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A Distributed Approach to Construct Hierarchical Structure for Routing with Balanced Energy Consumption in WSNs

Subhasis Dash*, Satya Sundar Mallick*, R. C. Hansdah† and Amulya Ratna Swain*
*School of Computer Engineering
KIIT University, Bhubaneswar, India
Email: {subhasisbbsr, mallick.satyasundar, swainamulya}@gmail.com
†Department of Computer Science and Automation
Indian Institute of Science, Bangalore, India
Email: hansdah@csa.iisc.ernet.in

***Abstract*—A wireless sensor network (WSN) consists of a large number of sensor nodes distributed over a geographical area. A basic problem of WSNs is to reduce their energy consumption in order to enhance their life time. So, minimizing energy consumption becomes the most critical factor in the design of almost all WSN protocols. For end-to-end data transmission, media access control (MAC) and routing protocols play an important role in WSNs. Besides, these protocols mostly use the hierarchical structure for end-to-end reliable data delivery. The time and energy required to generate a hierarchical structure in a sequential manner is always high. So, in order to mitigate the above challenges, in this paper, we propose a distributed algorithm to generate the hierarchical structure where each node has two parent nodes except the root node. The intermediate nodes of the generated tree remain awake as they are selected as parent node based on their energy level, and other nodes are to be kept in the sleep mode in order to conserve energy. The distributed tree structure is periodically reconstructed considering the remaining energy of each node with a view to balance energy consumption of nodes in the whole WSN. The proposed approach also considerably reduces the average energy consumption rate of each node as we are able to put more number of nodes in the sleep mode in a distributed manner as compared to the existing approaches. Simulation studies of the proposed approach have been carried out using Castalia simulator and its performance has been compared with the existing sequential approach.**

***Keywords*-Wireless sensor network, Energy efficiency, Routing, MAC.**

I. Introduction

Wireless sensor networks (WSNs) have wide range of practical applications, especially in civil and military environment [1]. They are usually used for periodic monitoring of environment or detection of random events. A wireless sensor network (WSN) is made up of hundreds or thousands of sensor nodes with various sensing devices to observe events in the real world over a geographical area. A sensor node consists of different types of sensors, processing unit, memory, and power supply unit. Each node is associated with limited power supply. Hence, during designing any protocols for WSNs, reducing energy consumption is the major concern. Individual sensors powered using battery can run for only 100-120 hours [2] when AAA batteries are used and nodes work in active mode. In addition, they might be deployed anywhere, i.e, remote, unattended, or hostile environments. In these situations, it is quite difficult and may not be possible to recharge or replace the battery in the sensor nodes. Therefore, prolonging the life time of WSNs is an important challenge. In spite of the above constraints in WSNs, the data transmission from any source to sink must be performed with high throughput.

In order to prolong the life time of sensor nodes along with maintaining data transmission with high throughput, both MAC as well as the routing protocol play an important role in WSNs. There are many existing MAC and routing protocols [3], [4], [5], [6], [7], [8] which have already been designed for WSNs. Among all these protocols, there are certain MAC protocols such as SMAC [5], RMAC [3], HEMAC [4], and token based MAC protocols [9], [10], [11] which mostly focus on how to mitigate energy consumption during transmission and ideal listening, and how to prevent collision of data packets during transmission. These MAC protocols are basically designed on top of a tree structure which is usually constructed in a centralized fashion. The major drawback of the centralized approach for designing these tree structures is that more energy is consumed during the establishment of the tree structure. In addition, the time required to establish such tree structures is also quite high, which directly or indirectly impacts on the overall network life time. Nevertheless, the main advantage of tree structure is that the connectivity among the whole network is easily maintained through the nodes participating in the tree structure.

In order to overcome the drawbacks of constructing the tree in a centralize manner, we propose a distributed algorithm to build the tree structure depending on their energy levels in a distributed manner. As compared to the sequential approach, the proposed distributed approach mitigates the energy wastage issue by reducing the number of nodes get selected as internal node as well as increases the end-to-end data delivery. The distributed approach ensures that

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the functionalities of individual sensor nodes can be used parallely as well as independently while constructing the tree. The basic communication in the network depends upon the construction of the tree structure in a periodic manner. In order to conserve energy in WSNs, we also incorporate the existing sleep scheduling scheme proposed in [12].

The rest of the paper is organized as follows. In section II, we give a survey of related works, and motivation for our proposed work. The detail about the proposed algorithm is described in section III. Performance evaluation of the proposed protocol and its comparisons with existing protocols are given in section IV. Section V concludes the paper.

II. Related Works

MAC and routing protocols in WSNs have two major aspects, viz., network structure and protocol operation. Network structure is basically of two types, viz. (i) flat structure and (ii) hierarchical structure. In flat structure, all distinct nodes do not play a distinct role. Evolution of clock synchronization protocols based on flat structure has been in the form of flooding, directed diffusion, etc [13]. The hierarchical structure is intended to improve the network in terms of scalability and efficiency. In this kind of structure, nodes have different roles as per their position in the network. There are many existing MAC or routing protocols [3], [4], [5], [6], [7], [8] which are based on the hierarchical structure. A few of these protocols are discussed in the following.

Bulut and Korpeoglu have proposed a dynamic sleep scheduling algorithm [14] in which a node is put into sleep mode or active mode depending upon its sensing area. Here, the sink node generates a tree structure by using the breadth first search. The configured topology is prepared for each re-configuration period, which depends upon the remaining energy of the sensor nodes. During each period, the information collected by the active nodes should be sent to the sink node. As sensor nodes are randomly deployed in a region, and the position of nodes is known using GPS, by periodically running the dynamic sleep scheduling algorithm at sink node, one can decide whether a node should be put to sleep or active mode. But, in this approach, when a node dies out in the middle of time period, the routing structure would get disturbed and the area remains un-covered. As an alternative solution, one can go for re-configuration as soon as possible but this would again involve high overhead.

Shah and Rabaey have proposed an energy aware routing protocol [15], in which the protocol typically tries to find the minimum energy path to optimize energy consumption and long term network connectivity on top of a tree structure. The protocol ensures that connectivity in the network is maintained and the energy level of entire network should be nearly the same everywhere. Energy aware scheme proposed in the protocol maintains a set of lowest energy path and chooses different paths at different times based on their remaining energy, so that a network hole is not created in any path. To start data transmission, a node broadcasts a wake-up signal in the selected path. On receiving this message, the nodes to which this request signal is addressed become active. The protocol uses localized flooding to find out all paths from sources towards the sink with respective costs.

In the past, Ye et al. have proposed a minimum cost forwarding algorithm [16], which deals with minimal path cost from any node to the sink in a hierarchical structure. This protocol consists of two phases, viz. (i) setup and (ii) data transmission. Setup phase is used for setting up the associated cost for each node with the sink node. The second phase is basically associated with data transmission from the source to its neighbors along the forwarding path till the data packet reaches the sink node. The basic problem with this protocol is that it consumes large bandwidth; in return, there may be some chances of getting duplicate copy of data at the sink node.

Kim and Yoo have proposed a multi-path routing protocol [6] in which nodes in the network must be arranged in a hierarchy based on their remaining energy using depth first search. Here, any node can be selected as the leader node depending upon its remaining energy. This leader node is responsible for forwarding the data to the sink in the network. However, selecting a unique leader at every re-configuration of the tree structure to avoid network hole is really very time consuming.

Hong and Yang have proposed a multi-path routing algorithm [17] based on rumor which attempts to find a different path from source node to the sink on top of a tree structure as per the nodes' residual energy. This algorithm tries to distribute energy consumption over a large part of the network by selecting each time a unique path for data transmission. As per the algorithm, network lifetime can increase or decrease depending on the energy consumption in the path and hop count distance to the sink node.

Chakchouk et al. have proposed a routing technique [7] which utilizes both energy availability information and hop-by-hop distance from any node to the sink node in order to make energy aware routing decision. The proposed method uses the highest residual energy of different nodes to create a hierarchical structure. The protocol also effectively balances the overall energy consumption among the nodes to prolong the network lifetime. It aggregates the sensed data by eliminating redundant information in order to reduce energy consumption and network congestion.

Du et al. have proposed a routing-enhanced MAC Protocol [3] which considers the different routing information to achieve energy consumption on top of a tree topology. In this protocol, a control frame, called PION, travels across different level of hops and fixes the upcoming data packet delivery through that path. Each intermediate sensor node used for data transmission is in sleep mode initially and intelligently wakes up as soon as an event is detected. At the same time, only the nodes that relayed the PION can wake up during the sleep period to relay the data packet and it remains awake until the sleep period starts again.

In the recent past, Amulya et al. have proposed an energy aware routing protocol [8] using sleep scheduling in order to reduce energy consumption in WSNs. This protocol is designed based on a hierarchical structure, where internal nodes remain awake and leaf nodes are put to sleep mode. In order to balance energy consumption over the whole network, the tree structure is periodically reconstructed considering the remaining energy of each node. The algorithm always chooses the path with the highest remaining energy and also construct a fault tolerant tree to communicate data in spite of single node failure.

Subhasis et al. have proposed a reliable energy aware multi-token based MAC protocol [12] that not only extends the network life time but also maintains the network connectivity. Here, the proposed MAC protocol periodically reconstructs the tree structure integrating with random sleep scheduling in order to achieve balance energy consumption along with congestion less data transmission even if a node runs out of energy.

From the above, it is observed that there are many routing and MAC protocols in the existing literature, which are designed based on some hierarchical structure. If we further look into them, then we find that most of these hierarchical structures are designed in a sequential manner, which is not only time consuming but also increases energy consumption. Therefore, in this paper, we propose a distributed approach to build the hierarchical structure, which not only takes less time and energy but also provides both reliability as well as scalability. This hierarchical structure is always reconstructed in order to balance energy consumption over the whole network along with support for reliable network connectivity from any source to the sink node. The distributed tree structure can also tolerate at single node failure to avoid network hole by providing two parents for each internal node.

III. Our Approach

In this paper, we have proposed a distributed algorithm for constructing a tree structure. This structure would be suitable for developing only the MAC or routing protocols which are designed on top of any hierarchical structure. The proposed structure improves data reliability during data transfer from source to sink. In order to provide effective energy consumption for WSNs, the proposed approach allows a reduced number nodes to be selected with the highest remaining energy as internal nodes of the proposed tree structure which would participate for transmitting the data from any source to sink. In the proposed approach, we assume that the sensor nodes are uniformly deployed, and each sensor node has a unique ID and communication is symmetric and bidirectional with a limited number of resources. The proposed algorithm consists of the following four phases:

i. Level Discovery Phase,
ii. Energy Discovery Phase,
iii. Parent Discovery Phase, and
iv. Data Transmission Phase.

A. Level Discovery Phase

In this phase, we decide the level of each node depending upon their position from the sink. Here, we consider that the sink node has level 0. The nodes which are one hop away from the sink, have level one. Similarly, each node gets its level depending upon the number of hops it is far away from the sink node. In order to execute this phase, at the very beginning, the sink node is initialized with level zero and the other nodes are initialized with level ∞ (infinity). First, the sink node sends a level discovery message containing its level number to all its neighbors. Once a node receives this message from the sink, it sets its level to one. After modifying the level number, each node broadcasts their level discovery message with their own level number to their corresponding neighbors. The neighbors can set their level as per the level number that they have received through the level discovery message from the others. A node can update its level number provided the level number that it has received should be at least two less than its current level number. What it means is that if a node with level number 8 receives a level discovery message with level number 6, then it can change its level to 7. Although we claim that the proposed approach is distributed, this level discovery phase is completely sequential. Among all these four phases as mentioned above, this is the only phase, which is executed only once at the very beginning just after the deployment. All other phases are executed periodically which are completely executed in a distributed fashion. Since the first phase is executed only once in the whole lifetime of WSN, and the number of packet transmission is not so high, it would not affect a lot in energy consumption. Although this level discovery phase is executed only once, there is still a possibility of change of level number of each node even after the completion of the level discovery phase. The change in the level number of a node would happen when a node receives any packet from its neighbors in any other phases, which are executed periodically, and the level number that it receives is at least two less than its current level number.

B. Energy Discovery Phase

After level discovery phase gets over, each node discovers remaining energy of its neighbor by broadcasting a “energy discovery” packet that consists of the node ID, level number, and remaining energy. Based on the remaining energy information received from the neighbors, each node stores two neighbor nodes information from the same level and two more neighbor nodes information from its immediate lower level depending upon the maximum energy of its neighbors. For example, if a node is present in the n^{th} level, then it stores two neighbors having maximum remaining energy present in n^{th} level and two more neighbor nodes having maximum energy present in $(n-1)^{th}$ level. For any node in the network, the neighbor information that a node stores during this phase will be used for deciding the preferable parent for that particular node.

C. Parent Discovery Phase

Once the energy discovery phase gets over, each node describe itself to become active or inactive in the future. To become active, each node compares its remaining energy with the remaining energy of its neighbors present in the same level that it has stored during the energy discovery phase. If a node's remaining energy is higher than the remaining energy of its neighbors present in the same level, then the node declare itself as active. These active nodes are further considered as parent of some other nodes present in the network.

Once a node set itself to be active, it sends a "parent discovery" packet to its neighbors, which consists of its node ID and level number. After receiving parent discovery packet, a node decides its parents based on the neighbor information that it has already collected during the energy discovery phase, and the information that it has received through parent discovery packet. In this phase, each node stores two parents information, which it decides based on certain criteria.

Let N_i be a node present in level n. Each node N_i stores four neighbors information during the energy discovery phase.

Let B_1^S, B_2^S, B_1^U, and B_2^U be four neighbor nodes, where B_1^S and B_2^S are the two neighbors present in the n^{th} level, and B_1^U and B_2^U are two neighbors present in the lower level i.e. in $(n-1)^{th}$ level.

In addition to that node N_i stores two parent information, i.e. PARENT1 and PARENT2 which are initialized to -1 and the level number corresponding to both these parents, i.e. LEVEL1 and LEVEL2 are also set to -1.

The parent discovery packet has following parameters.
$PARENT\_DISCOVERT = (N_j, l)$, where N_j is the node which has sent the parent discovery packet and l is the level of node N_j.

Based on the above inputs, the parent discovery phase works as per the procedure given in Algorithm 1.

As per the description given in algorithm 1, each node sets its two parents. The parent nodes of a node can either be present in the same level where the node is present or in the immediate lower level. For example, if a node present in n^{th} level then its parents will be present either in n^{th} or in $(n-1)^{th}$ level. But, during this process, for selecting a parent, more preference is given to the node which is present in the lower level in the proposed hierarchy, so that the

```
Procedure PARENT_DISCOVERY_PHASE
begin
    if (PARENT1 = = -1) then
        PARENT1 = N_j ;
        LEVEL1 = l;
    else if (PARENT2 = = -1) then
        PARENT2 = N_j;
        LEVEL2 = l;
    else
        if (l == n-1) then
            if (PARENT1 ∉ {B_1^U, B_2^U}) then
                if ( N_j ∈ {B_1^U, B_2^U}) || LEVEL1 == n)
                then
                    PARENT1 = N_j ;
                    LEVEL1 = l;
                end
            else if (PARENT2 ∉ {B_1^U, B_2^U}) then
                if ( N_j ∈ {B_1^U, B_2^U}) || LEVEL2 == n)
                then
                    PARENT2 = N_j;
                    LEVEL2 = l;
                end
            end
        else if (l == n) then
            if (LEVEL1 == n && PARENT1 ∉ {B_1^S,
            B_2^S} && N_j ∈ {B_1^S, B_2^S}) then
                PARENT1 = N_j ;
                LEVEL1 = l;
            else if (LEVEL2 == n && PARENT2 ∉
            {B_1^S, B_2^S} && N_j ∈ {B_1^S, B_2^S} ) then
                PARENT2 = N_J;
                LEVEL2 = l;
            end
        end
    end
end
```

Algorithm 1: Algorithm for Parent discovery phase

number of intermediate node from source to sink will be reduced. Among all the parent discovery messages received from the lower level, a node gives first preference to the active nodes which are already present in the neighbor list maintained by the node during the energy discovery phase. After setting the parents from the immediate lower level, if at least one parent field is still left, then it will be filled with any one of the parent discovery message received from the same level. Among all the parent discovery message received from the same level, a node gives more preference to the active nodes which are already present in the neighbor list maintained by the node during the energy discovery phase.

Since the above proposed hierarchical structure is created periodically, all the nodes get active during the formation of this hierarchical structure. Once all the nodes set their parents, each node decides to become either active or inactive depending upon the information collected during the energy discovery phase. At the end of this phase, all the inactive nodes go to sleep state in order to conserve energy. However, these inactive nodes periodically sense the environment, send the sensed data to the sink, and again go back to sleep mode.

D. Data Transmission Phase

Once each node sets its parent during the parent discovery phase, each node may transmit the sensed data to the sink through some active nodes or intermediate nodes selected in the proposed hierarchy. since each node has two parents, at a time a node can choose any one of its parent to send its data to the sink. During the data transmission phase, choosing a parent node can be done in many ways. It can be done in an alternative manner as proposed in [8], or depending upon current highest remaining energy, etc. The selection of these strategies completely depends upon the higher layers requirement. The advantages of keeping two parents at each node is that there will be always multiple path from source to sink. In addition, another advantage of keeping multiple parent is that even if one parent node goes down, there is still some possibility of getting a path from source to the sink.

IV. Simulation Results

The performance study of the proposed protocol and its comparison with the existing protocol have been carried out using the Castalia simulator[18]. In this simulation study, we have used variable number of sensor nodes from 100 to 1000. The sensor nodes are randomly deployed with uniform distribution in the environment with a fixed density. For this simulation, different parameters such as transmission range, transmission rate, sensitivity, transmission power, etc. and its values are specified similar to the parameters given in CC2420 [19] data sheet and TelosB [20] data sheet. We have considered initial energy of each sensor node to be 2000 joules for two AA batteries as given in the Castalia simulator. Since the proposed protocol is executed periodically, we have set its time interval to 1000 seconds. During each time interval, the nodes in the WSN can sense the environment and send the sensed data to the sink using the proposed hierarchical structure.

Figure 1 shows the number of active nodes present in 100, 300, 500, and 1000 node WSNs in each round during the construction of hierarchical structure using our proposed distributed approach. This figure shows that the number of active nodes in each round corresponding to a each size of the network dose not vary much. This indicates that the proposed protocol behaves nicely not only in different rounds but also in different size WSNs.

Figure 2 gives the number of active nodes, sleep nodes, and dead nodes in a 500 node size WSN. In this case, dead nodes are those nodes which does not have energy to run further. As per this figure, it is clear that the nodes start dying nearly at the same time, i.e. at around 120^{th} round. Not even a single node becomes dead before 120^{th} round. Also the number of active nodes and sleep nodes are nearly fixed.

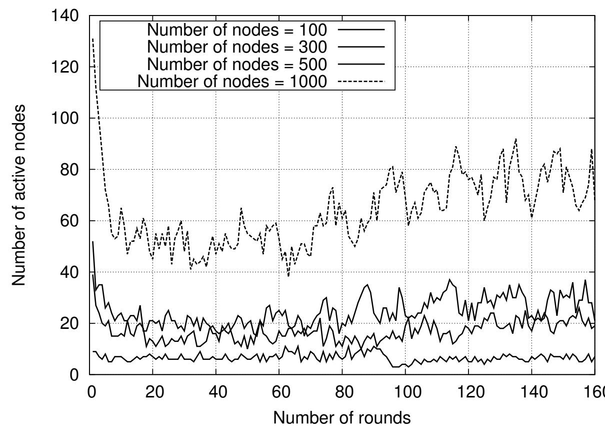

Figure 1. Number of active nodes in different size WSN

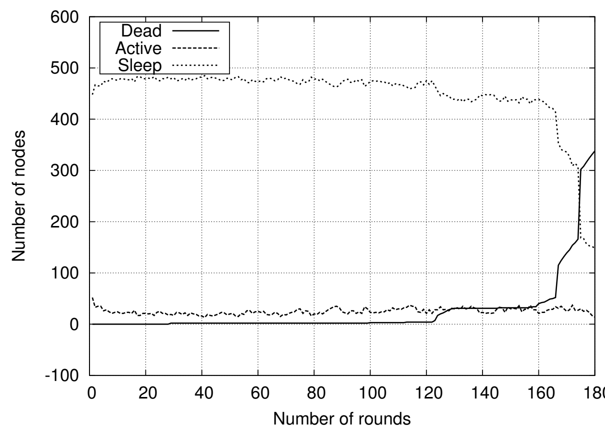

Figure 2. Number of active nodes, dead nodes, and sleep nodes in proposed distributed approach

With limited energy in WSNs, sleep scheduling is an important requirement for prolonging the network life time. Figure 3 gives understanding about the effect of sleep scheduling in WSN. From this particular performance study, we find that half of the total energy gets spent only in 16 number of rounds, which is nearly 16000 seconds, whereas with sleep scheduling only 5% of the total energy gets used during the same time period.

Figure 4 shows the number of active nodes in different size WSNs using the proposed distributed approach and sequential approach given in [8]. It is to be noted that with increase in network size, the difference of number of active nodes between these two approaches also increases. It is also found that the number of active nodes in the proposed distributed approach is always less than that in the sequential

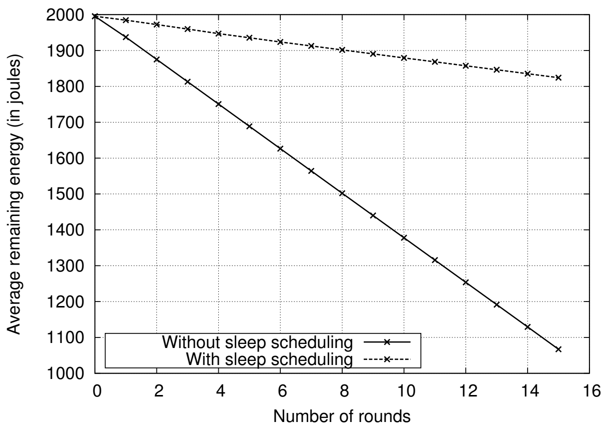

Figure 3. Average remaining energy in proposed distributed approach with sleep scheduling vs. without sleep scheduling

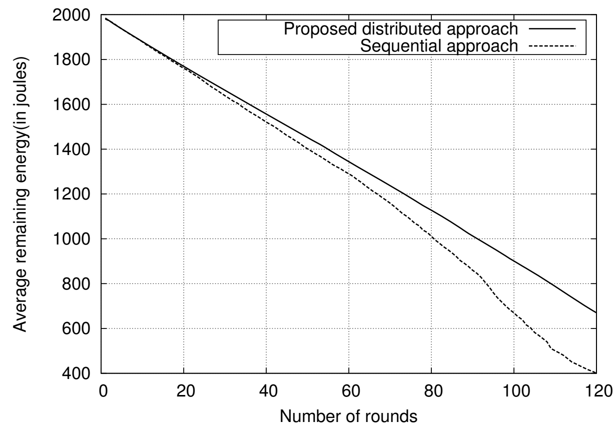

Figure 5. Average remaining energy in proposed distributed approach vs. sequential approach

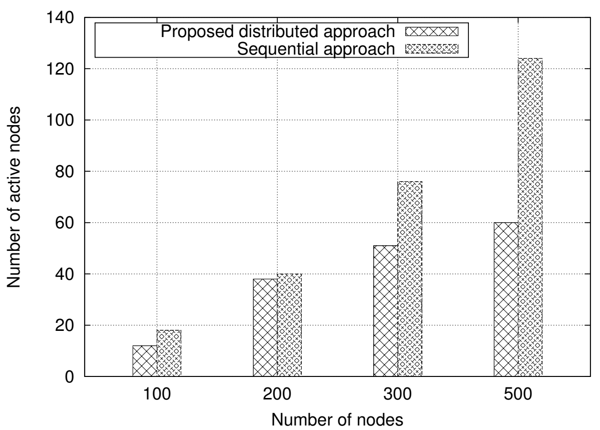

Figure 4. Number of active nodes in Average error in proposed distributed approach vs. sequential approach

approach for different size WSNs.

Figure 5 shows the difference in average remaining energy in the proposed distributed approach and sequential approach given in [8]. For this simulation, we have considered 500 nodes deployed over 150 X 100 m^2 area. From this figure, we can conclude that the average energy consumption in the proposed distributed approach for the construction of hierarchical structure is quite less as compared to that in the sequential approach. So, with progress in the number of rounds, the difference of average remaining energy in these two approaches also increases. This indicates the life time of WSN using the proposed distributed approach is more than that using the sequential approach.

V. Conclusions and Future Work

In this paper, we proposed a distributed approach for constructing hierarchical structure and a routing protocol on top of the proposed hierarchical structure that incorporates bsleep scheduling to prolong the network lifetime. The proposed protocol directly maintains the connectivity among active nodes in a WSN as well as provides reliability during data transmission even when a node in the network runs out of energy. As discussed earlier, the major constraint in a WSN is its limited energy, which we overcome by integrating sleep scheduling scheme in the proposed method as well as by providing a distributed approach to construct the tree structure. The protocol is dynamic enough to handle failures such as node failure or network hole by maintaining multiple parents and balancing energy consumption at each node in WSNs. Although distributed approach is more efficient and less time consuming as compare to sequential approach, for further improvement we can use multi-sink, so that data transmission from any source to sink will be faster, which we have taken as our future work. Future work also includes validating the performance of the protocol with proper theoretical analysis.

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