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Diagnosis of Failures in Zigbee Based Wireless Sensor Networks

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Abstract-In this work, based on the characteristics of ZigBee protocol, ZigBee technology is used to model and simulate a wireless sensor network. Nodes failures and their effect on the traffic are considered in different scenarios for cluster-tree topology to certify the reliability of this communication network. The parameters: throughput, delay, data traffic sent, and data traffic received are measured during these scenarios. These scenarios are performed taking into account the specific features and recommendations of the IEEE 802.15.4/ZigBee standard using OPNET Modeler 14.5. Simulation results quantify the impact of a ZigBee device failure on the performance factors.

Keywords: Wireless Sensor Network (WSN), WSN Failure, Cluster-Tree Topology, IEEE 802.15.4. ZigBee

1. INTRODUCTION

The problem of reliability is central to Wireless Sensor Networks (WSNs). Nodes are battery-powered and communications are radio-based. However, nodes in WSNs are prone to failure due to the energy depletion, hardware failure, communication link errors, malicious attacks, etc. which means nodes can fail and temporary/permanent disconnections may occur. The dysfunctioning of few nodes can cause significant topological changes and might require packets rerouting and network re-organization.

Bluetooth (over IEEE 802.15.1), UWB (over IEEE 802.15.3), ZigBee (over IEEE 802.15.4), and Wi-Fi (over IEEE 802.11a/b/g) are four protocol standards for short range wireless communications [1]. ZigBee is a new wireless communication technology based on wireless standard 802.15.4. Compared with other protocol standards, ZigBee stack offers a practical application solution coupled with low rate, low cost, low energy consumption characteristics for wireless sensor network [2].

ZigBee supports three kinds of networks, namely star, tree, and mesh networks. A ZigBee coordinator is responsible for initializing, maintaining, and controlling the network. A star network has a coordinator with devices directly connecting to the coordinator. For tree and mesh networks, devices can communicate with each other in a multihop fashion. The network is formed by one ZigBee coordinator and multiple ZigBee routers. A device can join a network as an end device by associating with the coordinator or a router. In a tree network, the coordinator and routers can announce beacons. However, in a mesh network, regular beacons are not allowed. Beacons are an important mechanism to support power management. Therefore, the tree topology is preferred, especially when energy saving is a desirable feature [3].

The purpose of this research is to dimension the effect of ZigBee WSN devices failures on the overall efficiency of the network. Modeling the fundamental performance limits of Wireless Sensor Networks (WSNs) is of paramount importance to understand their behavior under the worst-case conditions and to make the appropriate design choices so that the requested QoS of the sensor network application is satisfied.

This paper is organized as follows. Section 2 tackles related work; in section 3, ZigBee based system model is presented; section 4 introduces the adopted data transmission process; section 4 presents simulation scenarios; simulation results are discussed in section 5; section 6 gives final concluding remarks and directions for future research.

2. RELATED WORK

Since WSNs become more and more popular, the quality of service provided by a WSN in the aspects of information integrity, data correctness and transmission in a timely manner have drawn more and more attention to researchers and system designers.

Baronti et al. presented a comprehensive review of ZigBee/IEEE 802.15.4 dealing with different aspects and deployments of this protocol in wireless sensor networks [4]. Analysis of the QoS performance evaluation of the ZigBee protocol for different WSN topologies and routing schemes is addressed in [5, 6]. The energy consumption for the ZigBee-based WSNs is modeled and analyzed for potential applications in [7, 8]. Koubaa et al. proposed a synchronization mechanism based on Time Division Beacon Scheduling (TDBS) to build cluster-tree WSNs [9]. Pan and Tseng tackled a minimum delay beacon scheduling problem for quick convergecast in ZigBee tree-based wireless sensor networks and proved that this problem is NP-complete [3]. A power-source-aware routing algorithm for tree topology ZigBee networks that require only minor modifications to the current specification has been proposed in [10]. A contribution with a methodology based on network calculus, which enables quick and efficient worst-case dimensioning of static or even dynamically changing cluster-tree WSNs where the data sink can either be static or mobile is presented in [11]. Shih et al. exploited the regularity in node mobility patterns to reduce the frequency of route reconstructions and ensure that the transmission of data to mobile nodes is efficient. Cuomo et al. presented a cross-layer approach to address the problem of PAN coordinator election on topologies formed in accordance with the IEEE 802.15.4 [12].

Fault detection and recovery mechanism for ZigBee wireless sensor networks is presented in [13].Techniques for assessing the fault tolerance of ZigBee WSNs challenged by radio frequency (RF) interference or WSN node failure have been developed in [14]. To increase the data delivery ratio and mitigate the effects of packet loss caused by the node mobility, a ZigBee node deployment and tree construction framework has been proposed in [15].

3. SYSTEM TOPOLOGY

IEEE 802.15.4/ZigBee devices can be classified into Full Function Devices (FFD) that implement the full IEEE 802.15.4/ZigBee protocol stack and Reduced Function Devices (RFD) implementing a subset of the protocol stack. The ZigBee PAN (personal area network) coordinators and routers are categorized as FFD and end devices are categorized as RFD. The devised system distributes different ZigBee devices in an area (an office network scale) of (100m x 100m). The topology of a WSN formed according to the IEEE 802.15.4 MAC layer is a cluster-tree where the PAN coordinator is at the root of this tree. A cluster-tree topology has been considered due to its increased coverage area in contrast to other topologies as star and mesh. ZigBee cluster tree networks allow the per-cluster dynamic allocation of guaranteed bandwidth and duty-cycles, enabling real-time and energy-efficient communications in wireless sensor networks.

The system model has one ZigBee Coordinator (ZC) identifies the entire network and each ZigBee router (ZR) assumes the role of a cluster-head, allowing the association of other ZRs and ZigBee End Devices (ZEDs) in a parent-child relationship as shown in figure (1).

Each of these routers has different numbers of children represented by ZEDs connected to them as clusters. The PAN coordinator forms the first cluster by establishing itself as the cluster head with a cluster identifier of zero. There can be multiple clusters in a network. When the association process is successful, the child device (ZED or ZR) associates the network through its parent (ZR).

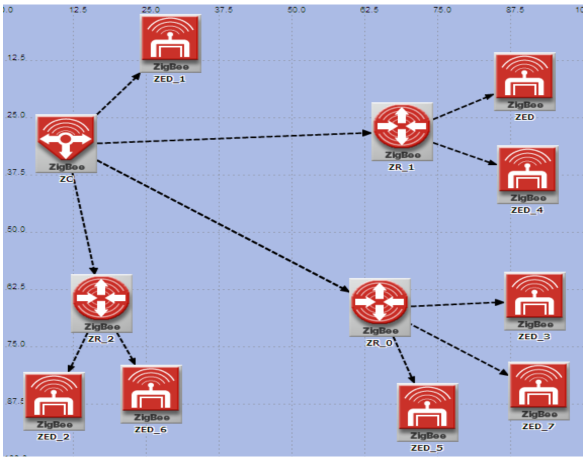

Figure 1: A Cluster-Tree Topology

Inside a cluster, the communication is established via the cluster-head and the direct communication between two children in the same cluster is not possible because ZED does not have the ability to relay messages. Devices can communicate with each other in a multi hop fashion. This topology allows for different levels of nodes, with the coordinator being at the highest level. For messages to be passed to other nodes in the same network, the source node must pass the message to its parent (ZR), which is the node higher up by one level of the source node, and the message is continually relayed higher up in the tree until it can be passed to the destination node for data transmission process. This topology allows the nodes (ZEDs and ZRs) to save their energy by entering the sleep mode. The assumed cluster ZigBee network parameters are presented in Table (1).

4. DATA TRANSMISSION PROCESS

The data transmission process of adopted ZigBee network is represented in figure (2). When the monitoring node sends an order to inquire about the state, the order is transmitted to the coordinator. The cluster head broadcasts towards its member nodes to activate the dormant nodes to carry out data communication. After receiving the data collected and sent by the nodes, the cluster head integrates and returns the data to the monitoring host along the original path. If the target network coordinator is not found or not connected, the order will be deserted and returned back to the monitoring node. Most nodes in the network are in a dormant state to save energy and extend the lifetime of the network.

Table 1: Traffic Parameters for Cluster-Tree Network

Parameters	Application Traffic					
	Device type	Packet Interval time	Packet Size	Start time	Stop time	Destination
Cluster-Tree Network	PAN Coordinator	Constant (1.0)	Constant(1024)	Uniform(20,21)	Infinity	All Coordinators & Routers
	Routers	Constant (1.0)	Constant(1024)	Uniform(20,21)	Infinity	All Coordinators & Routers
	End Device	Constant (1.0)	Constant(1024)	Uniform(20,21)	Infinity	Router (parent)

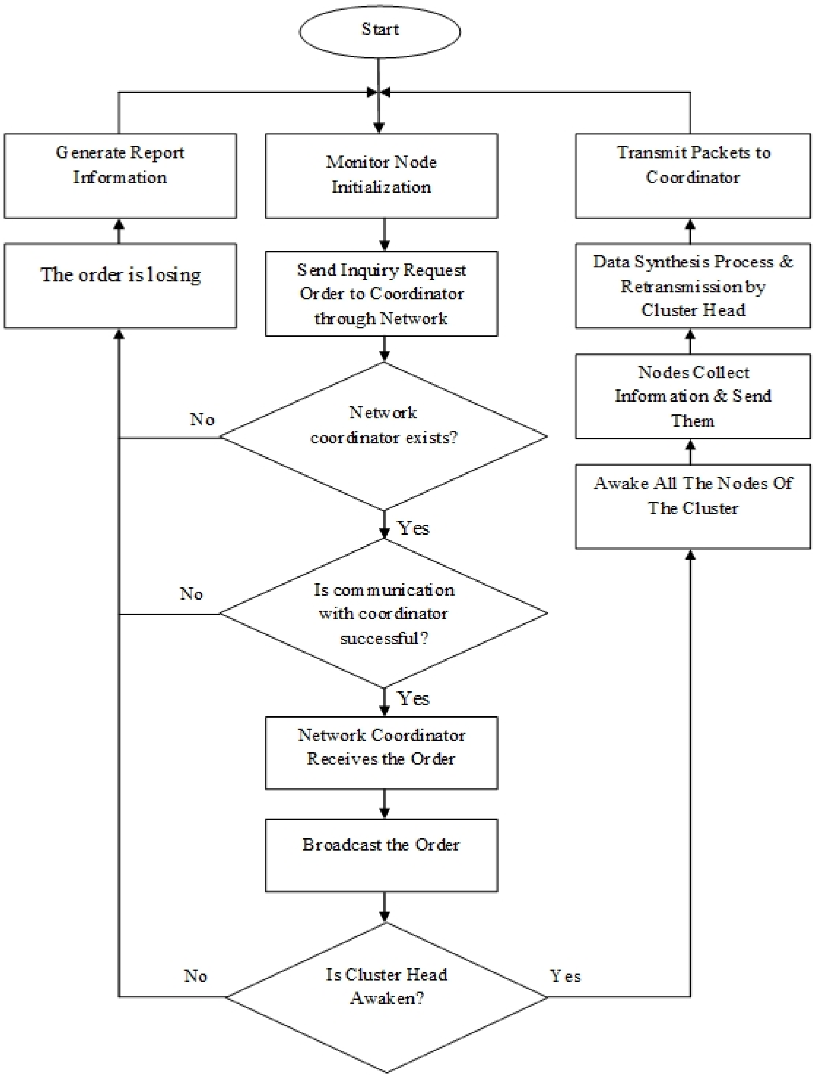

Figure 2: Data Transmission Process

5. FAILURE SIMULATION

There are three types of ZigBee devices; each of them has a special functionality. Failure can be differentiated based on the types of the nodes where the failure occurs. Three cases are simulated:

5.1 Coordinator Failure

In case of ZC failure, the routers and end devices take notice of the coordinator failure and decide to restart to join a new network. A device can recognize the ZC failure by sending "ACK message" to the coordinator in a pre-determined time. If the coordinator doesn't reply (coordinator failure or broken link), the device resets its MAC address and starts to find another network. This is illustrated by a sample code in figure 3. The system supports a native fault-tolerance mechanism called as the orphaned device realignment. This recovery/repair procedure is activated when there are repeated communication failures in the request for data transmission (data frames sent without receiving the requested acknowledgment) between the device and its parent or when the device loses synchronization with its parent. When a device is found orphaned, a realignment or a channel re-scan process will be invoked. To join a new network, the ZigBeeevice elects a new PAN coordinator on the basis based on the sensors' position: nodes that are close the ‘‘center’’ of a cluster are elected cluster-heads.

```
static void failNode(void * ptrVoid, int iCode);
void wpan_prj_init();
…
void wpan_prj_init() {
double dInterruptTime = 100.0; // time is second that the interrupt is scheduled
int iCode = 0; // verification code
void * ptrVoid = 0; // data structure to send to the called function
FIN (wpan_prj_init());
dInterruptTime += op_sim_time();
op_intrpt_schedule_call (dInterruptTime, iCode, failNode, ptrVoid);
FOUT;
}
```

Figure 3: Coordinator Failure Detection

5.2 Router Failure

The model configures a number of (ZRs and ZEDs) connected to one coordinator and one of ZRs practices failure as shown in figure (4). In cluster-tree network, the main reasons for failure are:

1. Problems on the wireless link between the parent and the child device that mainly result from high interference rates within the operating frequency band. This may occur at different moments:

- During a data transfer: in this situation, the data being transferred is lost and the data frame needs to be re-sent.
- During the synchronization: in this case, the device does not receive beacon frames and cannot properly synchronize with its parent.

2. The parent may be experiencing hardware, battery or software problems that prevent it from performing normal operation.

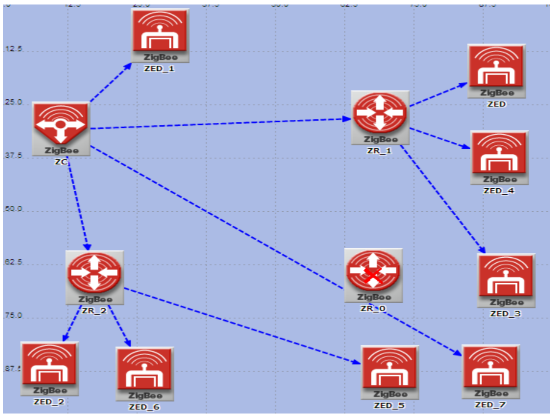

Figure 4: ZigBee Router Failure Scenario

5.3 End-Device Failure

The model configures a number of (ZRs and ZEDs) connected to one coordinator and some of ZEDs practice failure as shown in figure (5).

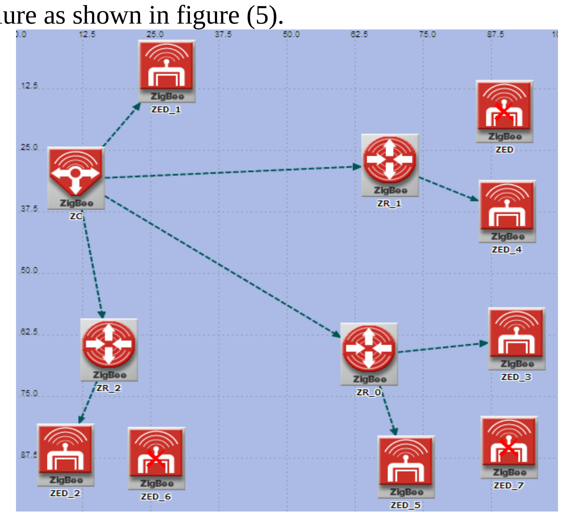

Figure 5: ZigBee End Devices Failure Scenario

When a node in the network goes down, all its child nodes look for a new parent. If a new parent is found, the child node's address changes. This in turn results in the changing of the address of all the children of the child node and continues recursively till it leaves the network. While obtaining a new parent, if the depth of the node increases, devices that were part of the network earlier may not be able to join. A total link failure occurs if a child device loses connectivity with its parent. In case of a total link failure, the child node will neither be able to exchange any data nor receive beacon frames from its parent. Link failure can be classified into two categories in terms of the number of broken links: single-link failure and multiple-link failure.

6. SIMULATION RESULTS

In this section simulation results are presented to show the impact of ZigBee device failure on the performance factors: throughput, delay, data traffic sent and data traffic received.

A- Throughput

Throughput is shown in figure (6). It indicates that the network with ZED failure has the same throughput of normal functioning network whereas the network with ZR failure has the lowest throughput. This result shows that the ZED does not have any noticeable effect on the global throughput but the effect appears when the network has a ZR failure.

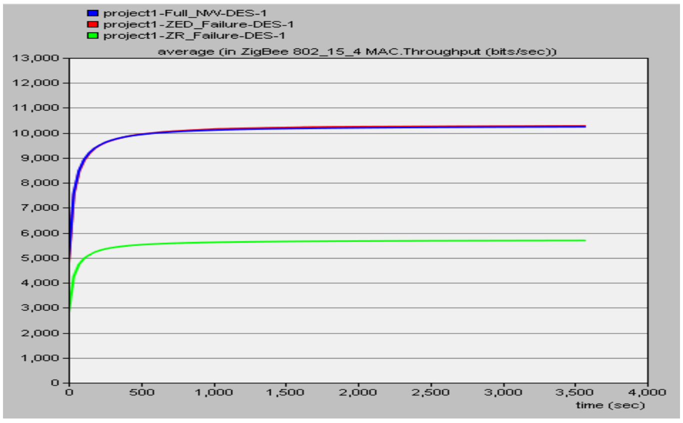

Figure 6: Throughput

B-Delay

Figure (6) shows the delay for normal functioning network, ZED failure and ZR failure respectively. Each ZED connects with the network by the routing table in ZRs so if ZED has a failure, ZR (parent of failed ZED) must update its routing table and this procedure takes some time depending on the type of used router. This result justifies the slight change in the delay while a network with a ZED failure has a higher delay than others because this network has three ZRs and the updating procedure causes a delay.

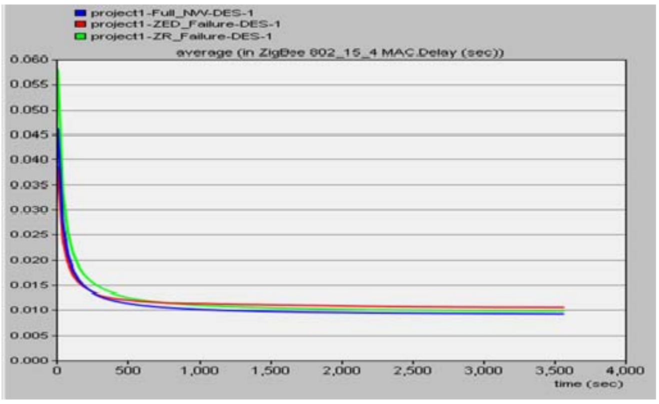

Figure 6: Delay

C- Data Traffic Sent

Data traffic sent in case of normal network, ZED failure and ZR failure is shown in figure (7). This result indicates that the ZED doesn't have any considerable effect on the global data traffic sent but the effect appears when the network has a ZR failure because RFDs do not have the ability to relay messages.

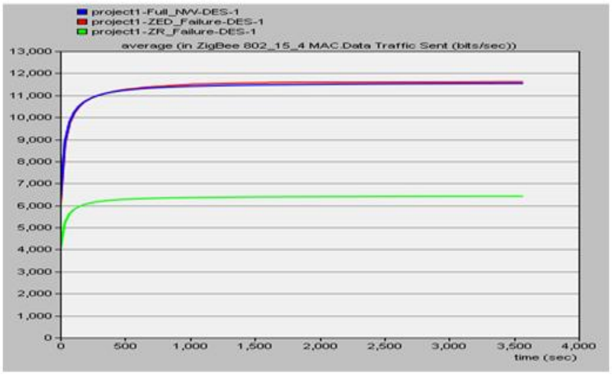

Figure 7: Data Traffic Sent

D- Data Traffic Received

Figure (8) shows that data traffic received for normal functioning network, ZED failure and ZR failure respectively. This result shows that the data traffic received varies considerably when any failure in any type of ZigBee device occurs. In case of ZED failure, the ZR (parent of failed ZED) suffers from packet losses so data traffic received will be decreased. Also data traffic received in ZR failure network is minimum because the failure router does not receive or send any traffic and its children need to continue to route the traffic to the destination. When they lose their original path, they try to find the next alternative path to its destination and this causes more collision and packet loss and reduces the received data traffic.

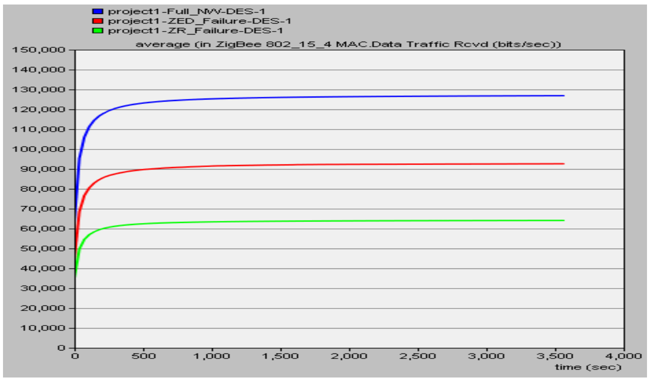

Figure 8: Data Traffic Received

7. Conclusions

This paper presents a measurement and analysis of the impact of failures in a ZigBee cluster-tree topology WSN. Overall effects of failures on the traffic factors are considered to certify the reliability of this communication network. The results indicate that throughput is low in case of ZR failure. Data traffic sent is low in case of ZR failure. Data traffic received is low in case of ZR failure. Delay is high in case of ZED failure. The result concludes that the coordinator failure prevents the whole network from communicating. Router failure blocks a part of the network and thus may be less critical than the coordinator failure. However, end device failure, usually, is not critical. Based on simulation and analysis of results this paper can be considered as a guide for researchers in evaluating Zigbee wireless sensor networks.

Ongoing and future work includes improving the current methodology to encompass a fault-tolerant cluster-tree operating to provide a model that enables real-time control actions, that is, the sensor/actuator nodes assuming the role of controlling sink.

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