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A Virtual MIMO Communication Strategy Based on Cooperative Groups for Wireless Sensor Networks

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Abstract

As we all know, virtual MIMO technology is an efficient way for energy saving in wireless sensor networks (WSNs). The present virtual MIMO communication strategies in WSNs depend on cluster heads collecting and forwarding source data, which causes big energy consumption. Aiming at this problem, we propose a new virtual-MIMO communication strategy based on cooperative group (CG) in this paper, called Group Collaboration MIMO (GCMIMO). GCMIMO clusters the WSN into several clusters. Each cluster is managed by two cluster heads, master cluster head (MCH) and vice cluster head (VCH). MCH divides the source nodes into several cooperative groups, every two nodes as a group. A CG can constitute a virtual dual-antenna transmitter for sending source data of both nodes directly. VCH and MCH are always seen as a CG, called master cooperative group (MCG), which can receive and forward the data from CGs of other clusters. Unlike the existing virtual MIMO communication strategy, GCMIMO doesn't require the cluster heads collecting the data of the source nodes, which can reduce the times of source data transmission and improve the energy efficiency. In the simulation, we analyze the energy consumption in each communication phase of GCMIMO. The results indicate that GCMIMO can effectively decrease the energy consumption in data transmission and improve energy efficiency.

Keywords: *Virtual-MIMO, WSNs, Multi-hop Transmission, Cooperative Communications*

1. Introduction

In recent years, MIMO technology has been increasingly used in communication systems with the continuous development of communication technology. MIMO technology can exponentially increase the wireless channel capacity, extend the transmission distance, reduce the bit error rate and save the energy consumed in the data transmission [1]. However, the bulk of a wireless sensor network node is usually small, and the multi-antenna transceiver can't be installed on it. Therefore, MIMO technology can't be directly applied to wireless sensor networks. To enable MIMO technology to apply to wireless sensor networks, the researchers combined cooperative communication and MIMO technology, then proposed the virtual MIMO technology. The basic idea of virtual MIMO is that several single antenna nodes form a virtual multi-antenna system through sharing antenna with each other, then this virtual multi-antenna system can communicate with other virtual or real multi-antenna systems. Virtual MIMO can make wireless sensor network obtain a similar communication performance to the MIMO communication. The energy consumption of the entire network can be saved and the communication range can be extended.

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Cui et al. proposed a model of virtual MIMO communication in single-hop wireless sensor networks with Alamouti coding [2]. They analyzed the energy consumption of the network and the data propagation delay, then compared the energy consumption of virtual MIMO with SISO's in the same bit error rate requirement. Their research indicated that the virtual MIMO was more suitable than SISO in the long-distance data transmission according to energy efficiency and data transfer delay. Jayaweera analyzed the effect of the modulation constellation size, the transmission distance, the increasing control overhead of the training sequence and delay performance of virtual MIMO in wireless sensor networks [3]. The research further proved that the virtual MIMO communication was more energy efficient than SISO communication and significantly reduced the transmission delay with selecting the appropriate parameters. V-BLAST space-time coding was introduced into the virtual MIMO communication by Jayaweera [4], which could avoid the cooperating encoding process of the transmitting nodes and further improve energy efficiency. Bravos analyzed and compared the energy consumption of virtual MIMO and multi-hop SISO [5]. The results showed that energy efficiency of the two methods depends on the density of network nodes, wireless channel condition and the distance to the sink node. The virtual MIMO was better than multi-hop SISO in certain condition. Rafique combined virtual MIMO and multi-carrier modulation and analyzed the effect of different virtual MIMO communication modulation schemes. The research verified that the BPSK-WOFDM was a very useful and energy-efficient modulation scheme for high-speed virtual MIMO transmission [6]. Marwan proposed a novel virtual MIMO communication strategy, called CMIMO (cooperative MIMO) [7], which involved clustering the WSN into several clusters, each managed by up to two cluster heads (CHs); a master CH (MCH) and a slave CH (SCH). CMIMO achieves energy efficiency by proper selection of the MCHs and SCHs, adaptation of the antenna elements and powers in the inter-cluster communications phase, and using a cross-layer MIMO-aware route selection algorithm for multi-hop transmission. The experimental results showed that CMIMO could significantly reduce energy consumption and longer the network lifetime. Nasim proposed an energy efficient hierarchical cooperative clustering scheme for wireless sensor networks [8]. According to this protocol, nodes cooperated to form clusters at each level of network hierarchy ensuring maximal coverage and minimal energy expenditure with relatively uniform distribution of load within the network. Simulation results indicated that this protocol could effectively reduce the number of hops in multi-hop transmission and achieve energy-saving purpose.

There is much research on virtual MIMO for wireless sensor networks, which increases the communication energy efficiency by improving the cooperative transmission process [7, 10 and 11]. However, in the intra-cluster communication phase, the source nodes send data to the cluster head, and then the data will be forwarded to the cooperative nodes preparing for the coming cooperative transmission. In this process, the source data is forwarded twice, so that the energy consumption increases. For this problem, we propose a new virtual-MIMO communication strategy based on cooperative group (CG) in this paper, called Group Collaboration MIMO (GCMIMO). In GCMIMO, each CG, composed by two source nodes, sends the source data directly through virtual MIMO link without forwarding data to the cluster head, which can reduce source data forwarding times and improve the energy efficiency of intra-cluster communication phase.

2. Network Model

Before describing how GCMIMO works, we set up a wireless sensor network has some features as following:

(a) The WSN in this paper is insensitive to data transmission delay, which is synchronized and use periodical MAC protocol to work;

(b) Any two neighbor nodes can form a virtual dual-antenna system and the wireless channel between the nodes is symmetric;

(c) The maximum transmission power of each node is defined as P_{max}. During communication, the nodes can control its communication distance by adjusting the transmission power.

3. The GCMIMO

GCMIMO clusters the wireless sensor network into several clusters and its clustering process is similar to CMIMO [7]. In the clustering process, the MCHs are generated through election, and then respectively choose VCHs from their neighbors. In GCMIMO, MCHs divide the source nodes into several cooperative groups, and each group, consisting of two adjacent source nodes, plays the role of a virtual dual-antenna transmitter, which can transmit their source data directly; VCH and MCH are always seen as a cooperative group, called master cooperative group (MCG), which can receive and forward the data from CGs of other clusters. MCGs are the foundation of multi-hop virtual MIMO transmission. After the clustering is completed, GCMIMO starts to build the routing table for the entire network. The routing table building algorithm of GCMIMO, similar to CMIMO, is based on Dijkstra algorithm, which can build the shortest routing path for each cluster. Then, GCMIMO officially enters periodic communication process. A communication cycle is divided into six phases shown as Figure 1: source nodes perception phase, cooperative groups allocation phase, inter-cluster communication resource allocation phase, broadcasting cooperative group allocation table phase, intra-cluster communication phase and inter-cluster communication phase.

In cooperative group allocation phase, MCH divides source nodes into several groups according to the cooperative group allocation algorithm proposed in this paper and allots time slots for intra-cluster communication to each CG. When the allocation process completes, MCH generates a cooperative group allocation table which contains the group information and time slots allocation information for intra-cluster communication. Due to the randomness of locations and number of the source nodes in the cluster, there may be some source nodes could not be assigned to any cooperative groups. If it happens, those source nodes without belonging to any CGs will abandon this communication cycle and wait the new cycle coming. If MCH does not generate cooperative group allocation table, all the nodes in addition to the MCG of this cluster will give up this communication cycle and go into sleeping state.

In inter-cluster communication resource allocation phase, the MCHs, having the cooperative group allocation table, start to apply inter-cluster communication slots for each CG according to routing table established before. Every MCH, using CSMA/CA protocol, sends "Channel Request" message to the next hop MCH to request time slots for inter-cluster communication. "Channel Request" message contains the number of CGs and the occupied time slots; The MCHs, receiving the "Channel Request" message, allocate the inter-cluster communication resource on the basis of minimum energy consumption and reply with "Channel Response" message. "Channel Response" message contains the information of the assigned time slots. After the data exchange among the MCHs, each MCH establishes an inter-cluster communication resource allocation table for its own CGs. If a CG is not assigned time slot, the MCH will remove it from the cooperative group table. After that, MCH updates cooperative group allocation table, based on the inter-cluster communication resource allocation table and the routing table. Then cooperative group allocation table contains group information, intra-cluster communication resource allocation table, inter-cluster communication resource allocation table and the routing information for next hop.

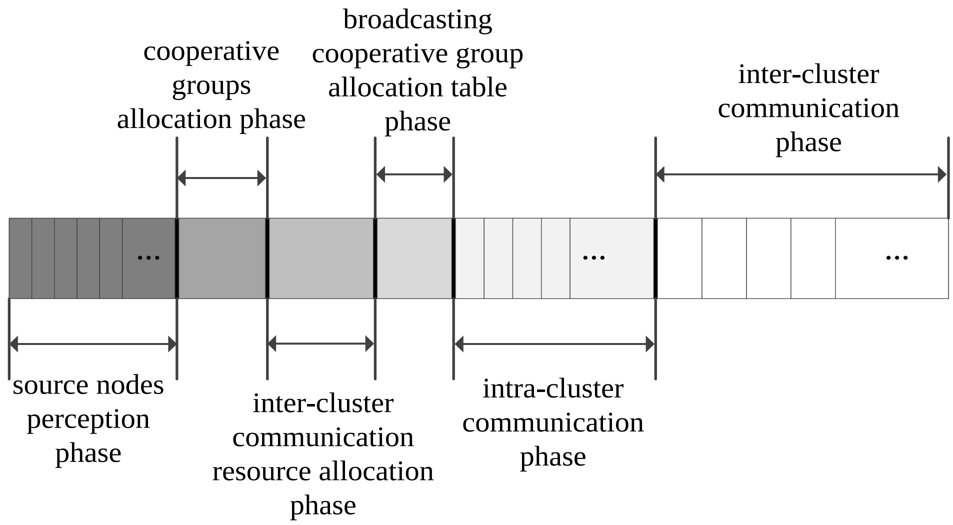

Figure 1. A Communication Cycle of GCMIMO

In broadcasting cooperative group allocation table phase, every MCH broadcasts the table to its source nodes. According to information on the table, all the nodes, assigned cooperative groups, enter into the intra-cluster communication phase; others give up this communication cycle and go into sleeping status until the next cycle coming.

In intra-cluster communication phase, the source nodes form cooperative groups basing on cooperative group allocation table. The two source nodes in each CG begin data exchange adopting RTS/CTS/ACK approach in the assigned time slot and complete space-time coding. During data exchange, the source nodes can adjust their transmit power according to the distance information in the table. On the one hand power adjustment can reduce the data collision, and on the other hand it can save energy. CGs, completing the space-time coding, go into sleeping state until the inter-cluster communication phase coming.

In inter-cluster communication phase, every CG establishes virtual MIMO link with the next hop MCG and completes source data transmission when the assigned time slot comes. MCG, receiving the source data, forwards it to its next hop MCG and realizes the multi-hop virtual MIMO transmission in the new communication cycle. Figure 2 shows the two-hop virtual MIMO transmission of GCMIMO. CGs, completing the inter-cluster communication, are off and the nodes go into sleeping state until the arrival of new cycle.

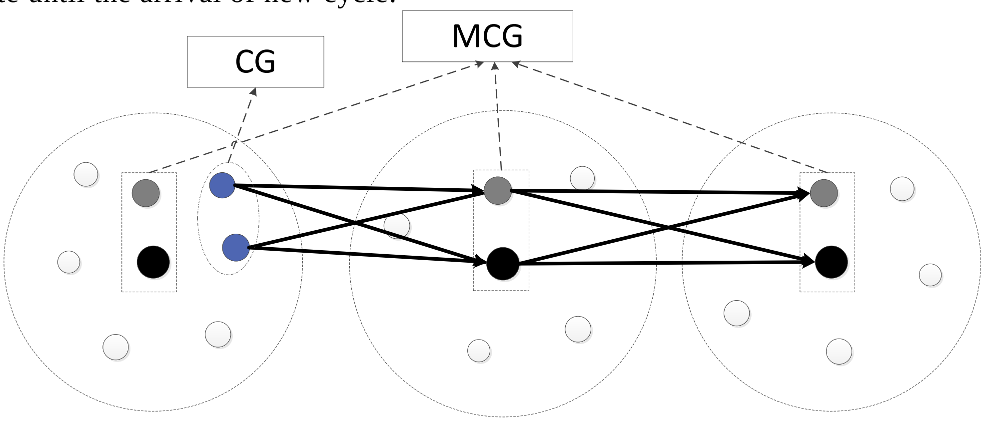

Figure 2. A Two-hop Virtual MIMO Transmission of GCMIMO

From the analysis above, GCMIMO has a primary specialty that source nodes in a CG exchange the data each other and compete the space-time coding in intra-cluster communication phase. The source data is transmitted once. However, the source data is transmitted twice for completing the space-time coding in most existing virtual MIMO communication strategy. Therefore, GCMIMO can reduce the energy consumption of intra-cluster communication and improve the energy efficiency. GCMIMO makes the CGs and their next hop MCGs form virtual MIMO links for inter-cluster communication, which is similar to CMIMO.

CG is the basic communication unit in GCMIMO. How to allocate cooperative groups is extremely significant. Therefore, cooperative group allocation algorithm will be discussed in detail below.

4. Cooperative Group Allocation Algorithm

CG is the basic communication unit in GCMIMO, so how to divide CGs has a great impact on the performance of communication in WSN. The cooperative croup allocation algorithm proposed in this paper divides the source nodes according to two conditions: communication range and communication quality.

4.1. Communication Range

In order to ensure the coverage of the WSN, the nodes need to have a large range of data transmission. However, energy consumption will increase so quickly that the nodes will die early because of their limited energy if the communication range is excessive. For balance between energy consumption and communication range, we set a maximum transmission power Pmax for every node. Correspondingly, the maximum communication range of a node is limited to d_{max}.

As the two nodes constructing a CG need to exchange data in intra-cluster communication phase to complete Space-Time Coding, so the distance between the two nodes can't exceed the maximum communication range d_{max}. Therefore, we get first qualification for cooperative group allocation algorithm:

$$d \le d_{\max} \tag{1}$$

Where d is the distance between two nodes consisting of a CG; d_{max} is the maximum communication range of the nodes, which can be changed by setting the maximum transmission power P_{max}.

4.2. Communication Quality

As the limitation in energy, computing, size and so on, it is very difficult for nodes to know the exact channel state information during communication, especially inter-cluster communication. Therefore, the cooperative group allocation algorithm generates the CGs with the purpose of ensuring the quality of the virtual MIMO communication in the condition of unknowing channel state information.

A CG is a virtual dual-antenna transmitter, and its transmission data is $\mathbf{x} = [\mathbf{x_1}, \mathbf{x_2}]$; the receiving MCG is a virtual dual-antenna receiver, and its receiving data is $\mathbf{y} = [\mathbf{y_1}, \mathbf{y_2}]$. The relationship between x and y can be expressed as:

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n} \tag{2}$$

Where **H** is a 2 × 2 matrix, indicating virtual MIMO communication channel gains; **n** is a vector, representing the noise in the channel. The larger **H** is the better virtual MIMO communication quality is. Therefore, the second qualification of cooperative group allocation algorithm is as follow:

$$\max\{\mathbf{H}\} \tag{3}$$

However, **H** is not known when the channel state information is unknown. Therefore, (3) cannot be directly applied. According to the cooperative node selection algorithm in [9], it is effective by selecting the farthest neighbor node as cluster head's cooperative node to ensure the quality of the virtual MIMO communication when the channel state information is unknown. Therefore, we can get the equivalent form of (3):

$$\max\{\mathbf{H}\} \Leftrightarrow \max\{d\} \tag{4}$$

Where d is the distance between two nodes consisting a CG.

4.3. The Process of Cooperative Group Allocation

According to the two conditions above, MCH splits all sources nodes into groups. First, MCH randomly selects a source node i; Then, MCH selects another source node j whose distance to node i meets the conditions (1) and (4), with i form a collaborative group. If MCH cannot find the node j, node i will give up this collaborative group allocation phase. When MCH checks all of the source nodes, it can form a collaborative group allocation table.

The execution of Cooperative Group allocation algorithm is shown as the Algorithm 1.

```
(1) for all i∈H do       /*i represents a source node;
                          H represents all the source node without
                          traversal*/
(2)    mark i as traversal, and update H;
(3)    for all j ∈H do      /*j represents a source node */
(4)      calculate the distance d between i and j;
(5)    end for
(6)    select the node k whose d satisfies Condition 1 and Condition 2;
                                   /* Condition 1: d<d_max;
                                    Condition 2: max{d}。 */
(7)     if k not unique then
(8)        randomly select a node from k and compose a CG with I;
(9)        store this CG in the allocation table;
(10)       mark this node as traversal, and update H;
(11)    else if k unique then
(12)       k and i compose a CG;
(13)       store this CG in the allocation table;
(14)       mark k as traversal, and update H;
(15)    else if k none then
(16)       end this cycle;
(17)    end if
(18) end for
```

Algorithm 1. Cooperative Group Allocation Algorithm

5. Energy Consumption of GCMIMO

In order to analyze energy consumption of GCMIMO, we must establish energy consumption model of wireless sensor network node firstly. In data transmission, the total power consumption can be divided into two main components [2, 3, and 7]: the power consumption of all the power amplifiers P_{PA} and the power consumption of all other circuit blocks P_C.

P_{PA} can be expressed as:

$$P_{PA}(d) = (1+\alpha)P_{out}(d) \tag{5}$$

Where d is the distance of nodes; α is a factor related to the drain efficiency; P_{out} (d) can be calculated using the following formula:

$$P_{out}(d) = \bar{E}_b R_b \frac{(4\pi)^2 d^k M_l N_f}{G_t G_r \lambda^2} \tag{6}$$

Where k is the path loss; G_t and G_r are the antenna gains; λ is the wavelength; M_l is the link margin for compensating the hardware process variations and other additive background noise or interference; N_f is the receiver noise figure; R_b is the bit rate; $\bar{E}_b$ is the average energy per bit required for a given bit-error-rate (BER), which can be calculated using the following equation:

$$\begin{aligned}\bar{P}_b = \frac{1}{2^{N_T N_R}} \left(1 - \frac{1}{\sqrt{1+2N_0/\bar{E}_b}}\right)^{N_T N_R} \times \\ \sum_{k=0}^{N_T N_R - 1} \frac{1}{2^k} \binom{N_T N_R - 1 + k}{k} \left(1 + \frac{1}{\sqrt{1+2N_0/\bar{E}_b}}\right)^k\end{aligned} \tag{7}$$

Where $\bar{P}_b$ is the given BER; N_T and N_R are the number of the sending node and the receiving node; N_0 is the noise power density.

P_C can be expressed as:

$$\begin{aligned}P_C \approx N_T(\mathrm{P}_{DAC} + \mathrm{P}_{mix} + \mathrm{P}_{filt}) + 2\,\mathrm{P}_{synth} + \\ N_R(\mathrm{P}_{LNA} + \mathrm{P}_{mix} + \mathrm{P}_{IFA} + \mathrm{P}_{filr} + \mathrm{P}_{ADC})\end{aligned} \tag{8}$$

Where P_{DAC} , P_{mix}, P_{LNA}, P_{IFA}, P_{filt}, P_{filr}, P_{ADC} and P_{synth} are the power consumption values for the digital-to-analog converter (DAC), the mixer, the low-noise amplifier (LNA), the intermediate frequency amplifier (IFA), the active filters at the transmitter side, the active filters at the receiver side, the analog-to-digital converter (ADC), and the frequency synthesizer, respectively.

Finally, the total energy consumption per bit can be expressed as:

$$E_{pb}(\mathrm{d}) = \frac{P_{PA}(d) + P_C}{R_b} \tag{9}$$

The energy consumption of GCMIMO focuses on the transmission of source data, which happens in intra-cluster communication phase and inter-cluster communication phase. Next, we use (9) to analyze the energy consumption of the two phases.

5.1. Intra-cluster Communication Phase

According to the previous description, the nodes, belonging to a CG, exchange their data using SISO mode. Therefore, the energy consumption for transmitting 1 bit data is:

$$E_{pb}^{SISO}(d) = E_{pb}(d)\,|_{N_T = N_R = 1} \tag{10}$$

For any one cluster, assume that it has G cooperative groups and each source data has LS bit data when the intra-cluster communication starts. CGs use the assigned time slots to finish this phase and the total energy consumed in this process is:

$$\mathrm{E}^{intra} = 2G\,\mathrm{L}_S\,E_{pb}^{SISO} \tag{11}$$

5.2. Inter-cluster Communication Phase

In the inter-cluster communication phase, every CG communicates with the next hop MCG through a 2×2 virtual MIMO link. Therefore, the energy consumption for transmitting 1 bit data is:

$$E_{pb}^{MIMO}(d) = \frac{R_b^{eff}}{R_b}[E_{pb}(d)|_{N_T=2,N_R=2}] \tag{12}$$

Where Reff b is the effective bit rate, which is expressed as:

$$R_b^{eff} = \frac{(F - pN_T)}{F} R_b \tag{13}$$

Where F is the block size of Space-Time Coding; p is the training overhead factor.

Using of assumptions in section 5.1, there are G cooperative groups and each source node has L_C bit data after Space-Time Coding in the inter-cluster communication phase. CGs use the assigned time slots to transmit data and the total energy consumed in this process is:

$$\mathrm{E}^{inter} = 2GL_C E_{pb}^{MIMO} \tag{14}$$

6. Simulation Analyses

To verify the energy conservation effect of GCMIMO, we establish a simulation platform to compare the energy consumption in different communication phase of GCMIMO with CMIMO. The main simulation parameters are shown in Table 1, which is same with [7].

Table 1. Simulation Parameters

λ = 0.125 m	α = 0.47
G_tG_r = 5 dBi	N_0 = -174 dBm/Hz
B = 10 KHz	P_{mix} = 30.3 mW
P_{IFA} = 20 mW	P_{syn} = 50 mW
$P_{filt} = P_{filr}$ = 2.5 mW	P_{LNA} = 20 mW
N_f = 10 dB	M_l = 40 dB

Figure 3 shows the communication energy consumption of GCMIMO and CMIMO in the intra-cluster communication phase. To be fair, the control overhead of GCMIMO is counted to the energy consumption of intra-cluster communication during the simulation. The result shows that GCMIMO has the better energy efficiency than CMIMO in intra-cluster communication phase. This is mainly because that GCMIMO improves the intra-cluster communication process, the source data is forwarded only once, while CMIMO has to forward source data twice. Although GCMIMO increases some control overhead, the energy consumption of source data transmission is still the main part in this phase. Therefore, GCMIMO is more energy-saving than CMIMO in intra-cluster communication, and the performance is growing with the increasing number of CGs (source nodes).

Figure 4 shows the communication energy consumption of GCMIMO and CMIMO in multi-hop virtual MIMO communication. During the simulation, we observe communication energy consumption of one CG (two source nodes) each time, and then calculate the average energy consumption after the multi-repeated observation. The simulation result shows that energy consumption of GCMIMO is less than CMIMO, but the gap is not large and remains almost unchanged with the increasing hops. This energy consumption gap is mainly produced in the initial intra-cluster communication. Therefore, GCMIMO have the similar performance in multi-hop virtual MIMO communication with CMIMO, but more energy efficient.

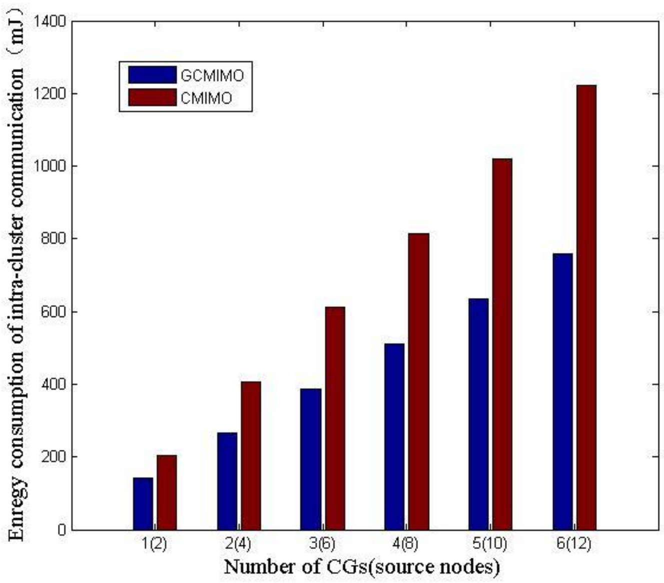

Figure 3. The Energy Consumption of GCMIMO and CMIMO in Intra-cluster Communication Phase

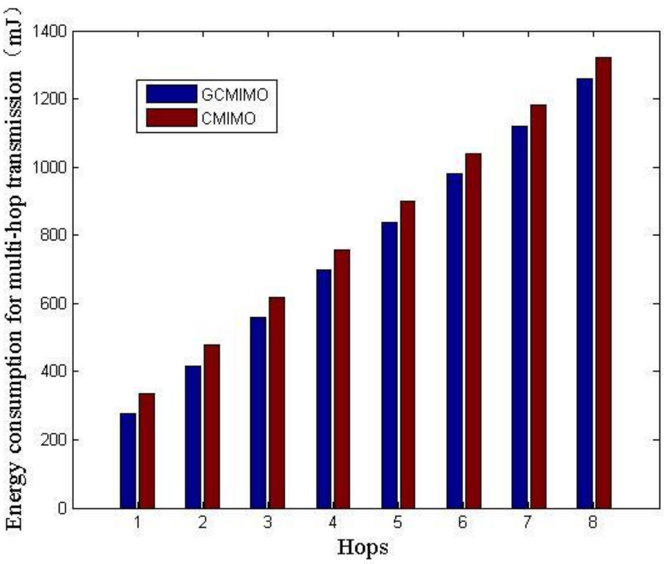

Figure 4. The Energy Consumption of GCMIMO and CMIMO in Multi-hop Transmission

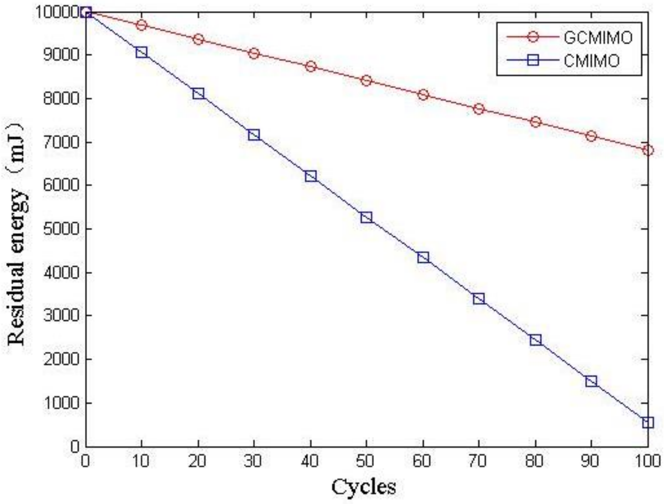

Figure 5. The Residual Energy of the Master Cluster Head (MCH)

Figure 5 shows the average energy consumption of the master cluster head (MCH). During the simulation, the MCH is fixed and the number of source nodes is the same in every communication cycle. As can be seen from the figure, with the increasing number of communication cycles, the remaining energy of both MCHs is declining. However, the energy consumption of GCMIMO's MCH is much lower than that of CMIMO. After 100 cycles, the remaining energy of CMIMO's MCH is less than 6%, while, GCMIMO's MCH has 68%. This is mainly because GCMIMO's MCH does not need to collect and forward the source data in intra-cluster communication, which can save a lot of energy. Therefore, the alternating of cluster head is not so frequent when the network runs GCMIMO, which can reduce the energy consumption for network maintenance.

7. Conclusion

Based on the existing virtual MIMO strategies for wireless sensor networks, we propose GCMIMO by improving intra-cluster communication. Different to the existing virtual MIMO communication strategies, GCMIMO use cooperative groups constituted by source nodes to transmit the data directly and the process of source data collecting and forwarding by cluster heads is removed, which can reduce the forwarding times of source data and energy consumption. The MCGs in GCMIMO can help WSN to realize the multi-hop virtual MIMO transmission by receiving and forwarding the data from CGs of other clusters. CG is the most basic communication unit in GCMIMO, so how to divide CGs has a great impact on the effectiveness of communication in WSN. The cooperative group allocation algorithm proposed in this paper can easily select the best allocation scheme enabling WSN to achieve the best communication performance.

Finally, by comparing the energy efficiency of GCMIMO with CMIMO in simulation experiment, we prove that GCMIMO has higher energy efficiency and less frequency in cluster head election, which can reduce the communication energy consumption and network maintenance overhead.

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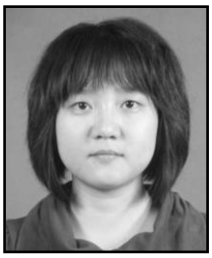

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