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Reliable differentiated services optimization for network coding cooperative communication system

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Software-Defined Networking (SDN) is a new network architecture with flexibility and scalability, researchers introduced the core idea of SDN into wireless network, and a cooperative communication system based on network coding is proposed. In this paper, we carry on an investigation in differentiated service strategy of network coding cooperative communication system. The meaning of differentiated services is for the different applications take different power for data transmission and the transmission power is associated with their reliability needs. In other words, transmission power control is performed in the presence of known reliability, we named the scheme Reliability-Bounded Transmission Power Control (RTPC) scheme. The RTPC scheme changes the way in which all the applications in the past have been able to maintain the power to be transmitted, but the reliability requirements of different applications will be transmitted with different transmission power. In addition, because of the nodes that far away from the sink node still exist a lot of energy when the network died, so consider to improve the transmission power of non-hotpots nodes in order to increase the reliability of data transmission. The experimental results show that the RTPC scheme can greatly improve the transmission reliability without affecting the network lifetime

Keywords: Wireless sensor networks, SDN, cooperative communication, network coding, power control, reliability

1. INTRODUCTION

Wireless sensor networks (WSNs) consist of a large number of sensor nodes which close to each other, they are responsible for data collection, processing and transmission tasks in the network [1, 2, 3, 9, 10, 11,12]. They communicate through wireless links and help each other to forward data to a single sink node [1, 2]. Software-defined networking (SDN) is a new network architecture, in the control layer, the centralized network controller is responsible for allocating the traffic on the data forwarding layer to the network components, which can realize the functions of topology aware, routing decision and so on [3, 4, 5, 6, 7, 8]. Aiming at the problems of low utilization rate of energies and poor scalability of the wireless network at present [9], researchers introduced the core idea of SDN into wireless network, then Software-Defined Wireless Networking (SDWN) emerged. In recent years, researchers have studied the key technologies and applications of SDWN, and a network coding-based cooperative communications scheme (NCCC) for wireless sensor networks is proposed to improve the success rate of data transmission [10].

Energy saving is one of the key issues to be considered in Wireless Sensor Networks [11, 12, 13]. In addition, wireless sensor networks need to provide services for different applications. For example, some sensing applications requires data transmission reliability to reach 90–95% [14, 15], which is adequate for these applications such as temperature and humidity measurement, fire and gas concentration monitoring [16, 17, 18]. Some studies show that in the real wireless sensor network environment, the wireless link error rate may be as high as 30% [19, 20], which can not meet the practical needs of transmission reliability. The lifetime of a sensor network is usually defined as the time at which the first node in the network is dead [21], the increase of the reliability demand represents the increase of the energy consumption of sensor nodes, which will also affect the overall life of the network [22, 23, 24, 25].

In this paper, the differentiated service strategy based on network coding cooperative communication system is studied from two aspects of improving transmission reliability and prolonging network lifetime. In the traditional scheme, all nodes always use the same transmission power, which leads to some application reliability demand is low but the actual energy consumption of nodes is greater than the actual demand, especially for the nodes near the sink node, excessive energy will lead to the early death of network. However, in the differentiated service strategy, considering the reliability of the application, it is necessary to set the transmit power for each node, which can save the unnecessary energy consumption while ensuring the reliability. Meanwhile, because of there are a lot of residual energy in the far distance region, it can improve the reliability of the data by increasing the transmission power of the non-hotpots nodes, and it will not affect the network lifetime. In summary, the main innovations of this paper are as follows?

1. The relationship between data transmission reliability and node transmission power is analyzed. In this paper, the transmission power E_A of the nodes in the network is determined when the reliability requirement is MFR, and the node energy consumption is minimized under the condition of guaranteeing the application reliability.

2. Under the premise of ensuring the reliability requirements of MFR, put forward a data collection algorithm which can be applied to improve the transmission power of non-hotpots nodes to maximize the reliability of the data, and calculate the particular transmit power of all nodes.

3. A simple and novel scheme: RTPC scheme is proposed. The RTPC scheme takes into account different applications and calculates the required transmission power according to their reliability requirements. For hotpots nodes, to meet the minimum transmission energy consumption under the premise of the application of reliability, this extends the network lifetime to a certain extent. For the non-hotpots nodes, as high as 90% of the energy kept when network died [26], so use of these residual energy appropriate to increase the transmission power of non-hotpots nodes to ensure its reliability. It is of great significance to study the RTPC scheme in terms of reliability and energy saving.

The rest of this article is organized as follows: Sec-tion 2 reviews related works. The network model, ener-gy consumption model and some important parame-ters described in Section 3. In Section 4, the data transmission model and reliability model are intro-duced. RTPC scheme and pseudo code description are proposed, and the parameters such as the amount of data, the network lifetime, the data transmission reliability and the energy utilization ratio are derived and calculated. In Section 5, the performance parame-ters of NCCC and RTPC are analyzed theoretically in the two scheme. Experimental results and compari-sons are introduced in Section 6. Finally, we conclude the paper in section 7.

2. RELATED WORK

With the continuous development of wireless sensor network, its application field is more and more exten-sive, and in many cases, the reliability of data trans-mission is also increasing. At present, many foreign and domestic scholars have devoted attention to the reliability of wireless sensor network research [27, 28, 29] the research on reliability is also increasing, which can be divided into the following categories?

1. Multipath routing protocol. Multipath routing protocol makes it possible to create multiple paths between source node and destination node, making more nodes to assume routing tasks. By using more of the good path instead of a single best path to transmit data, which can increase transmission reliability and achieve load balancing [30]. Multipath routing can be divided into the following two categories
   (a) Select only a single best path for data transmission, and other selected path as the alternate path. Only when used to transmit this path fails, use the alternate path to transmit data.
   (b) In the process of transferring data, are transmitted using multiple paths. Multipath routing is significant in terms of bandwidth utilization, reliability and fault tolerance.

2. Automatic repeat request (ARQ) technology. ARQ technology is one of the key technologies to improve the reliability of data transmission [31, 32]. There are three basic types of ARQ technology: stop-and-wait, go-back-N and selective-repeat. In the stop-and-wait system, the sender sends a packet to the receiving end, then waiting for the response of the receiver. If receiver's ACK is received, the sender sends the next packet. If they had received a negative response, the sender should retransmit the packet. In the go-back-N system, the sender sends a packet without waiting for the receiver of the answer, but directly sending the next packet. From the packet sent to the sender to receive the packet's state information or need a period of time, this time known as the round trip delay. It is assumed that during this time interval, subsequent $N - 1$ packets are transmitted. If the sender receives a positive answer, it has no effect on the transmission. If the sender receives a negative answer, returning to the packet corresponding to a negative response, and subsequent $N - 1$ packets are transmitted. In a selective-repeat system, similar to the go-back-N, a data packet may be continuously transmitted. After the sender sends out a packet, it can send the subsequent data without answering the message. However, the selective-repeat ARQ differs from the go-back-N ARQ in that the sender only needs to re-transmit packets corresponding to the NAK.

3. Forward error correction (FEC) technology. Forward error correction is a data encoding and decoding technology [33]. In the forward error correction technique, the transmitter first encodes the original data information. Channel coding technology uses a strict mathematical structure between

data symbols to construct a new data packet containing redundant information, and the packet can be found through the coding error of their own and to determine the location of the symbol error, which be corrected. After the receiver receives the data packet, it will automatically discover and correct the error in the transmission by decoding.

4. Cooperative communication. It' s an effective method to improve the reliability and channel capacity of the system in a multi-user network by sharing the antennas of each other in a certain way to form a virtual multi-channel to obtain the space diversity gain [34].

   A simple two-node cooperative communication model can be illustrated in Figure 1, in which both users A and B need to transmit data to the base station. In the traditional model, users A and B send data directly to the base station. If a channel has serious multipath fading or noise interference, the signal on this link can not be received accurately. In the cooperative communication scheme, the two nodes cooperate with each other, and user A broadcasts the message to user B, besides user A sends data to the base station. User B also sends the message again at idle time with its own resource. The same holds true for user B. Through cooperative communication, even if a link transmission problems lead to data damage, the base station can still receive other links from the data transmission from the cooperative node, which ensures high quality of the entire network to run.

5. Network coding. Different from the traditional store-and-forward model, network coding also allows the relay to encode multiple paths for information on fusion, and then forward again. In [35], scholars such as Ahlswede illustrate that the network coding technology can make the multicast communication reach the theoretical limit of maximum streaming.

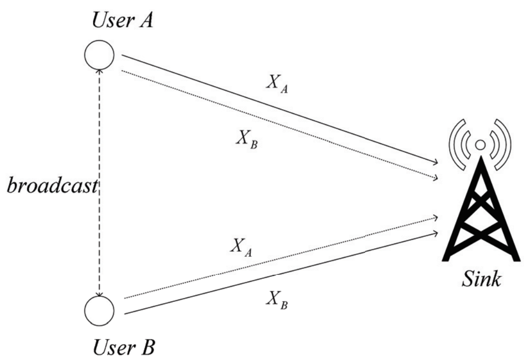

Figure 1 Two node cooperative communication model.

The basic process of the application of network coding technology is illustrated by the example of the butterfly network identified in Fig. 2. In Figure 2, there are six nodes, where the A node and the B node generate data X_A and X_B respectively, and finally send to the receiving node E and the node F, the arrow pointing to the direction that indicates the data transmission link.

Figure 2 uses the network coding technology. Node C waits for two data arriving from A and B, respectively. When both data are received, node C encodes the two data (XOR operation here), and two of the processed data is combined into a single. The data sent by node C to node D contains two data information, then node D sends the data to node E and node F through links DE and DF respectively. Node E receives the data from A and D then start XOR operation $X_A \oplus (X_A \oplus X_B) = X_B$ to get X_B.

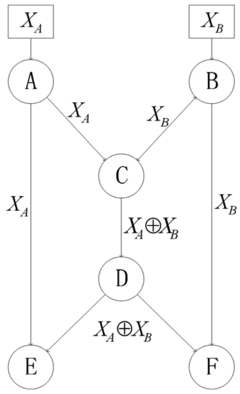

Figure 2 Example of the basic principle of network coding.

In General, using network coding not only can make full use of network bandwidth, and there are load balanced nodes, reducing energy consumption and so on.

3. SYSTEM MODEL

The network model used in this paper is similar to the reference [10]. The n common nodes are randomly distributed in a circle with a radius of R, according to the Poisson distribution and the density is ρ. The sink node is located at the center of the circular area as the base station. The network is clustered, with each cluster containing N sensor nodes. Each sensor sends packets at a fixed time, so the lifetime of the network can be defined as rounds.

3.1 Energy Consumption Model

If you want a more specific understanding of the energy consumption model can be read by reference [36]. The energy of the sensor node is mainly consumed in receive data and transmit data. The energy consumption of sensor node is attributed to power amplifier, receive and transmit data energy consumption in two parts. The energy consumption portion of the power amplifier is controllable and can be simply calculated as:

$$E_A = -\frac{(1+\partial)(4\pi)^2 N_l N_c SNR_0 N_0 d^k}{G_l G_r \lambda^2 d_0^{k-2} \sigma^2 \lg(1-P_{plr})} \quad (1)$$

where, $\partial = (\mu/\theta) - 1$, μ is the extreme value and the mean value ratio, θ is the drain efficiency of RF power amplifier. N_l is the link with interference or noise impacts, N_c is the receiver noise coefficient. SNR_0 denote the lower limit of noise ratio, d is transmission distance. G_l stand for transmit antenna gain, G_r represent receiving antenna gain, is carrier wavelength, d_0 is the reference distance between the transmitting node and the receiving node, P_{plr} denote the probability of packet loss.

Known data transmission distance and packet loss rate, using T_b to express the transmission bit rate, then the energy consumed by each node to send 1 bit data can be calculated:

$$E_t(d, P_{plr}) = E_A + P_T/T_b \quad (2)$$

The energy consumption of a node receiving the data per bit can be calculated as:

$$E_r = P_R/T_b \quad (3)$$

In this paper, some parameter settings can be seen in Table 1.

Table 1 Network Parameters.

Symbol	Description	Value
P_T	Tx circuit power consumption	98.2 mW
P_R	Rx circuit power consumption	112.5 mW
T_b	Transmission bit rate	10 kbps
C	Communication constant	3.47 × 108
k	Path loss exponent	3.0
σ^2	Scale parameter of Rayleigh distribution	1.0
P_f	Node failure probability	0.05
r_m	Data transfer distance per hop	100 m
N_0	Single side thermal noise power spectral density	−171 dBm/Hz
l_0	Original packet length	1000 bits
l_t	The length of the packet that transmitted in network	Calculation
l_h	The length of the packet header	44 bits
l_z	The length of the status information	100 bit

3.2 Problem statement

The network model used in this paper can be evaluated according to the following indicators:

Definition 1: Network energy utilization (denoted as ω). Network energy utilization refers to the proportion of the energy consumed by each node at the end of the network lifetime, which reflects the energy efficiency of the whole network. E_j is the initial energy of the node j, e_j is the energy consumed by the node j at the end of the network. If there are n nodes in the network, the network energy utilization can be calculated as:

$$\omega = \sum_{0\le j\le n} e_j / \sum_{0\le j\le n} E_j \quad (4)$$

Definition 2: Network lifetime (denoted as τ). In this paper, the lifetime of the network is defined as the death time of the first node in the network. Therefore, reducing the energy consumption of the most energy consumption of the node can prolong the life to the maximum value and maximize the network lifetime. E_{ori} represents the initial energy of each node, α is the energy consumption of the node with the largest energy consumption, the network lifetime can be calculated as:

$$\tau = E_{ori}/\alpha \quad (5)$$

Definition 3: Reliability of data collection (denoted as $\Im$). In the process of data transmission, it is necessary to ensure that the reliability of the link can not be less than the reliability of the application. If the demand for reliability of application is β, the transmission reliability of the first j hop in a multihop network with a total m hop number is R_j, and the reliability of the whole link data transmission can be expressed as:

$$\Im = \prod_{j\in(1,2,\ldots,m)} R_j \ge \beta \quad (6)$$

Obviously, the goal of RTPC scheme is to reduce the node energy consumption as much as possible while maximizing the end-to-end data transmission reliability under the premise of guaranteeing the same network life. In the process of improving the reliability, the network energy utilization rate will also be improved. This idea can be stated as follows:

$$\begin{cases} Maximize\ \omega,\ Maximize\ \tau,\ Maximize\ \Im \\ \max(\omega) = \max\left(\sum_{0\le j\le n} e_j / \sum_{0\le j\le n} E_j\right) \\ \max(\tau) = \max(E_{ori}/\alpha) \\ \max(\Im) = \max\left(\prod_{j\in(1,2,\ldots,m)} R_j \ge \beta\right) \end{cases} \quad (7)$$

4. MAIN DESIGN OF RTPC

4.1 Preliminary Information

The data transfer process in each round is shown in figure 3. First, the source node will be aware of the data and broadcast to other nodes in the cluster, all the nodes in the cluster to receive data, use of random network coding technology to encoding the data and then send data to all nodes of the next cluster. The nodes in the middle cluster receive the data, next re-encoding the data and then continue to transmit it to the next cluster. The process continues until the packet is received by the destination cluster. Finally, other nodes in the destination cluster send data to the sink except the sink node, which decodes all the received data.

4.1.1 Data Transmission Model

According to the NCCC model introduced in Ref. [10], the process of data collection based on network coding cooperative communication system consists of encoding phase, re-encoding phase and decoding phase.

1. Encoding phase. The encoding phase is performed in the source cluster. The source node senses the original data D and broadcasts it to all the other nodes in the source cluster. After receiving the data, the other nodes divide D into M blocks, so $D = (D_1, D_2, \ldots, D_M)^T$. Each node randomly generates an order-encoding vector on the finite field $GF(q)$, and then the original data block will be encoded as $V = (V_1, V_2, \ldots, V_M)$. The original packet block is encoded into: $P = V \cdot (D_1, D_2, \ldots, D_M)^T$. The data after the first encoding is shown in Fig. 4.

2. (2) Re-encoding phase. The re-encoding phase is performed in the intermediate cluster. After the intermediate cluster node receives the initial encoded data packet from

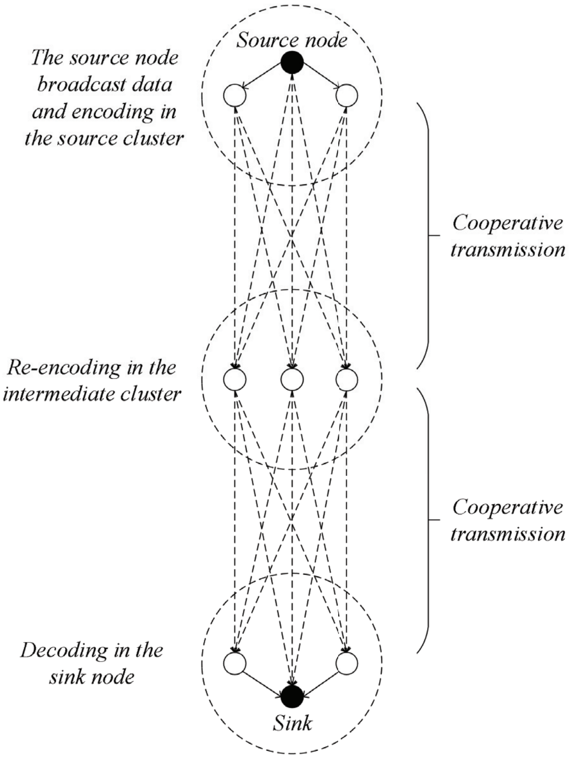

Figure 3 Network model.

the source cluster, it re-encodes the received data packet and transmit it to the cluster node that the next hop arrives. This process will continue until the packet is arrive at the destination cluster. It should be noted that, after receiving the data packet, the intermediate cluster node can re-encode the packet directly with the new coding vector, without decoding the data packet. For example, a node in the middle cluster receives the data packet $D_x = (D_{x_1}, D_{x_2}, \ldots, D_{x_n})$, the data packet contains two parts: the coding vector V_{x_1} and the encoded data P_{x_i}. After receiving the data, the data packets are re-encoded, m coding coefficients are generated randomly: $(V_1, V_2, \ldots, V_M)$, then calculate $V_N = \sum_{i=1}^{m} V_i \cdot V_{x_i}$, $P_N = \sum_{i=1}^{m} V_i \cdot P_{x_i}$. The intermediate cluster nodes set V_N and P_N represents encoded data and the coding vectors respectively, packets are encapsulated into the new data packets and transmitted to the next node. The encoding phase can be represented in figure 5.

3. Decoding stage. Decoding is done by the collection node in destination cluster. The sink node on the processing of duplicate removal for all the collected information and obtains the original data by decoding.

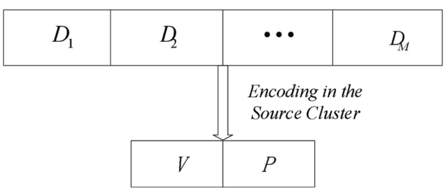

Figure 4 Encoding data structure diagram.

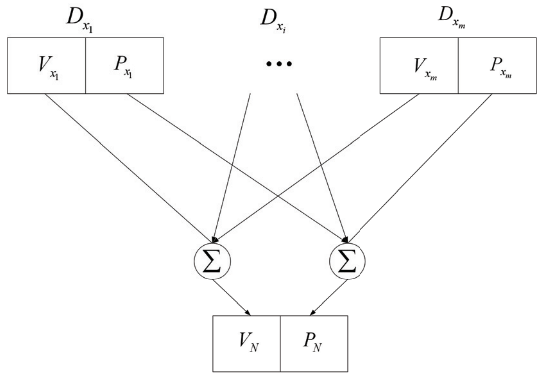

Figure 5 Schematic diagram of re-encoding in intermediate node.

4.1.2 Reliability Model

According to the idea of forward error correction, when the signal to noise ratio (*SNR*) of the transmitted signal exceeds the prescribed limit of SNR_0, the receiver can automatically change the error data frame to obtain the correct data information. The *SNR* can be calculated according to the formula (8):

$$SNR = g^2 \cdot E_A \cdot \frac{G_l G_r \lambda^2 d_0^{k-2}}{(1+\partial)(4\pi)^2 N_l N_c N_0 d^k} \tag{8}$$

when, g represents channel gain.

Also, we can get the relationship between packet loss probability and transmission power in wireless environment:

$$P_{plr}\left(E_A\right) = 1 - \exp\left[\frac{(1+\partial)\,(4\pi)^2 N_l N_c SNR_0 N_0 d^k}{E_A G_l G_r \lambda^2 d_0^{k-2} \sigma^2}\right] \tag{9}$$

According to the characteristics of the cooperative communication system, in the process of a round of data transmission, if there is a cluster of p survival nodes, then the next cluster node as long as received a packet successfully from the h node at least. Obviously, the probability of success is $1 - (P_{plr})^p$. Therefore, if there are N nodes in each cluster, the probability that the receiver can receive q packets from the N packets can be calculated as:

$$P(p,q) = C_N^q \cdot (P_{plr})^{p(N-q)} \cdot (1 - (P_{plr})^p)^q \tag{10}$$

From the above, we can draw the conclusion that each packet sent by each node is formed by the combination of M data blocks. Therefore, to recover the original data block can only use the rank of M coding matrix. Assuming a $v \times w$ encoding matrix are generate randomly, $P_{v,w}$ denotes that the matrix is less than the rank of the probability of w, we can calculate the $P_{v,w}$ as:

$$P_{v,w} = \begin{cases} 1 - \prod_{a=0}^{w-1} 1 - 1/S^{v-a}, & \text{for } v \geq w \\ 1 & \text{for } v < w \end{cases} \tag{11}$$

where S denotes the Gaussian field size of the randomly generated matrices.

In this paper, the reliability of the wireless transmission process is evaluated using the information failure transmission rate (*MFR*). Considering the probability of failure of nodes as Pf, according to the above analysis can be drawn, in addition to gathering nodes to collect data packets, the remaining *MFR* per hop can be calculated as:

$$MFR_0 = \sum_{p=0}^{N}\sum_{q=0}^{N} C_N^p (1-P_f)^p P_f^{N-p} \cdot P(p,q) \cdot P_{q,M} \quad (12)$$

In particular, in a network with sufficient energy of the sink node, the *MFR* of the sink node receiving the packet can be calculated as:

$$MFR_i = \sum_{p=0}^{N-1}\sum_{q=0}^{N} C_{N-1}(1-P_f)^p P_f^{N-p-1} \cdot C_N^p (P_{plr})^{(p-1)(N-q)} (1-(P_{plr})^{p+1})^q \cdot P_{q,M} \quad (13)$$

So, for a *hp* hop transmission, the whole link transmission *MFR* can be calculated by formula (14):

$$MFR = 1-(1-MFR_0)^{k_p-1} \cdot (1-MFR_i) \quad (14)$$

4.2 Research Motivation

The motivation of this paper is derived from two considerations: network lifetime and reliability of data transmission, which is inspired by the following two experiments:

Experiment 1. According to the formula (9), the relationship between the transmission power E_A and the data failure transmission rate P_{plr} can be calculated. By calculating the number of nodes N in the cluster changes in the case of the data shown in Table 2, and accordingly this to draw Figure 6. It can be clearly seen from Fig. 6 that increasing the transmission power can reduce the data transmission failure rate, that is, improve the transmission reliability. According to Table 2, when the number of cluster nodes is 3, if the transmission power from 0.005*J* to 0.095*J*, the *MFR* from 0.0245075 reduced to 1.5946E-4, which means that the transmission power will increase 19 times *MFR* will reduce 154 times. Therefore, by increasing the transmission power can effectively reduce the data transmission failure rate, improve transmission reliability. A similar idea has been applied to [37, 38].

Table 2 Computing Result.

MFR	N = 3	N = 4	N = 5
0.005	0.0245075	0.000611648	0.000010052
0.015	0.00101847	0.00001462	0.000010040
0.025	0.00040977	0.00000822	0.000010032
0.035	0.00027359	0.00000705	0.000010031
0.045	0.00022082	0.00000667	0.000010031
0.055	0.00019463	0.00000652	0.000010031
0.065	0.00017964	0.00000644	0.000010031
0.075	0.00017023	0.00000639	0.000010031
0.085	0.00016391	0.00000637	0.000010031
0.095	0.00015946	0.00000635	0.000010031

For a network with N number of nodes in the cluster, the source nodes transmit the data to the sink node through cooperation communication. When the number of hops hp is 3, 5 and 7, the relationship between the transmission power and the data failure transmission rate *MFR* is shown in Figure 7. It can be seen from Figure 7 that the number of hops does not affect the overall trend of transmission power and data reliability under the condition that the number of cluster nodes is constant. When the transmission power is increased, the end-to-end *MFR* is still in a falling state. The difference is that the more hops the packet passes, the higher the energy consumed to achieve the same *MFR*.

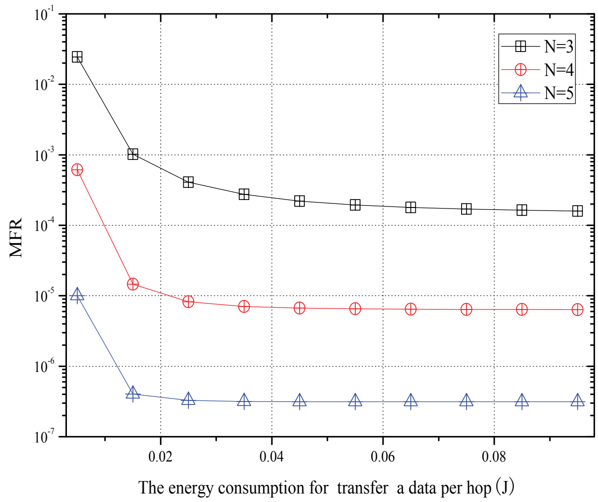

Figure 6 Relationship between node transmit power and *MFR* in each hop.

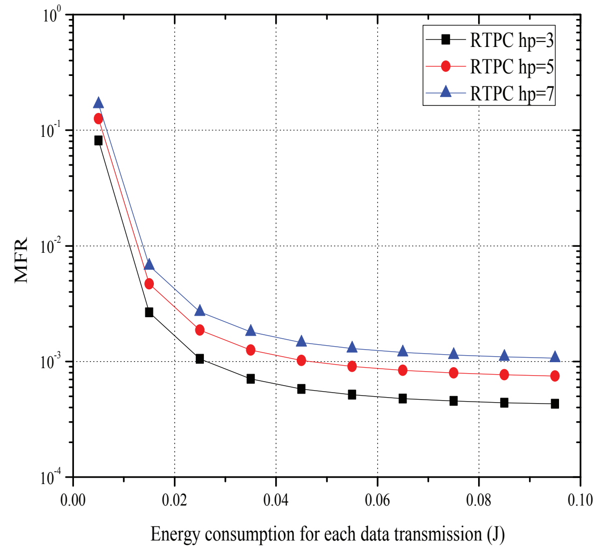

Figure 7 Relationship between node transmit power and *MFR* in multi hop.

Experiment 2. Figure 8 shows the overall energy consumption of the whole network in the case of the network when the network is transmitted by the same transmission power in the NCCC scheme. It can be seen from Figure 8 that the energy consumption of the nodes near the sink node is far greater than that of the sink node. Because of the initial energy of the nodes other than the sink node is the same, the nodes that are far away from the sink area still retain a large amount of residual energy when the network died. From the conclusion of the experiment 1, we can see that increasing transmit power can guarantee improve the reliability of data transmission effectively, therefore, we can consider using a larger power to transmit data in the en-

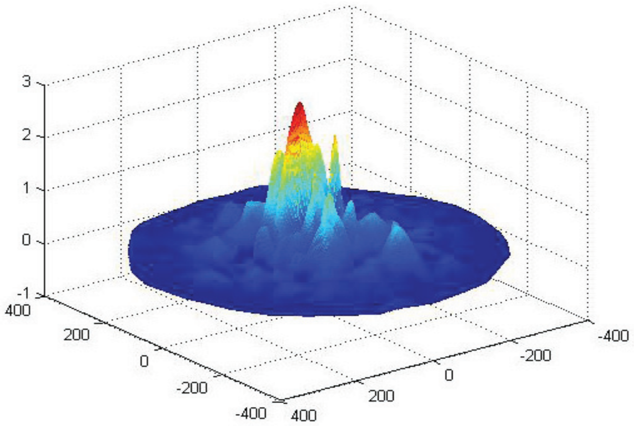

Figure 8 Schematic diagram of energy consumption in cooperative communication wireless sensor networks.

ergy remaining area. This does not affect the life of the network, and can enhance the transmission reliability.

4.3 Analysis of RTPC Scheme Data and Energy Consumption

The main idea of the RTPC scheme is that in the network coding cooperative communication wireless sensor network, every service of an application needs to calculate the energy consumption of all the nodes in the network according to its reliability. If there are multiple applications, the previous strategy to ensure the reliability of the highest application requirements, transmission power is uniformly set to $E_{\max}$. However, if the application of differentiated service strategy, the node for the application i service transmission power is determined to E_i can be determined. In other words, the node in the number of applications for the highest power $E_{\max}$, while in the remaining cases, energy consumption is less than $E_{\max}$, which means that the nodes in hotpots of its energy consumption has been reduced, network lifetime has been extended. In addition, nodes in non-hotpots also retain a lot of energy, through to improve the energy of these nodes within a certain range, the reliability will be improved.

4.3.1 Calculation of Node Data Load

The RTPC scheme to enhance the transmission power of nodes in the non-hotpots is not affected by the network lifetime, which requires that the energy dissipated by nodes in the non-hotpots nodes per round of transmission should not be higher than the node with the highest energy consumption. Therefore, we need to calculate the data loads at different distances from the sink nodes, and thus determine their energy consumption, so as to optimize the transmission power of the nodes in the non-hotpots after determining the transmission power of each application hot spot node to achieve the reliability improve. In this paper, each node has the probability of generating data packets, the transmission path of the entire network follows the shortest path algorithm.

Theorem 1. If the distance from the node to the con-vergence node is x, the radius of network is R, the farthest transmission distance of the sensor node is r_m. The number of packets sent by the node to the next-hop node is denoted by $\Theta_x^{i_1}$, Let $\Theta_x^{i_2}$ denote the number of raw packets that the data generation node broadcasts, the number of state information broadcasted by each node in this cluster is denoted by $\Theta_x^{i_2}$. O_x^i is the number of packets received by the node from the previous hop, $O_x^{i_2}$ indicates the number of received original packets, $O_x^{i_2}$ represents the number of state information collected by the node, we can conclude:

$$\begin{cases} \Theta_x^{t_1} = (1\text{-}P_f)\varepsilon\left(z + \frac{z(z+1)r_m}{2x} + 1\right), \\ \Theta_x^{t_2} = (1\text{-}P_f)\varepsilon, \\ \Theta_x^{t_3} = (1\text{-}P_f)^2\varepsilon\left(z + \frac{z(z+1)r_m}{2x}\right) + (1\text{-}P_f)\varepsilon, \\ \mathrm{O}_x^{r_1} = (1\text{-}P_f)^2\varepsilon N\left(z + \frac{z(z+1)r_m}{2x}\right), \\ \mathrm{O}_x^{r_2} = (1\text{-}P_f)^2\varepsilon\,(N-1), \\ \mathrm{O}_x^{r_3} = (1\text{-}P_f)^3\,(N\text{-}1)\left(z + \frac{z(z+1)r_m}{2x} + 1\right), \end{cases} \tag{15}$$

where $z = \lfloor (R - x)/r_m \rfloor$.

For the nodes in destination cluster, the received data is passed to the sink node directly, so they assume the data load is different from the other cluster nodes. Said hotspots nodes transmit and receive data packet respectively by Θ_{t_1} and O_{r_1}, Θ_{t_2} is original data packets broadcast number, O_{r_2} is the original data packets received number, N_{tot} is the total number of nodes distributed in the network, can be calculated by the following formula:

$$\begin{cases} \Theta_{t_1} = (1\text{-}P_f)^2\varepsilon\,(N_{all} - N + 1)\ , \\ \Theta_{t_2} = (1\text{-}P_f)\varepsilon\ , \\ \mathrm{O}_{r_1} = (1\text{-}P_f)^2\varepsilon N\,(N_{all} - N)\ , \\ \mathrm{O}_{r_2} = (1\text{-}P_f)^2\varepsilon\,(N-2)\,. \end{cases} \tag{16}$$

Proof. In a network of circular areas, for nodes v_x that far from the sink node is x, it will forward the node data from $x + ir_m$, where $i \in (1, 2, ..., z)$, z is an integer such that $x + ir_m$ is just less than the radius R of the network. Known the radius of network is R, the farthest transmission distance of the sensor node is rm, can be calculated $z = \lfloor (R - x)/r_m \rfloor$. From the cluster node to node v_x, there are two tangent lines, which form a ring-shaped area with the node cluster. The area of this area has a certain relationship with the number of packets received by the node. The angle between two tangent lines is denoted as ϕ, and the width of the annular area composed of clusters and tangent lines is denoted by d_c. In the case of d_c infinity, the annular region can be approximated as a rectangle, so that the area of the annular region is $S_{v_x} = x\varphi d_c$. For the $x + ir_m$ distance of the node can also get its ring range of area is $S_{v_{x+ir_m}} = (x + ir_m)\,\varphi d_c$. If node v_x has a probability of P_f to failure, then the number of receives packets from $x + ir_m$ sent is $(x + ir_m)\,\varphi d_c(1 - P_f)^2\varepsilon\rho$, so can be calculated for the total number of packets received by v_x is:

$$\begin{aligned} \mathrm{O}_x^{r_1} &= \frac{(1\text{-}P_f)^2\varepsilon\rho N \sum_{i=1}^{z}\left[(x+ir_m)\varphi d_c\right]}{\varphi d_c \rho x} \\ &= (1\text{-}P_f)^2\varepsilon N\left(z + \frac{z(z+1)r_m}{2x}\right) \end{aligned} \tag{17}$$

Node v_x transmission packet contains two parts, one is self-perceived data, the other is to forward the remaining nodes of the data. In accordance with the network model requirements, the node will be obtained N packets from the previous cluster nodes. In this case, if there are N nodes in the last cluster, each node transmits a packet. However, if there is already a node death, this time to send a data packet for each surviving node is not enough to achieve the number N, then you need to live nodes in the cluster instead of dead nodes to send data. In this case, some nodes do not just transmit a packet, but need to help other nodes within the cluster services, then need to transfer the number of packets to. We can get the node v_x transmission data load is:

$$\begin{aligned}\Theta_x^{t_1} &= (1\text{-}P_f)\varepsilon\left(z + \frac{z(z+1)r_m}{2x} + 1\right) \\ &\bullet(1\text{-}P_f)\left(\frac{NP_f}{N-NP_f} + 1\right) \\ &= (1\text{-}P_f)\varepsilon\left(z + \frac{z(z+1)r_m}{2x} + 1\right)\end{aligned} \tag{18}$$

In the case where the node survives and perceives the data, the node will send the data using cooperative communication. Known node survival probability is $(1 - P_f)$, then the the probability of broadcast the original packet of each nodes is:

$$\Theta_x^{t_2} = (1\text{-}P_f)\varepsilon \tag{19}$$

After the source node broadcasts data, $(N-1)$ nodes in the cluster will receive the data. For a node v_x, the primary condition for receiving data is that the node does not fail and the probability is $(1 - P_f)$. Of course, the need for nodes to broadcast data, the probability of $(1 - P_f)\varepsilon$. The probability that the node receives the original data packet broadcasted by this cluster cooperative node can be calculated as:

$$O_x^{r_2} = (1 - P_f)^2\varepsilon\,(N - 1) \tag{20}$$

In the cooperative communication system, it is necessary to know the survivability of the cooperative node at all times, which requires each node to broadcast the state information including the ID number to the other cooperating nodes during the broadcasting period, and also accept the status information of other nodes. Through the analysis of the above process can be drawn in each round of transmission of nodes v_x need to broadcast the number of state information is:

$$\Theta_x^{t_3} = (1 - P_f)^2\varepsilon\left(z + \frac{z(z+1)r_m}{2x}\right) + (1 - P_f)\varepsilon \tag{21}$$

The number of statuses received is:

$$O_x^{r_3} = (1 - P_f)^3\varepsilon\,(N - 1)\left(z + \frac{z(z+1)r_m}{2x} + 1\right) \tag{22}$$

The nodes in destination cluster to collect and send data packets are different from other nodes. This is because the nodes in the same cluster with the sink node need to send all the collected data to the sink node, and the sink node needs to receive all the data transmitted in the network. This proves once again that the energy consumption of nodes in the hot zone is much larger than that of other nodes. If the total number of nodes in the network is N_{all}, then the nodes in the hotpots need to forward $(N_{\text{all}} - N)$ data and send their own data, then the number of transmission packets is:

$$\Theta_{t_1} = (1 - P_f)^2\varepsilon\,(N_{\text{all}} - N + 1) \tag{23}$$

The number of received packets is:

$$O_{r_1} = (1 - P_f)^2\varepsilon N\,(N_{\text{all}} - N) \tag{24}$$

The number of original packets that broadcast in the cluster can be calculated as:

$$\Theta_{t_2} = (1 - P_f)\varepsilon \tag{25}$$

The number of raw packets that obtained from other cooperating nodes is:

$$O_{r_2} = (1 - P_f)^2\varepsilon\,(N - 2) \tag{26}$$

4.3.2 Calculation of Node Energy Consumption

Theorem 2. For the nodes with distance x from the sink, the energy consumption of the destination cluster node and the other nodes are denoted by Ψ_s and Ψ_x, where l_0 is the original packet length, l_t is the length of the packet actually transmitted, l_h is the packet header length, r_c is the cluster radius:

$$\begin{cases}\Psi_s = E_t\left((2r_c/3)^k, P_{plr}\right)\Theta_{t_1}l_t + E_t\left(r_c^k, P_{plr}\right) \\ \quad\bullet\Theta_{t_2}l_0 + E_r\left(O_{r_1}l_t + O_{r_2}l_0\right) \\ \Psi_x = E_t\left(d_x^k, P_{plr}\right)\Theta_x^{t_1}l_t + E_t\left(r_c^k, P_{plr}\right) \\ \quad\bullet\left(\Theta_x^{t_2}l_s + \Theta_x^{t_3}l_0\right) + E_r\left(O_x^{r_1}l_t + O_x^{r_2}l_s + O_x^{r_3}l_0\right)\end{cases} \tag{27}$$

where $d_x = \begin{cases} x\,, & for\ x < r_m \\ r_m, & for\ x \geq r_m \end{cases}$.

Proof. The energy consumption of a node is divided into two parts, one is the energy consumption of the received data and the other is the energy consumption of the transmitted data, both of which are related to the size of the data, that is, the bit rate. Known l_0, l_t, l_h said the original packet length, the actual transmission of the packet length, packet header length respectively. In the introduction of data transmission model mentioned in the original data is divided into M block, so the relationship between l_t and l_0, l_h can be expressed as: $l_t = (l_0/M + l_h)$.

The transmission data consumption is divided into three, namely, send data packets, broadcast the original data packet, broadcast status information. From the formula (2) can be seen that the data transmission energy consumption and transmission distance, and send data packets and broadcast message distance is different from the node. For the distance from the sink, send packet distance to the farthest transmission distance, that is $d_x = r_m$. For nodes closer to sink, the data can be sent directly to the sink, where the distance is $d_x = x$. Note that the broadcast distance of all nodes is the cluster radius r_c. It is thus possible to obtain the energy consumption is $E_t\left(d_x^k, P_{plr}\right)\Theta_x^{t_1}l_t$ of each sensor node that is far away from the sink is x, and the energy consumption of broadcasting the raw data and the broadcast state information is $E_t\left(r_c^k, P_{plr}\right)\bullet\left(\Theta_x^{t_2}l_s + \Theta_x^{t_3}l_0\right)$.

Similarly, the energy consumption of the received data is also divided into three, according to the formula (3) can know that the energy received per bit data is determined, it is concluded that the overall energy consumption of the received data. Therefore, for non-destination cluster nodes, the total energy consumption can be calculated as:

$$\begin{aligned}\Psi_x = E_t\left(d_x^k, P_{plr}\right)\Theta_x^{t_1}l_t + E_t\left(r_c^k, P_{plr}\right)\bullet\left(\Theta_x^{t_2}l_s\right. \\ \left. + \Theta_x^{t_3}l_0\right) + E_r\left(O_x^{r_1}l_t + O_x^{r_2}l_s + O_x^{r_3}l_0\right)\end{aligned} \tag{28}$$

Similar to the non-destination cluster nodes, the energy consumption of the cluster nodes can also be calculated as:

$$\begin{aligned}\Psi_s = E_t\left((2r_c/3)^k, P_{plr}\right)\Theta_{t_1}l_t + E_t\left(r_c^k, P_{plr}\right) \\ \bullet\Theta_{t_2}l_0 + E_r\left(O_{r_1}l_t + O_{r_2}l_0\right)\end{aligned} \tag{29}$$

Algorithm 1: Known reliability calculation of transmission power

Input: Reliability requirements *MFR*
Output: Transmission power E_A of the node
Initialize: Set $MFR_1 = MFR$, $MFR_2 = 0$, $E_A = 0$
double min=0 , max=0.1
$MFR_2 = MFRCount(E_A)$
//*MFR*Count is a function of input power to calculate //end to end reliability, need to use formula (9) and (14)
Do while($MFR_2 != MFR_1$)
if($MFR_2 < MFR_1$)
max=E_A
$E_{Amp} =$ (max - min)/2
else if($MFR_2 > MFR_1$)
min=E_A
$E_A = \min + (\max - \min)/2$
else
break
$MFR_2 = MFRCount(E_A)$
End Do
Output the transmitting power E_A
End

s

4.4 Reliability Differentiated Service Computing

In the differentiated service strategy, it is necessary to select transmission power for data transmission for applications with different reliability requirements. Here, the reliability requirement refers to the end-to-end data reliability, which is known as (14) E_A in equation (9). However, it is known that E_A in Eq. (9) can be used to find the *MFR* in Eq. (14), which is not easy. So we propose a known reliable transmission power calculation algorithm, Transmission reliability under the premise of each node need to set the minimum required to send the power size.

4.5 Numerical Calculation for Transmission Power of Non-Hotpots Nodes

Theorem 3. According to the RTPC scheme description, the transmission power of the sensor nodes that away from the sink is x while in the service for application i will be finally determined as:

$$E_{i,x} = \frac{\eta - \frac{P_T}{T_b} \bullet \Theta_{tot} - E_r \bullet \mathrm{O}_{tot}}{\mathrm{O}_x^{r1} l_t + \left(\frac{r_c}{d_x}\right)^k \left(\mathrm{O}_x^{r2} l_s + \mathrm{O}_x^{r3} l_0\right)} \tag{30}$$

where:

$$\eta = E_t\left(r_m^k, P_{plr}\right) \Theta_x^{t1} l_t + E_t\left(r_c^k, P_{plr}\right) \bullet \left(\Theta_x^{t2} l_s + \Theta_x^{t3} l_0\right) + E_r\left(\mathrm{O}_x^{r1} l_t + \mathrm{O}_x^{r2} l_s + \mathrm{O}_x^{r3} l_0\right) \tag{31}$$

$$\Theta_{tot} = \Theta_x^{t1} l_t + \Theta_x^{t2} l_s + \Theta_x^{t3} l_0, \mathrm{O}_{tot} = \mathrm{O}_x^{r1} l_t + \mathrm{O}_x^{r2} l_s \tag{32}$$

Proof. In the case of service for application i, the transmission power of all nodes is initialized to E_i, which satisfies the reliability requirement, and then the transmission power of the far sink node is increased. Excessive energy consumption can lead to premature death of the network, therefore, the transmission power of the increase should determine an upper limit. It is known that the closer to the sink node the more energy is consumed, so we only need to ensure that all other nodes do not consume more energy than the highest energy consumption of a node. In this paper, the upper limit of the energy consumption is defined as the energy consumption of the node at the edge of the hotpots, that is, the distance from the sink is r_m. In this case, the upper limit can be calculated as:

$$\eta = \Psi_{r_m} = E_t\left(r_m^k, P_{plr}\right) \Theta_x^{t1} l_t + E_t\left(r_c^k, P_{plr}\right) \bullet \left(\Theta_x^{t2} l_s + \Theta_x^{t3} l_0\right) + E_r\left(\mathrm{O}_x^{r1} l_t + \mathrm{O}_x^{r2} l_s + \mathrm{O}_x^{r3} l_0\right) \tag{33}$$

If the transmission power is not increased, the energy consumption of the node at this time can be calculated according to formula (27) as:

$$\begin{aligned}\Psi_x &= E_t\left(d_x^k, P_{plr}\right) \Theta_x^{t1} l_t + E_t\left(r_c^k, P_{plr}\right) \bullet \left(\Theta_x^{t2} l_s + \Theta_x^{t3} l_0\right) + E_r\left(\mathrm{O}_x^{r1} l_t + \mathrm{O}_x^{r2} l_s + \mathrm{O}_x^{r3} l_0\right) \\ &= \left(E_{i,x} + P_T/T_b\right) \Theta_x^{t1} l + \left(E_{r_c} + P_T/T_b\right) \bullet \left(\Theta_x^{t2} l_s + \Theta_x^{t3} l_0\right) + E_r\left(\mathrm{O}_x^{r1} l_t + \mathrm{O}_x^{r2} l_s + \mathrm{O}_x^{r3} l_0\right)\end{aligned} \tag{34}$$

Therefore, we consider to make full use of the node's current energy consumption and the difference between the upper bound η to enhance the transmission power, thereby enhancing the transmission reliability. Here, we can directly determine the final energy consumption of the node is η. Then, we can deduce the transmission power $E_{i,x}$ of the node that is far away from the sink distance x in the service for application i:

$$E_{i,x} = \frac{\eta - \frac{P_T}{T_b}\left(\Theta_x^{t1} l_t + \Theta_x^{t2} l_s + \Theta_x^{t3} l_0\right) - E_r\left(\mathrm{O}_x^{r1} l_t + \mathrm{O}_x^{r2} l_s + \mathrm{O}_x^{r3} l_0\right)}{\mathrm{O}_x^{r1} l_t + \left(\frac{r_c}{d_x}\right)^k \left(\mathrm{O}_x^{r2} l_s + \mathrm{O}_x^{r3} l_0\right)} \tag{35}$$

4.6 RTPC Scheme

RTPC scheme is mainly divided into three steps to achieve:

Step 1: Find the transmission power that meets the maximum reliability requirement. Traversing the reliability requirement *MFR* of each application and finding the maximum reliability requirement in these applications. Assuming that the maximum reliability requirement is $MFR_{\max}$, the transmission power $E_{\max}$ required by the node at this time is calculated according to Algorithm 1.

Step 2: Determine the transmission power for each application to meet the reliability requirements. If the reliability required by the application i is the same as in Step 1, the transmission power E_i can be obtained from the algorithm 1 in order. If there are S applications, the process needs to be repeated S times.

Step 3: Increase the transmission power of the node in the non-hotpots and calculate the determined value. The transmission power of the node near the sink while services for application i is fixed as E_i, the transmission power of the far sink is increased, and the transmission power of the node at distance x meters from the sink is calculated according to the formula (30) when serving for the ith application $E_{i,x}$.

According to the previous analysis and calculation, the pseudo-code of the RTPC scheme is described as follows.

Algorithm 2: RTPC algorithm
Input: Multiple reliability requirements R_i for applications i
Output: Transmission power $E_{i,x}$ of node x when serving the application i
Stage 1: Find the greatest need for reliability in multiple applications

```
To traverse the reliability requirements of all applications and find the maximum reliability requirements R_max
According to the formula (1) to calculate the transmission power E_max to meet the maximum reliability requirements R_max
```

Stage 2: The transmission power of each node is calculated for each application

```
For ( i=1 ; i<=n ; i++)
//n is the number of applications
Calculate the transmission power E_i to meet the reliability requirements R_i of the application i
if ( x<= r_m)
//x is the distance from node to sink, set the //transmission power of hotspots is E_i
E_{i,x} = E_i
End if
End For
```

Stage 3: Enhance the transmission power of non-hotpots nodes and calculate the determine value

```
For ( i=1 ; i<=n ; i++)
//For all applications the following calculation
if( x> r_m)
Initialize the transmission power of non-hotpots nodes, let=E_{i,x} = E_i
Calculate the node energy consumption Ψ_x
Calculate the energy consumption η of node that rm meters away from the sink node
//Calculate the upper bound of energy
if(Ψ_x < η)
//Determine whether the node power can //be improved
According to formula (30) to calculate the power E_{i,x}
End if
End if
Output transmission power E_{i,x} of each nodes
End For
```

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5. PERFORMANCE ANALYSIS IN THEORY

5.1 Network Lifetime Analysis

According to the data loads of the node can be calculated for each node energy consumption, the network life is closely related to the energy consumption of nodes that in hotpots, thus optimizing the network lifetime is to reduce the energy consumption of hotspots nodes.

Theorem 4. The ratio of NCCC and RTPC under two strategies of network lifetime:

$$\Omega = \frac{S\bullet\left(\begin{array}{c} E_t\left(\left(\frac{2r_c}{3}\right)^k, R_{\max}\right)\Theta_{t_1}l_t + E_t\left(r_c^k, R_{\max}\right) \\ \bullet\Theta_{t_2}l_0 + E_r\left(\mathrm{O}_{r_1}l_t + \mathrm{O}_{r_2}l_0\right) \end{array}\right)}{\sum_{i=1}^{S}\left(\begin{array}{c} E_t\left(\left(\frac{2r_c}{3}\right)^k, R_i\right)\Theta_{t_1}l_t + E_t\left(r_c^k, R_i\right) \\ \bullet\Theta_{t_2}l_0 + E_r\left(\mathrm{O}_{r_1}l_t + \mathrm{O}_{r_2}l_0\right) \end{array}\right)} \tag{36}$$

Proof. As can be seen from theorem 1, the data load of the destination cluster node is the largest, and the energy consumption is the most. Therefore, reducing the energy consumption of the cluster nodes is a direct method to optimize the network lifetime.

Assume that the network will provide services for S applications, where the highest requirement for reliability is $R_{\max}$, the proportion of each application i in all applications is s_i. In the NCCC scheme, the transmission power of all nodes must satisfy the maximum reliability demand $R_{\max}$, at this time the node transmission power can be calculated as $E_{\max}$. In this scheme, the energy consumption of the destination cluster node is:

$$\Psi_{s1} = S\bullet\left(\begin{array}{c} E_t\left(\left(\frac{2r_c}{3}\right)^k, R_{\max}\right)\Theta_{t_1}l_t + E_t\left(r_c^k, R_{\max}\right) \\ \bullet\Theta_{t_2}l_0 + E_r\left(\mathrm{O}_{r_1}l_t + \mathrm{O}_{r_2}l_0\right) \end{array}\right) \tag{37}$$

Differentiated service strategy proposed in this paper, the application i reliability requirements is R_i, if the node transmission power is fixed at E_i when service for application i, then according to the formula (16) can be obtained the data quantity of nodes in destination cluster while service for application i. According to the calculation formula (20) the energy consumption of nodes is $\Psi_{s,i}$. Under the RTPC scheme, the energy consumption of cluster nodes serving the S application is:

$$\Psi_{s2} = \sum_{i=1}^{S}\left(\begin{array}{c} E_t\left(\left(\frac{2r_c}{3}\right)^k, R_i\right)\Theta_{t_1}l_t + E_t\left(r_c^k, R_i\right) \\ \bullet\Theta_{t_2}l_0 + E_r\left(\mathrm{O}_{r_1}l_t + \mathrm{O}_{r_2}l_0\right) \end{array}\right) \tag{38}$$

According to the formula (5), the energy consumption of the nodes is inversely proportional to the lifetime of the network. Therefore, the ratio of network lifetime under NCCC and RTPC is:

$$\Omega = \frac{S\bullet\left(\begin{array}{c} E_t\left(\left(\frac{2r_c}{3}\right)^k, R_{\max}\right)\Theta_{t_1}l_t + E_t\left(r_c^k, R_{\max}\right) \\ \bullet\Theta_{t_2}l_0 + E_r\left(\mathrm{O}_{r_1}l_t + \mathrm{O}_{r_2}l_0\right) \end{array}\right)}{\sum_{i=1}^{S}\left(\begin{array}{c} E_t\left(\left(\frac{2r_c}{3}\right)^k, R_i\right)\Theta_{t_1}l_t + E_t\left(r_c^k, R_i\right) \\ \bullet\Theta_{t_2}l_0 + E_r\left(\mathrm{O}_{r_1}l_t + \mathrm{O}_{r_2}l_0\right) \end{array}\right)} \tag{39}$$

5.2 Comparison of Reliability

Theorem 5. The ratio of NCCC and RTPC reliability under two schemes:

$$\Lambda = \frac{1-(1-MFR_\alpha)^{hp-1}\bullet\left(1-MFR_\beta\right)}{1-(1-MFR_\delta)^{hp-1}\bullet\prod_{n=1}^{hp-1}\left(1-MFR_\vartheta^{x-nr_m}\right)} \tag{40}$$

Proof. Consider the data after the overall reliability of the whole transmission links here, according to the formula (14), can be calculated for the reliability of the entire link is $MFR = 1 - (1-MFR_0)^{hp-1}\bullet(1-MFR_l)$, which hp indicates the hops that transmit data packet from the source node to the sink node. If the source node and sink node distance is x can be obtained $hp = \lfloor x/r_m \rfloor$. In the transmission process of the data packet to the sink node, $x - r_m$, $x - 2r_m, \ldots, x-(hp-1)r_m$ node to forward the data, the power of these nodes to transmit data affects the packet end-to-end reliability directly.

Using NCCC scheme, all nodes transmit data using power $E_{\max}$. According to the formula (9), (12), (13) the overall reliability of the data at this time can be marked as:

$$MFR_x^{E_{\max}} = 1-(1-MFR_\alpha)^{hp-1}\bullet\left(1-MFR_\beta\right) \tag{41}$$

For the RTPC scheme, the transmit power of each node is different for different applications. According to Algorithm 1, we calculate the transmit power E_i, x, which should be set at the node far away from sink x meters when service for application i. Then the transmit power of each node of the packet is $E_{i,x}, E_{i,x-rm}, \ldots, E_{i,x-(hp-1)rm}$. Likewise, the overall reliability of the data at this time can be denoted as:

$$MFR_x^{E_i} = 1-(1-MFR_\delta)^{hp-1}\bullet\prod_{n=1}^{hp-1}\left(1-MFR_\vartheta^{x-nr_m}\right) \tag{42}$$

Therefore, using NCCC scheme and RTPC scheme, the ratio of end-to-end reliability is:

$$\Lambda = \frac{MFR_x^{E_{\max}}}{MFR_x^{E_i}} = \frac{1-(1-MFR_\alpha)^{hp-1}\bullet(1-MFR_\beta)}{1-(1-MFR_\delta)^{hp-1}\bullet\prod_{n=1}^{hp-1}\left(1-MFR_\vartheta^{x-nrm}\right)} \tag{43}$$

5.3 Improvement of Energy Efficiency

Theorem 6. To meet the application reliability condition, node j (the node is in non-hotspots) transmission power is set to E_j, improve the node transmission power to $E_{i,j}$, the method of improving non-hotspots node power so that the network can improve energy utilization ratio:

$$\Im = \frac{\sum_{0\le j\le m}\sum_{i=1}^{S}\left(\phi_i E_{i,j}\right)}{\sum_{0\le j\le m} E_j} \tag{44}$$

Proof. In the second step of the RTPC scheme, the energy consumption of the node j is calculated as E_j. If $E_{ini,j}$ represents the initial energy of node j, and m represents the total number of nodes:

$$\varpi = \sum_{0\le j\le m} E_j \Big/ \sum_{0\le j\le m} E_{ini,j} \tag{45}$$

In the third step of the RTPC algorithm, the transmission power of nodes in non-hotspots are improved, and at this time of the network life is not affected, but the transmission power to improve the reliability of the data has been improved. At this time, the transmission power of each node according to the different sink distance have a certain gap, the transmission power of node j can be calculated as $E_{i,j}$. If there are S applications, the proportion of application i in all applications is φ_i, then the average transmit power of node j with differentiated services is $\sum_{i=1}^{S}\left(\phi_i E_{i,j}\right)$, the network energy utilization rate is:

$$\varpi' = \sum_{0\le j\le m}\sum_{i=1}^{S}\left(\phi_i E_{i,j}\right) \Big/ \sum_{0\le j\le m} E_{ini,j} \tag{46}$$

It can be seen $Ei,j \ge E_j$ that is always satisfied, the energy use efficiency will also be improved. Therefore, the ratio of promotion energy utilization when use the idea of increase the power of non-hotpots nodes can be calculated:

$$\Im = \frac{\sum_{0\le j\le m}\sum_{i=1}^{S}\left(\phi_i E_{i,j}\right)/\sum_{0\le j\le m} E_{ini,j}}{\sum_{0\le j\le m} E_j/\sum_{0\le j\le m} E_{ini,j}} = \frac{\sum_{0\le j\le m}\sum_{i=1}^{S}\left(\phi_i E_{i,j}\right)}{\sum_{0\le j\le m} E_j} \tag{47}$$

6. EXPERIMENTAL RESULTS

In this paper, the network used in the experiment is the round network of the sink node at the center of the circle. The parameters are set as follows: the radius R of the network is 400m and the number of nodes is 1000. The maximum transmission distance rm of nodes is 100m. The other parameters are set to the reference Table 1.

6.1 Amount of Data Nodes

According to theorem 1, it can be seen that under the condition of network condition, the data load of each node varies with the number of nodes N, but not with the transmission power. Therefore, the data load of the two schemes is the same under

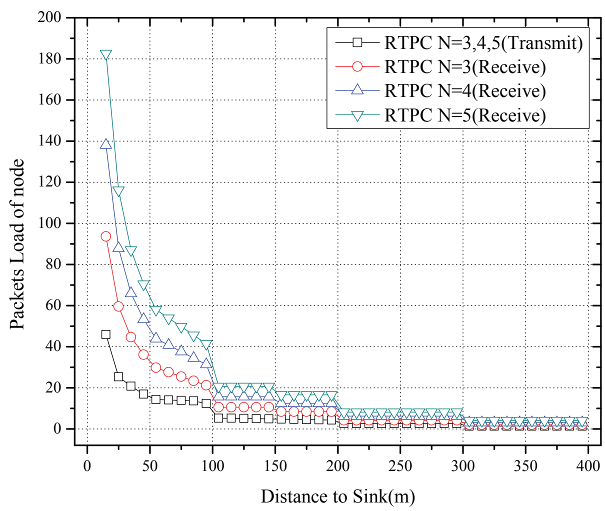

Figure 9 The data load of node in network.

the same network conditions, regardless of the RTPC scheme or the NCCC scheme. Figure 9 shows under the condition that the number of nodes N in the cluster changed, the amount of receive and forward data of nodes that distance from the sink is different when use of RTPC scheme. It can be seen from Fig. 9, with the change of the number of cluster nodes N does not affect the number of data transmitted, but only affects the amount of received data. When the number of cluster nodes gradually increases, the number of packets received per node also increases, because each node in the cooperative communication system needs to receive N packets from the cluster of the last hop. At the same time, we can observe a common phenomenon, that is, nodes near the sink undertake much more data load than non-hotpots nodes, so the energy consumption is more. On the contrary, the distance between nodes of sink is far less, and the energy consumption is less.

6.2 Energy Consumption Analysis of Nodes for Differentiated Service

In the energy consumption analysis of nodes for differentiated service, the number of cluster nodes N is always set to 3, and the reliability requirements of a specific application are assigned. In this specific case, the differentiated service strategy is compared with the traditional NCCC strategy, the difference of energy consumption between the two schemes is obtained.

If the network needs to provide services for twelve applications, using R_i to represent the reliability requirements of application i, reliability requirements for information transmission failure rate measured by the *MFR*. The smaller the application requirement of *MFR*, the greater the power needed to transmit data, as shown in Table 3.

Table 3 Requirements of Application about Reliability.

Application	R_1	R_2	R_3	R_4	R_5	R_6
MFR	0.1	0.3	0.05	0.2	0.1	0.2
Application	R_7	R_8	R_9	R_{10}	R_{11}	R_{12}
MFR	0.3	0.2	0.05	0.1	0.3	0.05

According to the reliability requirements in Table 4, apply the same reliability requirements for classified. In this case, it is possible to find the transmit power E_i required by the node of serving the application i, as shown in Table 4.

From the Table 4 can be summarized, $E_3 = E_9 = E_{12} = P_1 = 0.00614488$, $E_1 = E_5 = E_{10} = P_2 = 0.00505498$, $E_4 = E_6 = E_8 = P_3 = 0.00415483$, $E_2 = E_7 = E_{11} = P_4 = 0.00368438$.

In the NCCC scheme, when the transmit power of all the nodes satisfies the requirement of the message failure rate of 0.05, the maximum transmit power of the node is $E_{\max} = P_1 = 0.00614488$. While the use of differentiated services strategy, the average transmit power of each node: $E_{\text{avg}} = \sum_{i=1}^{S} (\varepsilon_i E_i) = (P_1 + P_2 + P_3 + P_4)/4 = 0.00475977$. In Figure 10, the transmit power of nodes with different distances from the sink and the average transmit power of the nodes under

Table 4 Classification based on Reliability.

Application	R_3, R_9, R_{12}	R_1, R_5, R_{10}
MFR	0.05	0.1
Transmit power marker	P_1	P_2
Transmission power /J	0.00614488	0.00505498
Application	R_4, R_6, R_8	R_2, R_7, R_{11}
MFR	0.2	0.3
Transmit power marker	P_3	P_4
Transmission power /J	0.00415483	0.00368438

the RTPC scheme step 2 are shown when the number of cluster nodes N identified as 3 and satisfying all kinds of application reliability requirements. Differentiated service curves are compared with the *MFR*=0.05, *MFR*=0.05 is the power setting of nodes under NCCC scheme. It can be seen that when the service is applied to multiple applications, the energy consumption of each node is reduced by using the differentiated service strategy , but did not affect the reliability of data, which is useful from the perspective of prolonging network lifetime.

After finding the transmission power of each node in the network, according to theorem 1 and theorem 2, we can get the energy consumption of the nodes at different distances of the sink node under the circumstances of setting the transmission power of $MFR = 0.3$, $MFR = 0.2$, $MFR = 0.1$, $MFR = 0.05$, and RTPC scheme respectively. That is shown in Figure 11.

From the four curves in Fig. 11 which the reliability requirements are different, it can be seen that the energy consumed by the near-sink node is far higher than that of the far sink node, and the higher reliability requirements, the higher the energy consumption of all nodes. Similarly, comparing the RTPC scheme with a curve with $MFR = 0.05$. In RTPC scheme, each application chooses different sending power, but NCCC is used to meet the maximum reliability requirements of $E_{\max}$ to send data. Compared with NCCC and RTPC, RTPC has advantages in energy saving. However, our purpose is not so, from the formula (9) can be seen to improve the transmission power of the node can improve the reliability of the data transmit, thereby affecting the end-to-end reliability of data, so the next RTPC scheme in step 3 will increase the energy of nodes in the non-hotpots nodes and guarantee the reliability requirement without affecting the network lifetime.

Figure 12 shows the comparison of the transmission power of each node after the energy of non-hotpots nodes is increased and the step taken only in step 2 when the RTPC step 3 is adopted. We can see that there is no change in the power of the hotpots nodes, but the energy of the remaining nodes has been improved. And the further the distance from the sink, the more power is improved, because the far sink area retains more energy, the more energy that can be used to enhance transmission reliability.

Based on the experimental results in Figure 12, we can also compare the energy consumption of the nodes in steps 3 and 2 of RTPC scheme. Comparing Fig. 13 and Fig. 11, it can be found that, after the improvement of step 3, the energy consumption of the nodes in the hotpots is not changed, but the energy consumption of all the nodes in the non-hotpots is increased, and

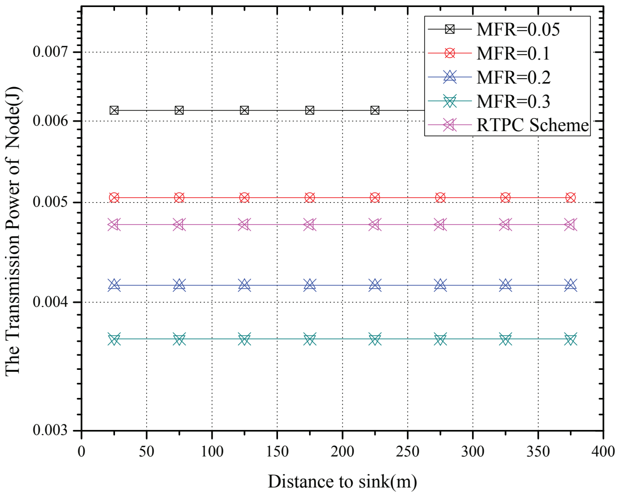

Figure 10 RTPC scheme step 2 power control comparison.

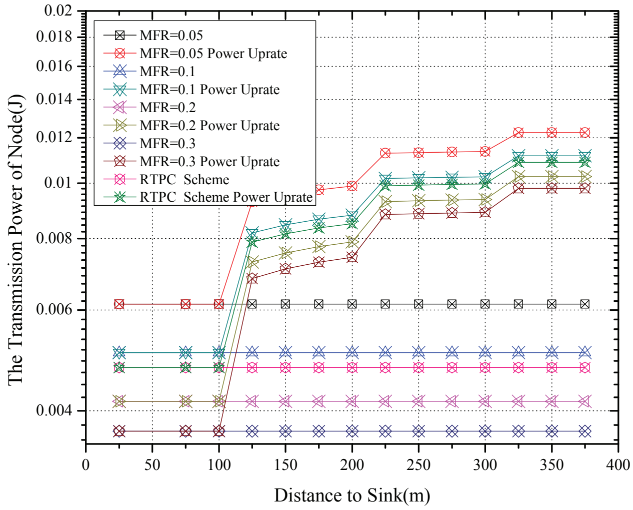

Figure 12 RTPC scheme step 3 and step 2 node transmission power comparison.

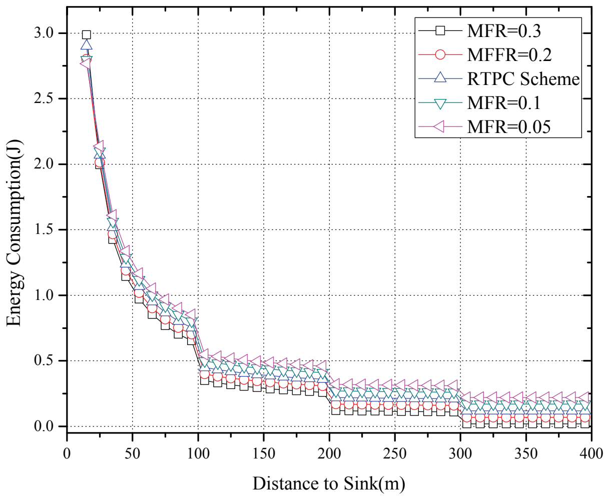

Figure 11 RTPC scheme step 2 energy consumption comparison.

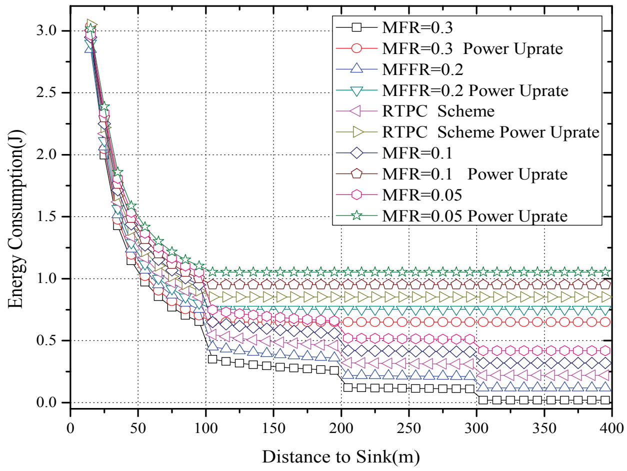

Figure 13 Comparison of RTPC scheme step 3 and step 2 node energy consumption.

the highest energy consumption of non-hotpots nodes is below the upper limit set η in Theorem 3. At the same time, it can be seen that for each application, the transmission power of non-hotpots nodes has been greatly improved, which improves the network energy utilization and guarantees the reliability of data sent by each node better. It has made great contribution to the application of reliability.

6.3 Network Lifetime

According to theorem 4, we can get the contrast diagram of network life in figure 14. In the number of cluster nodes is 3 and the network radius under the condition of different applications. For different reliability requirements using the RTPC and NCCC for transmission, from Figure 14 and Figure 15 network lifetime prolongation rate of the figure can be seen, under the premise of reliability is guaranteed will enhance the network lifetime of about 19% in the RTPC.

Figure 16 and Figure 17 shows the changes in the number of nodes in the cluster network lifetime while the network radius is 400 m. Can be seen from Figure 16, the RTPC scheme has always been able to get better network lifetime, but with the increase of the number of cluster nodes, the network lifetime of two schemes are declining, this is due to the increase in the number of hotpots nodes data load increase, accelerating the death of network Figure 17 shows the RTPC scheme to enhance the effect of the network lifetime. The number of nodes in the cluster is less, the network lifetime increase around 18%. With the increase of the number of cluster nodes, the data has a downward trend. This situation is caused by the cooperative communication system, the increase of the number of cluster nodes representing each node receives the data packet number is also increasing, although there is a certain effect on improving the reliability of the data, but also accelerate the consumption of energy, so we must be weighed in the two aspects of reliability and energy.

6.4 Data Reliability

In this experiment, the number of nodes in cluster is 3, and the application of reliability requirement $MFR = 0.05$ is transmitted

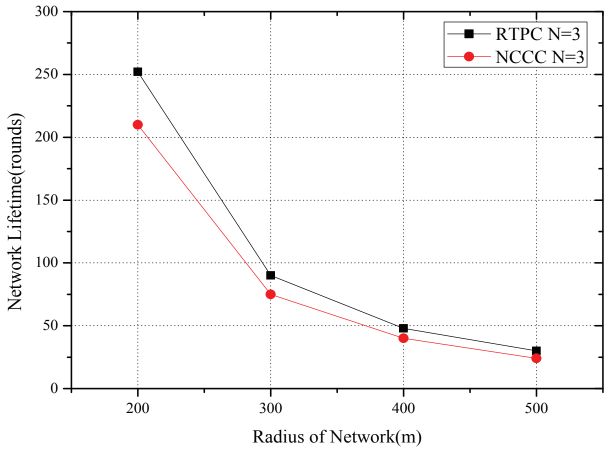

Figure 14 Theoretical comparison on the network lifetime with the number of cluster nodes is 3.

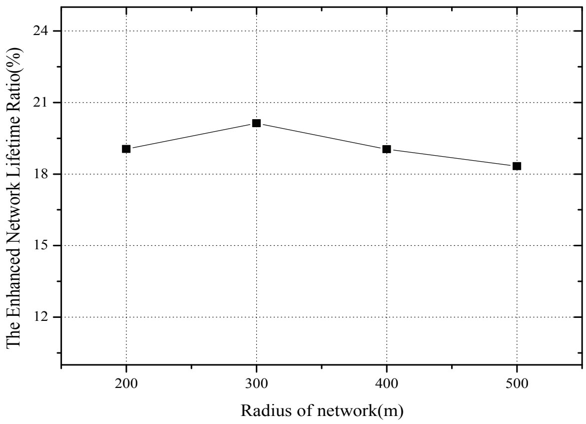

Figure 15 Network lifetime extension rate of different network radius.

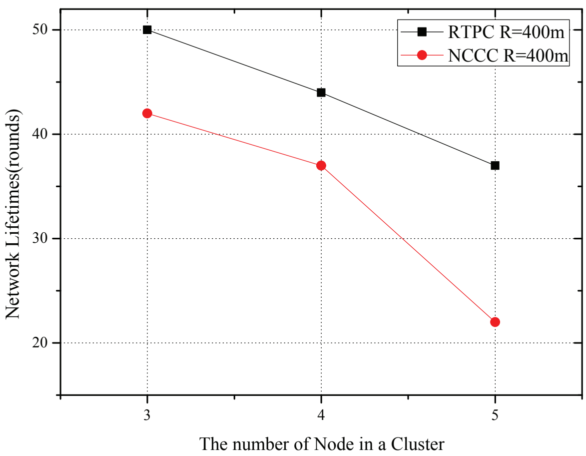

Figure 16 Theoretical comparison on the network lifetime with the network radius is 400 meter.

by RTPC and NCCC respectively. The reliability comparison of node transmission data under the two schemes is shown in Fig. 18. Although the reliability of the transmission of the near-sink node has not been improved, but the transmission power of the far sink node is improved, so that the transmission data failure rate *MFR* is greatly reduced.

In Fig. 19, show the reliability promotion ratio of nodes with different distance in the network when using the RTPC scheme

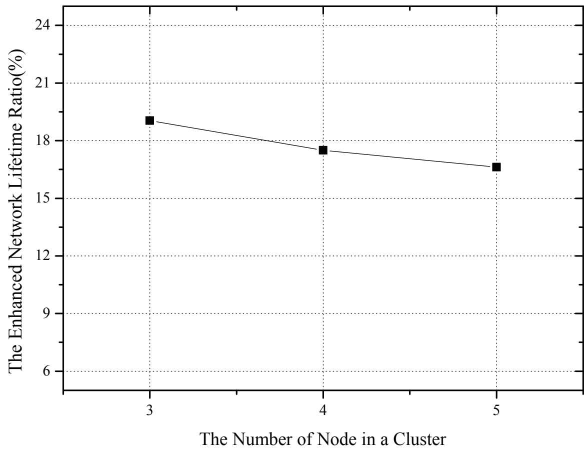

Figure 17 Network lifetime extension rate of different number of cluster nodes.

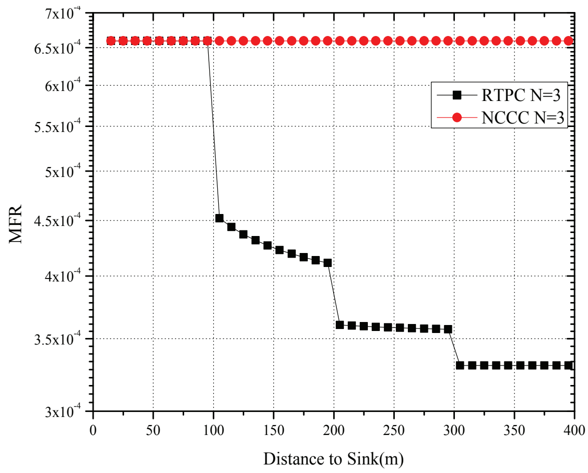

Figure 18 Comparison of reliability between RTPC and NCCC.

compared with the NCCC scheme while the number of nodes in cluster is changed. From Figure 19, we can see that the RTPC scheme has different advantages in the case of different number of cluster nodes. When the number of cluster nodes is 4, the reliability is the most, but in general, the RTPC strategy can achieve more than 30% of the reliability upgrade ratio. Moreover, the farther away from the sink the greater the contribution to the improvement of data reliability.

6.5 Energy Utilization

Figure 20 shows the energy consumption of one round of data transmission for the entire network under RTPC and NCCC schemes for different network radius. Obviously, the RTPC scheme consume much more energies than the NCCC scheme, because of the RTPC scheme makes full use of the residual energy of the far sink node. However, the increase in energy consumption does not affect the network lifetime, but increases the overall energy efficiency of the network, which can also be seen from Figure 21.

Figure 21 shows the comparison of the network energy usage of the RTPC and NCCC schemes for different network radius. It can be seen that the RTPC scheme makes the energy utilization

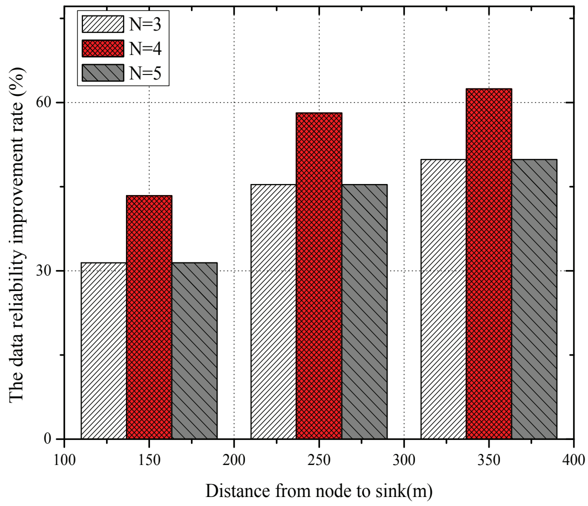

Figure 19 Comparison of RTPC and NCCC reliability enhancement.

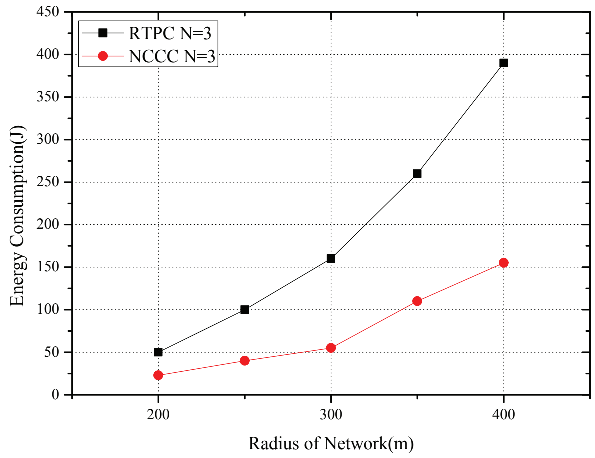

Figure 20 Comparison of RTPC and NCCC transmission data consumption in a round.

of the whole network nearly 54.5% higher than that of the NCCC scheme by utilizing the residual energy of the non-hotpots nodes. In the NCCC scheme, energy utilization is at most 15.84%, at least 6.05%. However, in the RTPC scheme, the energy efficiency of the network is extended to between 15.4% and 38.5%. From the two strategies in the numerical comparison of the performance of network utilization can be seen, RTPC scheme is more advantageous.

7. CONCLUSION

In this paper, differentiated service strategy based on network coding cooperative communication system is studied from two aspects: improving transmission reliability and extending network lifetime. Differentiated service strategy, consider according to the reliability required for each node to set their transmission power, which ensures the application of the required reliability of different circumstances, our scheme can make node energy consumption to a minimum. The transmission power of the nodes in the non-hotpots nodes is increased after the transmission power of each node is determined, but at the same time

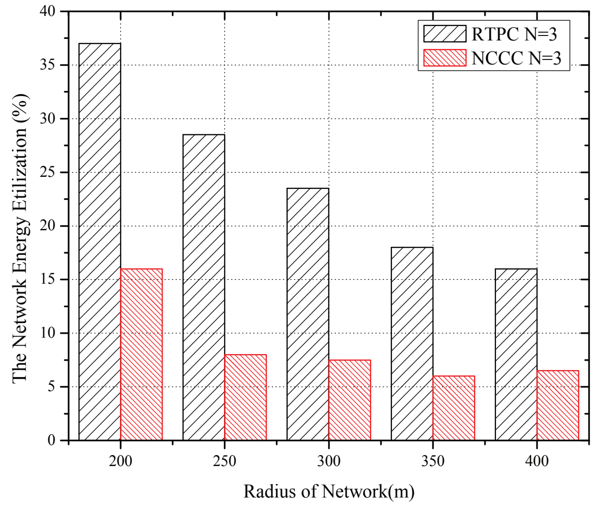

Figure 21 Comparison of RTPC and NCCC network energy utilization.

the energy consumption can not exceed the nodes in the hotpots, which ensures that the network lifetime is not reduced while data reliability has been a certain upgrade. From the experimental results, it can be seen that the RTPC scheme proposed in this paper can improve the network lifetime by 15.62%–19.05% under the premise of guaranteeing the application reliability. RTPC can also achieve a 30% increase in the reliability of the data transmission. Meanwhile, makes the energy utilization of the whole network nearly 54.5% higher than NCCC scheme by utilizing the residual energy of the non-hot nodes.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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