Energy Efficient Delay-aware Routing in Multi-tier Architecture for Wireless Sensor Networks

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***Abstract*— Wireless sensor network (WSN) is composed of a large number of sensor nodes densely deployed in inhospitable physical environments. Due to limitations of sensor nodes in terms of memory, energy and computational capacities, the most important issue for designing sensor network protocols is energy efficiency. Although energy efficiency is a major concern in WSNs, it often suffers from the addition network delay. In this work, we first propose an energy and delay efficient hierarchical clustering scheme called BHC (Bruijn Hierarchical Clustering) for WSNs. It allows data transmission from sensor nodes to the base station (BS) in the form of multi-hop, multi-path and ensure energy efficiency and reasonable delay. Next, we provide data distribution algorithms from the sensor nodes to BS as quickly as possible and the most energy efficient. To evaluate the appropriateness of our proposal, we analyze the simulation results against another protocol in terms of communication overhead, total amount of energy dissipated in system and network delay using ns-2 network simulator.**

***Keywords*— sensor network, energy efficiency, delay.**

I. INTRODUCTION

Sensor in WSN is the combination of wireless communication architecture and sensing technology. Instead of transmitting data to the BS via the wireless link directly, sensor nodes performs data transmission throught ad-hoc model using multi-hop connections. The sensor nodes are able to communicate within a narrow range, thus allowing data to be relayed through intermediate nodes toward the root node is actually needed, saving energy than using a direct connection from any node to the BS.

To take effect on design and implementation of network protocols when changing and expanding networks, clustering method is used. In this approach, the sensor nodes are allocated to clusters and a node is selected to be cluster head (CH) node for each cluster. Each CH node collects and aggregate data from different sensors in the cluster. After that it will distribute of such data to the BS [1]. In WSNs, data aggregation significantly reduces the transmisson traffic on the network as well as the energy used for the transmission of duplicate data. Energy consumption at each sensor node depends on many factors such as data sensing, data transmitting and receiving, data processing, and media listening, etc. Considering the sensor's energy model in [1], the energy used to send q bits a distance d from one node to another node is given by $E_{Tx} = (\alpha_1+\alpha_2 d^n)*q$, where α_1 is energy dissipated in transmitter electronics per bit, α_2 is energy dissipated in transmitter amplifier. It is clear that when the distance between the sensor nodes becomes larger, energy consumption will increase exponentially. Thus, shortening the distance between the sensor nodes is necessary if you want to reduce energy consumption on data transmission.

Although energy efficiency is considered as the core issue in the design of WSNs, but the fact that network delay is very important, especially in applications that require the timely response of the system confronted with changes of the environment, such as fire alarm systems, remotely health of patients monitoring system, etc. Clustering is one technique used very effectively to archive the energy efficiency in WSNs [2]. However, its main drawback is the high delay. Although many solutions have been proposed [3] [4] [5] [6] [7] [8] [9] to balance delay and energy consumpion in WSNs, but their effectiveness is negligible because of their covergence, algorithm complexity, overhead and unrealistic assumptions.

Motivated by the advantages of the de Bruijn graph admitting simple routing and processing good fault tolerant capacities in many interconnected networks, we introduce a novel model called the BHC – Bruijn Hierarchical Clusteting. In this model, data is transmitted from sensor nodes to the BS in the form of multi-hop, multi-path to ensure energy efficiency and reasonable delay. Technically, the BHC model is a combination of clustering model [1] and de Bruijn graph model [8]. This graph has good properties such as small diameter, high connectivity, and easy routing. The classification de Bruijn networks significantly improves the energy consumption on data transmission over long distances, while clustering model saves energy based on the ability to aggregate data during data transmission across the network. In addition, we also provide data distribution algorithms from sensor nodes to the BS as quickly as possible and the most energy efficient.

The remainder of the paper is organized as follows. In section 2, we present the related work. Section 3 describes the BHC model. Topology construction and Data distribution algorithms are shown in section 4. Section 5 provides simulation results in terms of energy efficiency and network delay. Finally, concluding remarks are given in section 6.

II. RELATED WORK

In recent years, many studies focus on solving the problem of energy saving in WSNs. An energy-efficient adaptive clustering routing algorithm for WSNs was proposed by Jia et al. [2] in order to overcome the drawbacks with the CHs in LEACH [1], such as over-accumulated energy consumption, irrational distribution, none-optimal proportion. Authors provide the improved CH-electing threshold, CH location regulating algorithm and Multi-hop routing algorithm inter-cluster in order to balance the total energy consumption, but also prolong the network lifetime. However, it is not concerned about the network delay.

Zhang et al. proposed a new heuristic approach [3] in which a subset of nodes served as the data collection points (CPs) and sinks served as mobile elements (MEs) to reveive data sent from CPs. Its purpose is determining the optimal number of CPs for trading-off between energy efficiency and the network delay which is determined by the number of CPs and the length of trajectory of MEs. Problem of this proposal is that when the distribution of sensors is randomly deployed in a wide range, MEs will not be evenly distributed.

Clu-DDAS [4] was proposed by Li et al., which presents an energy efficient distributed scheduling algorithm based on a cluster-based aggregation tree. Authors studied the well-known Minimum-Latency Aggregation Schedule problem to propose a collision free transmission schedule of data aggregation for all sensors such that the delay for aggregated data to reach the sink is minimized. By constructing a Cluster-based Data Aggregation Tree, this protocol permits the packet transmissions among different clusters are concurrent and collision free. However, constructing distributed trees using broadcasting technique generates more overhead.

T.T Huynh et al. proposed a new multi-hop routing scheme to balance energy efficiency and network delay in [5]. Energy*Delay routing algorithm is applied within 3-hop cluster for sensors within each cluster while energy-efficient chain construction algorithm is applied for CH nodes to construct energy-efficient chains from CH-nodes to the BS. However, this protocol shows the complexity of routing algorithms and costs for setting up the chains.

In order to reduce the number of relay nodes between the source node and the BS, Kajikawa et al. [6] proposed a grid-based routing protocol which divides the network area for square cells by using cell rotational technique. Each cell is divided into multiple sub-cells, and assumes one or two sub-cells to be active-cells. Then, it demarcates the existing area of active nodes to each active-cell. It reduces the delay of data delivery and the energy consumption. However, its main drawback is that each data source has overhead to exactly compute their location using unique geographical coordinates and proactively build a grid structure.

DEAR (Delay-bounded Adaptive Energy-constrained Routing) [7] is multi-path routing protocol. It is interested in many parameters such as reliability, delay and energy consumption. This protocol allows packets are continuously distributed across the network even if the paths are going to crash (turning to other paths). It balances the delay between the different paths by providing a polynomial-time algorithm for solving multi-objective optimization problem. However, energy and network delay efficiency is limited for the complexity of algorithm.

TT. Huynh proposed a method of organizing multi-tier sensor network [8] which sensor nodes at each layer interconnected as de Bruijn graph model to improve network delay, energy consumption and system reliability. Besides, the de Bruijn graph based multi-layered network to communicate between nodes in a WSN is also considered in [9]. This graph has a few unique features that make it suitable to implement a high-performance, low energy consumption, and more reliable network structure. Authors have proposed an energy efficient routing algorithm for the multi-layered structure. Experimental results show outperformance of the delay and energy consumption. However, they do not take full advantage of data aggregation to reduce transmission of duplicate data over network.

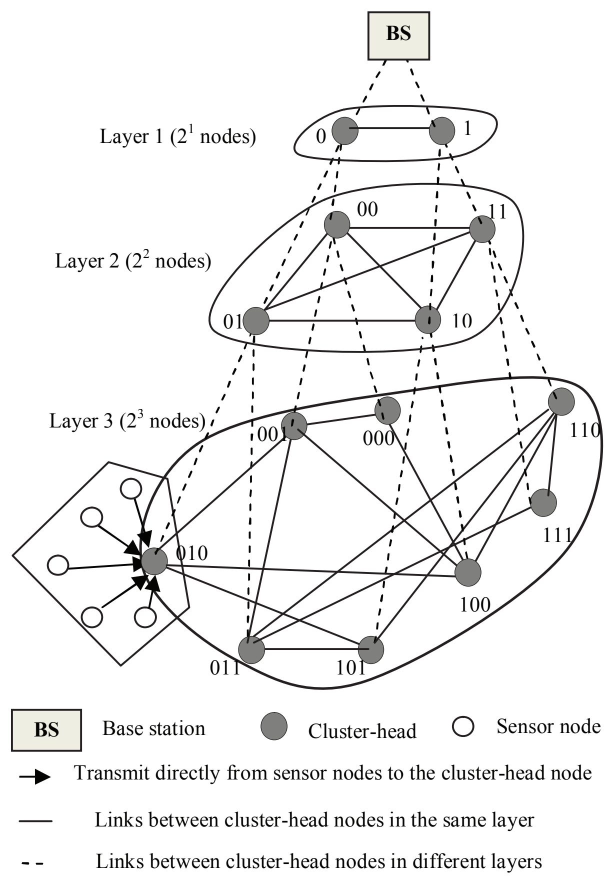

Fig. 1 Basic multi-tier model of wireless sensor network

III. THE PROPOSED MODEL – BHC (BRUIJN HIERARCHICAL CLUSTERING)

In this section we describe a new multi-tier architecture enables distribution of packets from sensor nodes to BS energy efficiency and reasonable delay. This architecture is shown in figure 1.

The formation process of this topology is divided into two steps. First, sensor nodes are distributed in clusters, each cluster has a CH node. CH node performs more tasks than other sensor nodes in the cluster. CH node periodically receives data from other sensor nodes, after that it will perform data aggregation to reduce the redundancy of correlated data from different sensor sources (including it). Next, CH nodes of the clusters are organized by hierarchical multi-layer model, where the CH nodes on the same layer connect to each other according to the rules of de Bruijn graph. We improve the approach in LEACH-C [1] to organize clusters and select CH nodes. Accordingly, each sensor node, upon sending a data packet, piggybacks related information. Upon receiving a data packet, the BS extracts this information for clustering, determining and distributing CH nodes into appropriate layer in BHC scheme to optimize the energy consumption. Our architecture features is addressed as follows:

- k^{th} layer has 2^k CH nodes.
- CH nodes are addressed with binary address form, CH nodes in k^{th} layer use *k* bits for node addressing.
- Each CH node at k^{th} layer is connected to two children CH nodes at $(k+1)^{th}$ layer and is connected to its parent CH node at $(k-1)^{th}$ layer (k>1).
- CH nodes in 1^{st} layer and 2^{nd} layer are connected completely. It means that, each node in the first layer has only one neighbor and 2 children. Each CH node in the second layer has 3 neighbors and 2 children CH nodes.
- We are interested in binary de Bruijn graph BG(2,k) which have N = 2^k nodes. A CH node *x* addressed $x_{k-1}x_{k-2}\ldots x_1x_0$ in k^{th} layer (k>2) has 4 neighbors as neig1(x) = $x_{k-2}\ldots x_1x_0 0$, neig2(x) = $x_{k-2}\ldots x_1x_0 1$, neig3(x) = $0x_{k-1}x_{k-2}\ldots x_1$, và neig4(x) = $1x_{k-1}x_{k-2}\ldots x_1$.
- The address of CH node in k^{th} layer consists of two parts. One is k bits derived from $(k-1)^{th}$ layer. The other is 1 bit (0 or 1) added from right side. CH node x addressed $x_{k-1}x_{k-2}\ldots x_1x_0$ has two children CH nodes and one parent CH node. These children are addressed as add($x_{k-1}x_{k-2}\ldots x_1x_0$,0) and add($x_{k-1}x_{k-2}\ldots x_1x_0$,1) while the parent is addressed as rmv($x_{k-1}x_{k-2}\ldots x_1x_0$). Let K be a k-bit number and y be a binary number (0 or 1). Then, add(K,y) = Ky; rmv($x_{k-1}x_{k-2}\ldots x_1x_0$) = $x_{k-1}x_{k-2}\ldots x_1$. For example, add(001,1) = 0011; rmv(0110) = 011.

IV. Topology Construction and Data Distribution Algorithms

A. Topology Construction

The operation of BHC is depicted in figure 2.

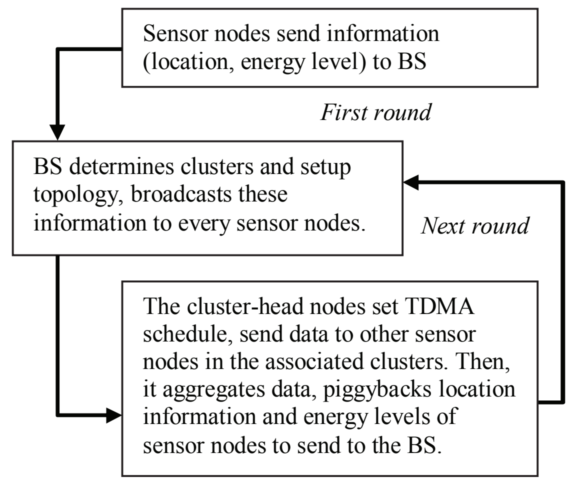

Fig. 2 Flowchart of BHC operation

In the first round, all sensors must send information about their location and current energy level to BS directly. The BS based on this information, uses the simulated annealing algorithm [10] to find out CH nodes and distribute remaining nodes into associated clusters. In subsequent rounds, to reform clusters and topology, the sensor nodes do not need to resend information about location and residual energy to BS anymore. Instead, information will be extracted from the Infor part (figure 3) in the data packets received from CH nodes at previous round.

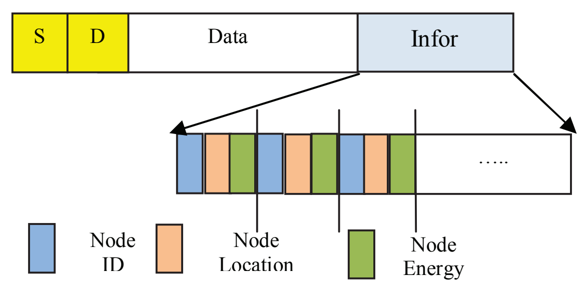

Fig. 3 Format of last data packet in each round was finally sent from cluster-head nodes

Besides creating good clusters, BS needs to ensure the energy distribution for the sensor nodes is equal. To do this, BS calculates the average energy level and determines which sensor node is lower than this average value to find out CH node for that round. The remaining nodes that are capable of becoming CH node is applied the simulated annealing algorithm to find out the optimal clusters. This algorithm reduces significantly the amount of energy that the sensor nodes used to transmit data to their CH node by minimizing the sum of squared distances between sensor nodes to the nearest CH node.

B. Data distribution algorithms (from sensor nodes to base station)

1) Data transmission from sensor nodes to the cluster-head node in each cluster

First, all sensor nodes in each cluster transmit data directly to the CH nodes corresponding to the given time slot TDMA schedule earlier submitted by the CH nodes. In turn, CH nodes aggregate data from multiple sources (including the sensing data from themselves) and then they participate in relaying data in direction of the BS based on the simple routing algorithm of de Bruijn graph known as the forwarding data from CH nodes to the BS.

code of the parent node. This procedure is continued until the child nodes are in the first layer, spreading code of the parent node is now spreading code of BS.

Routing in first class is very simple. Two CH nodes with ID 0 and 1 send the data directly to BS using spreading code of BS. If they do not get feedback from BS, one of them will forward data to remain neighbor node (0 forwards data to 1 and 1 forwards data to 0). In the 2nd layer or higher, the CH nodes send data directly to their parent node. In the case of the children did not receive responses from its parent node, it can transfer the data to its neighbor node which is not the same father using the spreading code of that neighbor node. If neighbor node cannot forward on (do not get feedback from its parent node), it will continue to forward to one of the neighbor nodes which is not the same father nor the neighbor node has been forwarded to it earlier.

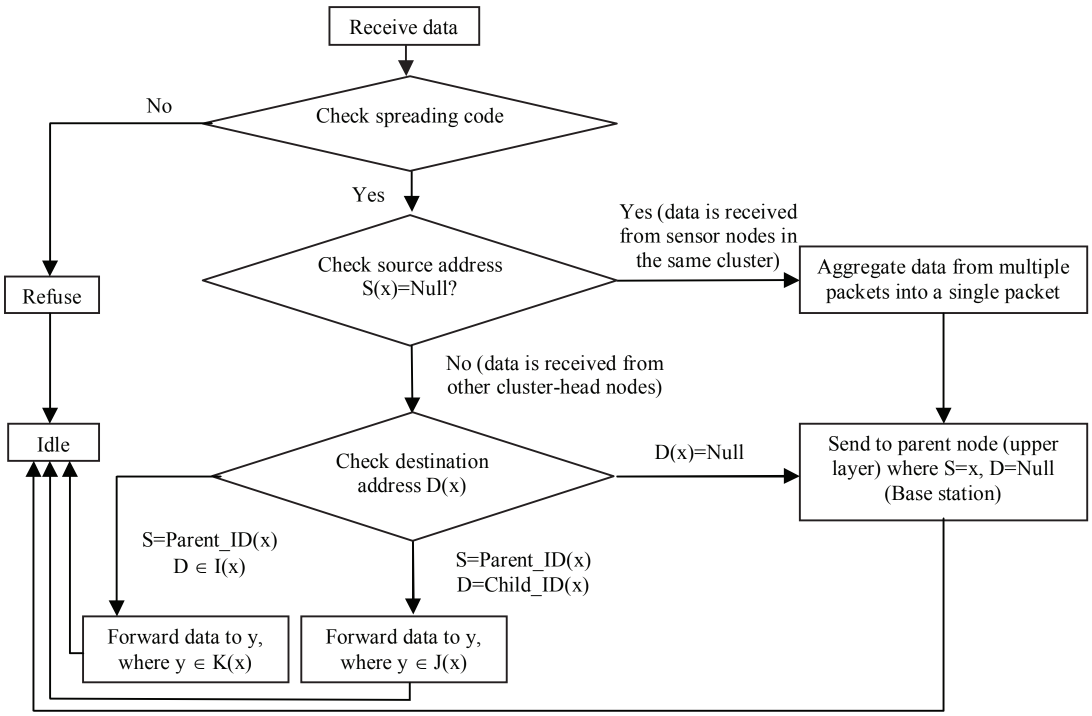

Fig. 4 Algorithm of data distribution from sensor nodes to BS

The data transmission from sensor nodes to CH node have to save energy and avoid data conflict within each cluster. However, the nature of wireless propagation environment is broadcast medium, so the transmission in a cluster will affect other clusters. To reduce the influence and interference between the clusters, we apply the method of direct-sequence spread spectrum (DSSS) for each cluster. Accordingly, each cluster uses a unique spreading code, all sensor nodes in the cluster transmit data to CH node using this code. Besides, CH node also uses this code to filter the received signals. This method is called transmitter-based code assignment [11], because all transmitting nodes use the same code.

2) Forward data from cluster-head node to BS

Data is forwarded from CH nodes to BS through the parent node in the hierarchical model de Bruijn graph using a fixed spreading code and media access method CSMA. Accordingly, child nodes forward data to their parent node using the same spreading code of the parent node (assigned by BS). When a CH node has data to send, it must sense the media to know whether remain child node (same father with it) is transmitting data to the parent node or not. If so, it has to wait, otherwise it immediately forwards data using the

The detail algorithm is as follow: *I(x)* is the set of neighbor nodes of x. *J(x)* is the set of neighbor nodes which is not the same parent with node x. *K(x)* is the set of neighbor nodes which is not the same father nor the neighbor node has been forwarded to x earlier. Then, at a CH node x, when it receives a packet, it routes data to the BS as in figure 4.

V. SIMULATION RESULTS

In this section, we analyze performance evaluation compared with C^2E^2S [5] in terms of communication overhead, total amount of energy dissipated in the system over time, network delay using a ns-2 network simulator [12]. In below figures, the red line is C^2E^2S protocol, and the green line is the protocol proposed in this study (BHC).

Our sensor field spans an area of 100x100m2 wherein 100 sensors are scattered randomly. A node is considered "dead" if it consumes more than 95% of its initial energy. For a node in the sensing state, packets are generated at a constant rate of 1 packet/sec. The communication media is contention and error free; hence, sensors do not have to retransmit any data. To compute energy consumption for each transaction sending and receiving, we use the radio energy dissipation model in [1]. In these experiments, each node begins with only 2J of energy and an unlimited amount of data to be sent to the BS.

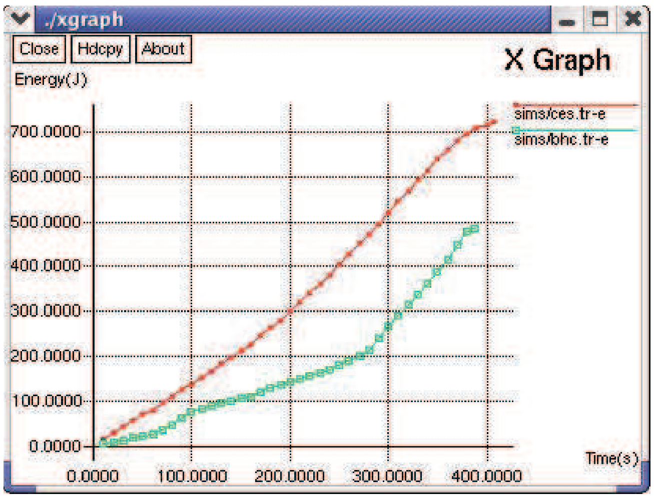

Fig. 5 Total dissipated energy over network time.

According to the results shown in figure 5 (X-axis is time (second), Y-axis is the total dissipated energy (Joule)), the total of amount energy dissipated in the network over time is significantly reduced compared with C^2E^2S. This is due to the efficiency and simplicity of routing algorithm.

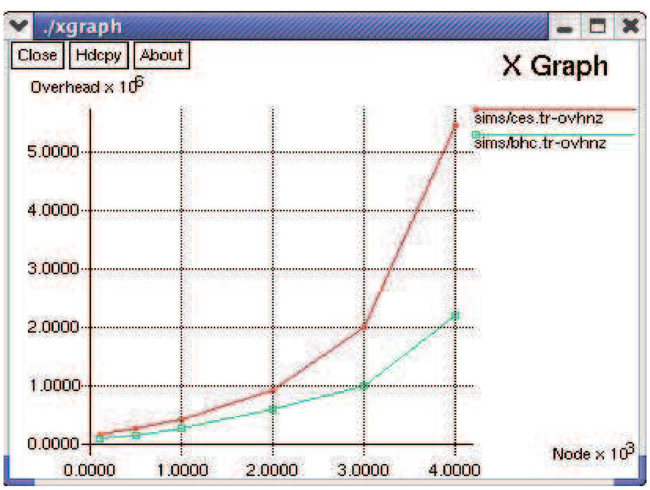

Fig. 6 Number of communication overhead in the network.

Figure 6 (X-axis is number of alive node, Y-axis is number of overhead) shows the effectiveness of our approach when conducting simulations on different network sizes (number of sensors). Result in Figure 6 shows that when the network size increases, the number of overhead soared in C^2E^2S while it increased more slowly in this study.

The reason is that, in our opreration model, each sensor node piggybacks related information (Infor part in figure 3) every time it sends data packet.

In addition, the network delay is effective in our approach. Figure 7 (X-axis is network delay, Y-axis is number of alive node) shows the network delay is lower than compared with C^2E^2S. However, in our approach, when the number of alive sensor decreased (under 10 nodes), the network delay is not effective anymore. So, we can say, BHC is a delay efficient scheme for large WSNs. Because, from this time, the topology re-construction and data transfering over the chain are more efficient.

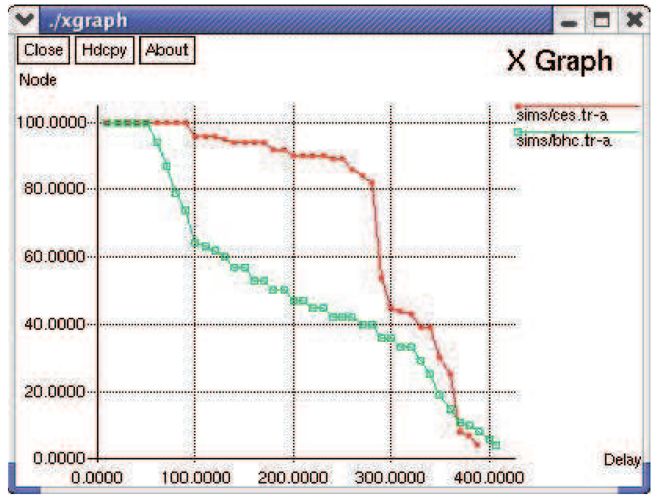

Fig. 7 Network delay upon Number of alive sensor.

We evaluate factor of energy*delay which is the combination of network delay and total dissipated energy. Result in figure 8 (X-axis is the energy*delay, Y-axis is the number of alive node) shows that energy*delay is more effective compared with C^2E^2S. However, when the number of alive sensor reduced to less than 40 nodes, the C^2E^2S is more effective. Because the simplicity of the routing is effective with the large number of nodes only. Again, it shows that our approach is really effective in large-size networks.

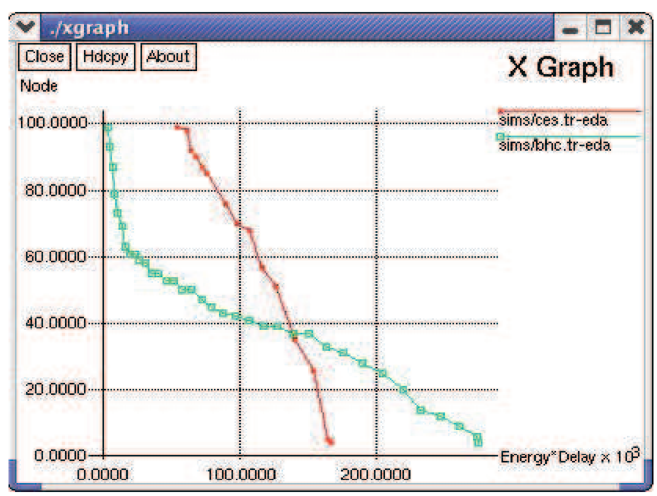

Fig. 8 The energy*delay upon the number of alive node.

VI. CONCLUSIONS

Though dissemination information with minimum energy consumption is a key concern in WSNs, it often introduces additional network delay. Energy efficiency while meeting the network delay in the large WSN is the main contribution in our research.

In this paper, we have proposed the Bruijn Hierarchical Clustering scheme (BHC) along with algorithm of data distribution from sensors to BS. By simulation, we have shown appropriateness of our approach evaluated against C^2E^2S in terms of communication overhead, total amount of energy dissipated in the system over time, network delay and the energy*delay.

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