Power Characterisation of IEEE 802.15.4 and Zigbee Wireless Networks

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Abstract: This paper analyses the power consumption and delivery ratio of Zigbee wireless networks using the mesh and star topologies for a single sink real time monitoring system. The analysis involves modelling the behaviour of a Zigbee network at varying traffic rates and examining the operation of the beacon and non beacon modes of its underlying IEEE 802.15.4 standard in the star network architecture. IEEE 802.15.4 networks have been analysed with NS-2 simulations and hardware experiments. Zigbee was only analysed using hardware experiments due to limitations with NS-2. The results show that non beacon mode has the lowest power consumption and best delivery ratio at all tested traffic rates.

Keywords: IEEE 802.15.4, Zigbee, NS-2, power characterisation, wireless networks.

1 INTRODUCTION

Zigbee is a relatively new wireless mesh networking standard with emphasis on low cost and energy conservation. It is intended for use is in wireless monitoring and control applications such as sensors and remotely operated switches where the end nodes are battery powered.

The Zigbee networking protocol was developed in response to the unsuitability of current wireless protocols like WIFI and Bluetooth for applications which require very long battery life, high reliability and low data rates such as remote monitoring and building automation. The first Zigbee specification was ratified in late 2004 and is based upon the physical (PHY) and media access control (MAC) layers of IEEE standard 802.15.4.

Since Zigbee and its underlying standard IEEE 802.15.4 are relatively new, there has been little research investigating the power consumption of the different network topologies and comparison between the operating modes. Most studies focus on the beacon enabled network mode because many applications require bi-directional data flow, and in star networks research has shown that it gives worthwhile energy savings. However in a real time monitoring application, data flow is mostly one way from the sensor node to a central storage device for processing and recording and therefore beacon enabled mode might not give the best energy savings.

This research investigates the power consumption of the transceiver and packet delivery ratio with a varying traffic rate for both Zigbee and pure IEEE 802.15.4 wireless networks under different system configurations. For IEEE 802.15.4 using the star network topology, the effect of two system parameters, Beacon Order (BO) and Superframe Order (SO) was recorded on the power consumption and delivery ratio of packets sent from nodes to the coordinator using simulations with NS-2 and results obtained from real network experiments.

The Zigbee network was analysed on a real network using both the star topology and the much more popular mesh network topology with a varying traffic rate. Due to limitations with NS-2, the Zigbee network was not able to be simulated.

1.1 Related Research

Since Zigbee and its underlying standard IEEE 802.15.4 are relatively new, there has been little research investigating the power consumption and delivery ratio of the different network topologies and comparison between the operating modes.

Zheng and Lee [1] developed a computer simulation model of the media access control (MAC) and physical (PHY) layers of IEEE 802.15.4 for Network Simulator-2 (NS-2)[2] to quantify its operation. Their research shows that IEEE 802.15.4 is an excellent low power low data rate wireless standard upon which applications can be built. The simulation model has been the subject of a large number of research projects, several of which are reviewed in the following paragraphs.

Huang and Pang [3] and Kovakka et al [4] investigated the effect of BO and SO on the power consumption of a small star network, while [5] also investigated non beacon mode. Their work showed that these parameters can considerably increase the power consumption if the parameters are set incorrectly.

A beacon enabled star network was also researched by Ling-xi et al. [6]. They demonstrated that adjusting the transmission power does not have a large effect on overall power consumption because the time spent in transmit mode is small. They and [7] showed that increasing the number of network nodes increases node power consumption due to extra network contention.

Research by [8] is one of the few studies that focused on real Zigbee devices. Their research focused on investigating data rate and delivery ratio with varying BO, number of nodes and data packet sizes. Although they only focused on the situation where BO = SO (duty cycle 100%) they show that a higher throughput is possible in non beacon mode.

Singh et al [9] highlighted several inconsistencies between the NS-2 IEEE 802.15.4 simulator model and the IEEE 802.15.4 standard and demonstrated that the clear channel assessment functionality in IEEE 802.15.4 consumes a significant amount of energy, particularly at higher data rates.

Rao [10] performed extensive analysis on a beacon mode IEEE 802.15.4 star network using NS-2. His research discovered several issues with the NS-2 simulation model which were resolved. Battery life was investigated which showed that IEEE 802.15.4 nodes are likely to have a long battery life and good delivery ratio.

1.2 IEEE 802.15.4 and Zigbee Overview

IEEE 802.15.4 was conceived due to the unsuitability of current wireless standards such as Wi-Fi and Bluetooth for low data rate battery powered ad hoc networks. The standard specifies the MAC and PHY layers of the open standards interconnection (OSI) network model while leaving the development of the upper layers to the designer.

The standard defines three types of network nodes, PAN coordinators, Full Function Devices (FFDs) and Reduced Function Devices (RFDs). The PAN coordinator is responsible for creating the network and is often used as a gateway to other networks such as Ethernet. There must be only one PAN coordinator per network. FFDs are capable of communicating with all device types as well as creating sub networks and managing routing and addressing of RFDs. RFDs are intended to be extremely simple devices with minimal hardware and software resources. RFDs can only communicate with FFDs or the PAN coordinator, not with another RFD.

1.2.1 IEEE 802.15.4 Network Topologies

IEEE 802.15.4 networks can be divided into two main topologies, star and peer-to-peer. A third topology called cluster tree is a variation of the peer-to-peer topology.

The star network topology is more structured than peer-to-peer. The PAN coordinator of the network is always the central node. Communication between devices always occurs via the PAN coordinator which relays messages between devices. Direct messaging between end devices is not permitted.

In the peer-to-peer topology, an arbitrary array of connections can be created between full function devices and the PAN coordinator. Since a network layer is not defined in the standard, routing is not directly supported.

A cluster tree topology is also possible. This is a special case of the peer-to-peer topology. This exploits the fact that RFDs can only associate with FFDs and is used where most devices in the network are FFDs.

1.2.2 IEEE 802.15.4 Physical Layer

The Physical layer in IEEE 802.15.4 is designed to operate in unlicensed frequency bands world wide. Since not all the frequency bands are the same world wide, IEEE 802.15.4 provides three possible operating frequencies, 868 MHz, 915 MHz and 2.4 GHz. Each frequency except 868 MHz has several channels which can be selected by the user. Table 1 lists the available frequencies and channels that can be used by IEEE 802.15.4.

For this research, the 2.4 GHz physical layer has been chosen due to the world wide availability of this frequency band and the wider availability of wireless transceivers at this frequency.

Table 1: Available channels at different frequency bands and locations

Frequency	**Available channels**	**Data rate (kbps)**	**Locale**
2.4 GHz	16	250	World wide
915 MHz	10	40	USA
868 MHz	1	20	Europe

1.2.3 IEEE 802.15.4 MAC Layer

IEEE 802.15.4 networks are able to operate in two different modes of operation, beacon mode or non beacon mode. In non beacon mode, nodes contend for channel access using CSMA/CA. In beacon mode, the network is fully synchronised as the coordinator sends out periodic packets or beacons. This enables nodes to sleep between beacons thus conserving energy. In beacon mode, all transmissions use the superframe structure illustrated in Fig 1.

The superframe is divided into 16 slots with the first slot for the beacon and the rest of the slots for nodes to communicate. At the end of the superframe is an inactive period where devices can sleep. The structure of the superframe is determined by the coordinator and consists of three main sections, the contention access period (CAP), an optional contention free period (CFP, also known as guaranteed time slots or GTS) and the inactive period. The coordinator also determines the composition of the superframe with the Beacon Interval (BI) and Superframe Duration (SD) being adjusted by the Beacon Order (BO) and Superframe Order (SO) parameters.

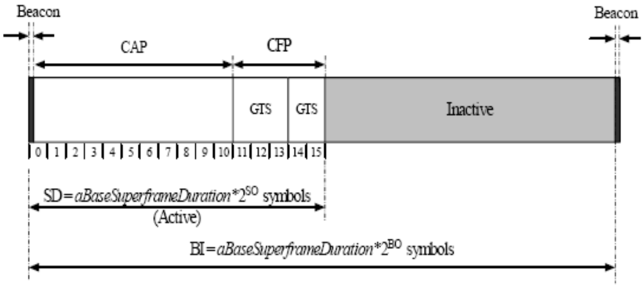

Figure 1: IEEE 802.15.4 superframe structure[11]

1.2.4 Zigbee

Zigbee is a wireless mesh networking standard which is based on the MAC and PHY layers of IEEE 802.15.4. The Zigbee stack layer sits above IEEE 802.15.4 and provides most of the network functionality for the network. This layer is responsible for network formation (if the device is a coordinator), assigning network addresses, routing, security and route discovery.

The network topologies possible with Zigbee are the same as with IEEE 802.15.4 but the peer-to-peer topology has been enhanced due to the routing mechanisms present in Zigbee and is now referred to as the mesh network topology.

With Zigbee the three device types are typically called Zigbee Coordinators (ZC), Zigbee Routers (ZR) and Zigbee End Devices (ZED or just end device).

2 SIMULATION & EXPERIMENTAL ENVIRONMENT

For this research, the following metrics were analysed:

Delivery ratio: This is the percentage of data packets which are successfully received versus the number of packets actually transmitted and is an indicator of how reliable the network link is.

Power consumption: This is the amount of power consumed by an end device in milliwatts.

Battery life: This is the node power consumption converted into a more human readable metric using a chosen battery capacity.

The performance of IEEE 802.15.4 was analysed using the star network topology using simulations and hardware experiments in both beacon and non beacon mode.

Experiments were also performed on hardware devices using the same parameters as the simulations. For this network topology, 10 end devices were arranged in a circle with a 10 metre radius. A single coordinator was located at the centre. This is illustrated in Fig 3.

The chosen hardware platform for this research was a Chipcon CC2431BB development board which can be seen in Fig 2. The simulator was configured to match the characteristics of this hardware.

Figure 2: CC2431BB development board

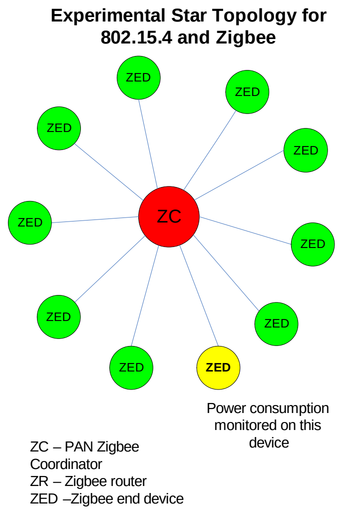

Figure 3: IEEE 802.15.4 and Zigbee star network topology

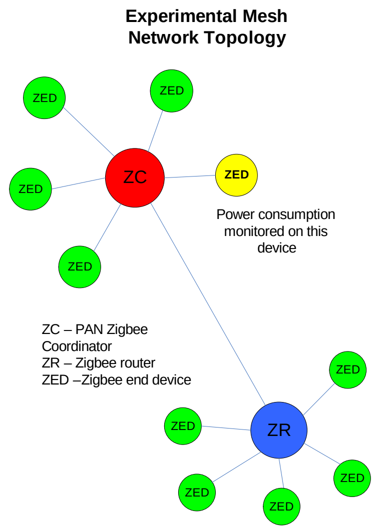

Figure 4: Zigbee mesh network topology

Experiments were also performed for Zigbee networks in both the star and mesh network architectures, however they were not able to be simulated due to limitations with the simulator. Fig 3 and 4 show the network topologies investigated and how the results were obtained from the nodes. Table 2 illustrates the parameters that were common to both the simulations and experiments.

2.1 Simulations

NS-2 is a discrete event simulator developed in a collaborative effort by many institutions and contains code contributions from many researchers. For this research, NS-2 version 2.33 [2] was used which was the most recent version at the time.

The Zigbee/IEEE 802.15.4 simulation model that has been used in this research and is now included in NS-2 was developed by Zheng and Lee [12] from the City College of New York. Ramachandran [13] also contributed many modifications to the original simulation model which have been used in this research.

To get accurate results from the simulations, the simulator needs to be configured to match the hardware characteristics of the Chipcon CC2431BB development board. The additional parameters that need to be configured which are specific to the simulator are listed in Table 3.

Several scripts were written to automate the simulation process. The scripts ran the simulation scenarios, automatically varying the required parameters over the required range as well as extracting the desired metrics from the NS-2 trace files and performing the require data analysis to determine the power consumption, battery life and packet delivery ratio.

2.1.1 Simulator Modifications

Initial simulator results were very different from the initial hardware experiments. After investigating the operation of the simulator the following modifications were made.

2.1.2 AODV and ARP Packets

During the simulations it was noticed that large numbers of Ad-Hoc On Demand Distance Vector (AODV) and Address Resolution Protocol (ARP) packets were being broadcast between nodes which did not match the experimental network traffic on the packet sniffer. Because the simulations involve a star network with the coordinator always being the destination, AODV routing broadcasts are not required. The AODV module in NS-2 was subsequently modified to prevent the route resolve procedures being called using modifications by Rao [10]. ARP was also deemed unnecessary as noted by [10] and [14] and was disabled using modifications provided by Rao [10].

2.1.3 State transitions

While the energy model in NS-2 took into account the energy consumed during state transitions i.e. from receive to transmit, it did not take into account the energy consumed during the power up phase. The Chipcon data sheet specifies a 320μS delay, which was added to the energy model.

2.2 Experiments

To validate the results of the simulator, the same experiments were performed on Chipcon CC2431BB development boards using the Texas Instruments IEEE 802.15.4 and Zigbee network software.

The power consumption was measured using a Measurement Computing data acquisition module connected to a PC running MATLAB which recorded the voltage drop across a precision resistor. A MATLAB script controlled the data acquisition module and calculated the power consumed of the device as well as calculating the battery life based on the battery capacity in Table 2. Due to the time taken to perform the experiments, the power consumption of a single node was measured, as shown in Fig 2 and 3 and it was assumed that it would be similar for the remaining 9 nodes. Research by [15] shows that this is likely to be a valid assumption.

The IEEE 802.15.4 energy model in NS-2 only models the power consumed by the transceiver, and does not include the microcontroller. Because of this, additional post processing was required to exclude the microcontroller power consumption during the wakeup phase from sleep mode before the packet is transmitted.

The coordinator was configured to output received packets to its serial port and an application on the computer analysed the received packets to calculate the delivery ratio for each node.

Zigbee was only able to be tested in non beacon mode due to limitations with the Texas Instruments Zigbee stack.

Table 2: Configuration parameters common to simulations and hardware experiments

Parameter	Range
BO	6-10 and 15(Non beacon mode)
SO	0-2 and 15 (Non beacon mode)
Data rate (s/packet)	30, 60, 100, 200 and 1000
Simulation/Experiment time	1000 seconds
Number of end devices	10
Distance between nodes	10 metres
Traffic direction	Node to coordinator
Packet size	64 bytes
Battery capacity	900 mAH

Table 3: Simulation specific configuration parameters

Parameter	Value
Transmit current consumption	30mA
Receive current consumption	33mA
Sleep current consumption	0.5μA
Random traffic jitter	Disabled
Energy capacity	9720 Joules
Network topology	Star

3 RESULTS

In this section the performance of IEEE 802.15.4 and Zigbee wireless networks are analysed to evaluate the power consumption and delivery ratio of both network types and to compare the simulation and experimental results. Results for the star network topology simulations in both beacon and non beacon mode are compared with results from experiments to determine the optimum network operating mode and also validate the accuracy of the simulator.

The graphs in the following sections illustrate the battery life and delivery ratio results. The power consumption figures have not been included as, for this evaluation, an estimate of battery life was more meaningful in evaluating the suitability of this technology for its use in a real time monitoring system. The aim is to maximise both battery life and packet delivery ratio.

3.1 Beacon mode results

For beacon mode networks, the modified simulator is able to estimate battery life to within 15 percent, often with much greater accuracy (Fig 5 and 7). The exception is beacon order 9 at 1000 seconds/packet, where the error is around 20 percent (due to a lack of space this figure was omitted).

Figures 6 and 8 show a considerable difference in delivery ratio between the simulated and experimental results. The experimental results usually had a 100 percent delivery ratio whereas the simulated deliver ratio began to decrease as soon as the beacon order increased. Analysing the NS-2 trace files shows that this is due to packet collisions between devices. It is suspected that this behaviour is due to a scheduling issue in the simulator as the nodes were started at slightly different times to avoid collisions.

These results show that when the network is operating in beacon mode, in order to maximise battery life (minimise power consumption) and delivery ratio, a good estimate of the traffic rate is required in order to determine the correct BO and SO. It is also noted that increasing SO usually results in a better delivery ratio but often results in a small increase in increase in power consumption due to the longer CAP.

3.2 Non beacon mode results

The delivery ratio graph for non beacon networks has been omitted as the delivery ratio was 100% for all results. Fig 9 shows that using Zigbee results in a significant decrease in battery life (increase in power consumption) compared to IEEE 802.15.4 networks due to the extra routing packets being broadcast. However the resulting battery life is so long that it would outlast the shelf life of most batteries.

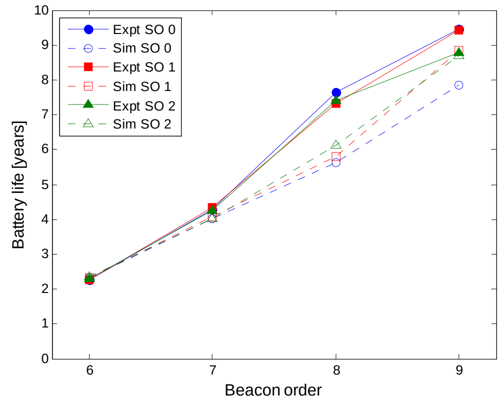

Figure 5: Battery life at 30 s/pkt

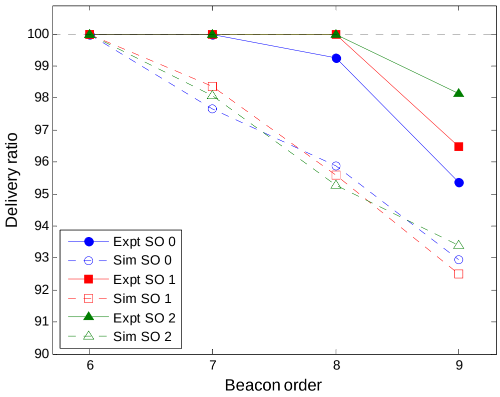

Figure 6: Delivery ratio at 30 s/pkt

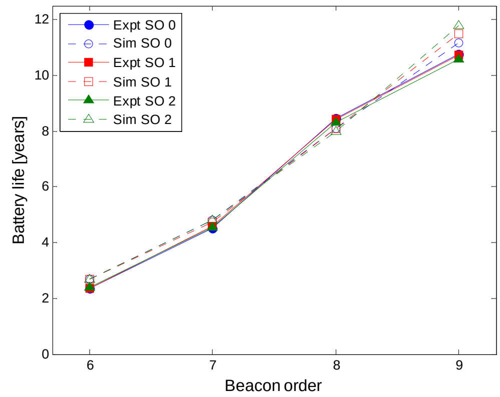

Figure 7: Battery life at 100 s/pkt

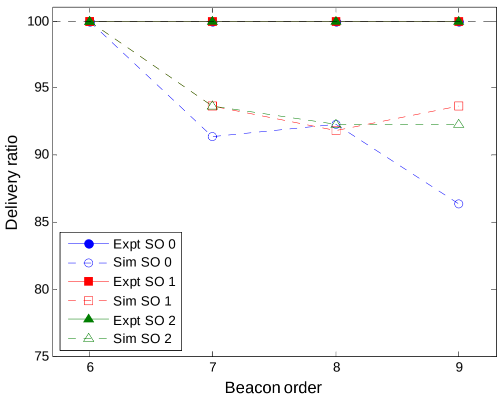

Figure 8: Delivery ratio at 100 s/pkt

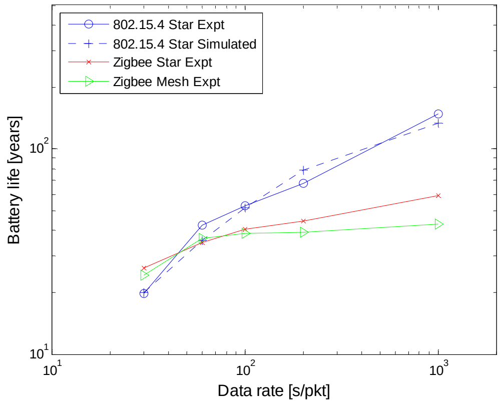

Figure 9: Non beacon mode results

4 CONCLUSIONS

This research has shown that despite previous research focusing on beacon mode, in single sink IEEE 802.15.4/Zigbee wireless networks non beacon mode gives the longest battery life (lowest power consumption) and the best delivery ratio at all tested data rates in both computer simulations and the experimental investigation.

From the results presented, IEEE 802.15.4 in beacon mode in a single sink wireless network results in significantly lower battery life (higher power consumption) and a poorer delivery ratio. However it is likely that in applications where there is bidirectional traffic, the synchronisation provided by beacon mode could be an advantage and could result in fewer collisions than in non beacon mode. This could be the subject of future research.

As mentioned by previous research, and as is apparent in the above results, when operating in beacon mode an idea of the traffic rate is required in order to correctly set BO and SO to maximise delivery ratio and minimise power consumption.

After performing the modifications described to NS-2, results obtained from the simulator were usually within 15 percent of the experimental results. However the poor agreement of the delivery ratio results and apparent scheduling issue indicates that further work is required on the simulator to improve its performance in this area.

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