

Design and Analysis of Virtual MIMO-Based Low-Power Control Algorithm for WSN

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Abstract: In order to fully reduce network energy consumption, an improved virtual MIMO technique applied to small and medium scale isomorphism WSN is proposed. The life of WSN is prolonged by combining the energy-efficient virtual MIMO communication technology with the method that cluster heads are selected randomly and cyclically and the network energy load is balanced. Influencing factors on the virtual MIMO WSN energy-saving performance are analyzed carefully in this study, including the network size, node density and path loss factor. And the longest life of the network is used as optimization objective, the ratio of cluster head (the ratio of the number of cluster head required and the total number of nodes) which is a key parameter of WSN are optimized by genetic algorithm. Simulation results show that compared with LEACH this novel algorithm is more efficient to save energy of consumption and prolong the living time of the whole network when the parameters of network structure are properly selected.

Keywords: Algorithm, energy efficiency, virtual Multiple-Input- Multiple-Output (MIMO)

INTRODUCTION

Wireless sensor network is an integrated intelligent information system which is composed of a large number of low-cost and energy-constrained sensor nodes by self-organization. In the Wireless Sensor Networks (WSN), the sensor nodes are usually deployed randomly, the nodes will die when the battery power runs out because of small batteries which are difficult to be replaced. So energy is a major factor which restricts the lifetime of WSN. To the extent possible to prolong the lifetime of WSN, it is very important to design of low-power structure of the node and research of energy-efficient routing algorithm.

In recent years, Multi-Input-Multi-Output (MIMO) systems have been extensively researched due to their ability to break through the channel capacity limitation which traditional Single-Input-Single-Output (SISO) wireless communication system has (Paulraj *et al.*, 2003) and compared with SISO systems, MIMO systems require less energy consumption when transmission distances are larger than a given threshold (Shuguang *et al.*, 2004). MIMO transmission strategy and node structure of a heterogeneous WSN were proposed in Zhao *et al.* (2006) and the results show that the approach is better in energy consumption and delay of the network than SISO. However, as technique of MIMO requires complexity transmitter circuit and powerful

signal processing capability, the realization of multi-antenna technique is impractical to sensor nodes whose physical size and energy are limited. With the increasing maturity of MIMO technique, the virtual MIMO technique which developed on the basis of the MIMO has been intensively studied (Jayaweera, 2006; Bravos and Kanatas, 2008; Zhang *et al.*, 2008; Sadek *et al.*, 2007; Jayaweera *et al.*, 2007). Virtual MIMO technique is a diversity transmission technique that is applicable to WSN, The study shows that although the additional circuit energy consumption and training overhead have been taken into account, the application of virtual MIMO technique will be more energy efficiency than SISO or multi-top transmission (Jayaweera, 2006; Bravos and Kanatas, 2008). The WSN transmission scheme based on the virtual MIMO was proposed in Sadek *et al.* (2007) and proved that the scheme can reduce the total network energy consumption. However, the scheme only applied virtual multi-input-single-output (MISO) technique to the data-centric clustering stag and increased the energy consumption for choosing cooperative cluster and coding complexity.

In order to fully reduce network energy consumption, an improved virtual MIMO technique is applied to all network nodes by VMC algorithm and the energy load is evenly distributed to each sensor node by rotation election of virtual MIMO cluster head nodes, so that the energy consumption of cluster head nodes can't

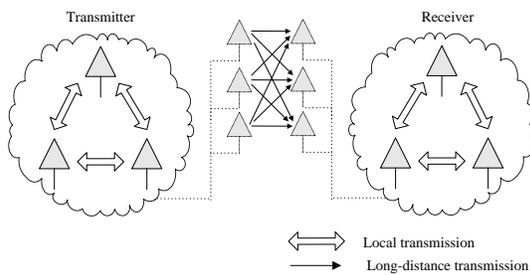


Fig. 1: Virtual MIMO transmission

deplete rapidly and the network lifetime can be effectively prolonged.

MIMO WSN MODEL

In recent years, with further study of MIMO wireless communication system, a Virtual MIMO communication model has formed (Shuguang *et al.*, 2004). Namely, In a Virtual MIMO communication system, each mobile terminal 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. As shown in Fig. 1, the Virtual MIMO transceivers are composed of cooperative mobile terminals, which form a virtual multi-antenna structure. Each terminal use both their own and its partners' channel space to transmit information jointly, so more spatial diversity gain is obtained and single-antenna mobile terminals' spatial diversity is implemented. It is proved that the virtual MIMO communication system can increase channel capacity, improve network service quality and system performance.

Due to the restrictions of quality, volume and power consumption, it is very difficult to implement multi-antenna structure for WSN nodes. However, a single antenna node can get the multi-antenna spatial diversity gain by using virtual MIMO. Assuming that each sending node has a set of data to be sent to the receiving node, two steps of the virtual MIMO communication are shown in Fig. 1. First, In the local communication process, the sender nodes broadcast its own information to its partners by TDMA, so that the sending terminal have all partners' data; Second, In the long range communication process, a single node is seen as a antenna of virtual antenna array, the encoded data is transmitted to the receiving terminal in parallel by the sending terminal.

Based on the structure of virtual MIMO communication, VMC algorithm of the homogeneous WSN network is proposed, the network structure is shown in Fig. 2. Every M_t nodes form a virtual MIMO transceiver and network terminals are divided into several clusters, each cluster has a virtual MIMO cluster head which consist of M_t nodes. Finally, the

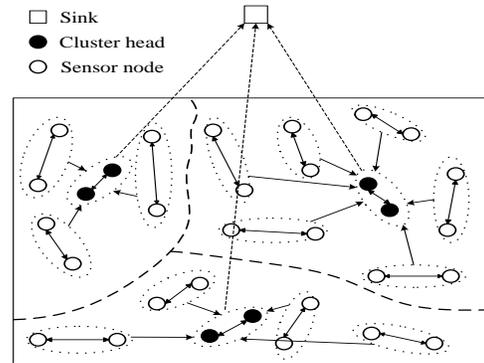


Fig. 2: Virtual MIMO cluster transmitting scheme

local clusters' terminal information which has collected is transmitted to SN (Sink Node) by VCH (VCH, virtual MIMO Cluster Head).

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

- Each sensor node has a dual work which is SISO and virtual MIMO and according to communication requirements, the two communication methods can be converted each other
- Virtual MIMO systems are coded with Space-Time Block Code (STBC) which has lower decoding complexity than Space-Time Trellis Code (STTC)
- The nodes have completed location and selected their collaboration nodes before the networks are formed and a virtual MIMO transceiver consists of M_t neighbor nodes
- M_t nodes of virtual MIMO transceiver can provide synchronous transmission when data is sent and received
- SN that has multiple sending and receiving antennas is not limited to aspects of any energy and volume, which can implement the MIMO communications

VMC scheme: VMC scheme is based on cluster-heads-random- selecting technology in a circular pattern which is adopted by LEACH. It also combines its technology with that of virtual MIMO and takes the characteristics of isomorphism WSN into consideration. Thus, it can be proposed as follows.

Initialization: SN broadcast AOS (Advertisement of sink) which is initialization information to all nodes in WSN region, then, the node operating parameters are initialized.

The selection of VCH: Assuming 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:

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

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

- **Cluster:** Information Aoch (advertisement of cluster head) that VCH have become cluster head is broadcast to all nodes in the region and the ID information of VCH has also been included. VSN (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.
- **Time-slot allocation:** TDMA slot is produced by VCH, which is sent to its cluster members and each VSN is assigned a time-slot.
- **Transmission in cluster:** Collaboration nodes of VSN exchange data by the way of SISO. According to the TDMA time-slot allocated by cluster head, data of M_t nodes are sent to VCH by virtual MIMO mode. Then VSN return to the sleep state to save energy until the step 2 is activated again.
- **Convergence:** VCH transmit the data of all the cluster nodes to SN, then, return to Step 2.

ENERGY CONSUMPTION ANALYSIS OF VIRTUAL MIMO AND SISO

Energy consumption model of node: The energy consumption that sent per bit data by node, which can be described by the following expressed (Bravos and Kanatas, 2008):

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

where, P_{syn} , $P_{detector}$ and P_c are the energy consumption of frequency synthesizer, detectors and other parts of the circuit, respectively. The time required to send L bits of data is given by $T_{on} = L/R_b$ and the bit-rate R_b is given by $R_b = bB$, 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 (Proakis, 2000):

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

where, G_t and G_r are the antenna gain of sending terminal and receiving terminal respectively. λ is the carrier wavelength, M_t 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, while the value is decided by the modulation. For local SISO communications, BPSK(multiple phase shift keying) modulation is adopted and $b = 1$; for MIMO communications, if BPSK modulation is adopted, compared with the SISO, the energy efficiency have no advantage, so MQAM (M-order quadrature amplitude modulation) modulation is adopted and $b = 2$ (Jayaweera, 2006). Assuming that Channel model is flat Rayleigh fading channel, the per bit energy consumption of SISO and MIMO have the following relations (Shuguang *et al.*, 2004):

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

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

We can derive from (2)-(5) that the energy consumption for each bit under SISO and MIMO transmission model is as follows:

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

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

Calculation of the network energy consumption: In the previous section, a single node energy consumption of two different modes is analyzed. In this section, the overall energy is considered from sending fixed data view point. Assuming that each node send L bits data, the energy consumption of virtual MIMO and SISO are as follows:

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

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

Virtual MIMO node needs to complete the local communication which distance is d_k , exchange the

information of M_i collaborative nodes of sender before sending data. Therefore, when the energy consumption of virtual MIMO communication is calculated, we consider the energy consumption not only the long range communication which distance is D , but also local communication between collaboration nodes.

ANALYSIS AND SIMULATION

Experiment environment: To analyze the energy efficiency of VCM and virtual MIMO, the experimental environment is established as follows.

Assuming that N sensor nodes are randomly distributed in the network domain, nodes density is ρ , the nodes distribute in the fashion of two-dimensional Poisson, The communication distance between collaboration nodes is the mean of d_k , which can be calculated by node density (Wang and Chen, 2003):

$$E[d_k] = \bar{d}_k = \sqrt{\frac{1}{4\rho}} \tag{10}$$

Due to STBC encoding, the complexity of MIMO receiver increases linearly with the number of antennas. Therefore, in order to simplify the model, we assume that the virtual MIMO system is a 2×2 system, which every two adjacent sensor nodes form a virtual MIMO terminal and SN is MIMO transceiver of two antennas. Other experimental parameters are shown in Table 1.

Virtual MIMO and SISO comparison of energy consumption: Based on the node distribution model established in the previous section, in this section, we simulate the data acquisition process of a cluster and compare the energy consumption of virtual MIMO and SISO. Assuming that the region's shape is a round which radius is R , and the cluster head is in the center, while each sensor node send L bits data to the cluster head. On the basis of the analysis of energy consumption in the previous section, the total energy consumption can be calculated as follows:

$$W_{V-MIMO} = \sum_{i=1}^N E_{V-MIMO,i} \tag{11}$$

$$W_{SISO} = \sum_{i=1}^N E_{SISO,i} \tag{12}$$

To study the energy-saving ratio (defined as $W_{SISO}-W_{MIMO}/W_{SISO}$) of virtual MIMO and SISO, when $n = 2.0$, W_{SISO} and W_{V-MIMO} are compared under the different nodes distribution density in Fig. 3. Figure 3 shows that the energy-saving ratio of virtual MIMO and SISO is getting higher with R increasing when the node density distribution is not changed. This is due to the

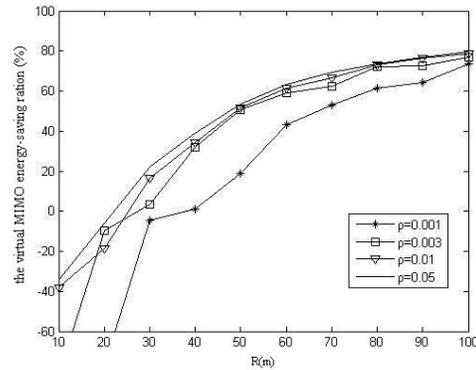


Fig. 3: The relationship between the virtual MIMO energy-saving ratio and R

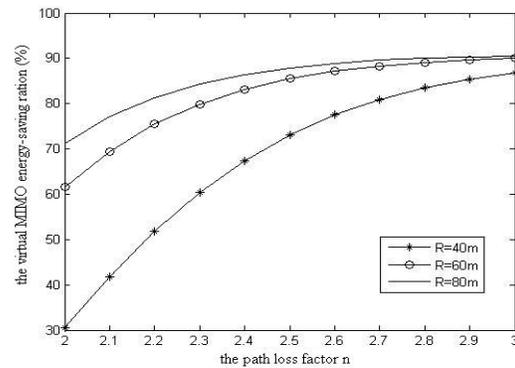


Fig. 4: The relationship between the virtual MIMO energy-saving ratio and n

virtual MIMO have higher energy efficiency than SISO in long transmission distance. At the same time, the node distribution density also impacts the energy efficiency of virtual MIMO, when R is not changed, the greater the node distribution density, the higher energy efficiency of the virtual MIMO. When $\rho = 0.001$ and $R > 40$, the energy efficiency of virtual MIMO is higher than SISO and when $\rho = 0.05$ and $R > 22$, the energy efficiency of virtual MIMO is higher than SISO. This is due to the energy consumption of local communication in virtual MIMO is taken into account, Therefore, the smaller the node distribution density, the longer distance between the collaboration nodes and the greater the energy consumption of the local communication.

Path loss is the attenuation of power density when the electromagnetic waves spread through space, it is an important factor for analyzing and designing of telecommunication systems link budget. The propagation environment, the transmit media, the transmit distance, the antenna height and location have influenced on the path loss. N represents the path loss index, which is usually in the range of 2-4. Propagation model is under an ideal free-space communication when $n = 2$ and it is in the case of earth model for the plane when $n = 4$.

In Fig. 3, the path loss factor is 2, Fig. 4 show the relationship between energy-saving ratio and n. Energy consumption of virtual MIMO and SISO will increase when the channel is not ideal, However, the bigger n, the higher energy-saving ratio and the energy efficiency ratio is more than 80% when n>3. It is proved that virtual MIMO have better energy-saving performance under higher path loss.

System optimization: The number of clusters is a key issue whether energy efficient of the clustering algorithm can be implemented under given network conditions. For energy-constrained WSN, the inappropriate number of clusters will increase the energy consumption and leading to rapid death of WSN. If the clusters are too little, the number of members in a cluster will increase, so the cluster-heads bear too heavy load of sending and receiving, Cluster-heads energy consumption to accelerate and energy consumption is imbalance. On the other hand, if the cluster-heads are too many, it will be excessive energy consumption for forming clusters and the network lifetime will be shortened. Therefore, in this section, the optimization problem of the number of cluster head is discussed to balance the node energy consumption and prolong the lifetime of WSN.

GA (genetic algorithm, GA) is an ideal algorithm to optimize the system parameters. 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 global search ability. In order to find optimal ratio of cluster head when the network's lifetime is longest, the GA toolbox that the Sheffield University introduce is used to obtain the optimal value of ρ_{CH} when VMC is operated in different distribution density of nodes.

For example, nodes density is ρ and it is distributed randomly in a square area whose edge's length is 100m. 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 is based on binary encoding. The number of individuals of the 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 Table 2.

Simulation of VMC scheme: LEACH is a classic clustering routing algorithm, which can effectively improve the energy efficiency of network. VMC scheme apply virtual MIMO to WSN and cluster head

Table 1: Experimental parameters

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

Table 2: Optimization results of ρ_{CH}

ρ	0.005	0.01	0.015	0.02	0.03
$\rho_{CH}(\%)$	2.46	3.85	4.59	3.67	4.10

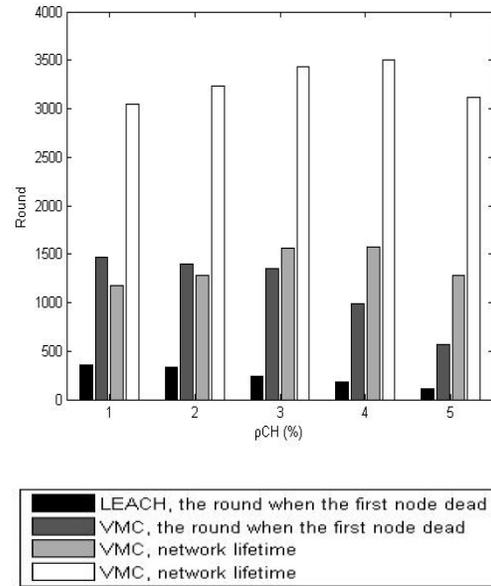


Fig. 5: Comparative analysis of VMC and LEACH algorithm

is selected randomly and cyclically by LEACH, So VCM can further improve energy efficiency of network and prolong the network lifetime. To compare the death round of the first node and network lifetime in VMC algorithm with those in LEACH algorithm, the nodes whose density ρ is 0.01 are distributed randomly in a square area, whose edge's length is 100m and they have the same initial energy, path loss factor n is 2.0. When all communication parameters which are shown in Table 1 and network conditions are the same, 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, as shown in Fig. 5.

Figure 5 shows that compared with LEACH VMC can significantly improve the network lifetime. The death round of the first node of VMC delay 4-6 times than LEACH and network lifetime is about 2-3 times that of the LEACH.

CONCLUSION

In this study, the clustering design and virtual MIMO technique are combined to improve energy efficiency. At first, we proposed the energy efficient VMC scheme which is applied to isomorphism WSN. Then, in order to obtain the most optimal ratio of the

cluster head which have longest lifetime under certain nodes density of the network and genetic algorithm is introduced, simulation and experiment show that the VMC algorithm can prolong the lifetime of network compared with the LEACH algorithm. Last, we analyze the evolution of the energy consumption ratio of Virtual MIMO and SISO in different cluster size, node density and path loss factor. It is proved that virtual MIMO networks have higher energy efficiency than SISO network in the appropriate network parameters.

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