Construction and Maintenance of Energy Aware Virtual Backbone Tree in Wireless Sensor Networks

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Abstract

Virtual Backbone has been proposed as a promising approach for providing an efficient communication infrastructure in wireless sensor networks. But the critical issue is to construct a Virtual Backbone in a distributed manner while satisfying several important features: low establishment cost, prolonged node lifetime, scalability and robustness. In this paper, we propose a distributed heuristic algorithm to construct an Energy-Aware Virtual Backbone Tree (EAVBT) for general-purpose communications in wireless sensor networks having some salient features: very low construction overhead; relief from maintaining routing table; minimum energy required to transmit data through the EAVBT. We also propose energy efficient localized maintenance scheme for the EAVBT. Apart from that the proposed algorithm is adaptive in nature: it automatically adapts to the addition and removal of the sensor nodes. Simulation results are shown that demonstrate the competence, reliability and effectiveness of the proposed algorithm.

1. Introduction

A wireless sensor network consists of a large number of sensor nodes spread across a geographical area. Wireless sensor networks [11] usually contain thousands or millions of sensors, which are randomly and densely deployed (10 to 20 sensors per sq. meter). The sensor nodes are small, lightweight, usually smaller than 1 cubic cm, weights less than 100 grams, which are known as Pico nodes [9] and having very low energy (typically 2 joule) [6]. There are various types of sensor nodes available: Seismic, Thermal, Visual, Infrared etc. Each sensor node typically consists of four components: sensing circuitry, data processor, power supply unit, and radio transceiver [8, 11]. Sensing circuits capture data from the target environment and convert them into electrical signal then it is processed and finally transmitted via radio transmitter to a command center either directly or through a data concentration center (Sink Node) [8]. The sink node can perform fusion of data received from the sensors and also filtering out erroneous data, before passing it to the command center or base station. Sensor networks are utilized for various types of application such as: Military, Environmental, Health, Home, Disaster relief, chemical processing and other type of applications [8].

A sensor network can be represented by a unit disk graph G= (V; E) [7], where V represents a set of wireless sensor nodes and E represents a set of edges. An edge between node pairs {v, u} indicates that both nodes v and u are within each other’s wireless transmitter ranges. A Dominating Set D is a subset of V such that each vertex in V is either adjacent to at least one vertex in D or a member D. If member of D connected with each other and form a subgraph then it is known as Connected Dominating Set (CDS). It can be thought as Virtual Backbone [1] of any infrastructure less network like sensor networks. Due to the limited energy of the sensor nodes, the constructed Virtual Backbone must be energy conscious and it should be constructed in a dynamic manner according to the energy level (much higher than predefined threshold E_th) of the sensor nodes. Our distributed algorithm formulates an Energy-Aware Virtual Backbone Tree (EAVBT), which is similar to energy aware CDS. Within a sensor node the dominant energy consumer is the radio transceiver. The ratios of energy for transmit, receive, idle and sleep are 14:10:8.3:1.3 [12]. Thus there is a massive difference between sleep mode and the rest of the modes. In our paper, we assume that members of EAVBT are in awake mode (idle, transmit, receiving) and rest of the nodes are in sleep mode in most of the time. Thus more the size of EAVBT more will be the energy consumption, which leads to reduce lifetime of the network. Hence to improve the lifespan of the network, we have to reduce the size of EAVBT as far as possible. Our main motto is to minimize the size of the EAVBT by means of distributed algorithm and also find a localized proposal to make the Virtual Backbone energy aware and continuously monitor and maintain EAVBT efficiently. The remaining paper is organized as follows. In section 1:- we state network model. In section 2:- We discuss related works in brief. In section3:- We describe our novel scheme in three segments (phase1, phase2, phase3) in details. In section 4:- The results of simulation are shown, and finally section 5:- We conclude and show the merits of our algorithm.

2. Network Model

The network can be modeled as unit disk graph [7], consists of one Sink Node and a number of sensor nodes. Here we assume that all the sensor nodes are static and energy limited. Each sensor node knows their energy level. We also assume that sink node is static and having a power generator. By means of Sink node packets, collected data, events can be communicated to the base station or control center. All instructions from base station must be routed through sink node to the nodes in sensor network. We further assume that sensor nodes have omnidirectional antennas with same transmission range i.e. all links between them are bidirectional. Each node has a unique ID from 1 to N.
3. Related Works

There are an enormous number of papers on the Virtual Backbone based routing [1][3][4]. We find two interesting and efficient algorithms, proposed in [1]. Their algorithms are excellent in terms of small size of the CDS but they did not address the issue of energy awareness and maintenance of Virtual Backbone. There are many papers [5][10][12] on the energy conscious Virtual Backbone but we found that either the size of the CDS is large and/or to maintain the Virtual Backbone [2][6] we have to restart the entire process, which leads to large amount of energy consumption. We modify algorithms in [1] to make the Virtual Backbone energy aware (phase-1) and explore the maintenance of it (phase-2), along with switch on/off of new nodes (phase-3) in the network.

4. Our Proposed Algorithm

Some important terminologies in connection with our algorithm are defined as follows:-
- **DEGREE**: Number of 1-hop neighbours of a node.
- **BLACK**: The member nodes (non-leaf) of the EAVBT form in phase 1.
- **GRAY**: The leaf of the formed EAVBT.
- **WHITE**: The node does not receive a control packet or message (initial state of all nodes except sink node).
- **BROWN**: A node which only receives GRAY message in the intermediate stages of phase1.
- **PARENT**: The BLACK upstream 1-hop neighbour.
- **CHILD**: If u is the parent of node v, then v is the child of u.
- **SISTER**: Two or more neighboring nodes, having same parent.
- **RANK**: The hop distance between a node and the sink node is define as rank of the node. It can be expressed as below:

\[
\text{Rank of a node} = \text{Rank of its parent node} + 1. \quad (1)
\]

Each node deals with the following parameters:
- **Pu**: Parent of node u, RKu: Rank of the node u, DEGu: Degree of the node u, Eth: Threshold energy of a node to become a BLACK node, Eu: Energy of node u, NATu: nature of node u (BLACK or GRAY). Every node u has a cost function which is defined as:

\[
\text{cost (u)} = k1/E_u + k2*RK_u + k3/DEGu. \quad (2)
\]

Where k1, k2, k3 are the tunable parameters. It represents the fitness or priority of each node to be a BLACK node.

These parameters are updated by the exchange of the following messages:
- **LEADER** (u, RKu): Sink node u transmits this message to its entire 1-hop neighbours.
- **BLACK** (u, Pu, RKu, Eu, DEGu): Node u transmits this message to all of its 1-hop neighbours when it becomes a BLACK node (non leaf).
- **GRAY** (u, Pu, RKu, Eu, DEGu): Node u transmits this message to all of its 1-hop neighbours when it becomes a GRAY node (leaf of EAVBT).
- **BROWN** (u, RKu, Eu, DEGu): Node u transmits this message to all of its 1-hop neighbours when it becomes a BROWN node.
- **UPDATE_PARENT** (u): Node u transmits this message to all of its 1-hop neighbours when its energy is reduced below threshold (Eth).
- **NEW_PARENT** (u, Pu, RKu, Eu): Node u transmits this message when it finds new parent in phase-2.
- **NEW_NEIGHBOUR** (u): Node u transmits this neighbour request when it switches on and wants to connect to the network.
- **WELCOME** (u, RKu, Eu, DEGu, NATu): Node u transmits this message when it receives NEW_NEIGHBOUR message.

A. Phase-1 (Construction)

**Step1**: At first the sink node starts the algorithm. Sink node u sets RKu=0 and broadcasts a message <LEADER (u, RKu)> to its 1-hop neighbours.

**Step2**: If u is in WHITE or BROWN state and receives message <LEADER (v, RKv)> form v, u sets Pu=v, RKu=RKv+1; or if <BLACK (v, Pu, RKv, Ev, DEGv)> from neighbour v and If Pv is neighbour of u, then u sets Pu=Pv, RKu=RKv, otherwise Pu=v, RKu=RKv+1; u will change itself to GRAY and broadcast message <GRAY(u, Pu, RKu, Eu, DEGu)>

**Step3**: If u is in WHITE state and receives message <GRAY (v, Pu, RKv, Ev, DEGv)> from neighbour v and Ev>Eth (predefined), u will move to BROWN state and broadcast message <BROWN (u, RKu, Eu, DEGu)> where Pu=v and RKu=RKv+1;

**Step4**: u is in BROWN state and receives <GRAY (v, Pu, RKu, Ev, DEGu)>, u sets Pu=v, RKu=RKv+1;

**Step5**: u is in BROWN state and there is no broadcasting in 1-hop neighbour of u for a time \(\zeta\) (predefined). If u has the smallest cost compared with all the brown nodes in 1-hop neighbour of u, u will mark itself as BLACK and broadcast <BLACK (u, Pu, RKu, Eu, DEGu)>.
Step 6:- If there is no such node having rank less than that of \( u \) as well as there is no \( \text{BLACK} \) node having same rank, then \( u \) selects the \( \text{GRAY} \) node having same rank (but not the sister of \( u \)) as its next parent. If there are two or more \( \text{GRAY} \) nodes are found, then it chooses the node having lowest cost. If cost comparison fails, then preference is given to the degree and then node ID.

Step 7:- If \( u \) finds that it has no neighbours except its parent, sisters and children (rank <= \( \text{RK}_u \)), then it waits for a predefined time (\( \zeta \), in the mean time if one of the sisters finds the new parent (in that case as the parent of the sister is changed they are no longer sister of each other) \( u \) follows step 2-6. Otherwise, transmits the message \(<\text{REINITIATE}_\text{PHASE-1}>\).

Step 8:- Child node \( m \) of \( u \) selects its next parent following the above steps, then modifies its rank (next rank= next parent rank+1) and its sister list. Then it transmits a message \(<\text{NEW}_\text{PARENT} (m, \text{P}_m, \text{RK}_m, \text{Em})>\). If the node \( v = \text{P}_m \) is \( \text{GRAY} \) in nature, it marks itself as \( \text{BLACK} \), transmits the message \(<\text{BLACK} (v, P_v, \text{RK}_v, E_v)>\).

Step 9:- If \( u \) receives a message \(<\text{REINITIATE}_\text{PHASE-1}>\) within \( \tau \) time from one of its children, it forwards this to the sink node, else it transmits to \( \text{GRAY} \). The sink node restarts phase-1 when it receives the message \(<\text{REINITIATE}_\text{PHASE-1}>\).

C. Phase-3

In this phase we focus on switching on/off a sensor node.

Step 1:- When a new node \( u \) enters into the network, it transmits a message \(<\text{NEW}_\text{NEIGHBOUR} (u)>\).

Step 2:- After receiving the message \(<\text{NEW}_\text{NEIGHBOUR} (v)>\) the recipient node \( u \) sends message \(<\text{WELCOME} (u, \text{RK}_u, \text{En}_u, \text{DEGu}, \text{NAT}_u)>\) to \( v \).

Step 3:- After receiving the message \(<\text{WELCOME} (v, \text{RK}_v, \text{Ev}, \text{DEG}_v, \text{NAT}_v)>\) from \( v \), node \( u \) selects parent \( v \) same as phase-2 (step 2 to 6 and step 8).

The three parameters \( k_1, k_2, k_3 \) in the cost function can be tuned to obtain EAVBT with minimum size while increasing the probability of a node having greater energy than its 1-hop neighbour to become a non leaf node. Each member in the EAVBT will forward packets to its parent if it receives packet from its children. Thus it eliminates the overhead of maintenance of routing table. Reverse direction communication is also possible by forwarding the packet to all of its children.
5. Simulation Results

We have implemented our algorithm in the platform of MATLAB (version: 6.5) to judge its efficiency. We assume that sensor nodes have omnidirectional antennas with same transmission range i.e. all links between them are bidirectional.

A pseudo environment is created for simulation, where N numbers of sensor nodes are randomly distributed in a field of 100mx100m. Unconnected Networks are discarded. We choose transmission range (R) 15 or 25 or 50 meters. Our algorithms are tested 500 times and average values are taken. We assume that energy of 10% of total number of nodes (N) reduce below $E_{th}$ arbitrarily. We set $k_1=100$, $k_2=5$, $k_3=10$ for our simulation. The averaged results are reported in following figures:-

In Figure-2:- x-axis corresponds to number of nodes (N) while y-axis corresponds to the average size of the generated EAVBT for two different transmission ranges $R=15m$ and $25m$ respectively.

In Figure-3: - x-axis corresponds to transmission range (R) while y-axis corresponds to the size of the generated EAVBT, for 3 different values of nodes (N=100,200&500).

Note that in Figure-3 the size of the EAVBT reduces considerably with increase in R.

In Figures 4&5:- x-axis corresponds to number of nodes while y-axis corresponds to the number of control packets for the transmission range 25m. Here one trace shows total number of control packets required for maintenance purpose while the other corresponds to the total number of control packets required for construction or reinitiating purpose, when energy of 10% of total number of nodes (N) reduces below $E_{th}$ at random.

In this regard if we consult existing algorithms [2][6] then we have to reinitiate the entire process i.e. reconstruction of the EAVBT from the very beginning. Hence an enormous amount of control packets are required which consumes an enormous amount of energy. But in case our novel strategy, the entire process is not started from the beginning, as a consequence of it we can save a massive amount of energy by exchanging lesser number of control packets compared to construction process starting from the very beginning. In this manner EAVBT is maintained in a localized way, as indicated in the Figure-4.

From the above figure, it is observed that there is more than 100 times improvement in the number of control packets in phase-2 as compared to phase-1.

In Figures 4&5:- x-axis corresponds to number of nodes while y-axis corresponds to the number of control packets for the transmission range 50m. Here one trace shows total number of control packets required for maintenance purpose while the other corresponds to the total number of control packets required for construction or reinitiating purpose, when energy of 10% of total number of nodes (N) reduces below $E_{th}$ at random.

In this regard if we consult existing algorithms [2][6] then we have to reinitiate the entire process i.e. reconstruction of the EAVBT from the very beginning. Hence an enormous amount of control packets are required which consumes an enormous amount of energy. But in case our novel strategy, the entire process is not started from the beginning, as a consequence of it we can save a massive amount of energy by exchanging lesser number of control packets compared to construction process starting from the very beginning. In this manner EAVBT is maintained in a localized way, as indicated in the Figure-4.

From the above figure, it is observed that there is more than 100 times improvement in the number of control packets in phase-2 as compared to phase-1.
In Figure-6:- we compare the performance of our algorithm with the E-Rule K in [4] (page12, fig.7 (d)) for R=20m. From this comparison we find that our algorithm outperforms E-Rule-K. It clearly indicates that the size of EAVBT is much smaller than E-Rule K in [4].

Figure6: Performance comparison with E-RuleK (R=20).

6. Conclusion

Energy Aware Virtual Backbone Tree based communication in wireless sensor network is found to be the most efficient and consistent technique to reduce communication overhead in comparison to pure flooding [1] mechanism. The novel distributed scheme (phase-1), described above, formulates an energy aware Virtual Backbone Tree. The algorithm select the nodes dynamically in such a manner that the member nodes of Virtual Backbone Tree always have adequate energy level (>Eth) to act as a node as well as a router in the network. We assign a cost function to each node and select those having lowest cost as the EAVBT member. As the cost function involve with energy, degree, and the rank of a node, the constructed EAVBT is not only energy aware but also size aware i.e. it makes size of EAVBT very small and the parameters k1, k2, k3 can be tuned to get a desire result. The algorithm also makes a child-parent relationship between the nodes which eliminates the overhead of maintaining routing tables. The maintenance algorithm (phase-2) exchange lesser number of control packets to broadcast as it works on localize information and saving a massive amount of energy as compared to reinitiating the whole process which improve the lifetime of the network. This is one of the important figures of merit of the performance of wireless sensor network. In addition to the energy efficiency, inclusion or exclusion of some nodes is allowed in the network. This novel proposal, fully graph based, although heuristic in nature always originates Energy Aware Virtual Backbone Tree of smaller size with energy levels (>Eth) and outperforms the scheme proposed by Wu, Dai in [4].

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8. References