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Optimal Network Topology in Wireless Sensor Networks

Navdeep Kaur Randhawa
(Department of ECE, GIMET, Amritsar(Punjab), India

Abstract

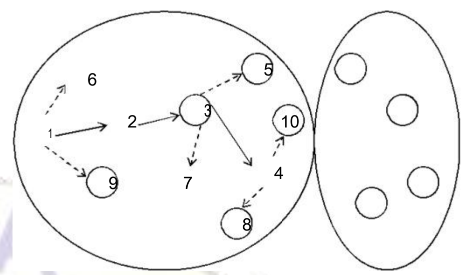
As the demand for wireless sensor networks increases in both military and civilian sector, the need for a stable networking scheme has increased. Wireless sensor network, or WSN, must be robust networks capable of handling many adverse conditions. If these adverse conditions cannot be handled effectively they can result in data loss and under extreme conditions total network failure. Through the use of a hybrid network topology, WSN can be stable and reliable throughout the life of the node. The paper introduces the network topology in a WSN environment called leader-based enhanced butterfly (LEB) network which is based on our previous work, enhanced butterfly network. The network guarantees the maximum reaching steps of n+1 in the $2 \cdot 2^n$ nodes. And also, in order to demonstrate the nodes behaviors in the network, Petri net modeling and simulation are conducted and showed the soundness of the network.

Keywords: **Wireless Sensor Network, Butterfly Network, Petri net, Network Efficiency.**

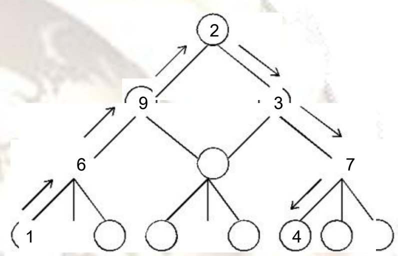
1. Introduction

Wireless sensor networks (WSNs) are an important emerging area of wireless computing and networking. The applications of the WSNs include environment monitoring, smart spaces, medical systems, robotic exploration, disaster recovery systems, and military systems. Because of their wide range of potential applications, both research community and industry have been fascinated by them.

WSNs are composed of a large number of battery-operated wireless sensor nodes. Each node has a low-power and short-range radio, and computational and multi-hop communicational abilities to conserve energy and transmit only the required processed data. Three main characteristics of these applications are ubiquities, users, and communication .
Especially, the last characteristic plays a major role in WSNs since they require effective communication between nodes, between humans, or between a node and a human to achieve the objectives in a certain application.



(a) Ad-hoc Routing



(b) Multi-Level Hierarchical Routing

Figure 1. An Example of Routing Schemes

The state-of -the-art in WSNs design is either ad-hoc or hierarchical based. Numerous network topologies and routing schemes have been developed for communication between nodes. For example, ad-hoc scheme (Figure 1 (a)) works well in a small network but collaboration with in the distance nodes is not a simple task with this scheme. In case of hierarchical routing scheme (Figure 1 (b)), it generates overhead easily and quite complex to maintain. The figure shows the communication between the nodes 1 and 4.

In a WSNs environment, a wireless link between nodes has experienced periodic disconnects and reconnects to save energy of each node. This may create some problems with sending a packet of information from one node to another, e.g., an undeliverable case or an excessive routing time due to inefficient network topology. Therefore, developing an efficient network topology is the essential task in the WSN. In addition to the efficient WSN design, clustering nodes is the other way to improve network performance. For example, at the Time Division Multiple Access (TDMA) scheme, one of Medium Access Control (MAC) protocol, by forming communication clusters, it reduces some interferences, and enhances the spatial reuse. However, managing communication and interference between clusters are not an easy task since wireless nodes are dynamic; they move one cluster to another. An improved clustering method is needed to overcome drawbacks.

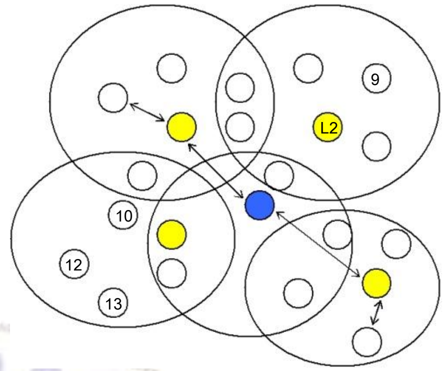
The main contribution of the paper is to develop an efficient WSN topology based on mesh scheme and attempt to simulate the network using Petri net simulation tool. The paper is organized as follows. Section 2 discusses the background and some issues in the WSN environment. Section 3 introduces the network scheme and Section 4 explores the modeling and simulation of the network and Section 5 concludes the paper.

2. Background and Terminology

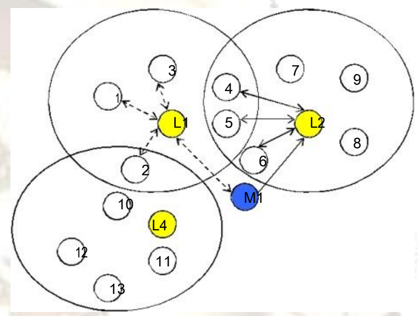
Researchers have been discussing many aspects of the WSNs: the uses and challenges in the WSNs, developing a system architecture or model for WSNs , designing of appropriate low-energy networks , routing strategies for the networks, reducing location management cost in the hierarchical architecture , and deploying application specific approaches.

As most of the wireless sensor nodes have limited battery life and restoring batteries on these nodes is almost impossible. Therefore, the lifetime of a sensor node is the lifetime of a battery. Many protocols and algorithms deployed in WSNs are based on energy efficient and aware .

Figure 2 demonstrates examples of different cases of communication. Figure 2 (a) shows simple communication between nodes 1 and 13. The node 1 does not wake (or activate) all neighbor nodes to find the routing information to the node 13. It needs to send information to the leader of the cluster (L1) and the cluster leader sends that information to its manager (M1). Then M1 transmits it to the cluster leader who is the leader of the node 13. In this way, the energy of non-related nodes and transmitting time from the source node to the destination node can be saved. However, what if the leader of the cluster is low-power? One of neighbor nodes should take in charge for leader of the cluster. For smooth transition of this, one needs to develop a way to transfer privilege of leader from one node to another.



(a) Communication between nodes 1 and 13



(b) Cases of leader 1 has low power

Figure 2. Examples Using Proposed Scheme

Figure 2 (b) illustrates different case: a leader node has low power. Let say, the cluster leader 1 has low power and it cannot communicate with other nodes. Manager 1 then cannot gather information from the nodes 1, 2, and 3 since there is no network connection established at the time. In order to solve this problem, one needs to develop an efficient network topology to control this situation.

Performance of a WSN is often limited by the underlying interconnection network. Collaboration and information reuse within the WSNs rely on group communication. Network schemes for the WSNs can be identified into two categories: tree and mesh based schemes. Tree-based (hierarchical) scheme is used in wired networks and several attempts to translate it to wireless networks have been developed. While tree based scheme must follow specific predefined paths in order for the packets to be delivered properly, mesh-based schemes do not. Because of a mesh based protocol’s ability to use multiple paths between nodes many researchers have found that the later one is more suitable for a WSN environment . One of well known mesh-based scheme is the butterfly network scheme

(BNS). The BNS is a multistage interconnection network scheme. The main advantages are the scalability, i.e., the logarithmic diameter of the network and the recursive structure of the network, and reachability, i.e., maximum 3n/2 steps required in the $2 \cdot 2^n$ nodes to reach from one node to another, of the network. The scalable network connectivity with the algebraic tools to investigate its structural properties were discussed in previous papers. To improve the reachability of the network, authors proposed the enhanced butterfly network and proved its efficiency, i.e., maximum n steps required in the $2 \cdot 2^n$ nodes, of reachability.

3. Developing an Optimal Network Topology

There is a significant interest in developing the optimal network topology in the WSNs. Developing a model of nodes' behavior is an important but difficult task. The proposed scheme, Leader-based Enhanced Butterfly (LEB) network topology, is the combination of hierarchical and ad-hoc network.

Figure 3 shows the top view of the proposed three-layered scheme in WSNs. The node layer consists of all wireless nodes. The leaders layer is the collection of cluster leaders. There are two leaders in each cluster and cluster leaders take care of collaboration between nodes within the cluster and between neighbor cluster leaders. The manager layer is responsible for managing cluster leaders and sending processed information to the users through the Internet.

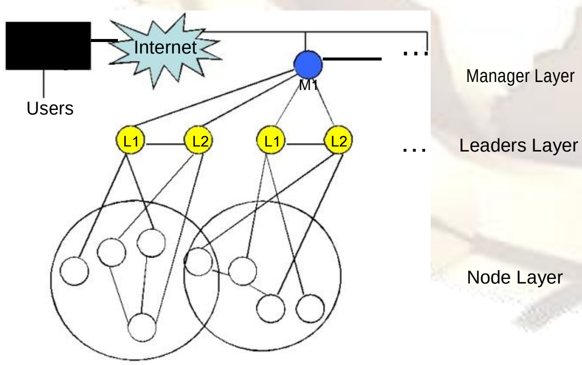


Figure 3. Proposed Three-Layered Scheme

The paper focuses on the node and leaders layers as majority of communication taking places in these two layers. The proposed leader-based enhanced butterfly (LEB) network scheme is shown in Figure 4. The two leaders in each cluster are in charge of managing node layer's nodes. In case of low battery power, one of leader nodes takes action to replace that node including the leader nodes.

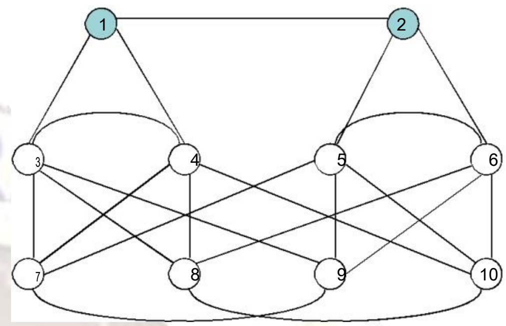


Figure 4. Leader-based Enhanced Butterfly Network Scheme.

One of main advantages of using butterfly network, as discussed, is the reachability. Without considering two leaders in Figure 4, the maximum 2 steps required to reach from one node to another in the 8 nodes, i.e., $2 \cdot 2^n = 8$ and $n = 2$. By adding two leaders in the network the maximum steps would be n+1 in the $2 \cdot 2^n$ nodes. In Figure 4, there are maximum 3 nodes, including source and target nodes, will be used to communicate each other. Figure 5 shows two examples of these scenarios. Figure 5(a) illustrates the communication path from node 1 to any of nodes 5, 6, 7, 8, 9, or 10. Similarly, the communication path from the node 7 to any of nodes 1, 8, 10, 5 or 2 is showing in Figure 5(b).

It is not easy to see the behavior of the network when the nodes are sending information from one to another by looking at the Figures 1, 2, 3, 4, and 5. Therefore, we adopt the Petri net simulation tool to demonstrate the behavior of the proposed network.

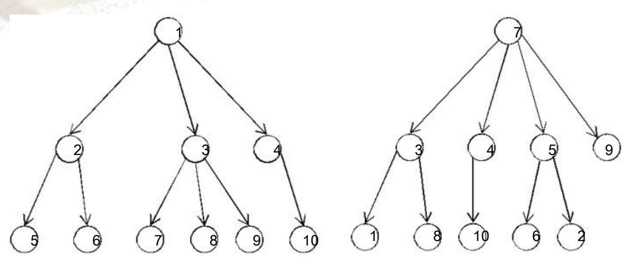


Figure 5. Reachability Diagram for the Scheme.

4. Modeling and Simulation of the Scheme using Petri net

HPSim [1] simulation tool was used to model and simulate the proposed architecture. HPSim was developed by Henryk Anschuetz and is free for academic use. HPSim has a graphical editor for editing and simulating Petri nets. It provides many functions to analyze the model. In this work, the HPSim tool was used to create simulations of the proposed architecture; to verify all underlying relationships among actors; to check for the absence of deadlock states during execution; and to ensure the completion of the Petri net's execution .

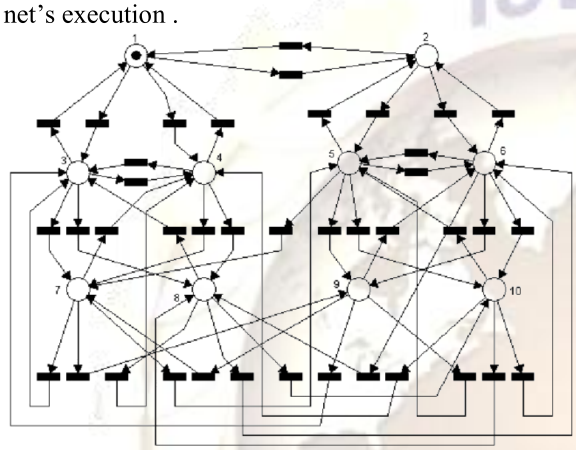
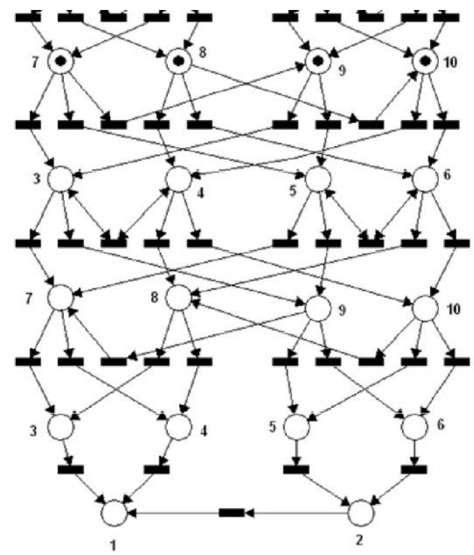
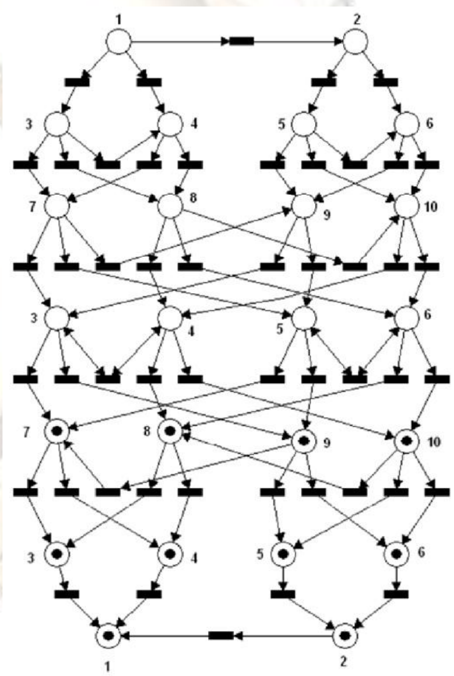


Figure 5. Petri net Modeling of the Proposed Network Topology

Because this modeling is developed by a structure process based on Petri net's algorithms the resulting net has the properties of soundness, liveness, and bounded. This implies that when the net is executing with a token in the place it guarantees that there is no deadlock during the running time.



(a) Before firing 10 tokens

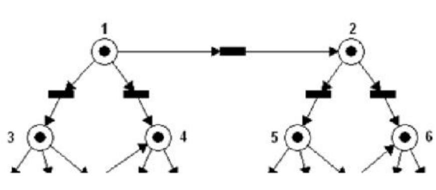


(b) After Firing 10 tokens

Figure 6. Butterfly Network Representation of the Proposed Network Topology

In order to demonstrate the communication path between nodes, the leader-based enhanced butterfly

(LEB) network representation is shown in Figure 6. The enhanced butterfly network has the symmetric property which can be seen in Figure 6. The figure is



the symmetric over the third layers. This representation is useful to show the node behaviors. As the second experiment, ten tokens are placed in the node 1 since there are 10 nodes in the scenario (figure is not shown). After 15 transitions firing, the result network is shown in Figure 6(b). Finally, one token is placed in each node from 1 to 10 for our next simulation (Figure 6(a)). After 10 transitions firing, the resulted tokens are placed as shown in Figure 6(b) again. The result indicates that the proposed network topology has no deadlock and can be reached any pair of nodes.

5. Conclusions

Designing efficient network topology is a one of key challenges in WSNs. Wireless sensor nodes in a system need to operate over a long period time and minimize the processing time for sending and receiving information. At the same time, users want to have the processed information quickly and safely. Using the conventional schemes, one may not achieve these objectives. This paper discussed the proposed network topology in a WSN environment. Enhanced butterfly network was discussed and adopted to develop leader-based enhanced butterfly (LEB) network. The proposed network guarantees the maximum reaching steps of n+1 in the $2 \cdot 2^n$ nodes. In order to demonstrate the nodes behaviors, Petri net modeling and simulation were conducted and showed the soundness of the network.

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