

A Novel Multi-layer Architecture for Wireless Sensor Networks

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Abstract — In this paper, we present a novel hierarchical architecture for a large wireless sensor network wherein sensors are arranged into a multi-layer architecture with the nodes at each layer interconnected as a de Bruijn graph and provide a hierarchical routing algorithm in the network. Using our approach, every sensor obtains a unique node identifier addressed by binary addressing fashion. We show that our algorithm has reasonable fault-tolerance, admits simple and decentralized routing, and offers easy extensibility. Besides, we also present simulation results using two metrics: the end-to-end delay and the success data delivery ratio. To evaluate how well our protocol support, we compare our protocol with other protocol using two these metrics.

Keywords — wireless sensor network, multi-layer, fault-tolerant, network delay, Bruijn graph, addressing.

1. Introduction

Wireless sensor networks (WSN) are composed of a large number of sensors densely deployed in inhospitable physical environments. Dissemination information throughout such a network that requires fault-tolerance is a challenge.

Although there are applications as described in [4], [9] which do not require addressing of sensors, we have argued many scenarios where addressing nodes is very essential. However, given that an addresses scheme needs to be build, IP-based addressing to this problem would not be a good solution. For one, IP-based addresses are global unique addresses but WSNs require local unique identifier. In our architecture, sensor nodes within a certain area interact with themselves in a distributed manner and come up with an addressing scheme in which each node obtains a unique local address.

Motivated by above issues and the advantages of the de Bruijn graph admitting simple routing and possessing good fault tolerant capabilities in many interconnected networks, we introduce a multi-layer architecture wherein sensor nodes are interconnected as de Bruijn graph at each layer.

To show how our algorithm supports simple routing, fault tolerance and scalability we introduce a hierarchical routing algorithm that is able to route packets along all possible paths between any pair of the source and destination nodes without

performing explicit route discovery, repair computation or maintaining explicit state information about available paths at the nodes.

The remainder of the paper is organized as follows. In section 2, we present the related work. The network architecture is shown in section 3. Section 4 provides routing algorithm for the multi-layer network. To evaluate the performance of our architecture, we provide some of results in section 5. Finally, we conclude the paper and mention future work in section 6.

2. Related Work

Many protocols have been proposed for wireless sensor networks in the last few years. In works addressed in [1], [3], [4], all sensors have been treated to be alike and are assumed to have similar functionality. In contrast, sensors in our architecture are heterogeneous.

Data dissemination protocols are proposed for wireless sensor networks in [2], [3]. SPIN [3] attempts to reduce the cost of flooding data, assuming that the network is source-centric. Directed diffusion [2], on the other hand, selects the most efficient paths to forward requests and replies on, assuming that the network is data-centric. This approach, in company with works addressed in [1], [3], use a powerful concept of data-centric networking for sensor applications. Though this model is very interesting, it may not be applicable to many sensor applications. Certain applications like parking lot networks may require addressability for every sensor node and a method for routing packet to specific nodes. Our architecture can support both data-centric networks and non data-centric networks.

Clustering algorithms have also been proposed in many literatures, such as GAF [6]. SPAN [7]...etc. The remarkable one among them is LEACH [8]. LEACH is an application-specific data dissemination protocol that uses clustering to prolong the network lifetime. However, LEACH assumes that all nodes have long-range transmission capability. This limits the capacity of protocol and application. Moreover, cluster head failure is also the problem in this approach. In contrast, our approach makes no assumptions like this and does not organize network as clustering architecture. Instead of this, our approach distributes sensors into multi-layers. Each layer is organized as a de Bruijn graph.

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3. Network Architecture

In this section, we give a detailed description of the network architecture. In this architecture, we assume that the sensors are immobile. This assumption is reliable especially for indoor applications such as smart home or smart building applications.

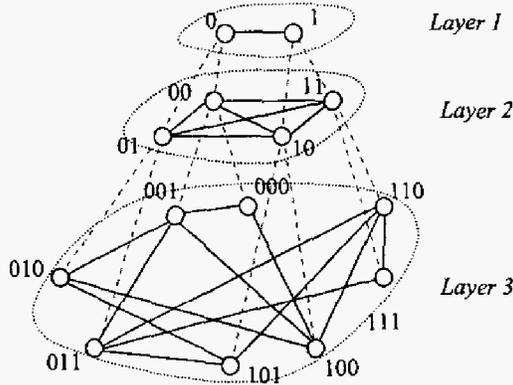


Fig. 1. A 3-layer hierarchical architecture. Node 01 (layer 2) is parent of two nodes 010 and 011 (layer 3) but is one of two children of node 0 (layer 1).

Assume that we deploy a network with N sensors. The network architecture can be organized under a hierarchical model which consists of several layers with the node at each layer interconnected as a de Bruijn graph. For a detailed discussion on features of de Bruijn graph, see the paper by Sanmatham et al. [5]. Our architecture features is addressed as follows:

- Sensors are organized in a multi-layer architecture with the order of layer numbered increasingly starting from 1.
- k^{th} layer has 2^k sensor nodes.
- Sensors are addressed with binary address form, sensors in k^{th} layer use k bits for node addressing.
- Each node at k^{th} layer is connected to two children nodes at $(k+1)^{\text{th}}$ layer and is connected to its parent node at $(k-1)^{\text{th}}$ layer ($k > 1$)
- Nodes in 1st layer and 2nd are connected completely. It means that, each node in the first layer has only one neighbor and 2 children. Each node in the second layer has 3 neighbors and 2 children nodes.
- Using graph theoretic notation, the de Bruijn graph $BG(d,k)$ has $N = d^k$ nodes with diameter k and degree $2d$. We are interested in binary de Bruijn graph $BG(2,k)$ which have $N = 2^k$. A node x addressed $x_{k-1}x_{k-2} \dots x_1x_0$ in k^{th} layer ($k > 2$) has 4 neighbors as follows:

$$\text{neig}_1(x) = x_{k-2} \dots x_1x_0x_{k-1}$$

$$\text{neig}_2(x) = x_{k-2} \dots x_1x_0\bar{x}_{k-1}$$

$$\text{neig}_3(x) = x_0x_{k-1} \dots x_2x_1$$

$$\text{neig}_4(x) = \bar{x}_0x_{k-1} \dots x_2x_1$$

where : \bar{x} is complement of x .

The address of a node in k^{th} layer consists of two parts. One is k bit derived from $(k-1)^{\text{th}}$ layer. The other is 1 bit (0 or 1) added from right side. Node x addressed $x_{k-1}x_{k-2} \dots x_1x_0$ has two children nodes and one parent node. These children are addressed as $\text{add}(x_{k-1}x_{k-2} \dots x_1x_0, 0)$ and $\text{add}(x_{k-1}x_{k-2} \dots x_1x_0, 1)$ while the parent is addressed as $\text{rmv}(x_{k-1}x_{k-2} \dots x_1x_0)$. The

following definitions describe two address transforming functions addition (add) and remove (rmv).

Let K be a k -bit number and y be a binary number. Then

$$\text{add}(K,y) = Ky;$$

$$\text{rmv}(x_{k-1}x_{k-2} \dots x_1x_0) = x_{k-1}x_{k-2} \dots x_1$$

For example, $\text{add}(001,1) = 0011$; $\text{rmv}(0110) = 011$.

Figure 1 shows an example of the 3-layer network architecture followed by above mentioned features.

Obviously, the network extension is not issue in this architecture. Whenever sensors need to be deployed into the network, they will be added at the highest layer of the hierarchical architecture. Thus extending network requires a fixed number of interconnections between the new nodes and the nodes at the last layer. If number of new nodes are more than that of the last layer can support, the remaining nodes will make up a new layer being last layer in new network architecture.

4. Routing Algorithm

In this section, we show that packets can be routed throughout the hierarchical architecture. We first consider routing within each layer and then consider routing across layers. To evaluate the routing complexity, we assume that a packet takes unit time to traverse a link.

4.1. Intra-Layer Routing

Routing in the first layer and second layer takes unit time step since the nodes are completely connected. In this section, we describe a simple routing algorithm which is based on the construction of the Bruijn graph.

Let a binary de Bruijn graph have $N = 2^k$ nodes and let $S = s_{k-1}s_{k-2} \dots s_1s_0$ be the source node that sends a packet to the destination node $D = d_{k-1}d_{k-2} \dots d_1d_0$.

The packet consists of the data and packet header. The packet header contains the routing information. The packet format is depicted in figure 2.

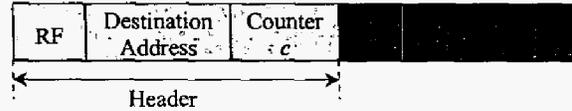


Fig. 2. Packet format contains the destination node addresses, a counter (c), and a routing flag (RF).

The RF is a 2-bit binary number set to

- 00: the source and destination nodes are in same layer and the source node use Path 1 to route packet to the destination. (default)
- 01: it is the same as 00 but Path 2 is used instead of Path 1. Path 1 and Path 2 will be addressed later.
- 10: the source and destination nodes are in different layers. The source node is at a higher layer than the destination.
- 11: the source node is at a lower layer than the destination.

The counter c is used to record the number of packet hops from the source node to the current node. In addition, it is also used to generate the address of the next node in the path.

Now, we describe the simple routing algorithm in each layer. From the construction of the de Bruijn graph, we know that the source node at k^{th} layer has the following neighbors - $d_0s_{k-1}s_{k-2} \dots s_1$ and $s_{k-2} \dots s_1s_0d_{k-1}$. Using this property we can now generate two paths by appending successive bits of the destination node to the source address.

Path 1

- ($c=0$) $s_{k-1}s_{k-2} \dots s_1s_0$ (source address)
- ($c=1$) $d_0s_{k-1}s_{k-2} \dots s_1$
- ($c=2$) $d_1d_0s_{k-1} \dots s_2$
- ...
- ($c=k$) $d_{k-1}d_{k-2} \dots d_1d_0$ (destination address)

Path 2

- ($c=0$) $s_{k-1}s_{k-2} \dots s_1s_0$ (source address)
- ($c=1$) $s_{k-2}s_{k-3} \dots s_1s_0d_{k-1}$
- ($c=2$) $s_{k-3} \dots s_0d_{k-1}d_{k-2}$
- ...
- ($c=k$) $d_{k-1}d_{k-2} \dots d_1d_0$ (destination address)

Let $x_{k-1}x_{k-2} \dots x_1x_0$ be the address of the node x . The figure 3 describes steps executed by x .

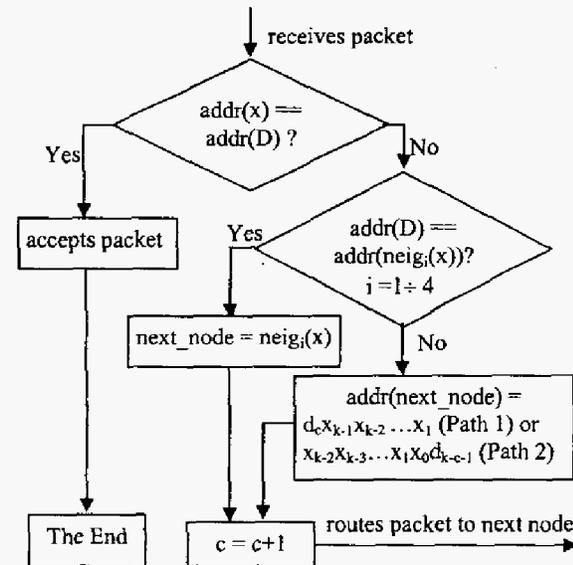


Fig. 3. Operations of node x . $\text{addr}(x)$, $\text{neig}_i(x)$, and D present address, i^{th} neighbor of node x , and destination respectively.

4.2. Inter-Layer Routing

In this session, we suppose that the source and destination nodes are in different layers. So, the RF is set to "10" or "11". In addition, the counter c is not incremented in order to maintain a proper value of the counter for intra-layer routing following the inter-layer routing.

In case that the source node is at a higher layer than the destination, the source node first routes the packet to its parent $\text{rmv}(S)$. This procedure is repeated recursively until the packet is received by a node at the same layer as the destination node. The RF is set to 00 or 01 now, and the source address is replaced by the address of the node that received the packet. The packet can then be routed to the destination using above intra-layer routing algorithm.

In contrast, when the source node is at a lower layer than the destination, the same procedure is used where the source node first routes the packet to its child using $\text{add}(S)$ to generate the address of the next node.

4.3. Fault Tolerant Routing Issue

In a large WSN, it is unrealistic to expect all nodes or links along a path to be free-fault at all times. Whenever some nodes or links fail, an alternative path that avoids faulty node or link must be derived.

Suppose that nodes x_2 ($d_c x_{k-1} x_{k-2} \dots x_1$) and x_3 ($x_{k-2} x_{k-3} \dots x_1 x_0 d_{k-c-1}$) are neighbors of node x_1 ($x_{k-1} x_{k-2} \dots x_1 x_0$). Also assume that if either node x_2 or the link between x_1 and x_2 has failed, then x_1 chooses the alternative path to node x_3 . In addition, x_1 sets RF to 01 (Path 2) and counter c to 0 as well. At worst if both x_2 and x_3 fail, node x_1 routes to one of its two remaining neighbors $d_c x_{k-1} x_{k-2} \dots x_1$ or $x_{k-1} x_{k-2} \dots x_1 x_0 d_{k-c-1}$ and sets counter c to 0.

For inter-layer routing, node x_1 chooses another child if the first child fails. In the worst case of both the children failing, node x_1 will route back to one of its neighbors. The approach is the same if parent of x_1 can not be reached. In all cases, counter c must be set to 0 and RF set to default.

5. Performance Evaluation

We developed a simulator based on SENSE simulation [10] to evaluate performance of our approach. The simulation use MAC IEEE 802.11 DCF that SENSE implements. Because network design choices: MAC scheme, network topology, node addressing, and packet routing vary among implementations, we do not compare our nodes to other solutions.

In this simulation, we take account on two metrics: the end-to-end delay and the success data delivery radio. The end-to-end delay refers the time taken for a data packet to be generated until the time it arrives at the destination. The success data delivery radio is the rate of the number of successfully received data packets at the destination and the total number of packet generated by a source.

To illustrate the performance of our architecture, we choose randomly pairs of source and destination nodes in order to communicate each other. Besides, we also compare these two metrics with Directed Diffusion protocol in order to evaluate how well our protocol can distribute to researches in wireless sensor networks. As a future work, we will inject some fault nodes or failure links into the network as well as generate many kinds of network scenarios in order to evaluate how well our architecture supports the fault tolerance and offers easy extensibility as well.

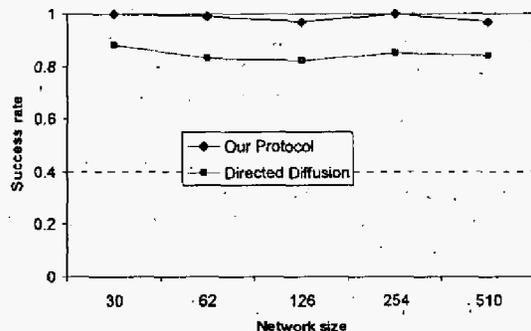


Fig. 4. Success data delivery ratio as a function of network sizes.

The simplicity and efficiency of our architecture are examined by simulation in figure 4. We study metric average success data delivery ratio as a function of sensor network size. To do this, we generate a variety of sensor fields of different sizes, ranging from 14 to 510 nodes in increments of 2^i ($i = 4, 5, 6, 7$, and 8). When the number of node is changed, network size is also proportionally changed by scaling the square and keeping the radio range constant in order to approximately keep the average density of sensor nodes constant. Results show that the data is delivered successfully in the network is quite high and higher than that of Directed Diffusion.

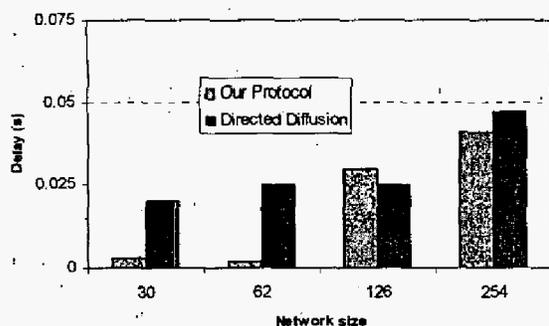


Fig. 5. End-to-End delay as a function of network sizes.

Besides, end-to-end delay is also factor showing the efficiency of our approach. As addressed in figure 5, the end-to-end delay is quite low and it is a promising value in many potential applications. Because our protocol support the very simple routing algorithm to disseminate data from source to any destination while Directed Diffusion is the complexity protocol (discovery phase, reinforcement phase, routing phase) that create high end-to-end delay.

6. Conclusion and Future Work

This paper describes a hierarchical architecture for WSNs wherein sensor nodes are distributed into layers. Nodes in each layer are interconnected as a de Bruijn graph. Our architecture easily solves fault tolerance and extensibility. We also provide a simple routing algorithm between any two nodes in the network.

We created simulations based on SENSE [10] in order to illustrate the performance and bring out the main goal while proposing this approach. Because sensors have limited computation, in this paper, we do not investigate into the shortest path algorithm that consumes much energy than above mentioned simple routing algorithm. As a future work, since multi-year battery life is preferable for future sensors, we need to future study on optimal routing to improve the goodness of our architecture. We also need to study an optimal energy scheme in order to save energy for sensors.

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