Sensors & Transducers, Vol. 171, Issue 5, May 2014, pp. 268-275

Sensors & Transducers

Research on Data Reliable Transmission Based on Energy Balance in WSN

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Received: 7 February 2014 /Accepted: 30 April 2014 /Published: 31 May 2014

Abstract: In view of energy load uneven distribution of WSN, some nodes will die prematurely due to excessive energy consumption, which lead to interruption of communication links and data packet loss, thus reliable data transmission is affected. On the basis of analyzing the main factors that affect energy consumption and existing energy saving technologies, combined with application of virtual multiple-input multiple-output (Virtual MIMO) routing algorithm in isomorphic wireless sensor network, virtual multiple-input multiple-output clustering algorithm (VMMCA) which applies to small and medium scale isomorphic WSN is proposed. VMMCA not only can select cluster head randomly, but also can achieve the life cycle optimization of WSN on the premise of assuring nodes communication quality. Virtual MIMO cluster network energy consumption model is established. On the condition of changing for different clusters size, node distribution density, the path loss index and sink nodes, the change of the energy consumption of virtual MIMO network and SISO network is analyzed. In order to balance network energy load and prolong lifetime of WSN, and the network lifetime is taken as the optimization target, the ratio of the clusters head is optimized by genetic algorithm. The experiment and simulation results show that compared with LEACH algorithm, VMMCA can achieve very good balance of energy and prolong network lifetime. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Clustering algorithm, Virtual multiple-input-multiple-output (MIMO), Energy efficiency, Load balancing.

1. Introduction

Wireless sensor network is an integrated intelligent information system that is composed of low cost and energy constrained sensor nodes by way of self-organization, the reliable data transmission is completed under the joint action of each node, if one node will die due to running out of battery energy, it can affect network connectivity and produce data packet loss, so that reliable data transmission slowdowns in performance, the node will become the limiting factor for reliable network data transmission, this phenomenon is called short board effect in wireless sensor network. In order to prolong the life of WSN, it is very important to design low power consumption structure and energy efficient routing algorithm of nodes. Multiple-input Multiple-output (MIMO) technology breaks through the problem of limited channel capacity in the traditional single input single output (SISO) wireless communication system[1], and when the communication distance exceed a certain threshold, compared with SISO, energy consumption of MIMO is less. Reference [2] proposed MIMO nodes structure and communication strategies for heterogeneous WSN, the results shown that this method was superior to SISO network in the aspects of energy consumption and latency. MIMO not only has complex transmission circuit, but also need to have powerful signal processing ability, and sensor nodes are limited by the volume and energy, so it is not realistic to install multiple antenna [3]. With the rapid development and increasingly mature of MIMO technology, more and more researchers study virtual MIMO technique [4]. Studies shown that compared with SISO transmission or multiple hops, virtual MIMO technology not only considered the additional circuit training cost and energy consumption, and its efficiency was higher [4-6]. Reference [4] effectively avoided energy consumption in cluster data broadcast process by virtual MIMO multi-cast transmission, and network parameters with minimal energy consumption were determined through joint optimization system. The simulation results shown that the life cycle of network have significantly increased in different cases. But the algorithm needs to further explore how to choose the optimal network structure and the appropriate cooperation nodes. Reference [7] put forward a kind of data transmission scheme based on virtual MIMO technique scheme in wireless sensor network, although this scheme can reduce the network energy consumption, the training energy consumption of choice collaborative cluster heads and encoding complexity will be increased due to adopt virtual multiple input single output (MISO) technology in data gathering stage. In order to further reduce energy consumption in Reference [8], data fusion and collaborative communication were effectively combined, and eliminated data redundancy between the nodes. The optimal cooperation nodes selection, the energy distribution between source nodes and collaboration nodes were studied in Reference [9], but the influence of optimal cluster head proportion and network scale was not considered.

Based on the above analysis, according to the characteristics of homogeneous WSN, combine the energy balance of LEACH algorithm and the characteristics of virtual MIMO technology, and put forward a kind of virtual multiple input multiple output clustering algorithm (VMMCA). In order to effectively reduce the network energy consumption, prolong network life cycle, and improve network data reliable transmission, virtual MIMO technology and dynamic energy saving technology are applied to the entire network in VMMCA algorithm. In order to make the energy load average assigned to each node, the virtual MIMO cluster head nodes are elected in turn, as to avoid premature death of cluster nodes that have the large energy consumption due to the excessive consumption, so the network life cycle is prolonged. On the condition of changing for different clusters size, node distribution density, the path loss index and sink nodes, the change of the energy consumption of virtual MIMO network and SISO network is analyzed. In order to balance network energy load and prolong lifetime of WSN, and the network lifetime is taken as the optimization target, the ratio of the clusters head is optimized by genetic algorithm. The experiment and simulation results show that compared with LEACH algorithm, VMMCA can achieve very good balance of energy and prolong network lifetime.

2. WSN Model Based on Virtual MIMO

For the past few years, with the continuous development of MIMO wireless communication system, and formed a communication means based on virtual MIMO [10]. That is to say, each mobile terminal of communication system based on Virtual MIMO not only has a single antenna, but also has one or more partners for cooperation transmission, and not only transmit its own information but also transmit its partners' information, it is shown in Fig. 1 [13]. Virtual MIMO transceivers are composed of cooperative mobile terminals, which form a virtual multi-antenna structure. Each terminal transmit information jointly by channel space of their own and its partners, so more spatial diversity gain is obtained and single-antenna mobile terminals' spatial diversity is implemented. So the virtual MIMO communication system not only can increase channel capacity, but also can improve network service quality and system performance.

Because of the restrictions of quality, volume and energy consumption, for WSN nodes, it is very difficult to implement multi-antenna structure. Fig. 1 shown that a single antenna node based on virtual MIMO can get the multi-antenna spatial diversity gain. Supposed that each sending node has a set of data to be sent to the receiving node, the sender nodes broadcast its own information to its partners by TDMA, and the sending terminal have all partners' data in the local communication process. A single node is seen as an antenna of virtual antenna array, the encoded data is transmitted to the receiving terminal in parallel by the sending terminal in the long range communication process.

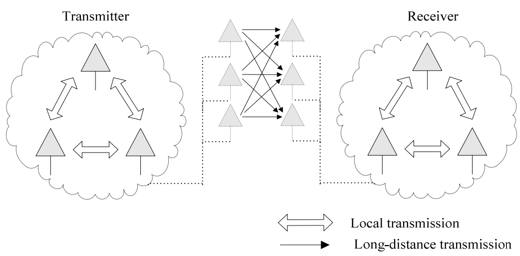


Fig. 1. Virtual MIMO transmission.

On the basis of structure of virtual MIMO communication, aiming to the homogeneous WSN network, a virtual MIMO cluster algorithm (VMMCA) is proposed, the network structure is shown in Fig. 2 [13]. A virtual MIMO transceiver is composed of M_t nodes, and network terminals are divided into several clusters, each cluster has a virtual MIMO cluster head which consists of M_t nodes, and the local clusters' terminal information which has collected is transmitted to Sink Node (SN) by virtual MIMO Cluster Head (VCH).

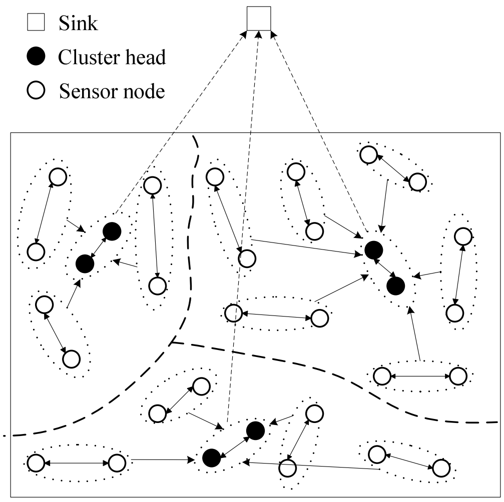


Fig. 2. Virtual MIMO cluster transmitting scheme.

In order to facilitate the research and discussion, we make the following assumptions:

1. According to communication requirements, each sensor node may adopt two kinds of communication methods, namely SISO and virtual MIMO, and the two communication methods can be converted each other.
2. Virtual MIMO systems adopt Space-Time Block Code (STBC), and the code is kind of Space-Time Trellis Code (STTC), its decoding is simple.
3. Supposed that the nodes have completed location and selected their collaboration nodes before the networks begin work, and each virtual MIMO transceiver consists of M_t neighbor nodes.
4. Supposed that the data sink nodes have not any limited in terms of energy and volume, and which have multiple antennas, so can realize MIMO communication.
5. Supposed that the position of all nodes in the network are equal, in the initial state, all nodes have the same energy, the energy management strategy adopt dynamic power management, and has the ability of adaptive adjustment of transmission power. If the transmission power for opposite side is obtained, the communication distance of nodes can be calculated according to the received signal strength indicator (RSSI).
6. Supposed that all nodes identity not only is the only, but also have the ability to get other node ID.
7. Supposed that communication is at a high signal-to-noise ratio area, communications within the cluster adopt the attenuation Gaussian white noise (AGWN) channel model, modulation form adopt two phase shift keying (BPSK). Communication between clusters adopt Rayleigh flat fading channel model, and modulation form adopt multi-band quadrature amplitude modulation (MQAM).

On the basis of cluster-heads-random- selecting technology in a circular pattern which is adopted by LEACH, combining virtual MIMO technology, and taking the characteristics of isomorphism WSN into consideration, VMMCA can be proposed as follows.

1. Initialization. SN broadcast initialization information to all nodes, namely, advertisement of sink (AOS), the node operating parameters are initialized, and ID identity information of collaboration nodes are included in the initial information .
2. The selection of virtual cluster heads (VCH). Monitoring area is divided into several clusters, according to the optimal proportion of cluster heads, communication area is divided by SN, supposed that ρ_{CH} is the proportion of cluster-heads (the ratio of the number of VCH required and the total number of nodes), so the R round Cluster-Head selection threshold is shown in (1).

$$T = \frac{\rho_{CH}}{1-\rho_{CH} * (r \bmod (1/\rho_{CH}))} \cdot \frac{1}{M_t}, \qquad (1)$$

where mod is the seeking modulo. Random number t that is generated by each node is between 0 and 1. If $t \prec T$, this node is chosen as the cluster head node, and send information of cooperation to its partners nodes to constitute the VCH.

3. Cluster. VCH broadcast ID and AOCH (advertisement of cluster head) that it has become cluster head to all nodes in the region. VMMSN (virtual MIMO sensor nodes) are virtual MIMO terminals except VCH, which judge the signal strength of AOCH that is broadcasted by different VCH, and send REG (registration) information to the VCH that have greatest signal strength, then, join in their domain.
4. Time-slot allocation. TDMA slot is produced by VCH, which is sent to its cluster members, and each VMMSN is assigned a time-slot.
5. Transmission in cluster. Collaboration nodes of VMMSN exchange data by the way of SISO. The transmitted power is calculated by distance of collaboration nodes, According to the TDMA time-slot allocated by cluster head, in their own time gap, data of M_t nodes are sent to VCH by virtual MIMO mode. Then VMMSN return to the sleep state to save energy until the step 2 is activated again.
6. Convergence. VCH transmit the data of all the cluster nodes to SN, then, return to Step 2, until most nodes of network failure due to run out of energy.

3. Energy Consumption Analysis

3.1. Energy Consumption Model of Node

The total energy consumption that sent per bit data by nodes, which can be described by (2) [11]:

$$E_{bt} = \frac{(\alpha+1)P_t T_{on} + (P_c + P_{detector})T_{on} + 2P_{syn}T_{tr}}{L}, \quad (2)$$

where P_t , P_t , and P_t represent the energy consumption of frequency synthesizer, detectors and other parts of the circuit respectively. $T_{on} = L / R_b$ represents the time that send L bits of data, and the bit-rate $R_b = bB$, where b is the number of bits that transmitted bit per second per Hz bandwidth and B is the modulation bandwidth. T_{tr} is the transitional period that node convert from the sleeping mode to working mode. α is ratio that determined by the modulation and b .

The transmitting power P_t can be expressed as a function of the communication distance d and path loss factor n [12]:

$$P_t(d,n) = \bar{E}_b R_b \times \frac{(4\pi)^2}{G_t G_r \lambda^2} d^n M_l N_f \quad (3)$$

where G_t and G_r represent the antenna gain of sending terminal and receiving terminal respectively. λ is the carrier wavelength, M_l is the link compensation coefficient of attenuation, N_f is the receiver noise figure.

$\bar{E}_b$ is per bit energy consumption for the receiving terminal in a certain bit error rate, whose value is decided by the modulation. For local SISO communications, it adopts BPSK(multiple phase shift keying) modulation and $b=1$; for MIMO communications, if it adopts BPSK modulation, compared with the SISO, the energy efficiency have no advantage, so it adopts MQAM (M-order quadrature amplitude modulation) modulation and $b=2$ [5]. Supposed that Channel model is flat Rayleigh fading channel, the per bit energy consumption of SISO and MIMO have shown in (4) and (5) [10]:

$$\bar{E}_b^{SISO} \le \frac{M_t N_0}{\bar{P}_b^{1/M_t}} \quad (4)$$

$$\bar{E}_b^{MIMO} \le \frac{2}{3}\left(\frac{\bar{P}_b}{4}\right)^{-\frac{1}{M_t}} \frac{2^b - 1}{b^{\frac{1}{M_t}+1}} M_t N_0 \quad (5)$$

The energy consumption for each bit under SISO and MIMO transmission model is obtained by (2) - (5), it has shown in (6) and (7) respectively.

$$E_{bt}^{SISO}(d,n) = (1+\alpha)\frac{M_t N_0}{\bar{P}_b^{1/M_t}} \times \frac{(4\pi)^2}{G_t G_r \lambda^2} d^n M_t N_f + (P_c + P_{detector}) R_{b,siso} + \frac{2P_{syn}T_{tr}}{L} \quad (6)$$

$$E_{bt}^{MIMO}(d,n) = \frac{2}{3}(1+\alpha)\left(\frac{\bar{P}_b}{4}\right)^{-\frac{1}{M_t}} \frac{2^b - 1}{b^{\frac{1}{M_t}+1}} M_t N_0 \times \frac{(4\pi)^2}{G_t G_r \lambda^2} d^n M_t N_f + (P_c + P_{detector}) R_{b,mimo} + \frac{2P_{syn}T_{tr}}{L} \quad (7)$$

3.2. Calculation of the Network Energy Consumption

In the previous section, single node energy consumption in SISO and MIMO modes is analyzed. On the basis of it, the overall energy is considered from sending fixed data view point. Supposed that each node send L bits data, the energy consumption of virtual MIMO and SISO has shown in (8) and (9) respectively.

$$E_{V-MIMO}(D, d_k, n) = L\sum_{i=1}^{M_t} E_{bt,i}^{MIMO}(D,n) + L\sum_{i=1}^{M_t} E_{bt}^{SISO}(d_k, n) \quad (8)$$

$$E_{SISO}(D,n) = LE_{bt}^{SISO}(D,n) \quad (9)$$

Before Virtual MIMO nodes send data, they need to complete the local communication which distance is d_k , and exchange the information of M_t collaborative nodes at the transmitting end. Therefore, for energy consumption of virtual MIMO communication, we not only consider the energy consumption in the long range communication, but also consider local communication energy consumption between collaboration nodes.

4. Time Delay Analysis and the Location Changes of Base Station Influence on Energy Consumption

In wireless communication system whose energy is limited, if the network transmission delay is too big, and the energy consumption of sensor nodes will be increased to some extent, thus the communication efficiency of whole network will be affected, especially in some special occasions, the system delay requirements will be higher. For the no-cooperative traditional transmission scheme which has a fixed transmission bandwidth B, the transmission delay is as follows:

$$T_{tra} = \sum_{i=1}^{M_t} \frac{N_i}{b_i} T_s \quad (10)$$

where b_i is the constellation size of the i^{th} node. N_i / b_i is the transmitted symbols of the ith node.

For the cooperative MIMO scheme, the total delay consists of local communication delay of the sending end and the receiving end and the long-distance transmission delay, and it is as follows.

$$T_{MIMO} = T_s \left(\sum_{i=1}^{M_t} \frac{N_i}{b_i} + \frac{\sum_{i=1}^{M_t} N_i}{b_m} + \sum_{j=1}^{M_r - 1} \frac{N_s n_r}{b_j} \right) \quad (11)$$

where b_i and b_j are the constellation size of the ith node in sending end cluster and the j^{th} node in receiving end cluster for the local communication respectively. The first part and the third part are local communication delay sending and receiving end respectively, the second is the delay caused by long-distance MIMO transmission.

The delay performance comparison chart between non-cooperative MIMO scheme and conventional scheme has shown in Fig. 3. As can be seen from Fig. 3, when the transmission distance is relatively smaller, the delay of MIMO is greater than the conventional scheme; and when the transmission distance is [23,200], MIMO can effectively reduce the delay and energy consumption.

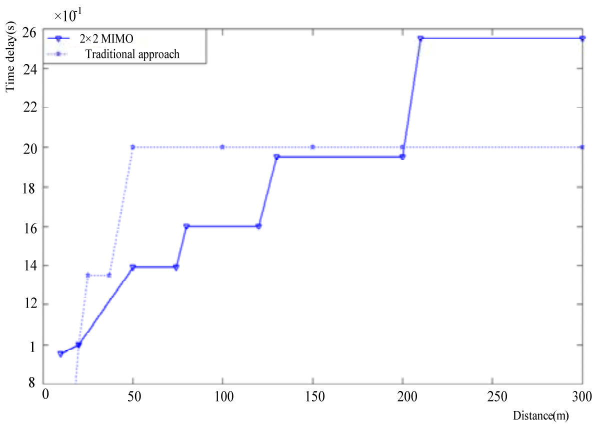
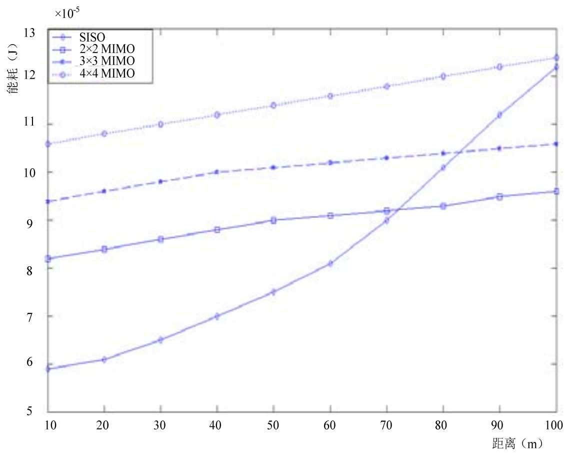


Fig. 3. The delay performance comparison chart between non-cooperative MIMO scheme and conventional scheme.

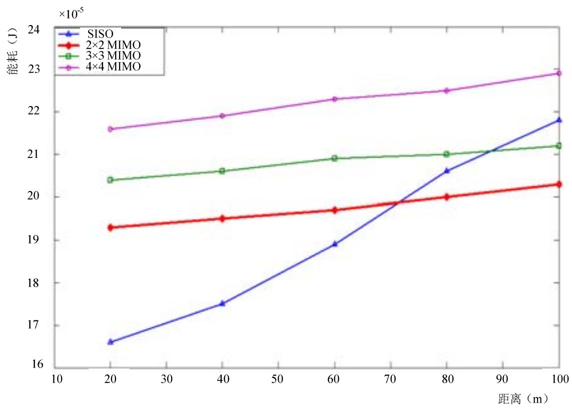
In order to fully test the energy performance of the system under different scenarios, this paper analyzed the influence sink nodes position changes on energy consumption through simulation. Supposed that the 50 nodes were randomly distributed in $M \times M$ ($M = 100m$) square area, the base station (sink node) located regional center firstly, then move along horizontal direction to observe the effect of distance changes, simulation parameters are shown in Table 1. When the cluster head changes were 10m and 20m respectively, the changes in energy consumption have shown in Fig. 4. As can be seen from Fig. 4, When the distance is shorter, the performance of SISO is better than that of MIMO, however, when the distance is relatively larger, compared with SISO, MIMO (2 × 2) has a relatively lower energy consumption, and MIMO (2 × 2) is also lower than other MIMO (3 × 3 and 4 × 4) energy. Fig. 4 has shown that the total energy consumption was increased when the cluster head changed from 10m to 20m. Due to the increased distance was reasonable communication range, so the results of Fig. 4 (a) and Fig. 4 (b) were similar.

Table 1. The simulation parameters.

$\alpha = 1.33$	$P_{syn} = 25mW$	$P_c = 22.9mW$	
$P_{detector} = 5mW$	$T_{tr} = 5\mu s$	$L = 10000bits$	$E_0 = 10000J$
$f_c = 2.4GHz$	$P_b = 10^{-3}$	$N_0 = -171dBm/Hz$	$N = 100$
$M_l = 40dB$	$N_f = 10dB$	$B = 10kHz$	$G_t G_r = 5dBi$



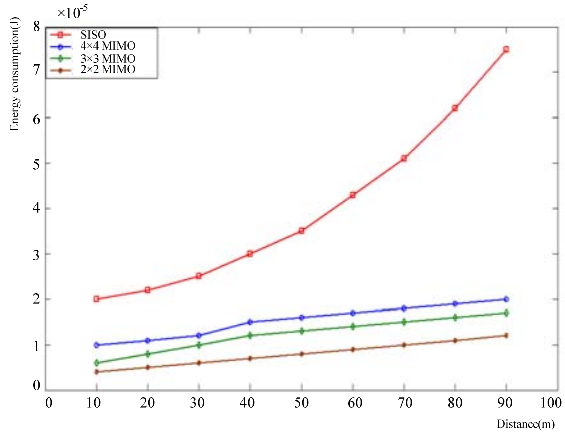
(a) Cluster-head distance is 10 m



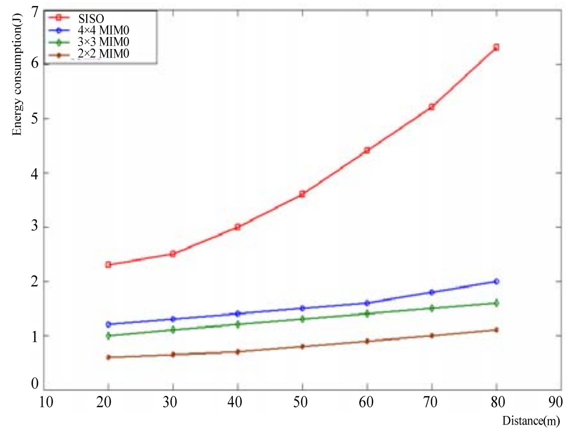
(b) Cluster-head distance is 20 m

Fig. 4. The total energy consumption changes of Virtual MIMO and SISO.

The energy consumption of SISO and MIMO have shown in Fig. 5 when the communication distance was longer, and in this case, the energy consumption of short-distance communication within a cluster was not considered, the communication performance of MIMO is better than that of SISO within the scope of the communication distance.



(a) Cluster-head distance is 10 m



(b) Cluster-head distance is 20 m

Fig. 5. The energy consumption of SISO and MIMO in long distance communication.

5. Analysis and Simulation

In the section, the data collection process of a cluster is simulated, Supposed that communication area is a circle which radius is R , N sensor nodes are distributed by way of two-dimensional Poisson in network area, nodes density is ρ ,and the cluster head locate in the center of circle, each sensor node send L bits data to the cluster head. The communication distance between collaboration nodes is the mean of d_k , it has shown in (12) [12].

$$E[d_k] = \bar{d}_k = \sqrt{\frac{1}{4\rho}} \tag{12}$$

On the basis of the preceding analysis, the total energy consumption of SISO and MIMO has shown in (13) and (14) respectively.

$$W_{V-MIMO} = \sum_{i=1}^{N} E_{V-MIMO,i} \tag{13}$$

$$W_{SISO} = \sum_{i=1}^{N} E_{SISO,i} \tag{14}$$

In order to analyze the energy-saving ratio (defined as $ECR = \frac{W_{SISO} - W_{MIMO}}{W_{SISO}}$) of virtual MIMO and SISO, and in the case of n = 2.0 and the different nodes distribution density, we compared W_{SISO} and W_{V-MIMO} , it has shown in Fig. 6. Fig. 6 shown that, compared with SISO, the virtual MIMO has higher energy efficiency in long transmission distance, the energy-saving ratio of virtual MIMO and SISO is getting higher with R increasing when the node density distribution is not changed. But the node distribution density has influence on the energy efficiency of virtual MIMO, When R remains constant, with the increase of distribution density, the energy efficiency of the virtual MIMO is increasing. When $\rho = 0.001$ and $R > 40$, compared with SISO, the energy efficiency of virtual MIMO is more higher, and when $\rho = 0.05$ and $R > 22$, compared with SISO, the energy efficiency of virtual MIMO is more higher. This is due to take the energy consumption of local communication into account in virtual MIMO, Therefore, the distance between the collaboration nodes increases with the reduction of node density.

Path loss is an important factor for analyzing and designing of telecommunication systems link budget. And it is often affected by propagation environment, transmit media, transmit distance, antenna height and location and so on. n is used to represent path loss index, which usually changes from 2 to 4. Propagation model is under an ideal free-space communication when $n=2$, and it is flat earth model when $n = 4$.

In Fig. 6, path loss factor is set to 2, Fig. 7 shown the relationship between energy-saving ratio and n . Energy consumption of virtual MIMO and SISO will increase when the channel is not ideal, However, with the increase of n , the energy-saving ratio is more higher, and the energy efficiency ratio is more than 80 % when $n>3$. It has shown that virtual MIMO has better energy-saving performance when path loss is higher.

5.3. System Optimization

Due to energy-constrained in WSN, The number of clusters is very key, if the number of clusters is inappropriate, the energy consumption will be increased, and leading to rapid death of WSN. If the number of clusters is too little, the number of members in a cluster will increase, so the cluster-heads bear too heavy load, energy consumption will be accelerated, and energy consumption is imbalance. On the contrary, if cluster-heads are too many, energy consumption in forming clusters will be increased, and network lifetime will be shortened. Therefore, the number of clusters is very important whether clustering algorithm can realize low cost and reliable data transmission or not in given condition. In order to balance energy consumption of nodes, prolong network lifetime, and improve the reliable data transmission, the optimization problem of the number of cluster head is discussed and analyzed.

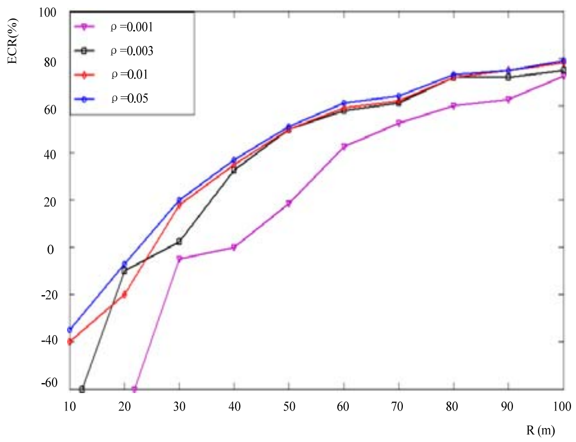


Fig. 6. The relationship between the virtual MIMO energy-saving ration and R.

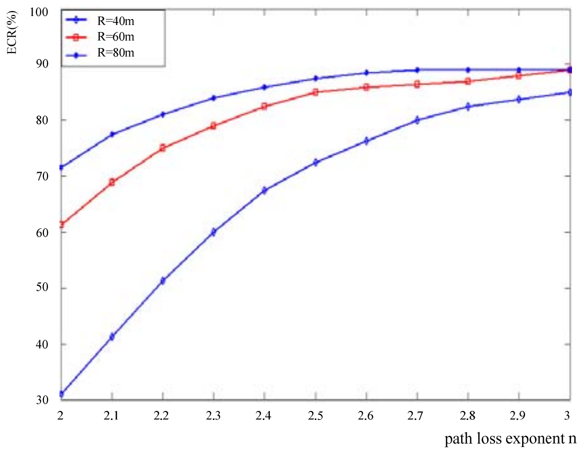


Fig. 7. The relationship between the virtual MIMO 1.energy-saving ratio and n

In the optimization of system parameters, genetic algorithm (GA) is an ideal algorithm. Its principle is that use the effective part of past searched information to do copying, crossover and mutation on population which a group of individual formed, so GA has strong ability in the aspect of global search. In order to obtain optimal ratio of cluster head when the network's lifetime is longest, cluster heads are calculated and simulated by GA toolbox of Matlab, the optimal value of ρ_{CH} is obtained when VMMCA is operated in different distribution density of nodes.

Supposed that nodes density is ρ , and they are distributed randomly in a $M \times M$ square area whose edge's length is 100 m. The lifetime of network is taken as the optimize target, (the lifetime is defined as the period that is from the beginning to half of nodes which have died) and ρ_{CH} is searched between 1 % and 20 %. Calculation coding adopts binary encoding. The individual number in population is 20, the length of each population is 20, and the maximum hereditary generation is 25. The individual of next generation is chosen by the random traversal sampling whose generation gap is 0.9. The reorganization is two-point crossover whose probability is 0.7. The mutation probability of each element in the chromosome is 0.5. After 25 times of calculation, the optimal solution of ρ_{CH} was obtained in several different values of ρ, it is shown in Fig. 8.

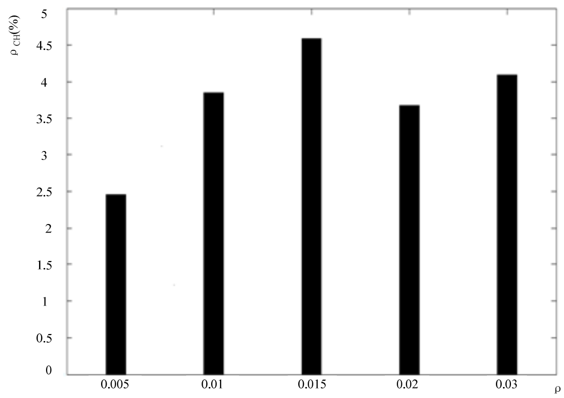


Fig. 8. The optimal solution of ρ_{CH} in several different values of ρ.

5.4. Simulation of VMMCA Scheme

LEACH is a classic clustering routing algorithm, which can effectively improve the energy efficiency of network. On the basis of it, cluster head is selected randomly and cyclically by LEACH, and virtual MIMO is applied to WSN, a routing clustering algorithm based on virtual MIMO (VMMCA) is proposed. VMMCA can further improve energy efficiency of network, prolong the network lifetime and improve data reliable transmission. VMMCA is compared with LEACH in the aspects of the first node death round and network lifetime and so on. Supposed that N sensor nodes are distributed randomly in a $M \times M$ square area whose edge's length is 100 m, and nodes density ρ is 0.01, and they have the same initial energy E_0, path loss factor n is 2.0. Other communication parameters are shown in Table 1, the two communication scheme are run under the different values of ρ_{CH} respectively, then the death round of the first node and the network lifetime is obtained, it is shown in Fig. 9.

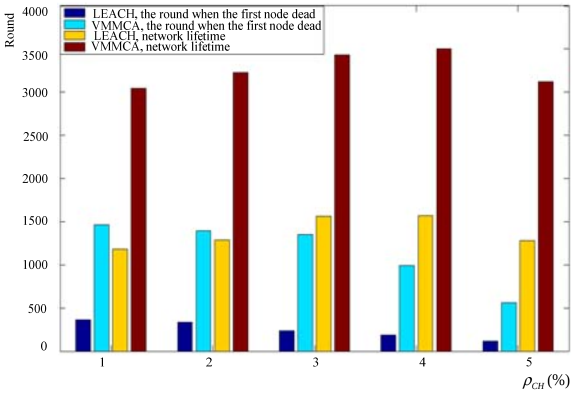


Fig. 9. Comparative analysis of VMMCA and LEACH algorithm.

As can be seen from Fig. 9, compared with LEACH, VMMCA can significantly improve the network lifetime. The death round of the first node of VMMCA delay 4-6 times than LEACH, and network lifetime is about 2-3 times that of the LEACH.

6. Conclusions

The paper introduced the virtual MIMO and dynamic power management technology to WSN, and put forward a kind of energy-efficient VMMCA algorithm that applied to small and medium-sized WSN, and the algorithm are analyzed in the aspects of design idea, design strategy, design steps, etc. And then energy balance and time delay of network are analyzed, the energy consumption of virtual MIMO and SISO are analyzed in different cluster size, node distribution density, the path loss index and changing of gathering node, and the proportion of cluster heads is optimized when the network lifetime is longest by using the genetic algorithm under a certain node distribution density. The simulation results shown that compared with LEACH algorithm, VMMCA algorithm can prolong the network lifetime, it has the very good energy balance and reliability, and energy efficiency of virtual MIMO network is better than that of SISO network under the suitable network parameters.

Acknowledgements

This work was supported the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

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