Energy-efficient Dynamic Cooperative Virtual MIMO Based Routing Protocol in Wireless Sensor Networks

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***Abstract*— Cooperative multiple-input multiple-output (MIMO) based communication architecture is used for energy efficient communication in wireless sensor networks. Without increasing transmission energy consumption of nodes, MIMO technology can make use of the cumulative energy of the sender node to increase the sending signal to noise ratio, thus reducing the error rate and improve the reliability of data communication. In the same transmit power and bit error rate situations, using MIMO technology can provide higher data rates, reduce the node sending time, thereby reduce the energy consumption. In this paper, dynamic cooperative virtual MIMO (DCVM) method based on residual energy information is proposed. In the specific application environment, simulation results show that the DCVM based routing protocol is more energy-efficient than single input single output (SISO) in case of long-distance communication and it prolongs sensor network lifetime as well.**

Keywords- V-MIMO; DCVM; LEACH; Energy-efficiency

I. INTRODUCTION

Recently, wireless sensor networks (WSNs) has been focused in various applications [1]-[3], due to their low deployment costs and a high potential to sense and collect object-oriented data through a large number of cheaper and resource-constrained wireless sensor nodes. A major design requirement of wireless sensor networks is to reduce the total energy consumption of the sensor nodes [4]-[7]. The transmission power can be reduced by providing the possible highest diversity gain which leads to higher link reliability and lower retransfer ratio [8]. Therefore the exploitation of multiple nodes in WSNs referred to as cooperative MIMO is inevitable in order to provide higher reliability communication link and reduce transmission power. The concept of virtual MIMO has been introduced in WSNs by utilizing the collaborative nature of dense sensor nodes with the broadcast wireless medium to provide reliable communication link in order to reduce the total energy consumption for each sensor node. However, direct application of MIMO techniques to sensor networks is impractical due to the limited physical size of sensor node which typically can only support a single antenna. Therefore, instead of using multiple antennas attached to one node or device such in the traditional MIMO concept, cooperative virtual MIMO presents the concepts of multiple sensor nodes cooperating to transmit and/or receive signals [9]. Multiple sensor nodes are physically grouped together to cooperatively transmit and / or receive. Within a group, sensor nodes can communicate with relatively low power as compared to inter-group communication.

Application of MIMO technology in wireless sensor networks research first began in 2004. So far scholars have conducted research on the relative challenging issues. When using collaborative MIMO wireless sensor networks, some key issues have been researched on nodes selection, synchronization requirements, routing and so on.

The rest of this paper is organized as follows: Section II presents some related works. In Section III, the model for DCVM system including energy consumption is discussed, and the proposed network architecture and methods for selection of transmitter and receiver nodes are described. Section IV presents the simulation parameters and results. Finally, Section V concludes the paper.

II. RELATED WORK

In various literatures, some cooperative node selection algorithms are proposed [10]-[12]. Taking into account the characteristics of collaborative MIMO and clustering WSN, in literature [13], collaboration MIMO method is adopted in which the collaboration nodes are selected by header nodes. In literature [14], in order to reduce the total energy consumption of entire WSN networks, the clustering method is proposed in which transmission rate and size are optimized.

In [11] many literatures assume the nodes deployment is dense in order to ensure a cluster head can find enough cooperative nodes. However, in practice, the nodes die easily along with the excessive energy consumption, and the networks deployment becomes sparser, therefore, a cluster head node cannot find enough nodes as collaborative nodes. In summary, most existing MIMO-based wireless sensor routing algorithms, in each round, the collaboration system is formed by selecting a few fixed collaboration nodes. But, when the WSNs deployment is sparse and perceptual information appears frequently, the collaboration nodes can consume more energy than the normal nodes because the information content is huge, this case could increase the network's energy imbalance.

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Considering all the insufficiency mentioned above, the paper proposes a routing protocol based on dynamic cooperative virtual MIMO (DCVM). The key point is that when sending a package it should include the node's residual energy as additional information, the MIMO systems is formed by selecting new cluster heads (CHs) dynamically and then obtain a certain percentage of nodes regarded as virtual antennas with the near optimal selection technique.

III. DCVM SYSTEM MODEL

In the WSNs, LEACH [15] algorithm is a typical topology adaptive clustering algorithm. Its implementation is periodic, in which each round is divided into the clustering establishment stage and the stable data communication stage. During the clustering stage, the cluster head is selected according to certain principles such as their available energy and current load requirements. In our scenarios, nodes with highest energy are selected as cluster heads. Then the cluster heads broadcast their advertisements and the other nodes will choose their cluster heads based on the received signal strength of advertisement messages. During the data communication stage, nodes send data to the cluster head, then, cluster head fuse these data and send it to the base station. LEACH clustering algorithm achieved a good effective energy saving and obtained the widespread attention. This article draws on the idea of LEACH algorithm.

Similar with LEACH, DCVM based on the circulative operation, but it is non-periodic. Because the cluster heads consume energy faster than normal nodes and cooperative nodes, we focus on taking into account the residual energy information of the cluster heads. Once its residual energy is below the predefined threshold, the network will update. Firstly, network collects all nodes' residual energy information, then choose the highest ones to be the new cluster heads; Secondly, the cluster heads broadcast their advertisements and the other nodes will choose their cluster head based on the received signal strength of advertisement messages; Finally, the new cluster heads choose new transmitter-receiver pairs.

In each round, firstly select new cluster heads according to the additional residual energy information and then form antenna nodes with the near optimum selection technique, then processing data transmission. The details of near optimum selection method are as follows:

1) For each potential transmitter, the transmitter cluster head will determine receivers that are nearest to these transmitters.
2) The transmitter-receiver pairs are sorted based on distance.
3) The cluster head will choose the required number of transmitters and receivers from the shortest route list.
4) If the number of transmitters and receivers are less than the required number of transmitter and receivers, the nodes nearest to the selected transmitters and receivers are selected.

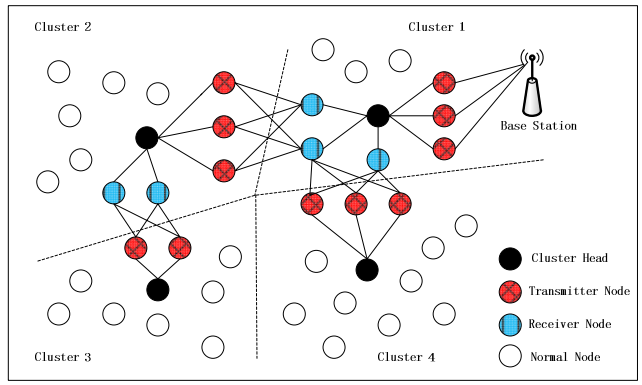

Figure 1: Dynamic Cooperative Virtual MIMO in WSNs

Figure 1 shows four clusters with different transmitter and receiver nodes. In this network model, assume that energy and capacity of the base station is not limited and the base station is of multiple antennas, base station receives space-time coding data by multi-antenna way, and get the original data by space-time decoding.

In a cluster, some nodes are selected as transmitter nodes and some nodes are selected as receiver nodes. The same node can be selected as both transmitters and receivers. In the proposed DCVM framework, there are four types of nodes: normal nodes, transmitter nodes, receiver nodes and cluster heads. The normal nodes sense the environment and collect the data. The cluster heads collect the data from the normal nodes and use transmitter nodes to transmit their data to the receivers of the neighboring cluster or send data directly to the base station. All the nodes in the cluster will transmit data to the cluster head using CSMA-CA slotted algorithm. Cluster head will aggregate the packets into a single packet and will broadcast to the transmitter nodes.

Energy-efficient techniques typically focus on minimizing the transmission energy only, which is reasonable in long range applications where the transmission energy is dominant in the total energy consumption. However, in short range applications such as wireless sensor networks, the circuit energy consumption is comparable to or even dominates the transmission energy. The circuit energy consumption includes the energy consumed by all the circuit blocks along the signal path: Analog to Digital converter (ADC), Digital to Analog converter (DAC), Mixer, Frequency Synthesizer, Low Noise Amplifier (LNA), Power Amplifier, and base band DSP. This problem becomes more significant in MIMO systems since the circuit complexity of MIMO structures is much higher than that of SISO structures.

We consider a communication link connecting two wireless sensor nodes, which can be either MIMO or SISO.

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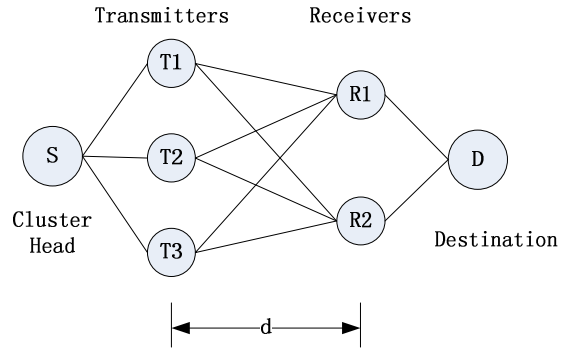

Figure 2: System Model for MIMO

Figure 2 shows the scenario of using three transmitters and two receivers. The cluster head is a sender node, S, who transmits the message to the destination node, D. Firstly S transmits the message to three transmitter nodes, T1, T2, and T3. These transmitter nodes transmit the message to the receiver nodes, R1 and R2. Then, the receiver nodes forward the message to the destination node, D.

The transmitter's bit rate, b, is defined as bits per symbol.

$$b = \frac{R_b}{B} \tag{1}$$

where B is bandwidth and R_b is data rate.

In WSNs, the sensor nodes have a low duty cycle and the nodes are off most of time in order to conserve the energy. The energy consumption is computed by adding the on, sleep, and transient states, as given below.

$$\begin{aligned} E &= P_{on}T_{on} + P_{sleep}T_{sleep} + P_{transient}T_{transient} \\ &= [P_{transmit}(1+\alpha) + P_{circuit}]T_{on} + 2P_{syn}T_{transient} \end{aligned} \tag{2}$$

Where $P_{on}, P_{sleep}, P_{transient}$ represents power on, sleep and transient respectively. Similarly, $T_{on}, T_{sleep}, T_{transient}$ are duration for on, sleep and transient states respectively. And $P_{on} = P_{transmission} + P_{circuit}, P_{transmission} = P_{transmit} + P_{amplifying}$, $P_{amlifying} = \alpha P_{transmit}, P_{transient} = 2P_{syn}$,where P_{syn} is power consumption for frequency synthesizer. As the power consumption in $T_{transient}$ is negligible as compared to $P_{circuit}$, the constant factor P_C is used to represent both circuitry consumption and synthesizer consumptions.

We obtain the average energy consumption per bit as follow:

$$\begin{aligned} E_a &= [P_{transmit}(1+\alpha) + P_C]T_{on} \\ &= \frac{2(1+\alpha)}{3}\left(\frac{P_b}{4}\right)^{\frac{1}{N_T N_R}} \frac{2^b - 1}{b^{\frac{1}{N_T N_R}+1}} N_o \frac{(4\pi)^2}{G_t G_r \lambda^2} M_l N_f \\ &\quad \times \sum_{i=1}^{N_T}\sum_{j=1}^{N_R} d_{ij}^{K_{ij}} + \frac{P_C}{bB} \end{aligned} \tag{3}$$

Where α is an amplifying factor, N_T, N_R are number of transmitters and receivers respectively. P_b is the average bit error rate, N_o is single sided noise power spectral density and total circuit power consumption $P_C = N_T P_{Ct} + N_R P_{Cr}$, G_t is transmitter antenna gain , G_r is receiver antenna gain , d_{ij} is the distance between node i and j , k_{ij} is the path loss factor from i to j , λ is wavelength, M_l is the link margin, and N_f is receiver noise.

We assume the power consumption of each bit for transmission, transmitter circuit and receiver circuit is P_T , P_{ct} and P_{cr} respectively. All the nodes in a particular data gathering period send data to the local cluster head. Energy consumption for baseband signal processing is negligible compared to the total energy consumption and neglected in this section. Assuming the same packet size (N bits), the energy consumption to transmit K packets from K nodes can be written as:

$$E_{node-head} = \frac{KN}{bB}(P_T + P_{ct} + P_{cr}) \tag{4}$$

Cluster head will aggregate the packets and send the aggregated packet to all transmitter (N_T) nodes. The energy consumption to transfer the packet to the transmitter nodes can be written as:

$$E_{head-trans} = \frac{KN}{bB}(P_T + P_{ct}) + \frac{NN_T P_{cr}}{bB} \tag{5}$$

Transmitter nodes communicate with the possible shortest distance node of the receiver cluster. The energy consumption for cluster to cluster communication can be stated from Equation 3

$$E_{trans-recei} = N\zeta \sum_{i=1}^{N_T}\sum_{j=1}^{N_R} d_{ij}^{K_{ij}} + \frac{NP_C}{bB} \tag{6}$$

The transmission from receiver nodes to cluster head which is local communication can be written as:

$$E_{recei-head} = \frac{N_R N}{bB}(P_{tra} + P_{ct} + P_{cr}) \tag{7}$$

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In the every round, total energy consumption model can be described as following:

$$E = E_{node-head} + E_{head-trans} \text{ (number of hops+1)} + E_{trans-recei} \text{ (number of hops +1)} + E_{recei-head} \text{ (number of hops)} \quad (8)$$

IV. SIMULATION RESULTS

The proposed dynamic cooperative virtual MIMO network is simulated using the model described in equation 3 and equation 8. The simulation details are as follows: number of deployed nodes is 80, network area is $200 \times 200 m^2$, and base station is located at center of the network. We also assume that the cluster head will trigger the network update when the residual energy is below 50% and each node has 100% initial energy. The network has two transmitter nodes and two receiver nodes. The simulation parameters are given as follows: bandwidth is 10 KHz, the traditional WSNs has a retransmission ratio between 0.3 and 1, $G_t G_r = 5dBi$, $M_l = 40dB$, $N_f = 10dB$, $P_C = 1.2mW$, path-loss exponent is 2, $P_b = 10^{-3}$.

A. Network nodes deployment

Figure 3 shows 80 nodes randomly deployed with 6 cluster heads. In the first round, we select the node with highest energy which is near the center of the cluster. Then we choose the transmitter nodes according to the optimum selection. When cluster head's residual energy is below the threshold it will trigger the network to update.

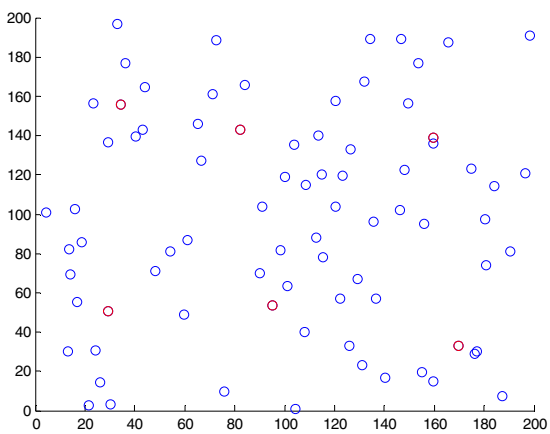

Figure 3: 80 nodes randomly deployed with 6 cluster head

B. Energy consumption

Figure 4 shows the energy consumption of dynamic cooperative virtual MIMO model and SISO wireless sensor network. We can see that the DCVM model is more efficient than SISO model, especially when the network transmits more packets.

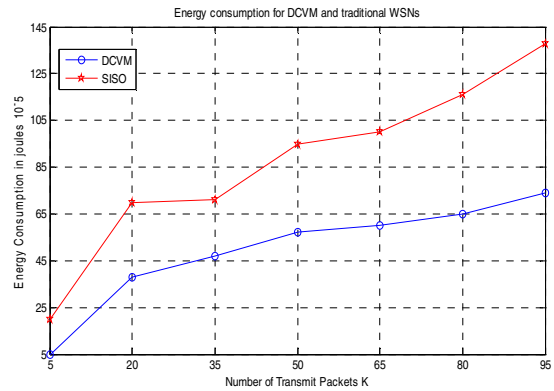

Figure 4: Energy consumption for the DCVM model and SISO model

C. Time Delay

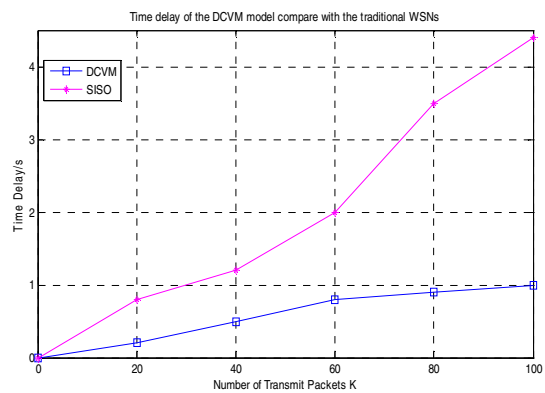

Figure 5: Time delay of the DCVM model and SISO mode

Figure 5 shows that, comparing time delay between the DCVM model and the SISO model, the DCVM has higher data rates and lower error rate, so the time delay is less than the traditional WSNs.

V. CONCLUSION

In this paper, we proposed DCVM which is based on the residual energy information of the cluster head to trigger the next round, and DVCM protocol using hierarchical network topology structure, combining MIMO technology with clustering topology structure and dynamic virtual antenna mechanism. Thus application of the MIMO technology in the sparse network is possible. And, according to the analysis of energy consumption, we can see that the DCVM based protocol prolongs sensor network lifetime. The simulation results show that DVCM performs better in the energy conservation aspect. The results also have certain guidance value for practical application.

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