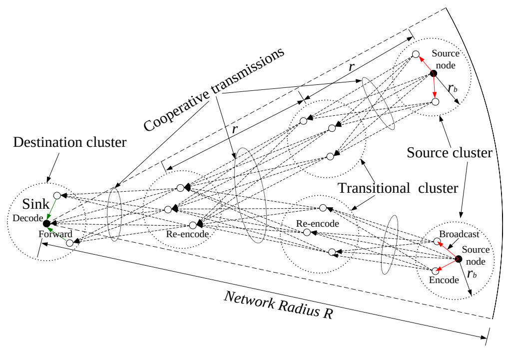

Figure 1. Network model.

2. Related Work

Many research works focus on improving the reliability of WSNs. In recent years, several methods and schemes with great data delivery rates have been proposed.

(1) Retransmission-based mechanism. Automatic Repeat-Request can improve reliability of data transmission compared with traditions scheme [32]. The main strategy of an ARQ protocol is as follows: once node transmits a data packet, it waits for an acknowledgement (ACK, a message sent by the receiver) indicating that its data packet was correctly received. The sender does not send any additional packets until it receives an ACK signal or a timeout. In contrast, with GBN and SR, the nodes transmit packets continuously without the need to wait for individual ACKs from the receiver; only the ACK for the last packet is required [32]. In WSNs, an ACK could possibly be lost, which results in the transmitter resending a packet that was already successfully transmitted but an ACK was not received correctly or in time. Thus, in [33], we proposed a scheme to reduce the retransmission of packets by increasing the transmissions times of ACK when the receiver manages to receive a packet. Additional ACK transmissions will not cause significant increases in energy consumption but can further improve the lifetime of the WSN [33]. The advantage of the retransmission-based mechanism is that it improves the network reliability at a low energy cost, so it is quite suitable for WSNs whose energy is extremely limited [4,32]. However, the unfavorable is that the network delay is usually long due to the repeat transmissions of data packets, especially in a link with high packet error rate [32] because the retransmission-based mechanism sends several data packets to the sink until the nodes receive ACK signals in response. If the ACK is dropped, nodes cannot receive the ACK and will send data packets to the sink, thereby increasing the transmission delay.

(2) Forward error correction (FEC) [34,35]. In the FEC scheme, when source node sends one data packet to the sink, the data packet is encoded through errors-correcting code. If the error ratio of data packet is in a certain value, the sink will correct the error of data packet using errors-correcting code. But the transmission bandwidth is higher, and the cost is higher [34,35]. The reliability of data packet in the FEC is improved, however, in this scheme, the cost for encoding the message in a redundant way is larger; thus, the network lifetime is shorter.

(3) Cooperative Communication (CC). Yu et al. [36], after an in-depth analysis on cooperative ARQ (automatic re-request), found that the cooperative ARQ protocols ensure the reliability of data packet better [33,36]. Zhang et al. [33], for the first time, determined the most appropriate value of the bit error ratio (BER) along with the number of cooperative nodes that reduce energy consumption for transmitting one bit of data through theoretical analysis. Then, they adjusted the transmission BER according to the energy left of nodes. As a result, not only could the energy of nodes in the clusters far from the sink node be fully used, but the energy cost of nodes in the nearer cluster could also be reduced, so the network lifetime was prolonged.

(4) Network coding techniques. In the network coding techniques, the source node encodes the packets at the application layer with some level of redundancy. Because the data transmitted by the source node have some redundancy, this approach will not affect the reception of the correct packets by the destination node. Network coding techniques have many advantages, such as small data transmission delay, while their main disadvantage is the relatively large energy consumption due to the complex algorithm. Other studies can be found in [37].

(5) Network-coding-based cooperative communications (NCCC). Reference [31] proposed a communication scheme whose main idea is the combination of coding techniques and cooperative communications. The scheme has two main operations: (a) the original data packets should be encoded before being sent from the source cluster and they should be re-encoded before being sent from the transitional cluster, where both encoding and re-encoding are performed using random network coding; and (b) in each hop, several sensor nodes with a certain probability of temporarily failing constitute a cluster to cooperatively send data packets. At the cost of acceptable delay, NCCC can achieve reliable performance. Although this scheme can achieve better reliability, the transmission delay is longer.

The major challenge of the schemes described above is balancing the transmission delay and network transmission reliability. When adopting a complex scheme, the network lifetime will be damaged due to the larger energy consumption. However, if the algorithm is simple, the network reliability cannot be guaranteed. Due to the disadvantage of these schemes, this paper uses the remaining energy of the nodes to increase the transmission power. In this way, the network reliability can be improved while preserving the network lifetime.

3. System Model and Problem Statement

3.1. Network Model

The network model is the same with Refs. [28,31,33], the network includes n homogenous sensor nodes. The studies area is a circular areas, its network radius is R (in meters), per-hop transfer distance r (in meters), and one sink node (base station) is in the center. Its density of nodes in the network is ρ. The network data collection strategy is the same as that of the NCCC algorithm proposed in [31]. The NCCC algorithm is a cluster-based data collection approach, and each cluster is assumed to be composed of N sensor nodes.

Node generates one data packet at probability λ. Considering sensor nodes is static, the energy of a common node is limited, and the energy of the sink is infinite [3,20,29]. In this paper, because the energy consumption for data transmission occupies a large part of the total energy consumption, only the energy consumption of data transmission is considered in this paper; the related studies are shown in References [29,30]. Although the total energy consumption of nodes includes the energy consumptions of small computations, sensing, and data encryption, the energy consumptions of these processes do not affect the effectiveness of the RICC scheme. The reasons are as follows: First, those energy consumptions are small compared to the energy consumption for data transmission; thus, most studies compute only the energy consumption for data transmission, such as References [3,6,24,28,31]. Second, the main innovation of the RICC scheme is to use the remaining energy of nodes in non-hotspot areas to increase the transmission power and thereby improve the communication reliability. Thus, the effectiveness of the RICC scheme is not affected by the remaining energy in the non-hotspot areas. Energy is left in non-hotspot areas because the amount of data relayed in these areas is smaller, so the energy consumption is smaller. The energy consumptions for computations and sensing of the nodes are equal; thus, the energy left in non-hotspot areas is not reduced. However, the energy consumption for data encryption is larger in hotspots areas, which causes more energy to be left in non-hotspot areas. Thus, the performance of the RICC scheme can be improved effectively.

3.2. Problem Statement

The problem studied in this paper is as follows [28,31]:

(1) Effective energy utilization (denoted as ϖ). ϖ is the ratio of the used energy to the total energy in the network. Considering e_i is the used energy of node v_i, and E_{ini} denotes the initial energy:

$$\max(\varpi) = \max\left(\left(\sum_{1\le i\le n} e_i\right) / \left(\sum_{1\le i\le n} E_{ini}\right)\right) \tag{1}$$

(2) Network lifetime (denoted as L). In our network model, the energy consumption of node v_i includes (a) the energy consumed for delivering data packets, e_d^i; (b) the energy used for transmitting and receiving original packets, e_o^i; and (c) the energy spent for broadcasting and receiving status messages from other nodes in the same cluster, e_s^i. As in [19], so maximizing L is as follows.

$$\max(L) = \max \min_{0<i\le n}\left(E_{ini} / \left(e_d^i + e_o^i + e_s^i\right)\right) \tag{2}$$

(3) End-to-end data collection reliability (denoted as ϕ_{e2e}). This should be guaranteed, which means it should be higher than the minimum reliability, $\phi_{\min}$, required by the application. Let ϕ_{e2e}^j stand for the end-to-end reliability of a data packet generated by node v_j, and let ϕ_i is the reliability of the packet at the i-th hop. Then, ϕ_{e2e} is as follows:

$$\underset{j\in\{1,\ldots,n\}}{\phi_{e2e}^j} = \prod_{(i\in path\ j)} \phi_i \ge \phi_{\min} \tag{3}$$

Obviously, the goal of RICC can be summarized as Equation (4):

$$\begin{cases} \text{Minimize } \varpi, \text{ Minimize } L, \text{ Minimize } \phi_{e2e} \\ \max(\varpi) = \max\left(\left(\sum_{1\le i\le n} e_i\right) / \left(\sum_{1\le i\le n} E_{ini}\right)\right) \\ \max(L) = \max \min_{0<i\le n}\left(E_{ini} / \left(e_d^i + e_o^i + e_s^i\right)\right) \\ s.\ t. \quad \underset{j\in\{1,\ldots,n\}}{\phi_{e2e}^j} = \prod_{(i\in path\ j)} \phi_i \ge \phi_{\min} \end{cases} \tag{4}$$

To facilitate the readers' understanding of this paper, the main parameters in this paper are listed in Table 1.

Table 1. Network Parameters.

Symbol	Meaning	Value	Symbol	Meaning	Value
P_{Ct}	the power consumption of receiving circuits	98.2 mW	k	the data time slot	3.0
P_{Ct}	the power consumption of transmitting circuits	112.5 mW	p_r	the probability that a node does not transmit a data packet successfully	0.05
R_b	a fixed data rate	10 kbps	p_b	the packet loss probability within the same cluster	10^{-6}
N_0	the single-sided thermal noise Power Spectral Density (PSD) at room temperature	−171 dBm/Hz	σ^2	the scale parameter of the distribution	1.0
N_f	the receiver noise figure	10 dB	w	the carrier wavelength	0.12 m
M_l	the link margin compensating the hardware process variations	40 dB	d_0	the close-range reference distance between the receiver and transmitter	1 m

Table 1. *Cont.*

Symbol	Meaning	Value	Symbol	Meaning	Value
N_f	the receiver noise figure	10 dB	w	the carrier wavelength	0.12 m
M_l	the link margin compensating the hardware process variations	40 dB	d_0	the close-range reference distance between the receiver and transmitter	1 m
U	communication constants	3.47×10^8	M	The number of splits of the network	2
G_tG_r	the transmitter and receiver antenna gains, respectively	7 dBi	l_h	the size of the packet header	44 bits
SNR_0	a threshold of Signal-to-Noise Ratio (SNR)	0 dB	l_d	the size of the data packet	1200 bits
λ	the probability of generating data in a period	0.1	l_s	the size of the status message	100 bits
d	the transmission distance	-	N_r	the PSD of the total effective noise at the receiver input	-
E_{Amp}	the energy consumption of the power amplifier for transmitting one bit of data	-	η	the drain efficiency of the RF power amplifier	-
h	the channel gain	-	ξ	the Peak-to-Average Ratio (PAR)	-

4. Main Design of RICC

4.1. Motivations of RICC

The research motivations of this paper originate from the two reasons:

Observation 1. Generally, a large data transmission power can improve the link quality between nodes, which we validated in a network using a communication scheme named NCCC and found that a higher data transmission power could achieve a lower MFR; however, the energy consumption was increased [28]. Thus, there must be a tradeoff between the energy usage and reliability [26,27]. According Equation (18), this situation is discussed by Figure 2. As the data transmission power increases from 0.015 to 0.1 (J/Hop/Message), the MFR reduces from 0.024 to 1.577×10^{-4}, which means that an increase in the data transmission power by a factor of 6.66 can reduce the MFR by a factor of 155. Therefore, increasing the data transmission power can effectively reduce the MFR, but it consumes more energy.

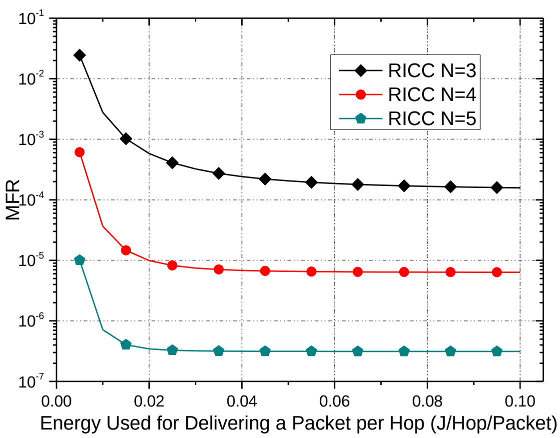

Figure 2. Message Fail Delivering Ratio (MFR) versus energy used for delivering a packet per hop (J/Hop/Packet).

Observation 2. In NCCC, which employs equal transmission power throughout the whole network [31], there is much remaining energy in the region far from the sink node (see Figure 3, which shows the experimental result in Section 6) due to the impact of the energy hole. We are inspired to adopt unequal transmission powers in different places in the network; more specifically, a higher transmission power is used in the area where much energy remains. Hence, the network can increase data collection reliability without reducing the network lifetime. Meanwhile, the energy utilization ratio is also improved.

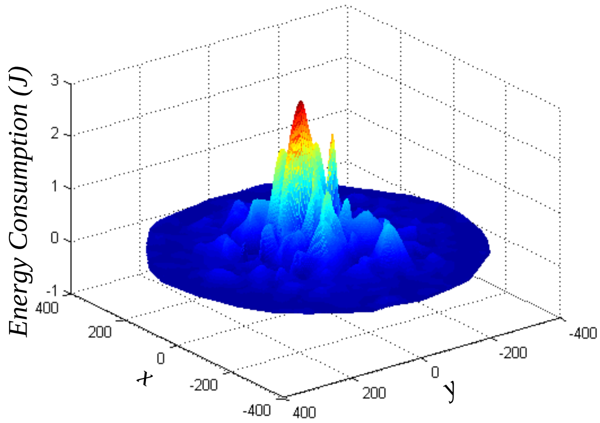

Figure 3. Energy consumption of Network Coding-based Cooperative Communications (NCCC).

For those two reasons, the Reliability Improved Cooperative Communications (RICC) data collection scheme is proposed. The main idea are that: the reliability is guaranteed by each node in the routing path; however, since the nodes have unbalanced energy consumption, RICC uses the remaining energy to increase the data transmission power, and adopts the same data transmission power in the area near to the sink as in previous studies. Thus, the goal of enhancing the network reliability without decreasing the lifetime can be achieved.

4.2. Preliminary Knowledge

Some relevant technologies and models for the proposed scheme should be introduced.

4.2.1. Data Transmission Model

According to NCCC model, the process of data collection is mainly composed of the following three stages: *Source Cluster routing stage*, *Transitional Cluster routing stage* and *Destination Cluster routing stage*, as shown in Figure 1.

(1) *Source Cluster routing stage*. First, the source node senses origin data **D** and distributes them to the neighboring nodes in the same source cluster through broadcasting. After the functioning nodes receive **D**, they split it into M blocks:

$$\mathbf{D} = (D_1, D_2, \ldots, D_M)^T \tag{5}$$

and generate a coding vector of size $1 \times M$ (denoted as **v**) over finite field $GF(q)$ randomly. Then, the encode method for data packet is:

$$\mathbf{C} = \mathbf{v} \times (D_1, D_2, \ldots, D_M)^T \tag{6}$$

(2) *Transitional Cluster routing stage*. When source node in the source cluster transmit data packet to the next cluster, which is called the transitional cluster. Then the data packet is transmitted

by the transitional cluster using the same way until this packet is transmitted to the destination cluster [31], which contains the sink node.

$$\mathbf{D_r} = (D_{r_1}, D_{r_2}, \ldots, D_{r_n}) \tag{7}$$

Assume n data packets are received by a node in a certain transitional cluster. $\mathbf{v_{r_i}}$ and $\mathbf{C_{r_i}}$ are the coding vector and coded data, respectively. The n coding coefficients $(v_1, v_2, \ldots, v_n)$ are produced by *GF(q)*, the encoding method of data packet is as follow:

$$\mathbf{v_{new}} = \sum_{i=1}^{n} v_i \times \mathbf{v_{r_i}} \tag{8}$$

$$\mathbf{C_{new}} = \sum_{i=1}^{n} v_i \times \mathbf{C_{r_i}} \tag{9}$$

where $\mathbf{v_{new}}$ and $\mathbf{C_{new}}$ are the coding vector and coded data of the new coded packet, respectively [31].

(3) *Destination Cluster routing stage*. All data packets are transmitted to the destination cluster, then some nodes will transmit data packet to destination cluster. Those redundancy data will be removed, and the other packets are decoded to retrieve the original packets.

In the packet transmission stage, N coded packets are transmitted from one cluster to another. Suppose there are τ functioning nodes in a cluster. If $\tau = N$, N packets will be equally delivered. If $\tau < N$, then $T_d = k$, for $k = 1, 2, \ldots, \tau$, the k-th node will transmit the corresponding k-th coded packet, and after the τ coded packets have been transmitted by the τ functioning nodes, the system will perform the operation $T_d\%\tau$ to make the 1-th node send the $(\tau + 1)$-th packet, and the 2-th node send the $(\tau + 2)$-th packet, and until other (N-τ) packets are transmitted to the next hop.

In the first two stages, some status messages containing the IDs of nodes are generated. The functioning nodes in both source clusters and transitional clusters declare their status at their broadcast slot, while in other time slots, they receive the status messages of other functioning nodes in the same cluster. All the status messages are stored in a *TransQueue* queue. After this process, all the functioning nodes' IDs are restored in the *TransQueue* queue [31].

4.2.2. Reliability Model

Considering the bit errors can be corrected through an FEC if the received Signal-to-Noise Ratio (SNR) is higher than a threshold, denoted as SNR_0 [9]; hence, in this case, the delivered packets can be obtained correctly by the sink node. The method for calculating received signal-to-noise ratio (SNR_r) is [9]:

$$SNR_r = h^2 \times \frac{G_t G_r w^2 d_0^{k-2}}{(1+\alpha)(4\pi)^2 M_l N_f d^k} \times \frac{E_{Amp}}{N_0} \tag{10}$$

Since the diameter of the cluster, r_b, is quite short, a high data transmission power is not necessary for extremely reliable intra-cluster communications; thus, the MFR within clusters will be set to a small constant value, e.g., $p_b = 10^{-6}$. The Probability Density Function (PDF) of wireless channel is:

$$f(x) = \frac{2x}{\sigma^2} \exp\left(\frac{-x^2}{\sigma^2}\right) \tag{11}$$

where σ^2 is the scale parameter of the distribution. Then, the packet loss probability is as follow

$$p_l = \Pr(SNR_r < SNR_0) \quad = \Pr\left(h \leq \sqrt{\frac{QN_0 d^k}{E_{Amp}}}\right) = 1 - \exp\left(-\frac{QN_0 d^k}{E_{Amp}\sigma^2}\right) \tag{12}$$

where

$$Q = \frac{(1+\alpha)(4\pi)^2 M_l N_f SNR_0}{G_t G_r w^2 d_0^{k-2}} \tag{13}$$

Define the communication constant U as follows:

$$U = \frac{(4\pi)^2 M_l N_f}{G_t G_r w^2} \tag{14}$$

Then,

$$Q = \frac{(1+\alpha)SNR_0}{d_0^{k-2}} \times U \tag{15}$$

Assume that in a certain data collection round, there are u functioning nodes in a certain transitional cluster. Then, each packet delivered from the previous cluster will not be received successfully by the cluster unless it can be received by at least one of these u nodes. Therefore, the probability for a packet to be successfully received is $(1-p_l)^u$. Hence, the probability of v among the N packets being obtained.

$$p(u,v) = \begin{pmatrix} N \\ v \end{pmatrix} (1-(p_l)^u)^v {p_l}^{u(N-v)} \tag{16}$$

The payload of each coded packet is the linear combination of the M original data blocks. However, this decoding constraint cannot always be satisfied because the encoding and re-coding vectors of the v received packets are generated over a Galois Field randomly. Let $p_{n,m}$ denote the probability that the rank of an $n \times m$ matrix generated randomly over a Galois Field is less than m [31]. thus, its value is as follows:

$$p_{n,m} = \begin{cases} 1, & \text{if } n < m \\ 1 - \prod_{x=0}^{m-1}\left(1 - \frac{1}{q^{n-x}}\right). & \text{if } n \geq m \end{cases} \tag{17}$$

As in [9], the Message Fail Delivering Ratio (MFR) is a performance index. From the above discussions, the MFR in one hop of transmission with the packet loss probability p_l and node failure probability p_r can be calculated as:

$$MFR_o = \sum_{u=0}^{N}\sum_{v=0}^{N} \begin{pmatrix} N \\ u \end{pmatrix} (1-p_r)^u p_r^{N-u} \times \begin{pmatrix} N \\ v \end{pmatrix} (1-(p_l)^u)^v (p_l)^{u(N-v)} \times p_{v,M} \tag{18}$$

In particular, when data packet is transmitted from destination cluster to the sink, the MFR is recalculated as:

$$MFR_s = \sum_{u=0}^{N-1}\sum_{v=0}^{N} \begin{pmatrix} N-1 \\ u \end{pmatrix} (1-p_r)^u p_r^{N-1-u} \times \begin{pmatrix} N \\ v \end{pmatrix} \left(1-(p_l)^{u+1}\right)^v (p_l)^{(u+1)(N-v)} \times p_{v,M} \tag{19}$$

4.3. Data Load of Node

Based on the above data transmission model, there are three kinds of packets for the communications of nodes: *data packet*, *original packet* and *status message*, which is analyzed in detail in this subsection.

Suppose the data transmission is failure-free between any two nodes. Then, according to [12], the amount of data received a node of distance l meters from the sink is:

$$\zeta_r^l = h_p + \frac{h_p(h_p+1)r}{2l} \tag{20}$$

To determine the amount of transmitted data, one packet generated by each node should be considered:

$$\zeta_t^l = (h_p+1) + \frac{h_p(h_p+1)r}{2l} \tag{21}$$

where $h_p = \lfloor (R-l)/r \rfloor$.

Theorem 1. *In the RICC model, for a node that is l meters far from the sink node, the numbers of data packets it transmits to and receives from other clusters (denoted as $\zeta_{l,t}^D$ and $\zeta_{l,r}^D$, respectively), the numbers of original packets it broadcasts to and receives from other nodes within its cluster (denoted as $\zeta_{l,b}^O$ and $\zeta_{l,r}^O$, respectively), and the numbers of status messages it broadcasts to and receives from other nodes within its cluster (denoted as $\zeta_{l,b}^S$ and $\zeta_{l,r}^S$, receptively) can be calculated as*:

$$\begin{cases} \zeta_{l,t}^D = \left(h_p + 1 + \frac{h_p(h_p+1)r}{2l}\right)\overline{p_r}\lambda \\ \zeta_{l,r}^D = \left(h_p + \frac{h_p(h_p+1)r}{2l}\right)N(\overline{p_r})^2\overline{p_l}\lambda \\ \zeta_{l,b}^O = \overline{p_r}\lambda,\ \zeta_{l,r}^O = (N-1)(\overline{p_r})^2\overline{p_b}\lambda \\ \zeta_{l,b}^S = \left(h_p + \frac{h_p(h_p+1)r}{2l}\right)N(\overline{p_r})^2\overline{p_l}\lambda + \overline{p_r}\lambda \\ \zeta_{l,r}^S = \left(h_p + \frac{h_p(h_p+1)r}{2l}\right)(N-1)(\overline{p_r})^2\overline{p_b}\lambda \end{cases} \tag{22}$$

where$h_p = \lfloor (R-l)/r \rfloor$,$\overline{p_r} = 1 - p_r$,$\overline{p_l} = 1 - p_l$, *and* $\overline{p_b} = 1 - p_b$.

Proof. For a data packet, a node will transmit a data packet if it has not failed, and it successfully generates one packet with probability $\overline{p_r}\lambda$. The precondition for a node to successfully receive a packet of any kind is that both the receiver and sender do not fail; the probability that this precondition is satisfied is $(1-p_r)^2$, and the probability of losing a packet is p_l, so the final probability for a node to receive a packet is $(\overline{p_r})^2\overline{p_l}\lambda$. As there are N nodes in each cluster and each node sends its data packet to the next cluster, each node will receive a data packet N times from the last cluster.

For an original data packet, in a single round of data collection, each functioning node will broadcast its original data packet only once if it generates an event with probability λ and will receive original data packets from its $N-1$ neighboring nodes (if it has any) in the same source cluster. As assumed before, the within-cluster packet loss probability is a constant value p_b, so the original data packet loads are $\overline{p_r}\lambda$ and $(N-1)(1-p_r)^2\overline{p_b}\lambda$.

For a status message, once a node receives a data packet or has original data to transmit, it will broadcast a status message containing its ID information, so the number of broadcasted status messages should be $\zeta_{l,b}^S = \zeta_{l,r}^D + \zeta_{l,b}^O$. Similarly, a node will receive status messages from its $N-1$ neighbors, under the event generation probability of λ.

According to Theorem 1, the data packet load of nodes is shown in Figure 4, from which we can see that nodes in different places in the network can have a very different data loads, bringing about the so-called "energy hole" phenomenon. Moreover, with more nodes in a cluster, each node receives more data packets, but the transmission data load remains the same. Note that the curves have some abruptions; this is because the nodes on the left side of the abrupt points must handle one more ring of packets than those on the right side.

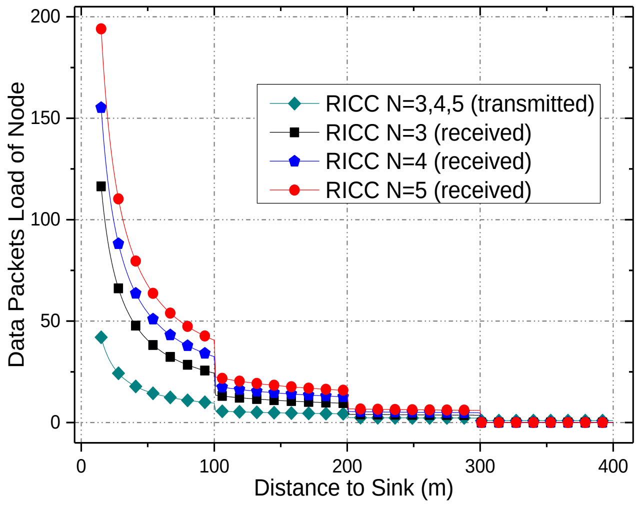

Figure 4. Data packet loads of nodes.

According to Theorem 1, Figure 5 shows the original data packet loads of nodes, which are very small compared with the later data packet loads. Similarly, with more nodes in a cluster, each node will receive more original data packets, and the broadcasting data load also stays the same. A node will receive more original packets if its failure probability is lower.

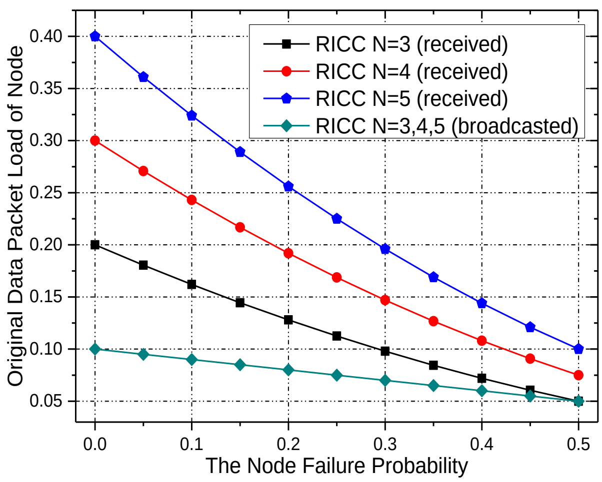

Figure 5. Original data packet loads of nodes.

According to Theorem 1, Figures 6 and 7 are introduced to show the status message loads of nodes. Compared with the data packet loads, the status message loads are also small, which indicates that the main source of energy consumption for a node is delivering data packets.

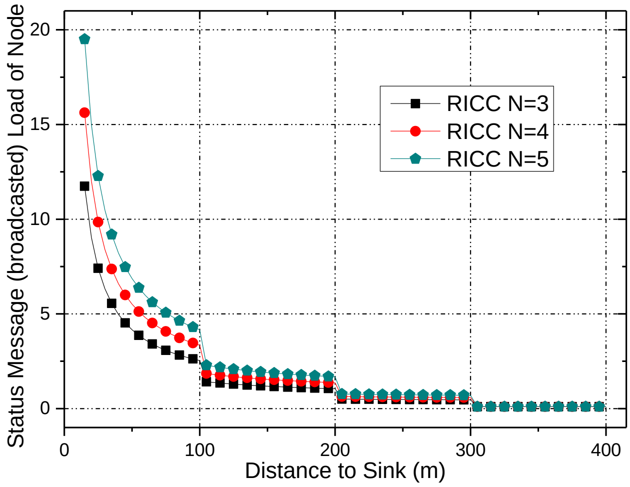

Figure 6. Status message (broadcasted) loads of nodes.

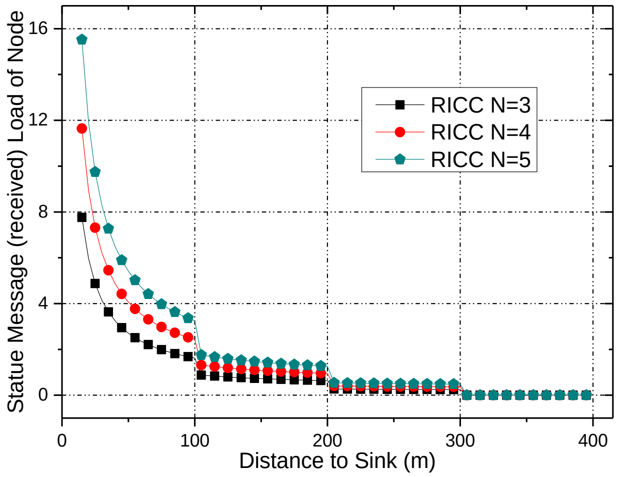

Figure 7. Status message (received) loads of nodes.

4.4. Energy Consumption of a Node

The power consumption of transmitting circuits P_{Ct} and the power consumption of receiving circuits P_{Cr}, P_{Ct} and P_{Cr} are given by:

$$P_{Ct} = P_{DAC} + P_{mix} + P_{filt} + P_{syn} \tag{23}$$

$$P_{Cr} = P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC} + P_{syn} \tag{24}$$

where P_{DAC}, P_{ADC}, P_{filt}, P_{filr}, P_{LNA}, P_{IFA}, P_{mix} and P_{syn} is the power consumption values for the Digital-to-Analog Converter (DAC), the Analog-to-Digital Converter (ADC), the active filters at transmitter side and receiver side, the Low Noise Amplifier (LNA), the Intermediate Frequency Amplifier (IFA), the mixer and the frequency synthesizer, respectively [9].

According to Equation (12), the power consumption of the amplifier is:

$$E_{Amp} = -\frac{QN_0 d^k}{\sigma^2 \lg(1 - p_l)} \tag{25}$$

Therefore, the total energy consumption per bit and the required packet loss probability can be calculated as:

$$e_T(d, p_l) = E_{Amp} + \frac{P_{Ct}}{R_b} = -\frac{QN_0 d^k}{\sigma^2 \lg(1 - p_l)} + \frac{P_{Ct}}{R_b} \tag{26}$$

where R_b denotes the transmission data rate. Finally, the power needed for receiving data packet per bit is:

$$E_R = \frac{P_{Cr}}{R_b} \tag{27}$$

Theorem 2. *With the routing strategy of the NCCC system model, for a node that is x meters away from the sink node, its energy consumption in one round, denoted as* $\omega_{p_l}^x$ *, can be calculated as follows:*

$$\begin{cases} \omega_{p_l}^x = & e_T(d^*, p_l) \cdot \zeta_{x,t}^D l_d + e_T(r_b, p_b) \times \left(\zeta_{x,b}^S l_s + \zeta_{x,b}^O l_o\right) \\ & + E_R \times (\zeta_{x,r}^D l_d + \zeta_{x,r}^S l_s + \zeta_{x,r}^O l_o) \\ d^* = \begin{cases} x, \; for \; x < r \\ r, \; for \; x \geq r \end{cases} \end{cases} \tag{28}$$

where l_d*,* l_o *and* l_s *stand for the sizes of the data packet, original packet and status message, respectively. A packet consists of a payload and a packet header containing a sequence number; therefore, the size of each data packet is* $l_d = (l_o/M + l_h)$ *, where* l_h *is the size of the packet header.*

Proof. As sending and receiving data are the critical sources of energy consumption of nodes, the latter is not considered here. The total number of bits that a node, e.g., v_i, receives in one round depends on the data packets received from the last hop, $\zeta_{l,r}^D l_d$; the original packets received from the source node in the same cluster, $\zeta_{l,r}^O l_o$; and the status messages received from other nodes in the same cluster, $\zeta_{l,r}^S l_s$. The power needed for the reception of one bit is $E_R = P_{Cr}/R_b$. Therefore, the energy consumption of node v_i to receive all those data bits can be computed as $E_R \times \left(\zeta_{l,r}^D l_d + \zeta_{l,r}^S l_s + \zeta_{l,r}^O l_o\right)$. Meanwhile, in one round, the total number of bits that node v_i needs to transmit depends on the data packets to be transmitted to the next hop, $\zeta_{l,t}^D l_d$; the original data packets, $\zeta_{l,b}^O l_o$; and the status messages to be broadcasted to other nodes in the same cluster, $\zeta_{l,b}^S l_s$. According to Equation (26), for a fixed data rate R_b and a required packet loss probability p_l, the energy consumption per bit is as $e_T(d^*, p_l) = -\frac{QN_0 d^{*k}}{\sigma^2 \lg(1-p_l)} + \frac{P_{Ct}}{R_b}$. Therefore, the energy consumption for node v_i to transmit all those data bits is $e_T(d^*, p_l) \times \zeta_{x,t}^D l_d + e_T(r_b, p_b) \times \left(\zeta_{x,b}^S l_s + \zeta_{x,b}^O l_o\right)$.

4.5. The Design of RICC

From the above analyses, we know that the linchpin of RICC is determining the transmission power of nodes in different places in the network to increase the cooperative communication performance. In this section, this problem is studied.

In NCCC, if the packet loss probability that the network adopts is determined, then according to Theorem 2, the energy consumption of each node in the network is calculated. First, considering the data transmission power is the minimum value that meets the reliability requirements of the application. Then, the residual energy of a node in the far-sink region is used to increase its data transmission power and thereby decrease the MFR of the transmission hop originating from it and further improve the reliability of the whole network.

Theorem 3. *In NCCC, suppose the required packet loss probability is* p_l *. Then, in RICC, for a certain node, say* v_x*, which is x m away from the sink node, the largest transmission power* E^x_{Amp} *that it can adopt without harming the network lifetime can be calculated as:*

$$\begin{cases} E^x_{Amp} = \frac{w^{x_0}_{p_l} - E_R \varepsilon_r - \frac{P_{Ct}}{R_b} \varepsilon_t}{\zeta^D_{x,t} \ell_d + \left(\zeta^S_{x,b} \ell_s + \zeta^O_{x,b} \ell_o\right) \frac{r^k}{d^{*k}} \log^{(1-p_l)}_{(1-p_b)}} \\ \varepsilon_r = \left(\zeta^D_{x,r} \ell_d + \zeta^S_{x,r} \ell_s + \zeta^O_{x,r} \ell_o\right) \\ \varepsilon_t = \left(\zeta^D_{x,t} \ell_d + \zeta^S_{x,b} \ell_s + \zeta^O_{x,b} \ell_o\right) \end{cases} \tag{29}$$

where x_0 *is the distance of the last hop that is from the last node to the sink.*

Proof. According to Equations (26) and (28), for the required node failure probability and a fixed data rate, the energy consumption of node v_x is $w^x_{p_l}$. In addition, from Theorem 1, we know that $w^{x_0}_{p_l}$ is the largest energy consumption. By subtracting $w^x_{p_l}$ from $w^{x_0}_{p_l}$, node v_x's energy left is:

$$w^x_\Delta = w^{x_0}_{p_l} - w^x_{p_l} \tag{30}$$

Here, $w^x_\Delta = 0$ means that node v_x makes full use of its residual energy, and we can directly solve for E^x_{Amp}:

$$\begin{aligned} & e_T(x_0, p_l)\zeta^D_{x_0,t} l_d + e_T(r_b, p_l)\left(\zeta^S_{x_0,b} l_s + \zeta^O_{x_0,b} l_o\right) + E_R \times \left(\zeta^D_{x_0,r} l_d + \zeta^S_{x_0,r} l_s + \zeta^O_{x_0,r} l_o\right) \\ & = e_T(x^*, p_l)\zeta^D_{x,t} l_d + e_T(r_b, p_l)\left(\zeta^S_{x,b} l_s + \zeta^O_{x,b} l_o\right) + E_R \times \left(\zeta^D_{x,r} l_d + \zeta^S_{x,r} l_s + \zeta^O_{x,r} l_o\right) \\ \Rightarrow \; & E^x_{Amp} \zeta^D_{x,t} l_d + E^0_{Amp}\left(\zeta^S_{x,b} l_s + \zeta^O_{x,b} l_o\right) + E_R \varepsilon_r + \frac{P_{Ct}}{R_b} \varepsilon_t = w^{x0}_{p_l} \\ \Rightarrow \; & E^x_{Amp}\left[\zeta^D_{x,t} l_d + \frac{r^k}{d^{*k}} \log^{(1-p_l)}_{(1-p_b)} \left(\zeta^S_{x,b} l_s + \zeta^O_{x,b} l_o\right)\right] = w^{x_0}_{p_l} - E_R \varepsilon_r - \frac{P_{Ct}}{R_b} \varepsilon_t \\ \Rightarrow \; & E^x_{Amp} = \frac{w^{x_0}_{p_l} - E_R \varepsilon_r - \frac{P_{Ct}}{R_b} \varepsilon_t}{\zeta^D_{x,t} l_d + \left(\zeta^S_{x,b} l_s + \zeta^O_{x,b} l_o\right) \frac{r^k}{d^{*k}} \log^{(1-p_l)}_{(1-p_b)}} \end{aligned} \tag{31}$$

where E^c_{Amp} stands for the power consumption of the amplifier within clusters and is calculated as:

$$E^c_{Amp} = -\frac{QN_0 r^k}{\sigma^2 \lg(1 - p_b)} \tag{31}$$

thus,

$$\frac{E^c_{Amp}}{E^x_{Amp}} = \frac{r^k}{d^{*k}} \log^{(1-p_l)}_{(1-p_b)} \tag{32}$$

5. Performance Analysis of RICC

5.1. Energy Consumption of RICC

Figure 8 is introduced to show the comparisons of energy consumptions between RICC and NCCC. As the previous analyses show, RICC and NCCC have the same largest energy consumption, so the network lifetime is maintained at the same level. However, in non-hotspot areas, RICC has a larger energy consumption than NCCC does, which is the consequence of increasing the data transmission power of the nodes. According to observation 1 in Section 4.1, when the transmission power of a node exceeds 0.1 J/Hop/Packet, the MFR does not significantly improve, which means that MFRs with different cluster sizes all reach their lower bounds, so we set an upper threshold for the power as 0.1 (J/Hop/Packet). But the energy utilization still cannot be perfectly balanced. The use of a more even energy utilization to achieve a better network performance is left for our future work. The corresponding energy used by nodes for delivering a packet per hop is given in Figure 9.

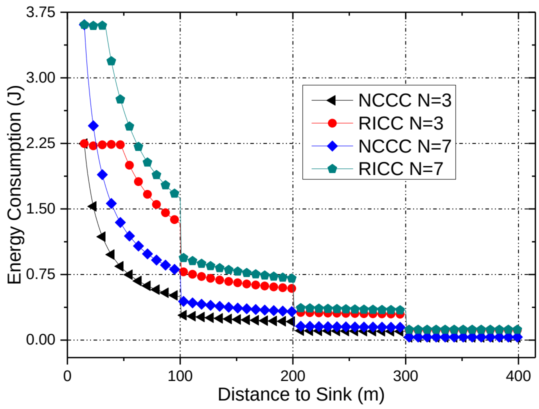

Figure 8. Total energy consumption of nodes.

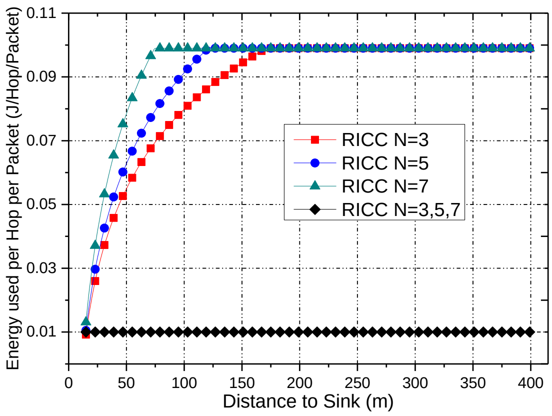

Figure 9. Energy used for delivering a packet per hop.

The average enhanced energy utilization ratio of the network is shown in Figure 10; specifically, the ratio is improved by 59.4%–62.8%, which indicates a higher energy usage efficiency of RICC compared with NCCC.

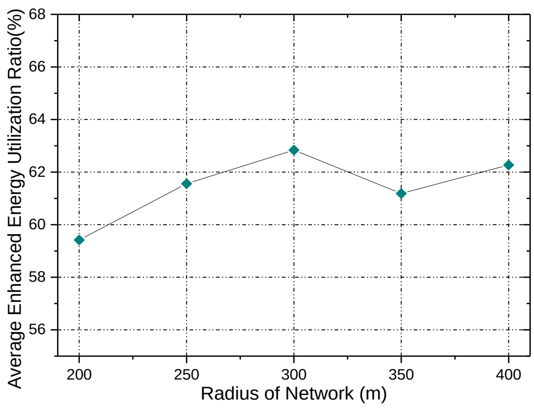

Figure 10. Average enhanced energy utilization ratios for different network sizes.

5.2. Network Reliability of RICC

5.2.1. End-to-end MFR

Theorem 4. End-to-end MFR is refer to the final MFR of a packet from the source cluster to the destination cluster. In RICC, *for a node that is* x *m away from the sink, the end-to-end MFR of a packet produced by this node is as follows.*

$$MFR_{e2e}^{x} = 1 - (1 - MFR_s) \times \prod_{i=1}^{h_p - 1} \left(1 - MFR_o^i\right) \tag{33}$$

where MFR_o^i *is the MFR of a packet at the* i-th *hop of a routing path,* MFR_s *is the last hop of the transmission, and* h_p *represents the total number of hops from this node to the sink, that is,* $h_p = \lfloor (R - x)/r \rfloor$ *. As shown in Equation (12), when* E_{Amp} *is large enough,* $p_l \to 0$ *and* MFR_{e2e}^{x} *can be rewritten as:*

$$MFR_{e2e}^{x} \to 1 - (1 - p_{N,M}) \times \left\{1 - \left[p_{N,M} + (p_r)^N\right]\right\}^{h_p - 1} \tag{34}$$

Proof. Considering the probability that the packet is obtained by sink node is the product of the probabilities that the packet can be successfully transmitted at each hop. In particular, the MFR of the last hop is different from others; see the reliability model in Section 4.

Figure 11 shows a comparison of the end-to-end MFR versus hops counts between RICC and NCCC. The results indicate that RICC can always achieve reliable cooperative communication. Having more nodes in a cluster weakens the improvement in reliability since increasing the size of the cluster can also enhance the reliability [9].

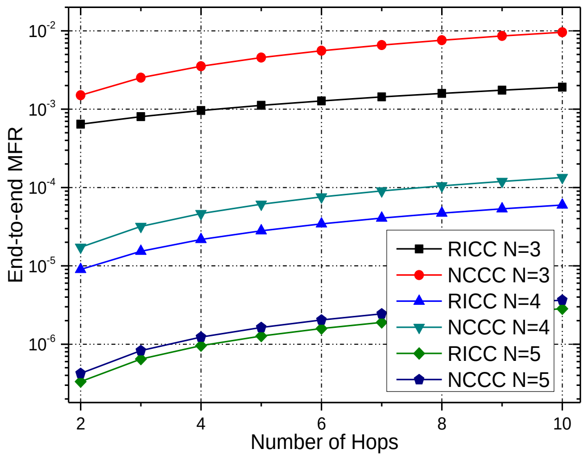

Figure 11. Comparison of end-to-end MFR.

5.2.2. Weighted End-to-end MFR

Theorem 5. In RICC, the weighted end-to-end MFR of the network is calculated, which reflects the universality of the data collection reliability with the RICC approach:

$$MFR_{e2e}^{w} = \int_0^R \int_0^{2\pi} MFR_{e2e}^{x} \times x \times d\theta \times dx \tag{35}$$

Proof. Considering network node that is x m far from the sink, where $|x \in \{0, \ldots, R\}$, we take a sector of fan-shaped ring θ with an angle $d\theta$ and a width of dx. The area of the sector is $xdxd\theta$. The probability of losing a packet from the generating node to the sink node, i.e., the end-to-end MFR, is MFR^{w}_{e2e}; see Equation (34). Integral to the end-to-end MFR in the entire network, the network weighted end-to-end MFR is as follows:

$$MFR^{w}_{e2e} = \int_0^R \int_0^{2\pi} MFR^{x}_{e2e} \times x \times d\theta \times dx \tag{37}$$

Figure 12 is introduced to show a comparison of the weighted end-to-end MFR between two schemes. In RICC, only nodes that are very close to the sink have the same MFR as in NCCC, and these nodes are only a small proportion of the whole network. Therefore, the weighted end-to-end MFR in RICC is much lower than that in NCCC; specifically, the percentage reduction is at least 50%.

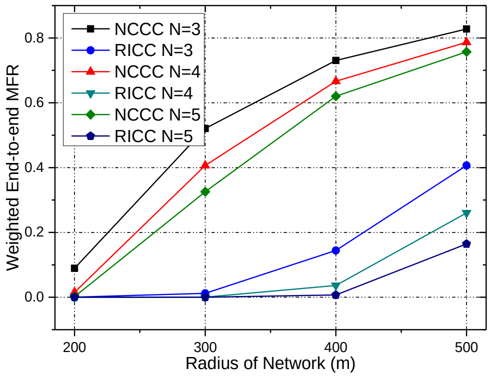

Figure 12. Comparison of weighted end-to-end MFR.

6. Experimental Results and Analyses

6.1. Energy Consumption

Omnet++ simulator [38] is used to evaluate the effectiveness of RICC. Figure 13 presents the simulation results of the energy consumptions of different nodes. With more nodes in a cluster, much energy is consumed because it must handle more amount of data packets, which can be seen from Equation (22). Since the power for transmitting a packet is increased with RICC, nodes always have a larger energy consumption compared with NCCC, except for those in the area very close to the sink. It shows that RICC scheme can improve the energy utilization rate.

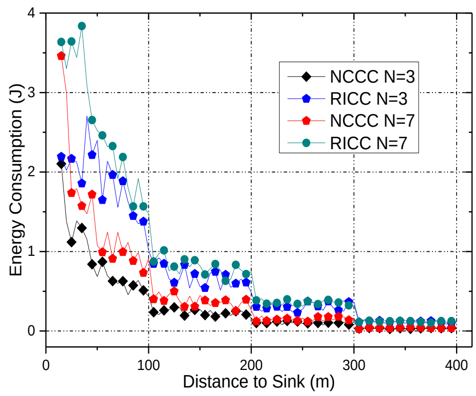

Figure 13. Comparison of energy consumptions.

Figure 14 shows that in NCCC, the energy consumption of nodes in hotspots is unbalanced in the network. In Figure 15, RICC causes the far-sink nodes to consume more energy; that is, the nodes in the network tend to have the same energy consumption. Hence, the energy usage of the network is more balanced, which improves the energy utilization rate and network reliability.

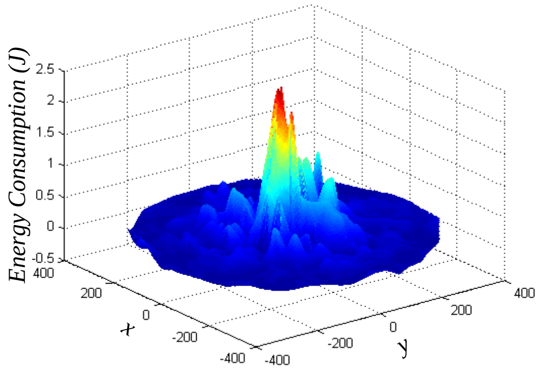

Figure 14. Energy consumption of NCCC (3D).

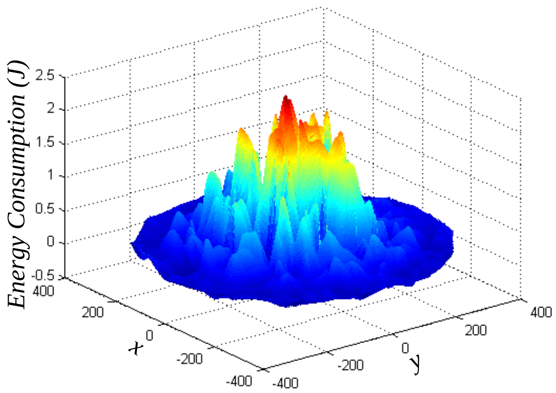

Figure 15. Energy consumption of Reliability Improved Cooperative Communications (RICC) (3D).

The corresponding energy used for delivering a data packet per hop is shown in Figure 16. The node that is closest to the sink uses the same energy power for transmitting a packet, but unlike in NCCC, in RICC, the power increases with the distance from the sink node, resulting in lower one-hop MFR of packets. The energy consumption for each hop in the area far from the sink in the RICC scheme is higher than that of each hop in the NCCC scheme due to the larger N in this area in the RICC scheme.

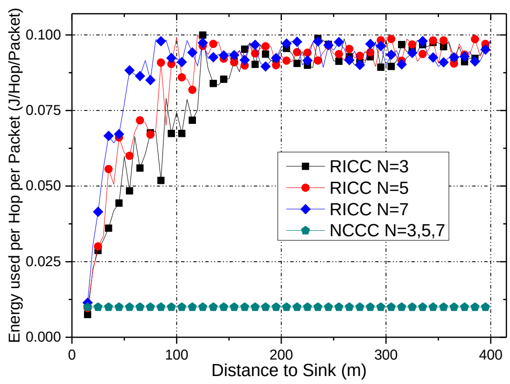

Figure 16. Energy used for delivering a packet per hop.

6.2. Network Reliability

Based on Figures 17 and 18, which show the one-hop MFRs of nodes for RICC and NCCC, the theoretical analyses match the simulation results well. In the near-sink area, the one-hop MFR is positively correlated with the distance to the sink node; however, when the distance exceeds the transmission radius r, the one-hop MFR becomes horizontal because the transmission distance stays at r. The one-hop MFR for RICC is significantly lower than that for NCCC, which fully illustrates the effectiveness of RICC in improving the reliability. The one-hop MFR in RICC is lower than the one-hop MFR in NCCC. This indicates that the network reliability in the RICC scheme is better.

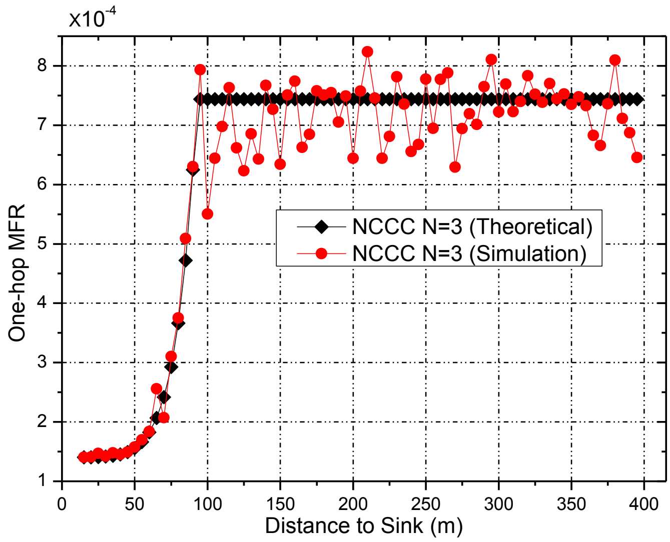

Figure 17. One-hop MFR of nodes with NCCC.

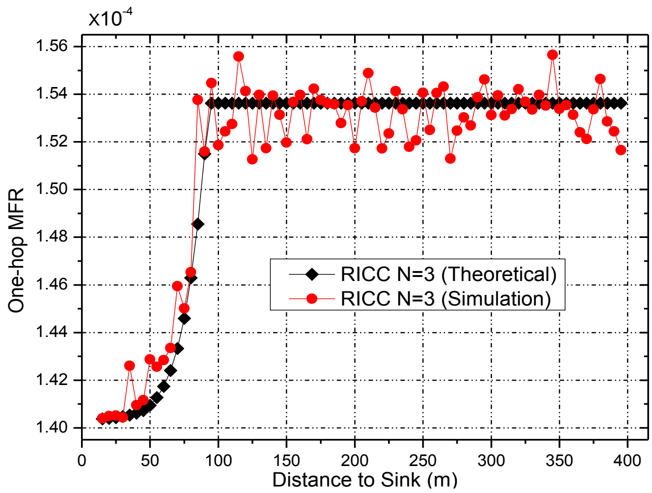

Figure 18. One-hop MFR of nodes with RICC.

The simulation results of weighted E2E MFR are presented in Figure 19, and they are consistent with the theoretical analysis shown in Figure 12. We also present the average reduced weighted end-to-end MFR in Figure 20, which shows that the weighted E2E MFR is improved by at least 50%; moreover, the larger the network is, the less of the reduced percentage.

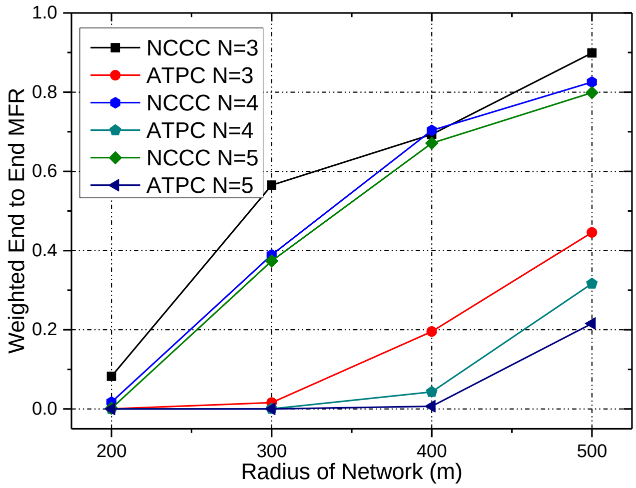

Figure 19. Simulated weighted end-to-end MFR.

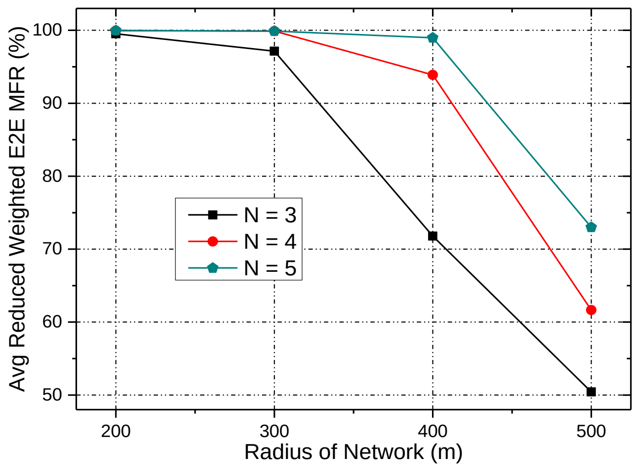

Figure 20. Average reduced weighted end-to-end MFR.

7. Conclusions and Future Work

In wireless sensor networks which the bit error rate (BER) is higher than wired network, the energy of sensor nodes is very limited, making it a problem to ensure a low end-to-end Message Fail Delivering Ratio (MFR) without leading a decline in the network lifetime. An efficient way to obtain a reliable data communication is that several sensors transmit sensed data cooperatively, which can be implemented through a technology named Wireless Software Define Networks (WSDNs). In this paper, based on a WSDN where software inside sensors can help them construct clusters to do the data collection task, we focus on the cooperation details, namely, a data collection scheme called Reliability Improved Cooperative Communications (RICC) with adjustable data transmitting power is proposed to achieve high reliability for random network coding based cooperative communications in multi-hop relay WSNs with long lifetime guaranteed. In RICC, high data transmitting power is adopted by nodes in far-sink areas to fully use their residual energy to further reduce the MFR, while the nodes in hotspots area adopt relatively low power to maintain network lifetime, so both of MFR and lifetime of network can be improved. Omnet++ simulator is used to evaluate the effectiveness of RICC. The evaluation results indicate that: with RICC, the utilization ratio of energy is approximately increased by as much as 59.4% to 62.8% compared with NCCC, and the weighted end-to-end MFR is reduced by as least 50%.

Although building a reliability cooperative communications network is the key issue for wireless sensor networks, there are many work to do for creating an efficient communication network. With the development of sensing devices for harvest energy from surrounding circumstance, its devices are getting smaller and smaller, and the function is getting stronger and stronger. So for the future work, we plan to seeking new techniques to improve communication reliability as well as lifetime for harvesting energy sensor networks especially in practice applications.

Acknowledgments: This work was supported in part by the National Natural Science Foundation of China (Grant No. 61772554, 61379110, 61572526, 61572528), the National Basic Research Program of China (973 Program) (Grant No. 2014CB046305).

Author Contributions: Zhuangbin Chen designed the algorithms and wrote the manuscript. Ming Ma wrote part of the manuscript. Xiao Liu analyzed the experiment results. Anfeng Liu conceived of the work, designed the algorithms. Ming Zhao commented the work.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Naranjo, P.G.V.; Shojafar, M.; Mostafaei, H.; Pooranian, Z.; Baccarelli, E. P-SEP: A prolong stable election routing algorithm for energy-limited heterogeneous fog-supported wireless sensor networks. *J. Supercomput.* **2017**, *73*, 733–755. [CrossRef]
2. Qin, G.; Wang, L.; Li, Q. Resource symmetric dispatch model for internet of things on advanced logistics. *Symmetry* **2016**, *8*, 20. [CrossRef]
3. Zhao, S.; Liu, A. High performance target tracking scheme with low prediction precision requirement in WSNs. *Int. J. Ad Hoc Ubiquitous Comput.* **2017**, in press.
4. Liu, X.; Zhao, S.; Liu, A.; Xiong, N.; Vasilakos, A.V. Knowledge-aware proactive nodes selection approach for energy management in Internet of Things. *Future Gener. Comput. Syst.* **2017**. [CrossRef]
5. Byun, S.S.; Gil, J.M. Fair Dynamic spectrum allocation using modified game theory for resource-constrained cognitive wireless sensor networks. *Symmetry* **2017**, *9*, 73. [CrossRef]
6. Liu, A.; Zhang, Q.; Li, Z.; Choi, Y.J.; Li, J.; Komuro, N. A green and reliable communication modeling for industrial internet of things. *Comput. Electr. Eng.* **2017**, *58*, 364–381. [CrossRef]
7. Baccarelli, E.; Naranjo, P.G.V.; Scarpiniti, M.; Shojafar, M.; Abawajy, J.H. Fog of everything: Energy-efficient networked computing architectures, research challenges, and a case study. *IEEE Access* **2017**, *5*, 9882–9910. [CrossRef]
8. Huang, C.; Ma, M.; Liu, Y.; Liu, A. Preserving source location privacy for energy harvesting WSNs. *Sensors* **2017**, *17*, 724. [CrossRef] [PubMed]
9. Li, T.; Liu, Y.; Gao, L.; Liu, A. A Cooperative-based model for smart-sensing tasks in fog computing. *IEEE Access.* **2017**. [CrossRef]
10. Chen, Z.; Liu, A.; Li, Z.; Choi, Y.J.; Sekiya, H.; Li, J. Energy-efficient broadcasting scheme for smart industrial wireless sensor networks. *Mob. Inform. Syst.* **2017**. [CrossRef]
11. Liu, X.; Dong, M.; Ota, K.; Yang, L.T.; Liu, A. Trace malicious source to guarantee cyber security for mass monitor critical infrastructure. *J. Comput. Syst. Sci.* **2016**. [CrossRef]
12. Li, T.; Liu, A.; Huang, C. A similarity scenario-based recommendation model with small disturbances for unknown items in social networks. *IEEE Access* **2016**, *4*, 9251–9272. [CrossRef]
13. Liu, A.; Chen, Z.; Xiong, N. An adaptive virtual relaying set scheme for loss-and-delay sensitive WSNs. *Inform. Sci.* **2017**. [CrossRef]
14. Liu, A.; Liu, X.; Wei, T.; Yang, L.T.; Rho, S.C.; Paul, A. Distributed multi-representative re-fusion approach for heterogeneous sensing data collection. *ACM Trans. Embed. Comput. Syst.* **2017**, *16*, 73. [CrossRef]
15. Liu, Y.; Liu, A.; Guo, S.; Li, Z.; Choi, Y.J.; Sekiya, H. Context-aware collect data with energy efficient in Cyber-physical cloud systems. *Future Gener. Comput. Syst.* **2017**. [CrossRef]
16. Liu, X.; Li, G.; Zhang, S.; Liu, A. Big program code dissemination scheme for emergency software-define wireless sensor networks. *Peer-to-Peer Netw. Appl.* **2017**. [CrossRef]
17. Liu, A.; Liu, X.; Tang, Z.; Yang, L.T.; Shao, Z. preserving smart sink location privacy with delay guaranteed routing scheme for WSNs. *ACM Trans. Embed. Comput. Syst.* **2017**, *16*, 68. [CrossRef]

18. Liu, Q.; Liu, A. On the hybrid using of unicast-broadcast in wireless sensor networks. *Comput. Electr. Eng.* **2017**. [CrossRef]
19. Chen, X.; Ma, M.; Liu, A. Dynamic power management and adaptive packet size selection for IoT in e-Healthcare. *Comput. Electr. Eng.* **2017**. [CrossRef]
20. Chen, X.; Xu, Y.; Liu, A. Cross layer design for optimal delay, energy efficiency and lifetime in body sensor networks. *Sensors* **2017**, *17*, 900. [CrossRef] [PubMed]
21. Xu, Y.; Chen, X.; Liu, A.; Hu, C. A latency and coverage optimized data collection scheme for smart cities based on vehicular ad-hoc networks. *Sensors* **2017**, *17*, 888. [CrossRef] [PubMed]
22. Wang, J.; Liu, A.; Zhang, S. Key parameters decision for cloud computing: Insights from a multiple game model. *Concurr. Comput. Pract. Exp.* **2017**. [CrossRef]
23. Wang, J.; Liu, A.; Yan, T.; Zeng, Z. A resource allocation model based on double-sided combinational auctions for transparent computing. *Peer-to-Peer Netw. Appl.* **2017**. [CrossRef]
24. Liu, X.; Liu, Y.; Song, H.; Liu, A. Big data orchestration as a service networking. *IEEE Commun. Mag.* **2017**, *55*, 94–101.
25. Liu, Y.; Liu, A.; Li, Y.; Li, Z.; Choi, Y.J.; Sekiya, H.; Li, J. APMD: A fast data transmission protocol with reliability guarantee for pervasive sensing data communication. *Pervasive Mob. Comput.* **2017**. [CrossRef]
26. Zhang, Q.; Liu, A. An unequal redundancy level based mechanism for reliable data collection in wireless sensor networks. *EURASIP J. Wirel. Commun. Netw.* **2016**. [CrossRef]
27. Xu, Y.; Liu, A.; Huang, C. Delay-aware program codes dissemination scheme in Internet of everything. *Mob. Inform. Syst.* **2016**. [CrossRef]
28. Liu, X.; Liu, A.; Li, Z.; Tian, S.; Choi, Y.J.; Sekiya, H.; Li, J. Distributed cooperative communication nodes control and optimization reliability for resource-constrained WSNs. *Neurocomputing* **2017**. [CrossRef]
29. Chen, Z.; Liu, A.; Li, Z.; Choi, Y.J.; Li, J. Distributed duty cycle control for delay improvement in wireless sensor networks. *Peer-to-Peer Netw. Appl.* **2017**, *10*, 559–578. [CrossRef]
30. Cui, S.; Goldsmith, A.J.; Bahai, A. Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks. *IEEE J. Sel. Areas Commun.* **2004**, *22*, 1089–1098. [CrossRef]
31. Liu, X.; Gong, X.; Zheng, Y. Reliable cooperative communications based on random network coding in multi-hop relay WSNs. *IEEE Sens. J.* **2014**, *14*, 2514–2523. [CrossRef]
32. Rosberg, Z.; Liu, R.P.; Le Dinh, T.; Dong, Y.F.; Jha, S. Statistical reliability for energy efficient data transport in wireless sensor networks. *Wirel. Netw.* **2010**, *16*, 1913–1927. [CrossRef]
33. Zhang, D.; Chen, Z. Energy-efficiency of cooperative communication with guaranteed E2E reliability in WSNs. *Int. J. Distrib. Sens. Netw.* **2013**, *9*. [CrossRef]
34. Noda, C.; Prabh, S.; Alves, M.; Voigt, T. On packet size and error correction optimisations in low-power wireless networks. In Proceedings of the 2013 10th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON), New Orleans, LA, USA, 24–27 June 2013.
35. Zhou, M.; Jin, C. QoS-aware forward error correction cooperating with opportunistic routing in wireless multi-hop networks. *Wirel. Pers. Commun.* **2017**, *92*, 1407–1422. [CrossRef]
36. Yu, G.; Zhang, Z.; Qiu, P. Efficient ARQ protocols for exploiting cooperative relaying in wireless sensor networks. *Comput. Commun.* **2007**, *30*, 2765–2773. [CrossRef]
37. Keller, L.; Atsan, E.; Argyraki, K.; Fragouli, C. SenseCode: Network coding for reliable sensor networks. *ACM Trans. Sens. Netw. (TOSN)* **2013**, *9*. [CrossRef]
38. The OMNET++ Simulator. Available online: http://www.omnetpp.org/ (accessed on 23 March 2016).