~ Abstract ~

We conduct a literature survey of four papers examining the performance of the ZigBee standard. The first and second papers describe the maximum throughput and minimum delay of the ZigBee protocol, with the second one focusing on indoor settings, and the third and fourth papers describe its energy consumption. We then discuss these four papers as they relate to two important metrics for the ZigBee wireless standard: throughput and energy efficiency. Finally, we briefly identify the potential future impact of the ZigBee protocol and the suggested optimizing algorithms.

I. INTRODUCTION

As the world becomes increasingly interconnected, wireless networks are becoming increasingly important – from controlling remote video systems to monitoring equipment status, from operating sensor systems to communicating with smart devices, these nearly-ubiquitous networks allow people to communicate, acquire information, and connect with others. The Internet of Things (IoT), in particular, has recently gained traction as a way for billions of devices to be interconnected and to collect and exchange data. However, this vision also presents a new set of challenges. For instance, communication across IoT channels requires both sufficient power and throughput. One wireless standard that has shown some promise in solving these problems is the ZigBee standard.

The ZigBee specification is designed for low data rate, low power applications. This IEEE 802.15.4-based protocol uses a mesh network to transmit data, and provides a relatively simple and low-cost solution for maintaining long device battery life. The low power consumption of the ZigBee standard limits its transmission distance to relatively short ranges, but with a mesh network of ZigBee devices, data can be relayed longer distances.

Two important metrics for evaluating any wireless protocol are its throughput and its energy consumption. The throughput measures the rate of successful message delivery over the channel, and thus it provides valuable information about the amount of data that can be transmitted. Additionally, because the ZigBee standard is designed for low power applications, its energy consumption is essential to any assessment of its performance, and determines the lifetime of battery-powered devices.

For this project, we examine four papers that study the ZigBee protocol and its performance under several metrics; we will focus on throughput and energy consumption. The rest of this report is organized as follows. In Section II, we summarize the four main papers considered in this literature survey. In Section III, we discuss the throughput and energy efficiency achieved by the schemes proposed in the papers. In Section IV, we comment briefly on the potential impact of the ZigBee protocols. Finally, Section V concludes the report.
II. SUMMARY OF PAPERS

A. Maximum Throughput and Minimum Delay in IEEE 802.15.4 [1]

In *Maximum Throughput and Minimum Delay in IEEE 802.15.4*, Latré et al. investigate the maximum throughput and minimum delay of the then-new ZigBee standard and study the impact of various address schemes.

The authors assume a perfect channel with a BER of zero and consider the case of a single sender and a single receiver which are located close to each other, with no losses from collisions or buffer overflow. They examine the unslotted version of the ZigBee protocol in the 2.4 GHz band using CSMA with a back-off scheme. An example of a ZigBee frame sequence is shown in Fig. 1 below.

![ZigBee frame sequence](image)

They then calculate the maximum throughput as follows:

$$TP = \frac{8x}{\text{delay}(x)}$$

where $TP$ represents the throughput and $x$ represents the number of bytes received from the upper layer. The delay includes the back off period, the transmission time for a payload of $x$ bytes, the turn around time, the transmission time for an ACK, and the IFS time. The authors include equations for calculating each term in the delay as well as a table with delay times for different numbers of address bits.

After providing analytical equations for the throughput and delay times, Latré et al. discuss the ZigBee throughput, bandwidth efficiency, and lower delay limit. They consider the following scenarios: a 64 bit address, a 16 bit address, and no address, both with and without the use of ACKs in all cases. They use the following formula for bandwidth efficiency:

$$\eta = \frac{TP}{R_{\text{data}}}$$

where $R_{\text{data}}$ is the raw data rate, and find the results shown in Fig. 2. They note that the efficiency increases with the number of payload bits and is also higher with no ACK. Under optimal circumstances (no address, no ACK), they find an efficiency of 64.9%. Under the worst conditions (long address, using ACK), the efficiency is only about 49.8%. The highest throughput under the optimal circumstances is about 163 kbps.

![ZigBee bandwidth efficiency](image)

Finally, the authors experimentally validate the theoretically calculated maximum throughput using two radios, obtaining the curves shown in Fig. 3. The two curves have the same shape, but the experimental curve is about 11% lower than the analytical curve.

In their paper, Ferrari et al. consider the delay and throughput of ZigBee and Z-Wave protocols for sensor networks in indoor settings. They compare the two technologies and study how different performance metrics (including delay and packet error rate) are affected by the distribution of the sensors.

They begin the paper with an overview of the ZigBee and Z-Wave standards. Like ZigBee, Z-Wave is designed to be high efficiency and low-cost, and it also uses a mesh topology. However, unlike ZigBee, it is a proprietary wireless communication protocol intended for home control.

The authors then create the experimental setup shown in Fig. 4 for ZigBee and Fig. 5 for Z-Wave. With the ZigBee networks, four topologies are considered, and each experimental trial is repeated 500 times. All experiments occur indoors, with node distances of only a few meters. With the Z-Wave networks, two topologies are considered, and measurements are averaged over 10,000 trials.

The topology of Fig. 4a is used to determine the received signal strength indication (RSSI) as a function of the distance between two nodes for three different transmit powers: 0 dBm, -10 dBm, and -25 dBm. The authors ascertain that the RSSI decreases log-linearly as a function of distance, and that increasing the transmit power leads to better performance.

Ferrari et al. then measure throughput for all four of the cases shown in Fig. 4. For the point-to-point link of Fig. 4a, they assess throughput as a function of the packet length and find that it increases less than linearly. For the topologies shown in Figs. 4b and 4c, packets are relayed by one and two routers, respectively, from an end device (or reduced...
function device, RFD) to a coordinator. The presence of a router has a strong effect on the data rate because according to the CSMA protocol, a node sends data only when the channel is free; with a single RFD, the channel is always free for transmission. Thus, with two hops, the throughput is halved, and in general, the throughput decreases as $1/n_{hops}$, where $n_{hops}$ is the number of hops traversed by a packet in route to its destination. Results from the first two configurations are shown in Fig. 6. With two routers (as in Fig. 4c), the authors of this paper find results that are very similar to those of the one router case even though in theory the throughput should be smaller than the ideal case by a factor of three; however, because the nodes tend to route packets through paths that minimize the number of hops with the ZigBee protocol, the first router communicates directly with the coordinator, skipping the second router. In the presence of two RFDs transmitting simultaneously to the coordinator (as in Fig. 4d), the number of collisions increases and the throughput goes down slightly.

The average delay between two consecutive packets is another important metric that is measured. The delay $D_{direct}$ can be described by the equation

$$D_{direct} = \frac{L}{R_b} + T_{prop} + T_{proc}$$

where $L$ is the packet length, $R_b$ is the transmission rate, $T_{prop}$ is the propagation delay, and $T_{proc}$ is the processing time at the node. This equation is further approximated by

$$D_{direct} \approx \frac{L}{R_b} + T_{proc}$$

The results obtained for a direct transmission and indirect transmission through a router are shown in Fig. 7.

![Fig. 6. Throughput measurements for ZigBee network configurations shown in Fig. 4a (black circles) and Fig. 4b (red squares)](image)

![Fig. 7. Delay measurements for ZigBee network configurations shown in Fig. 4a (black circles) and Fig. 4b (red squares)](image)

The last ZigBee metric tested in the paper is the packet error rate (PER), or the ratio of the number of erroneous received packets to the total number of transmitted packets. They find that at short distances, the network experiences full connectivity and communication can be sustained with low PER. However, as the distance increases beyond a certain threshold, the connectivity falls rapidly, and the PER shoots up. The
maximum distance for connectivity indoors seems to be around 20 m.

The Z-Wave metrics that are characterized are the PER and the delay. The PER is measured in three different scenarios: the topology of Fig. 5a, with no retransmission and no routing, the topology of Fig. 5a, with retransmission but no routing, and the topology of Fig. 5b, with both retransmission and routing. The PER increases with distance, and is highest for the first scenario.

The delay of a packet in the Z-Wave network is calculated as the difference in time between the beginning of the transmission of one packet and the beginning of the transmission of the next packet. The authors find delays of 39 to 86 ms amongst the different scenarios tested, and realize that the delay with a variable value transmission (where the transmitted value needs to written into the flash memory every time) is higher than with a fixed value transmission.

After all of these experimental proceedings, Ferrari et al. perform simulations to verify their results for the ZigBee networks. A direct comparison between experimental and simulation results is performed for a single-RFD scenario, and although the trends remain the same, the simulation yields somewhat better results than observed experimentally – the throughput is higher and the delay lower.


Di Francesco et al. describe a new algorithm under the ZigBee standard for near-optimal energy efficiency while still achieving an application’s reliability requirements. They take an adaptive and cross-layer approach for data collection in wireless sensor networks; specifically, they propose the relatively simple ADaptive Access Parameters Tuning (ADAPT) algorithm, which works under a wide range of operating conditions and can be integrated into ZigBee based sensor networks without requiring any further modifications.

The proposed scheme adds a vertical component to the communication channel’s layered architecture (see Fig. 8) to make it easier to share information between layers. Doing this allows for a more efficient system design, since information from one layer can be used to tune parameters in another. The adaptation module then continuously monitors the MAC layer performance and tunes parameters. ADAPT estimates current traffic conditions and changes MAC parameters according to the required reliability level.

![Fig. 8. Channel’s layered architecture, along with cross-layer adaptation module](image)

The authors describe a method for estimating communication reliability using the proxies of contention and channel errors. Contention occurs when multiple nodes attempt to access the channel at the same time, while channel errors affect already transmitted messages independently of contention. Using local nodes that can differentiate between messages dropped because the maximum number of backoff stages was exceeded and those dropped
because the maximum number of retransmissions was exceeded, the authors claim that the former case is due to contention, and the latter due to channel errors, and thus these sensor nodes can provide a good estimate for channel reliability.

To mitigate the effects of contention, a scheme is suggested in which the ADAPT algorithm uses two thresholds, $d_{\text{low}}$ and $d_{\text{high}}$, such that the delivery ratio is at least $d_{\text{low}}$ and at most $d_{\text{high}}$. To mitigate the effects of channel errors, an approach exploiting timeouts/acknowledgments and retransmissions is suggested, and a threshold value $d^{\text{loss}} = d^{\text{des}} \times (1 + v)$ is used, where $v$ indicates sensitivity to the message loss and $d^{\text{des}}$ is the desired delivery ratio. These schemes are shown in Fig. 9.

![Fig. 9. Estimation-based adaptation of the delivery ratio for (a) congestion control; (b) error control](image)

Di Francesco et al. then run some simulations to evaluate the performance of the proposed ADAPT algorithm. They consider the performance metrics of delivery ratio, average energy per message, and average latency, and compare the proposed algorithm against three other parameter setting schemes – Default Parameters Set (DPS), Constant Parameters Set (CPS), and Optimal Parameters Set (OPS).

For the single-hop scenario, a network with 20 sensor nodes is placed in a circle with a 10 meter radius with a sink node in the center. Evaluating the delivery ratio as a function of the number of nodes for each of the four schemes, the authors show that ADAPT performs comparably to CPS and OPS, and significantly better than DPS. In terms of the energy consumption, ADAPT achieves almost the same level as the optimal solution (OPS) – see Fig. 10. In terms of latency, ADAPT achieves the lowest latency among the schemes with sufficient delivery ratios. Even when measured as a function of the number of messages per beacon interval, ADAPT achieves almost the same delivery ratio as OPS for large numbers of messages, close to optimal energy efficiency, and low latency.

![Fig. 10. Energy consumption as a function of the number of nodes in the single-hop scenario](image)

Several of the experiments are then repeated under dynamic conditions. ADAPT again performs close to OPS in terms of the delivery ratio, close to optimally for the energy consumption, and with the lowest latency of the schemes with high delivery ratios.

Even when considering a multi-hop scenario, ADAPT performs similarly to the
other schemes in all metrics tested, and it consumes energy close to the optimal value in almost all cases. Thus, the framework proposed in this paper guarantees the reliability value specified by the application while maintaining very low energy consumption and low latency. The framework autonomously tunes the parameters of the ZigBee MAC protocol without requiring any modification to the standard and can be adapted for diverse policies.

D. ZigBee Routing Selection Strategy Based on Data Services and Energy-balanced ZigBee Routing [4]

In [4], Peng et al. propose a power control strategy in the ZigBee specification to reduce energy consumption and also balances the nodes’ energy; doing this decreases the probability of having a single node in the network that uses up all of the available power.

Because the authors want to avoid nodes that act as power hogs, their energy-balancing algorithm takes factors into consideration when calculating the link loss such as the energy of a node, the energy of adjacent nodes, and the link quality. They define the link loss $p_l$ as

$$p_l = P(\alpha \cdot f(E_i, E_j, E_{avg}) + \beta \cdot g(LQI))$$

where $f$ is a function of the energy of a node itself $E_i$, the energy of the adjacent node $E_j$, and the mean area energy $E_{avg}$. $g$ is a function of the link quality $LQI$, and $\alpha$ and $\beta$ are quantities that are experimentally determined – in this case $\alpha = 1$ and $\beta = 0$. $P(x)$ ensures that the link loss remains between 0 and a developer-defined constant (7 in this case). They then use this link loss definition in the ZigBee standard to choose the routing path. Using simulations, Peng et al. find that when using this energy balancing algorithm, the nodes in the network have a smaller standard deviation in energy compared to a constant-cost algorithm, and thus assert that their algorithm is effective.

III. DISCUSSION

A. Throughput

The first two papers both discuss and evaluate the ZigBee protocol in relation to several metrics, including throughput. Since Latré et al. is an earlier paper, it focuses on a more fundamental understanding of ZigBee. The authors of that paper consider their metrics in ideal scenarios, with a BER of zero, a single sender and a single receiver located close to each other, and no losses from collisions or buffer overflow. They also perform a theoretical analysis of the protocol, deriving analytical equations for the throughput for example, before attempting to validate their model experimentally.

Ferrari et al., meanwhile, consider a wider range of topologies but limit their analyses to indoor settings. They also consider environmental interference such as people walking across the sensor network (which has a deleterious effect). The authors experimentally characterize the ZigBee and Z-Wave protocols with a variety of metrics before turning to simulations to corroborate their results.

Because of the more realistic non-idealities considered in Ferrari et al., the throughputs that they obtain are much lower than those of Latré et al. in both the analytical and the experimental cases. For instance, Latré et al. obtain an experimental bitrate of about $8 \times 10^4$ bps for a payload size of 60 bytes, which is approximately three times higher than the value obtained for the same payload size from the highest throughput topology of the Ferrari paper.

B. Energy Consumption
The third and fourth papers both propose algorithms to optimize ZigBee wireless networks with respect to energy efficiency. They then characterize the network performance under these newly proposed algorithms with a few metrics including energy consumption. Di Francesco et al. propose an algorithm that satisfies an application’s reliability requirements and then optimizes for energy consumption. This scheme autonomously tunes the parameters of the ZigBee MAC protocol, and because it does not require any modification to the standard, it can be integrated into a diverse set of ZigBee sensor networks. It sustains near optimal energy consumption and very low latency.

Peng et al. propose a strategy to balance the energy of the nodes in a network, such that no single node consumes the majority of the power. This algorithm would help extend battery life, but requires some tuning of parameters.

Although the two papers have somewhat different goals with respect to the energy consumption in a ZigBee network, both provide potentially useful optimizations; perhaps both algorithms could be used in conjunction to provide even greater total energy savings.

IV. POTENTIAL IMPACT

As the Internet of Things and the low power devices associated with it become more ubiquitous, low power communication systems such as ZigBee will become increasingly important. These wireless communication networks will benefit from relatively high latency so that data can be transferred more quickly as well as low energy consumption so that devices in the network can be powered for a long time. The papers examined in this report provide useful insights for understanding what can currently be achieved under the ZigBee specifications.

The optimizations suggested may also be significant for further extending device battery life.

V. CONCLUSION

Several papers were examined which benchmarked ZigBee network performance with various metrics and under various topologies. We discussed them with an emphasis on throughput and energy efficiency, and considered proposed optimizations to the protocol.

REFERENCES