Effects Of Topological Variation To Energy Consumption In Zigbee Networks

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Abstract— This paper evaluates the effects of topological variation on performance of ZigBee paying attention to throughput and energy consumption. Zigbee is based on the IEEE802.15.4 standard in the wireless sensor networks. Current trends of conserving power/energy have led to a rise in its demand for office, home, and industrial automation. Topology is one of the critical parameters in Wireless Sensor Networks. Simulation of the Zigbee standard has been done using the REVERBED Academic Edition17.5 for the star, tree, and mesh topologies with 10,20,30 and 40 nodes. Mathematical analysis of results from the simulation was done in MATLAB 2020a to determine energy consumption. A measure of merit used is goodput per joule. Tree achieved the best efficiency for network with less than 40 nodes and mesh proving to be the best for 40 nodes and above.

I. INTRODUCTION

ZigBee is wireless networking technology defined by ZigBee Alliance and standardised in 2003 as IEEE 802.15.4. The name refers to the waggle dance of honeybees after they have returned to the beehive. Applications such as building automation networks, home security systems, industrial control networks, remote metering and PC peripherals have benefited from Zigbee protocol. More research work in this area may add to the number of applications which benefit. Some of its notable attributes are high data reliability, low cost, less consumption of power, less maintenance and high security. The frequency bands supported by ZigBee are 868 MHz, 915 MHz and 2.4GHz with data rate of 250 kbps. It is best suited for periodic or discontinuous data or a single signal transmission from a sensor or input device.[1]

Recommended transmission in home automation is 10 to 100 meters line-of-sight, depending on power output, environmental characteristics amongst other factors. The ZigBee protocol can support over 64,000 nodes and can operate in three network topologies: Star, Tree and Mesh. The large number of supported nodes is another appealing characteristic, specifically in industrial applications.[2] This paper evaluates the ZigBee topologies by using an OPNET simulator and an analysis using MATLAB to find the best topology in terms of energy consumption using goodput as a figure of merit.

This paper constitutes 5 sections:

Section	*Title*
1	Introduction
2	Zigbee Topologies
3	Simulation and Analysis
4	Results and Discussion
5	Conclusion

II. ZIGBEE TOPOLOGIES

Topology is the configuration of the hardware components and how the data is transmitted through that configuration.[1] ZigBee uses various topologies offered by ZigBee Alliance which specifies the networking layer of ZigBee.[2] The selection of topology in network depends on the required task and Quality-of-Service priorities. The network topologies are:

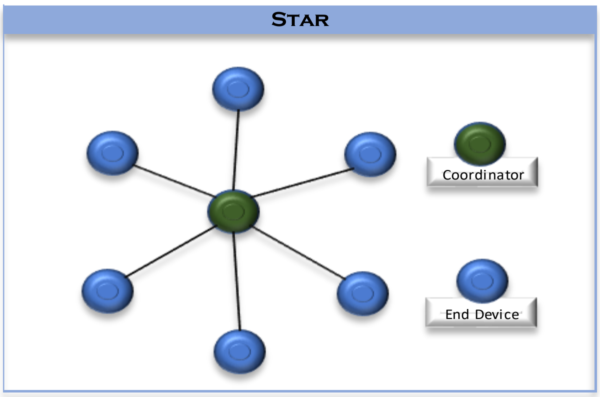

Figure 1 shows the Star Topology in ZigBee network

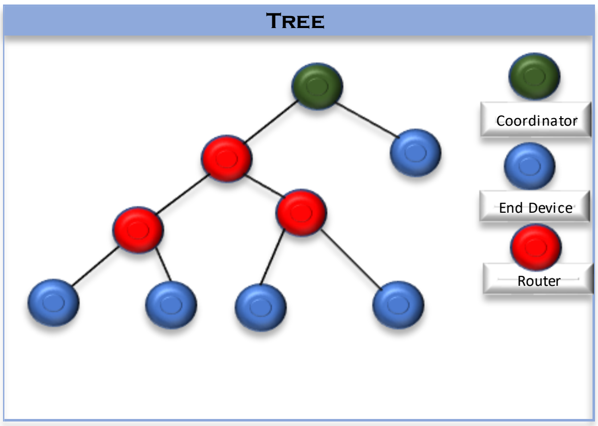

Figure 2 shows the Tree Topology in ZigBee network

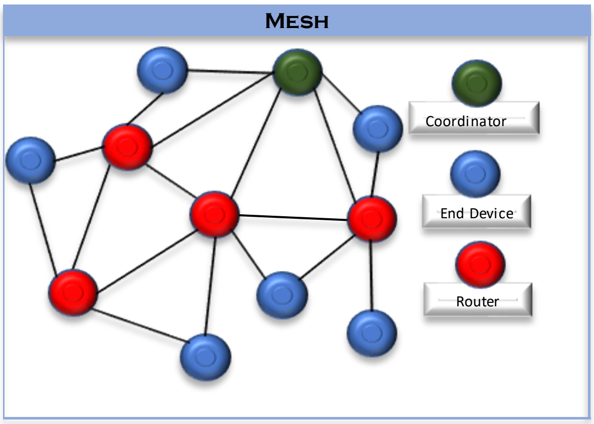

Figure 3 shows the Mesh Topology in ZigBee network

Star Topology

It mainly consists of coordinators and end devices as shown in figure 1. Many find this topology easy wire and install because end devices are connected directly to the coordinator for data transmission. All components are arranged in a way that causes no disruptions to the network connecting or disconnecting devices. In times of network challenges, it is easier to troubleshoot compared to other topologies. The major disadvantage of this topology is that the network operation relies on ZigBee Coordinator and there is no alternative path from sender to receiver. It offers no other alternative routes in the case of transmission failure. Its simplicity, of all traffic passing through the coordinator maybe a drawback as it quickly gets overwhelmed or congested as traffic increases.[3]

Tree Topology

The Tree topology is made up of a coordinator which are usually connected to the routers that will connect to the end devices/other equipment as shown in figure 2. However, a coordinator can connect directly to end devices and a router can also be connected to several routers. The structure described above can have several hierarchies. It usually ends up in a tree like visual which has coordinator at the top.

While the router is used to diffuse messages, it can also be used as an end device though with a different functionality. It is noteworthy that components of a lower level cannot perform the functions of a superior component. This means that while a router can be used as an end device, the reverse is not true. Therefore, an end device cannot have children.

Packets can only move in one direction. Therefore, another of this topology is that there is no alternative if the bond necessary to reach the destination fails.[4]

Mesh Topology

The Mesh topology has a structure same as the one of tree with a coordinator at the top of the tree as depicted in figure 3. It has a flexible protocol which allow packets to take the most cost-effective route. Coordinator can be linked to several routers and end devices which can be referred to as children. A mesh topology is characterized with a more effective propagation of the packets using logic which is usually referred to as self-healing. This means that it has capacity to detect alternate roads if a bond breaks down or if there are congestions. A concept of link budget is usually used to help the network find the open shortest path first.[5]

III. SIMULATION AND ANALYSIS

In order to evaluate the energy consumption performance of the three topologies for ZigBee, a model was created using the OPNET network modeler. This will give us an insight into Quality-of-Service statistics which are key in calculating energy consumption.

The model is comprised four scenarios differentiated by the number of nodes, that is, 10, 20,30 and 40. Deployed in a square area of 2500 square meters. The three topologies were implemented directly without multi-hopping.

Find the parameters detailed below.

Parameters	Star	Mesh	Tree
No. of Sensor Nodes	10 | 20 | 30 | 40	10 | 20 | 30 | 40	10 | 20 | 30 | 40
Number of Retransmissions	5	5	5
Minimum Backoff exponent	3	3	3
Maximum Backoff exponent	4	4	4
Packet power Threshold	-80	-80	-80
Mesh Routing	Disabled	Enabled	Disabled
Transmission band (MHz)	2450	2450	2450
Transmit power	0.4	0.4	0.4
Transmit power(coordinator)	0.5	0.5	0.5
Packet size (bytes)	128	128	128
Packet inter arrival time(sec)	1	1	1
Data Rate (Kbps)	250	250	250

Table 1. Zigbee Model Specifications

MATLAB ANALYSIS

In this paper a methodology which is uniform to all WSN when it comes to energy consumption calculations. Therefore, regardless of the wireless standard deployed and the topology of the network, energy consumption is based on the following Equations:

$$E_{total} = V \times \sum_i I_i \times t_i$$

According to Equation above, the energy consumed by a WSN is comprised of three components: a constant operating voltage (V), a current (I) consumed by the node at different operation states and the corresponding time (t) for each operation state. Subscript i denotes the four different operation states: transmission, reception, idle and sleep.[6]

The Four States

Each cycle has four states. A cycle is basically, the inter-arrival time between packets. The power consumed is characterized by voltage and current. This is a technology dependent parameter that varies from one node to another. However, the time durations are usually protocol dependent. In our case duration was determined by the following factors. Which are the number of end devices/nodes, data sent and interference in the environment. Therefore, great attention will be given to time duration which correspond to the state in operation. Ideally, all nodes follow the same cycle or sequence as they go through the four operational states. [7]

Transmission	Receiving	Idle	Sleep
32	25	10	3

Table 2. Current Specifications(mA)

A. *First State : Transmission Time (T_{Tx})*

The first state is transmission during which both the processor and the radio component are active, processing and transmitting bits. Additionally, these components are active in the reception state to receive packets, waiting for acknowledgements or to scan the medium to carry out channel assessment. [6]

$$T_{Tx} = (Payload + Overhead) / Data\ Rate$$

B. *Second state : Reception Time (T_{rx})*

The model adopted in this paper is based on Bianchi's work for the IEEE 802.11 wireless standard. The model is based on the M/G/l queuing system in which the receiving time is mainly comprised of the random backoff time as well as the CCA time. Packet arrival rate and number of contending nodes are the key factors that determine receiving time. The purpose of this model is to estimate the expected service time of the M/G/l queuing system, $E[D_{HoL}]$, where HoL denotes Head of Line. The value of $E[D_{HoL}]$ depends on the probability that the channel is busy at the CCA time.[7]

$$T_{rx} = \sum_{i=0}^{M} \alpha^i (1-\alpha) \times (i+1) + \alpha^{M+1} \times (M+1)$$

$$\alpha = \frac{(n-1) \times (1-P_{loss}) \times E[\Gamma] \times (T_{CCA} + T_X + (2 \times T_{tr}) + T_{ACK})}{\left(\frac{1}{\lambda}\right) + E[\Gamma] \times E[D_{HoL}]}$$

$$E[D_{HOL}] = \sum_{v=0}^{M} \alpha^v (1 - \alpha) \{\sum_{i=0}^{v} \frac{W_i - 1}{2} \times \sigma + (v+1) \times T_{CCa}\} + \alpha^{M+1} \{ \sum_{i=0}^{M} \frac{W_i - 1}{2} \times \sigma + (M+1) X\, T_{CCa} \}$$

Where: M - maximum number of retry

α - probability of the medium being busy

n - number of nodes

P_{loss} – packet loss probability

CCA – Clear Channel Assessment

$E[D_{HoL}]$ – Duration for Head of Line

C. *Third State : Idle Time (T_{idle})*

During the third operational state, idle current is consumed by the processor to process the sensed data. The total CCA time is NCCA multiplied by Tcca. Accordingly, subtracting the total CCA time from $E[D_{HoL}]$, the idle time is obtained. During this time, the network will be busy causing the node to be in backoff. Therefore, the radio component of the node will be off during idle time.[8] Idle Time = $E[D_{HoL}]$ – Total CCA

D. *Fourth State: Sleep Time*

In this state both the radio component and the processor are OFF. It is worth mentioning that, before a node goes into the sleep or idle state, it sets a timer to be able to determine the exact duration over which the radio component remains OFF.[7]

Sleep Time = Cycle Time – Idle Time - NCCA - T_{Tx}

IV. RESULTS AND DISCUSSION

Throughput is the amount of data quantity transferred successfully from one node to another (from sender to receiver) within a specific period of time in seconds.[9] This will vary based on network topology. In our case data throughput is generally high in Mesh followed by Tree and Star .

Nodes	10	20	30	40
Star	2,947	5,482	7,698	10,487
Tree	8,724	17,368	21,010	25,686
Mesh	9,061	18,267	19,383	39,985

Table 3. Throughput (Bytes/Sec)

Data sent usually follows the same pattern with throughput while considering data dropped.

Nodes	10	20	30	40
Star	3,339	6,210	8,721	11,880
Tree	3,946	7,187	11,049	12,573
Mesh	3,839	6,800	10,400	12,789

Table 4. Data Sent (Bytes/Sec)

Goodput per Joule

Ignoring all Quality-of-Service factors and considering energy consumed by the system only may be is deceptive. Therefore, a figure of merit has been developed to account for the data dropped in the energy calculation of each system. The figure of merit is obtained by dividing the useful data transmitted by total energy consumed. It is referred to as goodput per joule, where the goodput denotes the useful data received by the sink or coordinator excluding any overheads by the protocol [6]. The goodput per joule for each topology by number of nodes is shown below:

Goodput per Joule = Data Sent / Total Energy Consumed

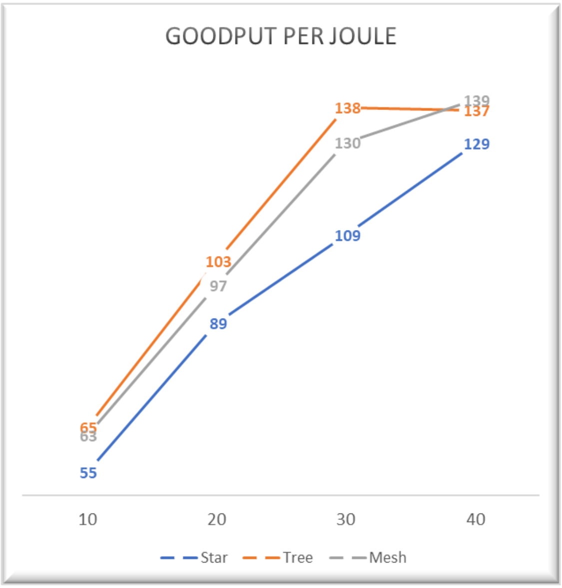

Chart 1. Goodput Per Joule

V. CONCLUSION

The study performed in this paper provides a basic

methodology for obtaining the energy efficiency of a Zigbee network considering variation in topology. It also gives guidance as to which topology to deploy according to the requirements of different applications and Quality of Service-QoS priorities. This guidance is facilitated through the figure of merit discussed in this paper, goodput per joule. This figure of merit accounts for the energy consumed per useful data received by the sink, thereby producing a methodology for measuring the performance of a given system taking into consideration data retransmitted and dropped.

Basically, the most efficient is Mesh. It is noteworthy that no topology is superior to the other, but rather each topology is most suitable in terms of performance efficiency required for a given application. As expected, Mesh would perform much better in an application where the emphasis is on high energy consumption with several nodes. However, this is not cast in concrete as in some cases Tree topology performed better than Mesh. Therefore, it is necessary to simulate each scenario using feasible parameters before adopting any topology.

It is worth noting that the study at hand offers a generic method of studying energy efficiency of Zigbee networks based on topology. Additionally, the paper discusses an algorithm for energy calculations. Thereby providing general trends as well as relations between different parameters, thus offering a guideline as to which protocol to use for a given application.

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