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Power control based topology construction for the distributed wireless sensor networks

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Abstract

Wireless sensor network consists of large number of sensor nodes with limited battery power, which are randomly deployed over certain area for several applications. Due to limited energy resource of sensors, each of them should minimize the energy consumption to prolong the network lifetime. In this paper, a distributed algorithm for the multi-hop wireless sensor network is proposed to construct a novel energy efficient tree topology, without having location information of the nodes. Energy conservation of the nodes is accomplished by controlling transmission power of the nodes. Besides, maintenance of the network topology due to energy scarcity of the gateway nodes is also proposed in the protocol. Simulation results show that our distributed protocol can achieve energy conservation up to an optimum level similar to the centralized algorithm that we have considered and can extend the network lifetime as compared to other distributed algorithms without any power control.

Keywords: Wireless sensor network; Distributed algorithm; Power control; Topology construction

1. Introduction

Recent advances in hardware and software for the wireless network technologies have enabled the development of small sized, low-power, low-cost and multi-functional sensor nodes [1], which consist of sensing, data processing and wireless communicating components. These nodes are operated with very low powered batteries and deployed hundreds to thousands in the wireless sensor network (WSN). In wireless sensor network, signal processing, communication activities using higher transmission power and forwarding of similar data packets along the multi-hop paths are main consumers of sensor energy. Besides, replenishing energy by replacing and recharging batteries on hundreds of nodes in most of the sensor network applications, particularly in harsh terrains is very difficult and sometimes infeasible too. Hence, energy conservation [2–4] of the sensor nodes is a critical issue in WSN, as the network lifetime totally depends on the durability of the battery.

Sensor nodes are generally self organized to build the wireless sensor network, monitor the activities of the target and report the event or information to the sink or the base station (BS) in a multi-hop fashion. There are four main reporting models of the sensor network: event driven, query driven, periodical and mixed reporting. In event driven model, nodes report the sink, while sensing some events such as fire or flood alarm. In periodical reporting model, nodes collect the sensed data and may aggregate the required information into a set and then send them to the upstream periodically. The method of combining data is called data fusion [5–8], which reduces the amount of transmitted data. Some of the examples of such applications may be cited here, like the reporting of temperature or humidity readings of a locality. So, collection of sensed data, fusing similar data to a single packet, route them in a multi-hop environment to the sink and thereby to save

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energy are also important research issues in sensor network.

In [9], the power consumption comparison of each unit of sensor node is analyzed and it is observed that the energy consumption of the received power and idle state are almost same and the power consumption of CPU is very low. In [10], the authors propose the transmission power control in MAC protocols for wireless sensor network to assess the ideal transmission power by the nodes through node interaction and signal attenuation. The proposed algorithm calculates the ideal transmission power by repeated refinements and stores the current ideal transmission power for each neighboring nodes. In [11], authors present a two-level strategy for topology control in wireless sensor networks, which integrates the active subnetwork and short hop methods to achieve the energy saving. The problem of topology control in a network of heterogeneous wireless devices with different maximum transmission ranges, where asymmetric wireless links are not uncommon, is analyzed in [12]. Since, nodes are heterogeneous, they have different maximum transmission power and radio ranges, which requires omni-directional antenna with adjustable transmission power. Taking a set of active nodes and transmission ranges of the nodes, authors in [13] propose the minimum power configuration approach to minimize the total power consumption of WSN.

In [14], authors have proposed an analysis of the routing protocol based on the variable transmission range scheme. From their analysis, it is observed that the variable transmission range scheme can improve the overall network performance. The LEACH [15] based algorithm let some nodes to be the cluster leader and uses the higher transmission power to help the neighbor transmitting data to the BS. However, LEACH needs the global knowledge of the sensor network and assumes each node in the radio proximity of the BS. So, it may not be suitable in multi-hop sensor networks. In [16], two localized topology control algorithms for the heterogeneous wireless multi-hop networks with non-uniform transmission ranges are proposed. Though the protocols preserve network connectivity and talk how to control the topology, it does not talk about the construction of network topology and the energy consumption issues for higher density of nodes such as WSN. Span [17] is a power saving technique for multi-hop ad hoc wireless networks, which reduces energy consumption without significantly diminishing the capacity or connectivity of the network. It is a distributed, randomized algorithm to turn off and on the battery in order to save power to the maximum. But, it uses fixed transmission power range and the algorithm is applicable for the low density wireless nodes such as IEEE 802.11 networks.

In [18], the authors present a centralized greedy algorithm to construct an optimized topology for a static wireless network. According to this algorithm, initially each node has its own component. Then, it works interactively by merging the connected components until there is just one. After all components are connected, a post-processing removes the loop and optimizes the power consumption of the network. Although this algorithm [18] is meant for an optimized topology of wireless network, it is a centralized one and cannot change the transmission power dynamically. The distributed algorithms for the transmission power control in WSN is proposed in [19]. They assign an arbitrarily chosen transmission power level to all sensor nodes, which may split the network. Also, they propose the global solution with diverse transmission power algorithm that creates a connected network and set different transmission ranges for all the nodes, even if the topology construction is over. So, in their work the energy consumption of the nodes may be more, as the nodes in WSN are close to each other.

In WSN, communication is the main factor of the energy consumption [20]. However, transmission power adjustment to control the topology can extend the network lifetime and enhance the capability of the sensor network. Moreover, without controlling the transmission power level and always using a fixed higher power level for all nodes of the network will make the nodes die quickly and minimize the network life time. Since, the collected sensed data may contain some important information as required by the sink, providing a connected topology for the multi-hop network is highly essential for the wireless sensor network. Hence, in our work we propose how to control the transmission power level of each nodes of the network to save energy. We propose a distributed algorithm that adjusts the transmission power levels of the nodes dynamically and constructs a single tree topology with an intermediate power level between the minimum and maximum, among different group of nodes to achieve a connected network. Our algorithm works in a multi-hop wireless sensor network without taking location information of the nodes and constructs the connected topology distributively.

The rest of the paper is organized as follows. System model of our protocol is presented in Section 2. Our distributed power control protocol is described in Section 3. Performance analysis and simulation results are presented in Section 4 and conclusion is drawn in Section 5 of the paper.

2. System model

Let us consider a multi-hop, homogeneous wireless sensor network, in which sensor nodes are randomly and densely deployed over certain geographical area such that small connectivity holes exist among different group of nodes, as shown in Fig. 1. It is also assumed that the sink is within communication range of at least one node of the network. The connectivity holes in the network may occur due to small physical gaps among different group of nodes at the time of deployment or due to gap among the nodes of the same region, as they are unable to be connected with minimum transmission power level ($P_{\min}$). However, initially all nodes either from the same or different groups

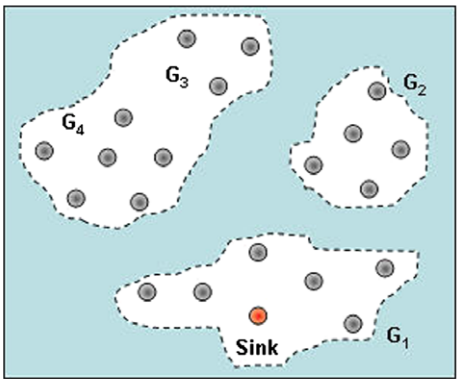

Fig. 1. Randomly deployed sensor nodes with connectivity holes among different group of nodes.

use a fixed transmission power level for communication and form a connected network without any power control. This fixed transmission power level could be assumed as the maximum (P_{max}) or in between the minimum and maximum power levels. As per our experimental results performed using Mica mote [21] with RF frequency 866 MHz and given in Table 1, 0 is considered as the minimum (P_{min}) and 3 as the maximum (P_{max}) transmission power level for communicating among nodes and we consider this value throughout our paper. Before proceeding to the next section of the paper, we define few technical terms that are used in our protocol.

2.1. Definitions

- ***Upstream and Downstream Groups***: Let $\{G_1, G_2, G_3, \ldots\}$ be the set of group of nodes distributed over certain area. If $\exists$ two groups G_i and G_j, for $i \neq j$, such that a control packet is forwarded from any node of G_i to G_j, then G_i is known as the *upstream group* with respect to G_j and G_j is the *downstream group* with respect to G_i.

For example, in Fig. 1, group G_1 that contains the sink node is considered as the upstream group with respect to the groups G_2, G_3 and G_4, as the control packet is initially broadcast from the group containing the sink to other groups of the network. G_2, G_3 and G_4 are the downstream groups with respect to G_1. Similarly, G_2 can be an upstream group for the groups G_3 and G_4, if control packets are broadcast from G_2 to those groups and in that case, G_3 and G_4 are treated as the downstream groups for G_2.

Table 1
Energy consumption for different power levels and corresponding communication distances, obtained from our experimental result

Power levels	0	1	2	3
Output power (dBm)	−13	−7	−1	5
Range (m)	2.1 ± 0.2	3.4 ± 0.2	5.9 ± 0.2	10.2 ± 0.2
Current consumption (mA)	9.5	10.8	15.8	25.4

- ***Local Hop Counts (LHC)***: It is a counter, which represents the number of hops that a control packet traverses locally within a group, when it is forwarded from one node to other.

The value of LHC of a control packet is initialized to 0 and incremented by 1 for each subsequent hopping of the packet within the same group. In general, $LHC = LHC + 1$. Within a group, if node A forwards a packet to B, and then B forwards the same packet to C, value of LHC in the control packet of $A = 0$, $B = 1$ and $C = 2$.

- ***Group Hop Counts (GHC)***: It is a counter, which represents the number of hops that a control packet passes, when it is transmitted from one group to other. The value of GHC is unique for all nodes of a particular group and it is incremented by 1, if the packet is transmitted from one group to other. Value of GHC is initialized to 0 and in general $GHC = GHC + 1$, for the subsequent hopping of the packet from one group to other.

Mathematically, let $G = \{g_1, g_2, \ldots, g_n\}$ be the set of n sensor nodes in a group and $\overline{G} = \{g_1, g_2, \ldots, g_m\}$ be the set of m sensor nodes in another group, for same or different value of m and n. If value of $GHC = p$, $\forall g_i \in G$, then $\forall g_j \in \overline{G}$, value of $GHC = q$, where $p \neq q$, as G and $\overline{G}$ are different group of nodes. In our protocol, since sink node initiates the construction phase, which is in G_1, value of GHC for all nodes of G_1 in Fig. 2, is 0 and if the packet is forwarded from G_1 to any other groups like G_2 or G_4, value of GHC in the packet is increment by 1. Hence, value of $GHC = 1$, for G_2 or G_4.

- ***Parent Gateway ID (PGID)***: The node that leads all nodes of a group to connect with a node of an upstream group is known as the *Parent Gateway* and its ID is termed as *PGID*. In each group of nodes, there exists only one Parent Gateway.

Mathematically, let $G = \{g_1, g_2, \ldots, g_n\}$ be the set of n sensor nodes in a group G, and $\exists$ a node $g_j \in G$, such that

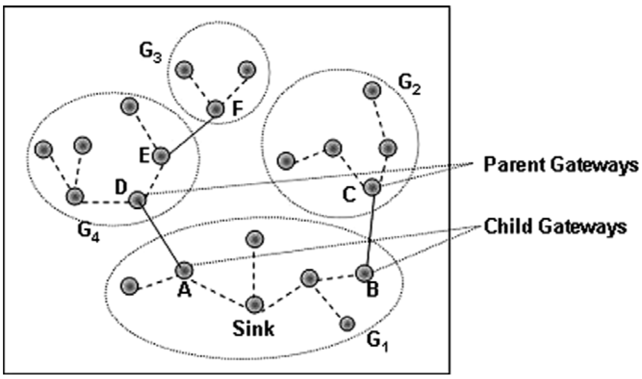

Fig. 2. Parent and child gateways of different group of nodes.

g_j is the leader of the group G, which can be connected to an upstream group. If L_{id}, is the ID of g_j, for $1 \leqslant j \leqslant n$, then L_{id} is the *PGID* of g_j. In Fig. 2, nodes C and D are the parent gateways for the groups G_2 and G_4, respectively. It is to be noted that sink is always the parent gateway for its group G_1.

- ***Child Gateway***: The node that connects to the parent gateway of a downstream group is known as the *Child Gateway*. In a group, there exists at least one child gateway. In certain cases, if a group contains only one node, that single node is treated as both parent and child gateway for that group.

In Fig. 2, nodes A and B of group G_1 are the child gateways of nodes D and C, respectively.

- ***Node Energy Level (NEL)***: The current energy level of a node is called *NEL*. For example, at the time of broadcasting a control packet, if energy level of a node is x units, *NEL* is assigned as x units in the control packet.
- ***Parent Gateway Power Level (PGPL)***: The transmission power level of the parent gateway of any group with which it can be connected with the child gateway of an upstream group is known as *Parent Gateway Power Level* (*PGPL*). Since, sink is always the parent gateway in its group, its *PGPL* is assigned to 0. However, for the parent gateway of other groups, $P_{\min} < PGPL \leqslant P_{\max}$, which may have value between 1 and 3, as per our assumption.
- ***Source ID (SID)***: If ***A*** and ***B*** are two different sensor nodes of the same or different groups such that ***A*** sends packet to ***B***, ***A*** is the source for ***B*** and ID of node ***A*** is the *Source* ID (*SID*).

3. The distributed power control protocol

In this section we present our power control based topology construction protocol, which constructs the topology dynamically. We assume that each node in the network has a unique ID and each of them knows its one-hop neighbor's ID prior to the construction of the topology. As per the system model of our protocol, since connectivity holes exist among each group of nodes, we assume that the network may be disconnected, if they use low transmission power level between one group of nodes with another and can consume more energy, if they use maximum transmission power level for communication. Moreover, in our assumption the transmission power level for all nodes in the network after deployment could be maximum or in between minimum and maximum. So, in our protocol, a tree topology is constructed among each group of nodes using minimum transmission power level ($P_{\min} = 0$ here) and a connected tree topology of the whole network is formed among different group of nodes using an effective power level (P_{T_x}), where $(P_{\min} = 0) < P_{T_x} \leqslant (P_{\max} = 3)$. The different phases of this distributed protocol are described as follows.

3.1. Construction phase

As soon as the nodes are deployed on the network, the sink initiates the construction phase by broadcasting a construct packet with minimum transmission power ($P_{\min} = 0$) to get connected with its immediate neighbors, as shown in Fig. 4(a). The format of the construct packet is shown in Fig. 3 and the parameters of the packet are initialized as: *SID* = Sink's ID, *PGID* = Sink's ID, *NEL* = Sink's power level, *LHC* = 0, *GHC* = 0, *PGPL* = 0. Since, sink node generally receives the data, its *PGPL* is assigned to 0, which is different for other parent gateways of the network. Upon receiving the construct packet, the neighbors of the sink within its minimum transmission power range ($P_{\min} = 0$), scan all parameters of the packet. They wait for the random time W_i, as defined in Eq. (1), and get connected with the sink. Let N_i, be the number of neighbors of ith node, out of N nodes in the network. Upon receiving a construct packet, the waiting time of the ith node can be considered as:

$$W_i = N_i + \alpha_i, \quad \forall i = 1, 2, 3, \ldots, N, \tag{1}$$

where α_i is a small random number compatible with CSMA-CA mechanism [22]. Then, each of them rebroadcasts the construct packet using the same minimum power level $P_{\min} = 0$ to their neighbors with necessary increments to the parameters of the construct packet and waits for time T_i units, as defined in Eq. (2).

$$T_i = E_i \beta_i, \quad \forall i = 1, 2, 3, \ldots, N, \tag{2}$$

where E_i is the current energy level of ith node and β_i is a very small random number such that $0.00001 \leqslant \beta_i \leqslant 0.0001$.

In order to avoid the packet collision among group of nodes in a dense network, we propose that the sink also waits for T_i units after broadcasting the construct packet and then goes to the information phase, as described in Section 3.2. It is to be noted that sink must be within at least one of the sensor node's minimum or maximum transmission power range. However, if the sink does not find any neighbor with $P_{\min} = 0$, it goes to the information phase to construct the link with its neighbors, after the waiting time T_i has elapsed (Tables 2 and 3).

Upon receiving the construct packets, the nodes scan all parameters in it and consider the node having least *LHC* as its source. The receiver nodes wait for W_i units, get connected with its source and then follow the same procedure, as described above. This process continues till a node does not receive any construct packet further and the first tree

Header	SID	PGID	NEL	LHC	GHC	PGPL

Fig. 3. Format of the construct packet.

Table 2
Construction phase algorithm for the sink and any node of the network

ALGORITHM 1: Construction Phase

For the Sink:
1. Initialize: Parameters and Local Hop Count (*LHC*)=0;
2. Set: Transmission power $P_{\min}$=0;
3. Broadcast the *Construct* packet;
4. Wait for T_i units;
5. Go to *Information Phase*;

For any node(i):
1. **If:** (Receives *Construct* packet)
2. {
3. Waits for W_i units;
4. Scan *LHC* of each received packets;
5. Get connected with the sender whose *LHC* has least value;
6. Set: $P_{\min}$=0;
7. Increment: *LHC* by 1 in the *Construct* packet;
8. Broadcast the *Construct* packet;
9. Wait for T_i units;
10. Go to *Information Phase*;
11. }
12. **Else:** Wait for $T = (W_i + T_i)$ units;
13. Go to *Maintenance Phase*, as described in Section 3.3.1 (C).

Table 3
Information phase algorithm for both Sender and Receiver

ALGORITHM 2: Information Phase

For any Sender(i):
1. **If**: (Receives *Construct* packet)
2. {
3. Copy value of *PGID* and *GHC* from the *Construct* packet;
4. Increment: Value of *GHC* by 1;
5. Initialize: All parameters of the *Inform* packet;
6. Set: Transmission power $P_{\max} = 3$;
7. Broadcast the *Inform* packet;
8. }
9. **Else**: Go to *Maintenance Phase*, as described in Section 3.3.1 (C);

For any Receiver(j):
1. **If:** (Receives *Inform* packet)
2. {
3. Wait for random time compatible to CSMA-CA mechanism;
4. Estimate physical distance between itself and each senders;
5. Estimate effective transmission power ($P_{T_x}(ij)$) between the closest sender and itself;
6. Set: Value of $P_{T_x}(ij)$ as *PGPL* in the *Construct* packet;
7. Copy value of *GHC* from the *Inform* packet to the respective field of the *Construct* packet;
8. Initialize: *PGID* as its own ID;
9. Go to *Construction Phase*;
10. }
11. **Else:** Go to *Maintenance Phase*, as described in Section 3.3.1 (C).

topology is constructed among the nodes of a group, as shown in Fig. 4(b) with sink as the root and other nodes within minimum transmission power level to it as the children of the sink. Since, we assume that there are connectivity holes among different group of nodes or some nodes are unable to construct link using $P_{\min}$, the construction phase is terminated after a finite interval of time. The next group of tree topology is formed after the information phase is executed. It is to be noted that the construct packet is always transmitted using minimum transmission power level and each time *LHC* is incremented by 1, when it hops from one node to another. In a group, it could be possible that some nodes might have received the same construct packets from other neighbors, too. Then, how a node decides its own source node? We have discussed this part of the problem in the maintenance phase, as described in Section 3.3.1 (A).

3.2. Information phase

The purpose of this phase is to construct a distributed tree topology in the whole network, using most effective power level among different group of nodes. It is accomplished by broadcasting the inform packets using maximum transmission power level ($P_{\max} = 3$). The format of the inform packet is shown in Fig. 5. It is to be noted that each group of nodes has a unique parent gateway. For example, the sink is the unique parent gateway in its group. So, prior to broadcasting the inform packet, a node copies the value of *PGID* to the inform packet from the construct packet, which may differentiate one construct packet from another. Besides, the value of *GHC* in the construct packet is incremented by 1, and then added to the respective field of the inform packet. Substituting necessary values in the inform packet, it is broadcast using $P_{\max} = 3$. Upon receiving the packet, a node knows from its header information that it is an inform packet and waits for a random time, which is compatible to the CSMA-CA mechanism [22]. Besides, each node estimates its physical distance using the following formula, from each of its senders.

$$P_r = \xi \times (d^{-\gamma}) \times P_t, \tag{3}$$

where P_t is the transmission power that a node uses to broadcast the inform packet. In our protocol, each node uses the transmission power (P_t) corresponding to $P_{\max} = 3$ to broadcast an inform packet, as given in Table 1. P_r is the received power by a node during the reception of an inform packet. The received power varies with $d^{-\gamma}$, where γ is the path loss (attenuation) factor that satisfies $2 \leqslant \gamma \leqslant 4$. Here, the proportionality constant ξ is assumed to be 1 for notational simplicity and the value of γ is typically taken to be 2 for the free space. It is to be noted that the set of sender nodes are considered as the upstream group, as per the definition given in Section 2. Upon receiving the inform packet, the physical distance d between the sender and receiver can be estimated using Eq. (3). The effective transmission power (P_{T_x}), by which it can communicate with the sender of the upstream group could be estimated as follows. Let,

$$S = \{S_i / \forall i = 1, 2, \ldots, m;\ \text{and } m < N\} \tag{4}$$

be the set of senders who broadcast inform packets. Considering N as the total number nodes in the network, let,

$$R = \{R_j /\ \forall j = 1, 2, \ldots, n;\ \text{and } n < N\} \tag{5}$$

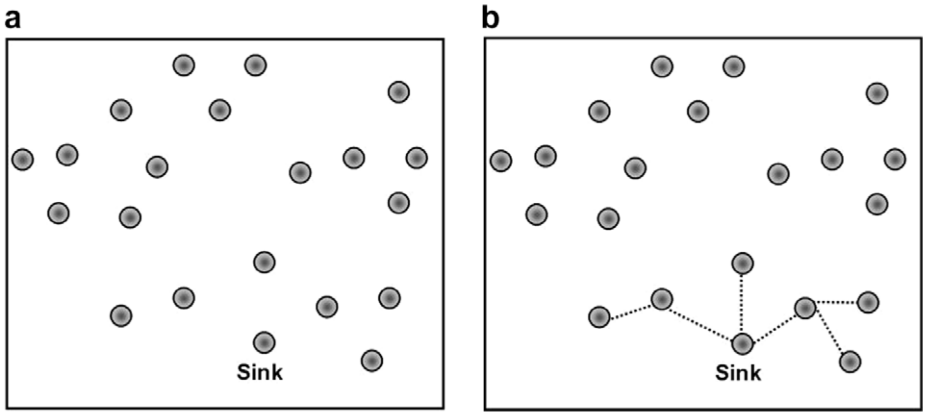

Fig. 4. (a) Randomly distributed sensor nodes over an area. (b) Construction of the first tree topology.

Header	SID	GHC	PGID

Fig. 5. Format of the inform packet.

be the set of nodes who receive the inform packets. After getting the inform packet and using Eq. (3), let $\{d_{ij}\}$ be the estimated distance between the sender S_i and receiver R_j, $\forall i = 1,2,\ldots,m$; and $\forall j = 1,2,\ldots n$. Let,

$$D_{ij} = \min(\{d_{ij}\}), \quad \text{for } i = 1,2,\ldots,m; \text{ and } \; j = 1,2,\ldots,n. \tag{6}$$

It is to be noted that a node of one group might have received several inform packets from the nodes of another one. So, each node uses Eq. (6) to find the shortest distance i.e. $\{D_{ij}\} = \min(\{d_{ij}\})$, among all nodes (senders) of a group with itself (receiver). After calculating the value of $\{D_{ij}\}$, a node again uses Eq. (3) to estimate the effective transmission power between the closest sender (i) and itself (j), which is denoted as $P_{T_x}(ij)$. As evidenced from our simulation results given in Fig. 12 of Section 4, we find that probability of using maximum transmission power level is very small for the high density network. So, it is worth to mention here that a few number of nodes may use maximum power ($P_{\max} = 3$) as the effective transmission power to communicate with a node of an upstream group. Accordingly, in our protocol, the effective power level $P_{T_x}(ij)$ may be 1 or 2. However, in the worst case, $P_{T_x}(ij) = 3$ may be used as the possible effective transmission power level.

After the random time has elapsed, the nodes who have already received the inform packets, broadcast the construct packets using the minimum transmission power level as described in the construction phase of Section 3.1. The effective power level with which a node can be connected with the upstream group is given in the *PGPL* field of the packet. The value of *GHC* is copied from the inform packet to the respective field of the construct packet. The nodes add their own ID to the *PGID* field, declaring itself as the parent gateway and other parameters like *SID*, *LHC*, *GHC* and *NEL* are also added to the respective fields of the construct packet according to the definitions.

Upon receiving multiple construct packets, a node has to first select the parent gateway for the group from the values of the *GHC*, *PGPL* and *NEL* based on the following rules.

i. If value of *GHC* in the received construct packets are different, the sender whose construct packet contains the least value of *GHC* is selected as the parent gateway.
ii. If value of *GHC* for all the packets are same, the sender having least value of *PGPL* is selected as the parent gateway.
iii. If value of *GHC* and *PGPL* for all the received packets are same, sender having the highest value of *NEL* is selected as the parent gateway.
iv. If value of *GHC*, *PGPL* and *NEL* are same for all of the construct packets, node having least value of *SID* is selected as the parent gateway.

It is to be noted that value of *SID* changes, when the construct packet hops from one node to other and is replaced by the ID of the sender, whereas replacement of *PGID* is based on parent gateway selection rules. During the selection of parent gateway, each node selects its own parent from the value of *LHC*. A sender, whose construct packet contains the least value of *LHC* is considered as the parent for the receiver and same procedure is followed to built the link, as described in the construction phase. Thus, another tree topology is constructed among the nodes within the minimum transmission power level with the parent gateway as the root and this process continues in a distributed manner.

The sender of the upstream group, which establishes connection with the parent gateway of the downstream group using the least effective power level is selected as the child gateway of that group. Based on this procedure, second and third tree topologies are constructed, as shown in Fig. 6(a). Besides, each node of the second topology goes to the information phase, then to the construction phase, and the process continues in a distributed manner and sev-

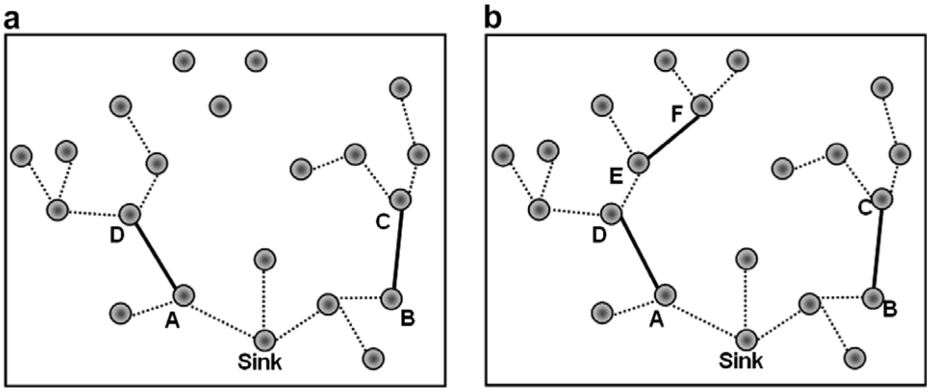

Fig. 6. (a) Formation of second tree topology. (b) Formation of other tree topologies.

eral tree topologies are constructed, as shown in Fig. 6(b). The dotted lines in Fig. 6(b) represent the link among the nodes with $P_{\min} = 0$ and the clear bold lines represent the link with effective power, i.e. P_{T_x}. Since, we consider a dense WSNs, a node of the downstream group might have received multiple inform packets from the nodes of the upstream groups. Then, how a node decides to accept or reject those packets? This part is explained in the maintenance phase of our protocol in Section 3.3.1 (B).

3.3. Maintenance phase

This phase is applicable to maintain the network before and after the construction of the topology. Accordingly, it is divided into pre-construction and post-construction maintenance phases, as described below.

3.3.1. Pre-construction maintenance phase

This phase is applied to maintain the network during the construction of the topology. Since, the nodes in WSNs are densely deployed, there is every possibility that a node might have received multiple packets and some packets might have lost due to collision. Hence, this part of the protocol describes how a node decides whether to accept or reject either a construct or an inform packet and recover from the collision.

A. Algorithm for accepting or rejecting the construct packets:

- Initially, receiving buffer of all nodes is empty.
- If a node receives multiple construct packets, it scans all parameters in it.
- If value of (*GHC*) for all the construct packets are same, packet having least value of (*LHC*) is accepted, else the receiver accepts the packet having least value of *GHC*.
- If value of *GHC* and *LHC* are same for all the construct packets, packet having least value of *PGPL* is accepted.
- If value of *GHC*, *LHC* and *PGPL* are same for all the construct packets, packet having highest value of *NEL* is accepted.
- Other than the above steps, the construct packet is rejected by the receiver.

In each of the above cases, ID of the sender (*SID*) is noted down by the receiver and then it is connected with the sender.

B. Algorithm for accepting or rejecting the inform packets:

- Initially, receiving buffer of all nodes is empty.
- If a node receives multiple inform packets with different values of (*GHC*), packet having least value of *GHC* is accepted.
- If value of *GHC* are same for all the inform packets, packet having ID of the sink in the *PGID* field is accepted.
- If value of *GHC* is same for all the inform packets without having the sink ID in the *PGID* field, packet having least value of *PGID* is accepted.
- If value of *GHC* and *PGID* are same for all the inform packets, packet having least value of *SID* is accepted.

In each of the above cases, the value of *GHC* and *PGID* are copied to the respective fields of the construct packet, which is later broadcast to the neighboring nodes with $P_{\min}$.

C. Post-collision recovery scheme:

This part of the protocol describes how a node recovers from the collision during the broadcast of either construct or inform packets. In certain situations, a node may not receive the construct packet due to collision or interference in the channel. For each node of the network, though we define different waiting time before broadcasting any type of packet to avoid collision, the construct packet may be lost due to some other reasons. For example, the nodes may not receive construct packets, if they are not within the minimum transmission range ($P_{\min} = 0$) of the sink. So, this scheme proposes how to overcome such problems, as described below.

C-1: Node does not receive construct packet, but receives the inform packet:

- Upon receiving an inform packet, a node executes the information phase and estimates the effective transmission power P_{T_x}, as described in Section 3.2.

- If P_{T_x} is equal to the minimum transmission power level, destination node is connected as a child to that source node, else, it considers the source as a parent gateway and executes the construction phase, as described in Section 3.1.
- If the node receives several inform packets, it executes the procedure to accept or reject the inform packet, as described in Section 3.3.1 (B).

C-2: Node receives construct packet, but does not receive any inform packet:

- If any node i does not receive any inform packet, it waits for $T = (W_i + T_i + \varepsilon)$ units, where ε is a small random number generated by each node.
- Starts its own searching procedure by broadcasting an inquiry packet, using the minimum transmission power level.
- Checks, if its one-hop neighbors have parent gateway.
- If so, it simply forms the link using $P_{\min}$ with that neighbor.
- Else, it uses $P_{\max}$ and executes the information phase, as described in Section 3.2.

C-3: Node neither receives a construct nor an inform packet:

- After the waiting time, as defined in the construction phase is elapsed, the node uses $P_{\min} = 0$ and executes the construction phase.
- If it finds a neighbor, it forms the link.
- Else, the node increases its transmission power level step by step such that $P_{\min} < P_{T_x} \leqslant P_{\max}$, until the node finds any response from other nodes.

3.3.2. Post-construction maintenance phase

In our protocol, we assume that the data collected by different sensors of a group are fused together using data aggregation algorithms [5–8] and routed through the parent gateway of that group to the child gateway of another one and finally to the sink. In this situation, there is possibility that the parent gateway may run out of energy. So, we propose here how to manage this situation and maintain the network connectivity. As soon as a gateway node runs out of energy, it broadcasts that information to its one-hop child nodes. Upon receiving that information, the one-hop child nodes of that group search a closest node from another group by increasing its transmission power level step by step such that $P_{\min} < P_{T_x} \leqslant P_{\max}$ and selects a node from a group, which becomes the source group for that node. Then, each one-hop neighbors unicast their current energy level (*NEL*), source group's parent gateway ID (*PGID*) and the required power level (*PGPL*) with which it can be connected with that group. After getting the response from its one-hop neighbors, the dying parent gateway implements the following steps to select the next gateway node.

- The dying parent gateway scans the *PGID* given in the response packet.
- If *PGID* is same as its own upstream group's parent gateway ID, it selects the same child node with whom it is currently connected as the next gateway; else it verifies the energy levels (*NEL*) of those one-hop child nodes.
- If two or more nodes have the same highest energy levels (*NEL*), one of them is randomly selected as the next parent gateway.
- Else, the child node having the highest energy level (*NEL*) is chosen as the next parent gateway.

Finally, the dying parent gateway broadcasts a packet containing ID of its child gateway, ID of the would be parent gateway and its own timeout to die to its one-hop neighbors. Upon receiving this packet, the one-hop child nodes can know whether it is selected as the next parent gateway or not. The node that is selected as the next parent gateway broadcasts a search packet using the higher transmission power level (power level 1, 2 or finally 3) to be connected with the child gateway of the dying parent gateway or the closest node selected by it from another group.

4. Performance evaluation

4.1. Simulation setup

In order to evaluate the impact of our transmission power control protocol of energy consumption and network lifetime, it is simulated using Tiny OS (TOSIM) [23]. In our simulation, variable number of nodes in different groups are randomly deployed over a squared area of 100 m × 100 m with small communication holes among different group of nodes so that at least one node of each group can transmit data using either $P_{T_x} = 3$ or $P_{T_x} = 1$ or 2. The number of deployed nodes ranges from 400 to 1000. Under such deployment strategy, initially the tree topologies are formed among different group of nodes with minimum transmission power level $(P_{T_x}) = 0$. Then, the probabilities of transmission power levels to connect the child gateway of one group with the parent gateway of another are estimated. In order to get the most probable result, we run our simulation for 80 rounds. However, it is observed that the probability of using maximum transmission power level i.e. $P_{\max} = 3$ is very small in our protocol, as shown in Fig. 12. Hence, to study other performance metrics of our protocol, we have mainly used the power levels 1 and 2 and occasionally the power level 3 to connect the tree topology of one group with other. Throughout our simulation, all nodes use the CSMA-CA mechanism for accessing the channel. After every packet is sent or received, the node waits for a small amount of time, which is susceptible to the hidden and exposed terminal problems. Initially the simulations are run to find the possible number of neighbors of each node. A fixed amount of 50 J reserved energy is considered for each node of the network. The data rate for routing the control packet is kept as 250 kbps and cost of energy consumption due to this is considered for the centralized and our distributed protocols. Based on different transmission power levels, energy consumption for all the sensor nodes is computed and the simulation is run for 30 different rounds to get an accurate measurement of the energy consumption and network lifetime.

4.2. Observations

4.2.1. Energy consumption

The most important performance metric of the distributed wireless sensor networks is the average energy consumption due to data transmission with different power levels. Since, the computational component is a small fraction as compared to the communication, energy consumption due to computation is not considered in our simulation. We have simulated the average energy consumption for different node numbers of the network for different power levels, as shown in Fig. 7. As for a typical wireless sensor network with time slotted MAC protocol [24], nodes are assigned time slots to wake up and several nodes are considered backups of each other with respect to traffic forwarding and maintaining the time synchronization. Based on this implementation strategy, it is found that the energy consumption of our protocol for the higher node densities, attains the optimal condition. Our protocol, even if being a distributed one, maintains the optimal energy condition similar to the centralized algorithm [18]. From Fig. 8, it is observed that the energy consumption of our protocol is almost same to that of the optimal centralized algorithm for higher node density and different node configurations. Since, energy consumption of the centralized algorithm [18] is optimal, we are delighted with our simulation results, as our protocol also maintains the same optimal condition for higher node densities of a distributed WSNs. To analyze the importance of our protocol in terms of energy consumption, we estimate the total energy consumption for different number of nodes considering with and without the transmission power control. As shown in Fig. 9, it is interesting to note that total energy consumption of our protocol is very small due to transmission power control as compared to the energy consumption without power control.

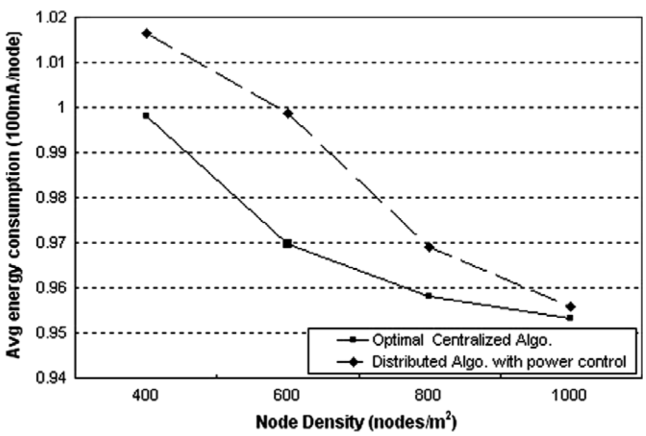

Fig. 7. Average energy consumption for different node densities with transmission power control.

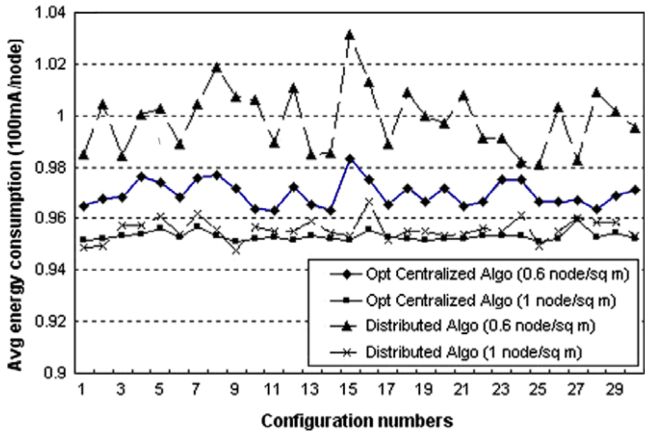

Fig. 8. Average energy consumption for different configurations with different node densities.

4.2.2. Network lifetime

Generally, network lifetime is defined as the time until the network no longer able to fulfill the tasks it is designed for. So, in our simulation, we define the network lifetime when the network is disconnected and packets can no longer be routed between any pair of group of nodes. Accordingly, the network lifetime of our protocol is analyzed for different node densities and configurations. Besides, we provide extensive comparative simulation studies on parameters those affect the lifetime of a network. The simulation result is also compared with the optimal centralized algorithm [18] and the distributed algorithms without power control [19]. Though, the centralized algorithm gives an optimal condition for the total energy consumption of the network, our protocol outperforms the centralized algorithm based on our definition of the network lifetime for higher number of nodes, as shown in Fig. 10. Besides, the network lifetime of our protocol is also much better than the lifetime of the distributed algorithm without any

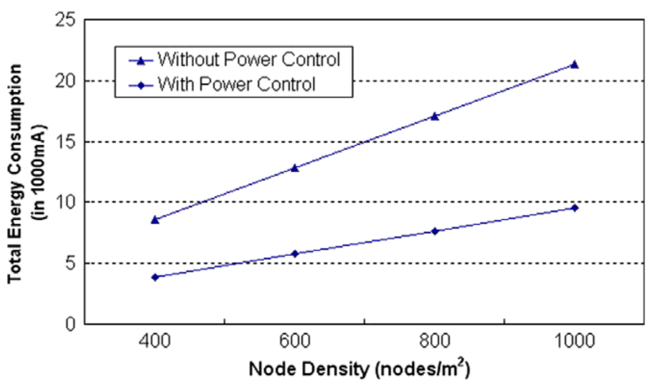

Fig. 9. Total energy consumption for different node densities with and without power control.

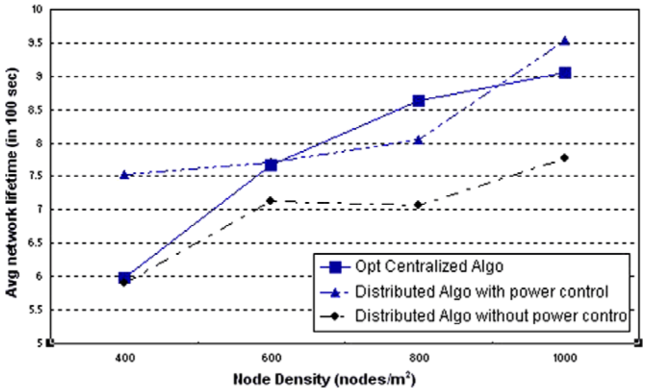

Fig. 10. Average network lifetime for different node numbers with and without power control.

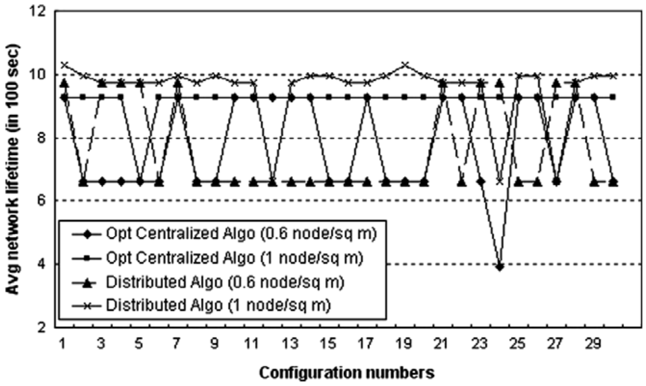

Fig. 11. Average network lifetime for different configurations with different node densities.

power control [19]. From Fig. 11, we got the mostly expected results, in which network life time of our protocol is higher than the centralized algorithm for higher number of nodes with different configurations. Since network lifetime of the sensor nodes is a critical issue in wireless sensor network, we think our protocol is the best solution of its kind.

4.2.3. Topology construction

We have analyzed the construction of tree topologies taking 100 and 200 sensor nodes deployed over

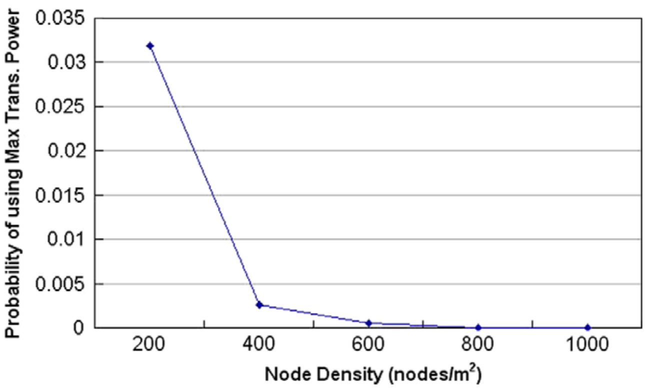

Fig. 12. Probability of using maximum transmission power for various node numbers.

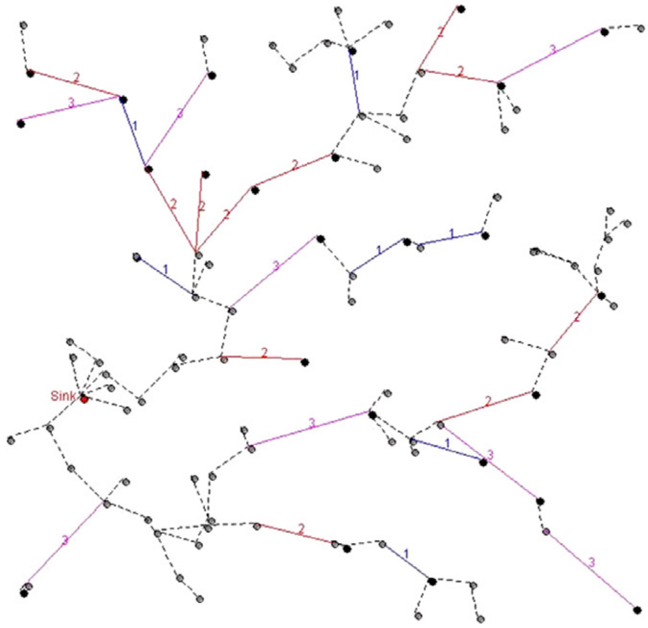

Fig. 13. Configuration of 100 nodes with variable transmission power deployed over 100 m × 100 m area.

100 m × 100 m geographical area, as shown in Fig. 13 and Fig. 14, respectively. The topology construction is initiated from the sink and based on the algorithms of our protocol. The tree topologies are drawn on the applet using Java programming (JDK-1.4), for different power levels and without taking location information of the nodes.

The dark circles represent the parent gateway and the dotted line marks the transmission power levels between the parent gateway of one group with the child gateways of another. From this distributed topology, it is observed that the probability of using maximum transmission power level

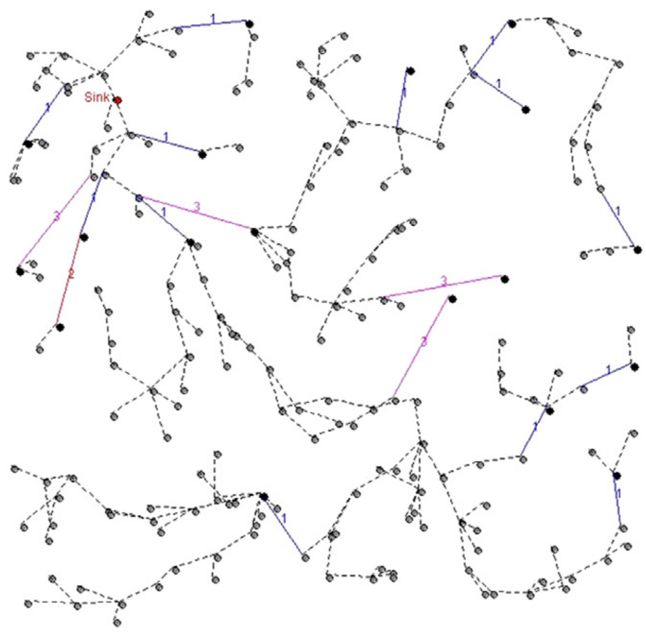

Fig. 14. Configuration of 200 nodes with variable transmission power deployed over 100 m × 100 m area.

between the parent and the child gateway is very small, which complies with our simulation results, as drawn in Fig. 12.

5. Conclusion

In this paper, we propose a distributed transmission power control protocol for the wireless sensor network to achieve energy conservation of the nodes. We construct a connected tree topology without taking location information of the nodes. Our protocol uses the distributed algorithm to build the power saving tree topologies without taking location information of the nodes and provides a simple way to maintain the whole network by changing the transmission power, if the gateway node of any group runs out of energy. It is observed that our algorithm, being a distributed one, maintains the optimality of energy conservation similar to that of centralized one that we have considered. Besides, the network lifetime of our protocol outperforms the distributed algorithm without any power control and better than the centralized algorithm for higher node density. Therefore, we can state that our protocol can be useful for the wireless sensor networks in environmental monitoring applications such as collecting temperature, pressure and humidity of a locality.

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