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Improved Cluster-Tree Topology Adapted for Indoor environement in Zigbee Sensor Network

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Abstract

Wireless Sensor Network (WSN) is a collection of small sensor nodes with aptitude to sense, compute and transmit data that are deployed to observe a physical environment. The sensor node has limited capabilities, especially for energy reserve and memory storage, that is why topology and routing protocols should be defined for a good network's performances. In this paper, we focus on Zigbee sensor networks based on IEEE 802.15.4 standard for which we improve the topology control by proposing an efficient clustering topology based on Minimum Spanning Tree (MST). In fact, our proposed algorithm tend to propose a topology where the cost of total transmissions into the network should be minimal. Our topology takes also into consideration the indoor environment by proposing a metric that deal with the path loss and signal attenuation due to walls and obstacles to compute the weight of connections between nodes. Finally, our topology showed better results than typical Cluster-tree and mesh topology generally used in Zigbee sensor networks in terms of energy consumption and network's lifetime.

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Keywords: Topology control ; Zigbee ; Minimum Spanning Tree ; Path loss ; Network's lifetime.

1. Introduction

Today, we can assist to the great emergence of wireless sensor networks. This kind of networks are self-organized and consists in general on a large amount of autonomous sensor nodes with low resources transmitting sensed data to the base stations[1]. A sensor network can be easily deployed over large areas, but once deployed it can be very difficult or even impossible to access. That's why most of these networks intend to optimize the use of limited energy contained in each node. Energy optimization can be obtained by efficient hardware architecture, efficient data routing and aggregation, energy harvesting and many other ways. There are a lot of application fields for wireless sensor networks, such as temperature and humidity monitoring, surveillance, rescue operations and home automation. Most of applications that requires large scale networks, as detection of forest fires, uses high range transmission standards

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like IEEE 802.11b. Other applications as home automation that requires less transmission range uses other standards as IEEE 802.15.4. This standard is usually used by most of indoor applications for home automation and industrial monitoring. In fact, many previous works have demonstrated that conventional wireless standards such as Bluetooth or "WLAN"[2,3] are not suitable to be used in this type of networks. It was shown in previous works that the best standard taking into consideration the constraints of an indoor networks is the 802.15.4[4]. It has also been shown that ZigBee network is the least, compared with other wireless networks, in term of SNR[5,6] which made it the optimal standard for indoor applications where noise has a strong presence especially in industrial manufactures.

In this work, we focus on building efficient topology based on minimum spanning tree (MST) for what we took into consideration different parameters related to indoor environment as path loss and signal attenuation due to walls and obstacles. This paper is organized as follows, we start with talking about the network's model and existing topologies based on IEEE 802.15.4 standard, in next section we present the indoor propagation model adapted with our network's model, then we present our improved cluster topology based on Minimum Spanning Tree (MST), we show our simulations and experimental tests and results and deduce how we improved the energy consumption and network's lifetime with our algorithm for topology construction and control. Finally, by the end of paper, we conclude and present our perspectives for future works.

2. Network Model

In this paper we propose a network model based on tree called the cluster-tree network defined in 802.15.4 standard[6]. In fact, since the energy is a crucial parameter to take into consideration in wireless sensor networks, the cluster-tree topology has proved its efficiency in terms of energy consumption[13] The cluster-tree is a simple hierarchical topology based on a relationship between father and children[12] as shown in figure 1. In this topology topology, we find that several clusters are present and are able to communicate using Multi-hop routes. They are also controlled with a PAN coordinator[7]. Each cluster can have its own cluster head (parent) and can communicate with the PAN Coordinator. We can choose a PAN coordinator among several existing clusters. The cluster topology performs as follow: After network's construction based on association request and association response, the parents of the clusters form a tree structure and act as an intermediate routers. For better network typology's control in ZigBee, the maximum number of children that each router and the maximum depth of the tree has to bee fixed. The depth in a cluster-tree is the distance to the sink in terms of hops from nodes to PAN coordinator. For example, node at level "0" is the PAN coordinator and nodes at level "1" are the children of the PAN coordinator. The cluster-tree topology may be used by the upper layers to carry on specific functions such as data aggregation.

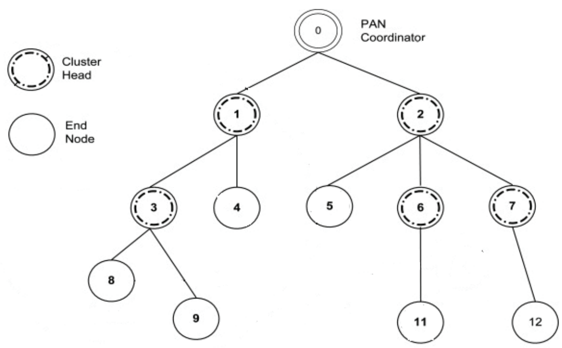

Fig. 1. Cluster-Tree topology.

3. Indoor propagation model

In our network, the coordinator has to compute the weights of links between all connected sensor nodes. The weight of edges is calculated based on the indoor propagation model[14,15] presented below. This model for indoor propagation must be taken into consideration when calculating the weight of edges between nodes. It concern the placement of walls and partitions in the building that dictates the signal path inside a building. Generally ,in an indoor environment, the average path loss P L(d) for a transmitter and receiver over a distance d:

$$PL(db) = PL(d_0) + 10nlog(d/d_0) + X_\sigma \tag{1}$$

Where $PL(d_0)$ is the path loss for 1 meter, n the path loss exponent, and X_σ is a zero-mean Gaussian distributed random variable with standard deviation σ. This model can be generalized to a Multi-Wall environment us for our network. This will consist on adding further attenuation term due to losses introduced by the walls penetrated by the direct path between receiver and transmitter:

$$L(db) = PL(db) + M_\omega \tag{2}$$

where M_ω represent the multi-wall component expressed as:

$$M_\omega = l_c + \sum_{i=1}^{I} k_{wi} l_i \tag{3}$$

Where k_{wi} is the number of penetrated walls, l_c is constant, and l_i depends on wall size as: l_1 for light wall [0 20cm], l_2 for medium wall [20cm 40cm], and l_d for door.

The weight of connection between nodes is not only calculated based on euclidean distance between nodes, but will also take in consideration the model above according to the equation:

$$Weigh = Euclidean_{distance} - \epsilon_r \times \frac{P_r}{P} \tag{4}$$

Where ϵ_r is the dielectric constant of the reflected surface.

4. MSCT Topology

4.1. MSCT creation

In the MSCT topology, the process of network creation different from the typical Cluster-tree explained above. It's based on Minimum Spanning tree that is a graph that spans all the nodes of network as vertices and connections as edges without containing cycles[11 8]. We Suppose a graph $G = (V, E)$ representing the topology of the static sensor network, where V represents the sensor nodes and E represents the link weight between two connected nodes. In theory, the link weight for sensor network represents the euclidean distance between the two nodes, but as explained in the previous section, path loss and signal attenuation due to obstacles of indoor environment must be take into consideration. We used algorithm 1 based on "Kruskal" to sort the weight of edges in a increasing order, and then consider each sorted edge for inclusion in the tree if it doesn't create a cycle. Following this algorithm, we obtain a topology where cost of communication (transmission) is minimal.

The total cost of the spanning tree created by this algorithm is minimal. In our case, the cost represents the energy dissipated during transmission. As we mentioned before, this energy depends highly on the distance between the node parent and children in the network and the obstacles (if there is) due to the indoor environment.

4.2. MSCT topology control

We presented in the previous chapter how the minimum spanning cluster-tree topology is created from a given graph, we know explain how this topology is applied to the Zigbee network. We consider first that only the coordinator exists in the network. Contrary to the typical cluster-tree topology construction, when a node request to join the

Algorithm 1 MSCT topology creation

Input Graph (G, w) with N nodes
Output Topology T

$T \leftarrow \emptyset$ /* Empty spanning tree*/

For each vertex V
Make-set(V)

Sort the edges of the graph in increasing order by weight W

For(i = 1, i ≤ N, i++)
Select the next smallest weight edge **if**(No cycle is created) $T \leftarrow edge(i)$ /* add the connection to T*/

return T

network,the coordinator adds the node to the network (assign the PAN id) but not to the topology. In fact, for a given lapse of time τ, the coordinator does not create any topology, it only receives join-requests from nodes. After the time τ elapsed, the coordinator create the topology following the algorithm 1 steps. The coordinator will not accept any join request from any sensor node during an other time lapse τ', but will store it in a standby table. That will permit a save of energy because, in fact, modifying topology will generate several computations for topology re-construction and address re-assignment. To better understand how network is created and controlled, figure 2 presents a flowchart of the operations. Note that to simplify it, we assume that all association requests from nodes to the coordinator are accepted.

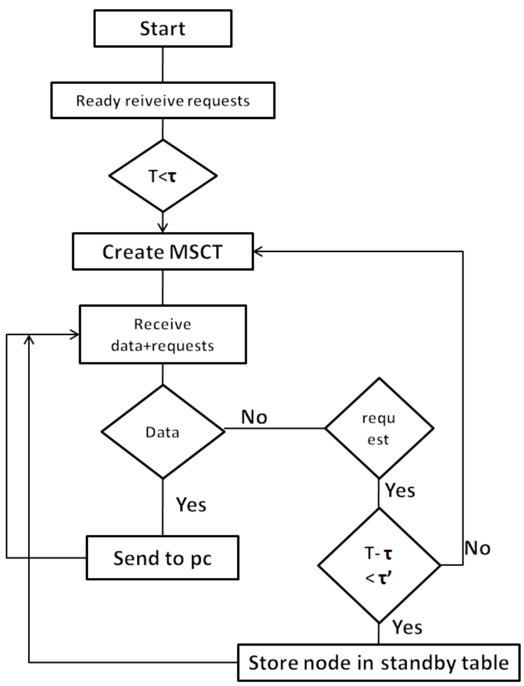

Fig. 2. Network's operations Flowchart.

Note also that the steps in the flowchart operates once there is no node failure. If a node, for any reason, loose it connection with the coordinator, it will be considered that the network is dead and the coordinator will have to re-build the topology and re-assign addresses to all nodes. By this way, we built an energy efficient Zigbee network that is totally independent and where total cost of transmissions is minimal. We present in the next chapter our experiment results for our network topology.

5. Performances evaluation

5.1. Preliminary simulations

We conducted first some simulations to test the performances of our $MSCT$ topology before real implementation. The simulations were conducted using Matlab under almost the same conditions of the experiments presented in next section. In fact, the simulation was conducted for a network with 20 nodes (including the coordinator), deployed uniformly in a 200m x 50m area. All nodes have the same initial energy $E_0 = 1J$ and frequency transmission of 30sec. The path loss exponent for indoor environment was $\phi = 3$. The longest distance of transmission in one hop was 30 m.

figures 3 shows the constructed topology over a given deployment of sensor nodes on Matlab simulations using both typical Cluster-Tree and MSCT topology. The simulations have considered the same conditions for indoor environment. To simplify the tests, the weight of connections was given manually. When we compute the total cost of transmission in both topologies, the improvement MSCT is trivial. While the cost of transmission in simple Cluster-Tree topology is 47, this value is much lower in the MSCT for the this case, and more exactly 33. Thus, the topology has considerably improved the cost of communications in the network, this can be viewed in the energy consumption analysis below.

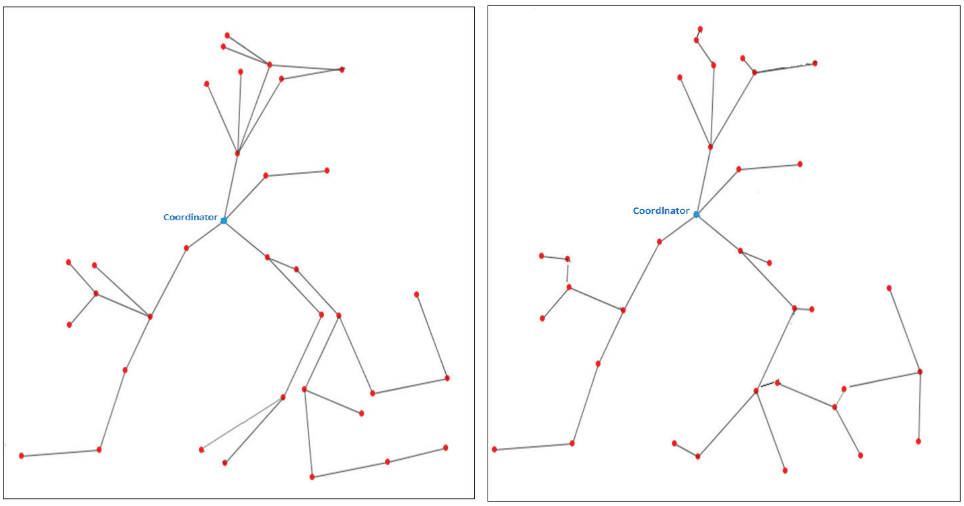

Fig. 3. Cluster-Tree and MSCT Topology.

To test the performances of our MSCT topology, we compared it with two other topologies under the same simulation conditions. Figure 4 shows the network's lifetime as function of time for our topology compared with typical Cluster-tree and mesh topology. The simulation shows clearly the high performance of our MSCT compared with the other topologies.

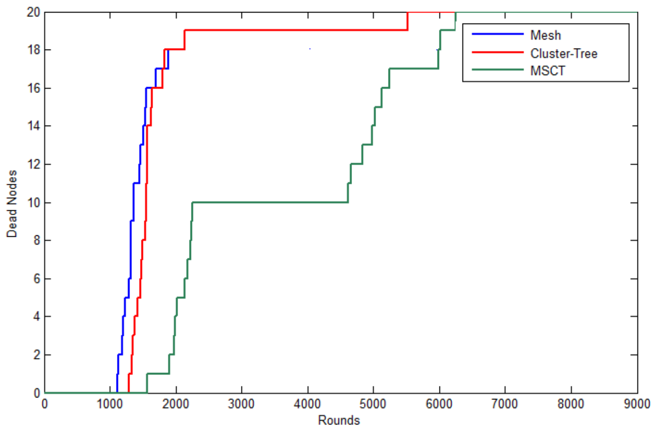

Fig. 4. Comparison of network's lifetime between Mesh, Cluster-Tree and MSCT topology.

5.2. Experiments and results

To evaluate the performances of our system in real world, we conducted experiments in an indoor environment. We used a hardware we developed in lab based on Arduino micro-controller[9] and MRF24J40 Zigbee transceiver of Microchip[10]. This hardware architecture based on Arduino and Microship has shown it efficiency in term of energy consumption and indoor range. Thus, the energy consumption for one node never exceed $35mA$ and the indoor range is about 100 ft. Our system bases is composed by a limited number of this Zigbee-Arduino sensor nodes connected to a control system. The control system have the task of managing the network by constructing, controlling topology, and also receive and process data. The system uses IEEE 802.15.4 standard described in previous chapters to perform communications.

The system was programmed in order to all sensors (routers and end-devices) sense temperature and humidity every 30 seconds. Node that the end-device only send data to the parent node, and the router that sense it own data and also aggregate data coming from it children and route it toward the coordinator.

As mentioned before, the system was made in order to sense temperature and humidity every $30sec$. The coordinator sends obtained data from other nodes to user's pc. Figure 5 shows the coordinator node next to a router node. The connection between coordinator and user's pc is wired to insure effective transmission of collected data from the coordinator.

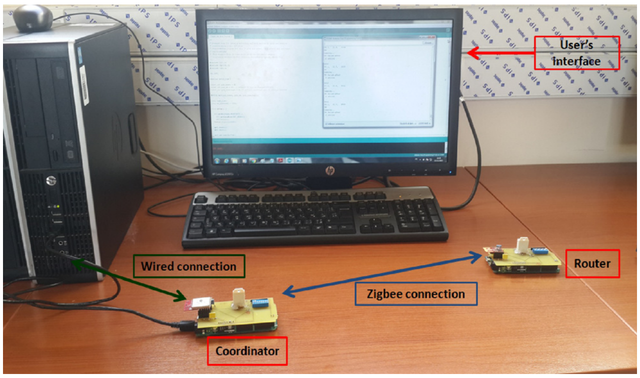

Fig. 5. Architecture at the coordinator area.

Concerning main results, we focus on energy consumption of sensor nodes to test the performances of the $MSCT$ topology.

Our first result concern the discharge process. In Figure 6, we show a comparison between the different topologies in term of battery's voltage discharge in router nodes according to the time. The initial voltage for all router nodes is 5 V. We can clearly note that the process of the discharge when MSCT topology is used takes longer time than the same process for mesh and typical cluster tree topologies. This first result gives already a view that energy consumption for our MSCT topology is lower than the others.

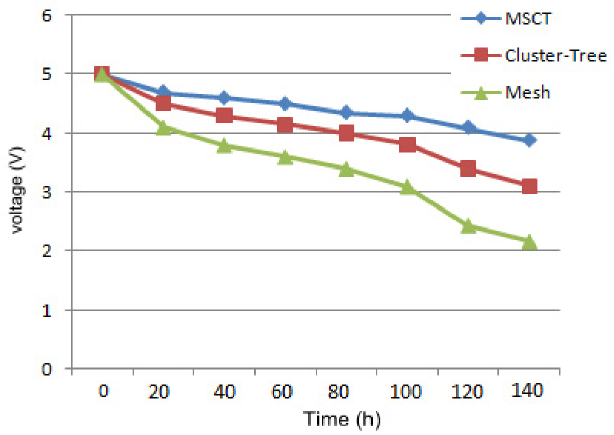

Fig. 6. Average of voltage of the batteries according to time and topology.

The fact that the discharge process for the router nodes is slowed for the MSCT topology as shown in figure 6, will affect directly the next result concerning network's lifetime. The figure 7 shows as the times when the first node dies and also the network's lifetime for different topologies. It's clear that the moment of first node dead (FND) in the network for $MSCT$ is previous than the same moment for Cluster-Tree and mesh topologies as well as the network's lifetime (NL). We can clearly deduce that the network's lifetime has been significantly improved by using our improved MSCT topology.

Fig. 7. First node dead and Network's lifetime according to topology.

In summary, the simulations and experimental results shows satisfactory performances of our MSCT topology in terms of energy consumption and network's lifetime in both simulation and experiment results compared with other existing and typical topologies. That demonstrates that our topology improved the performances of the sensor network by optimizing the process of topology construction and control and taking into consideration the indoor environment that include walls and obstacles that attenuate the transmitted signal between nodes of the network.

6. Conclusion

In conclusion, Zigbee sensor networks have been widely used for indoor applications as home automation and industrial monitoring because of their low cost, low power consumption and easy implementation. In this paper, we developed an energy efficient indoor sensing system based on IEEE 802.15.4 standard and Zigbee specifications. We presented our improved cluster-tree topology based on minimum spanning trees called Minimum Spanning Cluster Tree (MSCT). This topology takes into consideration the indoor environment constrains as walls and obstacles, and calculates the weight of connection between nodes by taking into consideration the path loss model. This topology process that starts with network's construction and then control the network using an algorithm we presented in the paper showed very satisfactory results in term of energy consumption and network's lifetime.

Extensions of this work includes testing performances of MSCT topology in large scale network and industrial platform. We also project to introduce new energy harvesting technologies to prolong network's lifetime in this kind of sensor networks.

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