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Original Article

A Higher Order Throughput Model for 802.15.4 MAC

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Abstract *- IEEE 802.15.4 is one of the most popular protocols for Wireless Sensor Networks (WSNs) and Wireless Body Area Networks (WBANs) because of its low power consumption and flexible superframe structure, but throughput performance is affected by a considerable number of interrelated MAC layer parameters with high sensitivity. The current investigations are dominated by single-parameter tuning as well as heuristic reconfigurations, with little understanding of how the key configuration variables interact. In this paper, a general semi-analytical model to estimate the throughput is proposed for the IEEE 802.15.4 MAC in beacon-enabled mode with star topology. The joint effect of beacon order, superframe order, packet size, rate, and number of nodes, including guaranteed time slots, is analysed through a fractional factorial design-of-experiments approach to reduce experimentation complexity. Main and interaction effects found to be statistically significant are determined through the analysis method of variance, with the interpretable throughput model being established as a function of SO–BO ratio, aggregated traffic load, packet size, and GTS allocation. The results show that the throughput performance is predominantly through multiple parameter interactions rather than through its individual settings and that an informed configuration in a based IEEE 802.15.4 framework can achieve noticeable throughput enhancements with no change to the protocol stack. The proposed method offers a feasible criterion to determine the MAC parameter setting for throughput-oriented WBANs and WSNs in constrained environments.*

Keywords *- Throughput, Fractional Factorial Design, IEEE 802.15.4 MAC, Wireless Sensor Networks (WSNs), Wireless Body-Area Networks (WBANs).*

1. Introduction

Wireless sensor networks are made up of tens of thousands of battery-operated Wireless Sensor Nodes (WSNs). Due to access issues in a deployed network, it could be difficult to recharge these drained batteries. The WSN must thus last as long as is practicable.

The WSN must have the capacity to transmit as much data as is practical during the course of its existence, to provide the WSN with the maximum possible throughput. The PHY and MAC layers are built based on the IEEE 802.15.4 [1] specification, which is intended for transmission speeds up to 250kbps. Besides 10 channels between 902 and 928 MHz, and one channel from 868-868.6 MHz, the PHY uses 16 channels in the range of between 2.4 and 2.4835 GHz. The WBAN (wireless body-area network), which uses the 802.15.4 protocol, is an illustration of a WSN [1].

Several IEEE 802.15.4 protocol settings have an impact on a WBAN's throughput. The number of nodes demanding guaranteed transmission slots, the Beacon Order (BO), Superframe Order (SO), packet rate, and packet size are a few of the variables. These characteristics are a part of a model for boosting WBAN throughput that might be used to find the best configurations for a given demand. We have presented such a model in our work. The super frame structure of the IEEE 802.15.4 protocol is then described. The superframe structure for the IEEE 802.15.4 protocol is shown in Figure 1 [1].

Active time and inactive duration are the two components that make up the Superframe. Contention Access Period (CAP) and contention-free time make up the active phase. Each slotted CSMA/CA device during CAP must travel through them in order to send or receive data. Devices could get the content right away because of CFP's Guaranteed Time Slots (GTSs). A network coordinator, often referred to as a PAN coordinator, broadcasts superframe beacons at predefined intervals. There are 16 evenly spaced intervals in the time between each pair of beacons.

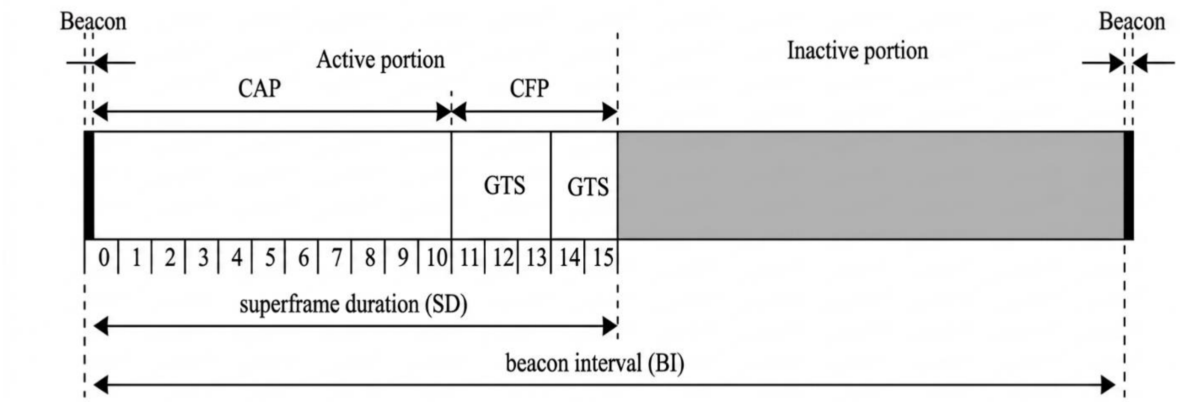

Fig. 1 Superframe structure used by IEEE 802.15.4 [1]

Two factors that influence the growth of superframes are the Superframe Order (SO) and the Beacon Order (BO). The superframe order in a ZigBeeMAC superframe determines how long the active segment is. The size of a superframe is determined by the beacon sequence. The beacon interval is the interval between two subsequent transmissions. The equation is BI=a Base Superframe Duration*2 for 0=BO=14. For the whole Superframe, there is a Beacon, a Contention Access Period (CAP), and a Guaranteed Time Slot. It is not taken into account how much time is wasted doing nothing—SD=a Base Superframe Duration*2SO, where 0=SO=BO=14, yields the duration of the active phase. The fundamental minimum size of the Superframe is indicated by A Base Superframe Duration. The Guaranteed Time Slot (GTS) technology, which is based on TDMA, allows devices to connect to the Internet only during specific hours.

In past research [4-9] for enhancing ZigbeeMAC's energy efficiency (based on 802.15.4) or the 802.15.4 protocol, the authors did not pay enough attention to how the various components interacted to create a higher-order model for throughput. For the ZigbeeMAC protocol, we provide a customised throughput model that accounts for the packet size, packet rate, SO (Superframe Order), number of nodes, number of GTSs, and BO (Beacon Order). Studies that employ fractional factorial designs provide credence to our hypothesis. The document is organised as shown below. The literature review is described in Section 2 of the essay. Section 3 presents our setup and experiment design. Section 4 presents the discussions and findings. Section 5 is the concluding paragraph of the text. However, while there have been numerous studies on how to improve the performance of the IEEE 802.15.4 MAC protocol, very few addressable works concentrate on a better configuration of some parameters, or propose heuristic-based adaptations for throughput efficiency, or power consumption alone. Such methods usually consider the impact of beacon order, superframe order, packet rate, packet size, GTS allocation, or node density separately, and do not comprehensively reflect their joint influence as well as interaction. Therefore, there is a disinterest among practitioners to develop predictive models that can systematically quantify high-order parameter interactions and assist in the determination of the best configuration for different application situations. More generally, no structured DSE framework has been proposed to simulate multiple combined effects, such as the SO-BO ratio, traffic generation rate, packet size, and number of nodes, and GTS allocation impact in beacon-enabled 802.15.4 networks on the achievable throughput. This also limits the decision-making of network designers based on quantitative data for throughput-sensitive WBAN deployments.

Unlike prior research that concentrates on tuning a single parameter in isolation or adaptive heuristics, protocol-level improvements such as e-modes for IEEE 802.15.4, this paper offers a second-order, interaction- aware throughput model for the standard IEEE 802.15.4 MAC early design exploration using the principled design-of-experiments process.

The main contributions of this paper are outlined as follows:

- A structured fractional factorial design-of-experiments framework is employed to systematically analyze the combined impact of key IEEE 802.15.4 MAC parameters on throughput in beacon-enabled, star-topology networks.
- A higher-order, interaction-aware throughput model is derived that captures the joint effects of SO–BO ratio,

packet rate, packet size, number of nodes, and guaranteed time slots, rather than treating these parameters independently.

- Statistically significant main and interaction effects are identified using analysis of variance, enabling interpretable insights into MAC-layer behavior under different traffic and network conditions.
- The proposed model provides predictive capability to assist in selecting near-optimal MAC parameter configurations for throughput-critical WBAN applications without modifying the IEEE 802.15.4 protocol.

2. Review of Literature

Examples of 802.15.4 networks include star, mesh, and cluster tree networks. The two modes of operation are beacon mode and non-beacon mode , depending on the topology and need for guaranteed bandwidth. We used the star topology and beacon mode for our tests. When beacons are enabled, the PAN coordinator delivers a beacon frame once every Beacon Interval (BI).

Then, we discuss tried-and-true methods for boosting the ZigbeeMAC/802.15.4 protocol's throughput. To increase the throughput and energy efficiency of the IEEE 802.15.4 MAC, Mohammad Hossein et al. [4] proposed an adaptive CSMA/TDMA hybrid MAC protocol that takes advantage of the star topology in the beacon-enabled mode. Implementing a dynamic TDMA period in CAP is the key idea. The coordinator randomly separates the CAP into slotted CSMA-CA slots and TDMA slots according to conditions of data queues, the state of nodes, and the number of collisions detected over the network.

For IEEE 802.15.4 networks, Yong-Geun et al. created the Adaptive GTS Allocation (AGA) technique to support many devices while reducing channel bandwidth waste. When compared to the conventional Superframe, throughput, power consumption, and latency have all increased. The Duty-Cycle Adaption Algorithm (DCA), developed by Joseph Jeon et al., regulates the duty cycle by maintaining a constant BO and altering the SO. The queue size is one of the elements the PAN coordinator takes into account while adjusting SO. Data rate and energy use are further considerations. In contrast to IEEE 802.15.4, DCA offers a modest throughput (=1Kbps), low energy consumption (below 0.2 Joules), and a quick end-to-end latancy (above 0.2 sec).

Routine data, like body temperature, were merged with recurring data and emergency data, such as an ECG, by Z.A. Khan et al (like data a doctor requires at regular intervals of time, such as video or audio data). This is achieved by altering the Superframe structure (ENPMSS). The normal traffic is managed via the CSMA/CA strategy. Through TDMA-based time slots, periodic traffic is transported. The suggested protocol beats the 802.15.4 MAC in terms of throughput, latency, and energy use.

Another approach for Tele-Medicine Protocol (TMP) that employs IEEE 802.15.4 Slotted CSMA/CA with beacon-enabled mode was proposed by Muhammad Sajjad Akbar et al., which may be applied for remote patient monitoring devices [8]. TMP uses techniques including duty cycle optimization and MAC layer parameter adjustment. Delay-reliability factor, superframe duration, and the chosen network traffic load all have an impact on duty cycle. For remote medical monitoring applications, it outperforms in terms of lower latency, acceptable dependability, larger throughput, and less energy consumption.

Shashwat Pathak et al. studied energy-awareness in IEEE 802.15.4 beacon-enabled mode [9]. The Adjustable Duty Cycle (ADC) can be used by modifying the Beacon Order system constraints (BO) and Superframe Order system constraints. The authors reported on a method to monitor cardiac patients wirelessly using an ECG recording. In terms of energy consumption, end-to-end latency, and throughput, the proposed approach outperforms the 802.15.4 MAC standard with a sliding window mechanism.

Farhad et al Traffic's Traffic Aware Dynamic Superframe Adaptation Approach (TDSA) [10] modifies Superframes using Superframe Order and Beacon Order (BO) in order to boost throughput while reducing latency and energy consumption (SO). The process was created for a network employing IEEE 802.15.4 beacons and a star topology. The TDSA implies that the GTS has not been utilised and considers the CAP period. The PAN coordinator must also be familiar with the different TDSA traffic types generated by the various sensors and the events they cause. The alteration of SO and BO for the beacon interval and its active component is known as Superframe adjustment. TDSA performs better than IEEE 802.15.4 in terms of speed.

In literature [4-9], the previous researchers have not formulated a higher-order throughput model of the MAC layer for the IEEE802.15.4 [10] to enhance energy efficiency and increase throughput performance of an IEEE802.15.4 MAC Protocol in a Wireless Body Area Network (WBAN) [11]. In [11], a comparison between the 802.15.4 MAC protocol and the TSCH and DSME CSMA/CA modes in IEEE 802.15.4e was made: 802.15.4 MAC consumes less energy for decreased latency, and throughput is lower. However, for high throughput or low latency, the 802.15.4 MAC reduces its sleep time by expanding the active period, which increases received incoming frames. This is more costly than the TSCH and DSME modes, after an expected delay and throughput.

In [12], an analytical Markov-chain model of the Enhanced Slotted CSMA/CA scheme for IEEE 802.15.4 MAC, which efficiently exploits the GTSs under saturated traffic scenarios, is proposed. The variability of CAP is modelled by a five-dimensional Markov chain. Real-world networks with non-uniform data traffic are considered for the analysis. The results demonstrate that, under high load applications, this new approach enhances the throughput of the IEEE 802.15.4 MAC protocol in an energy-efficient way.

In [13], simulation of both the IEEE802.15.4 and S-MAC, the IEEE802.15.4 has a greater throughput and PDR due to its easy operation and low energy consumption design. Because more energy was used in the construction of PAN coordinators, the PDR and throughput utilizing IEEE802.15.4 are initially low for smaller networks.

In [14], the authors have introduced an Optimal Superframe and Data Buffer Scheme (OSDBS) for enhancing the throughput performance of IEEE 802.15.4 beacon-enabled energy harvesting wireless sensor networks known as EH-WSN. It is important to design a high-throughput data transfer scheme that can adapt to the variation of collected energy by EH-WSN nodes. An Optimal Superframe and Data Buffer Strategy (OSDBS), which is the focus of this paper, patterned an IEEE 802.15.4 beacon-enabled EH-WSN to improve its throughput. By determining the ideal Superframe and buffer sizes for each node, the OSDBS solves an optimization issue that maximizes network throughput. This allows for the highest possible throughput. According to the simulation results, the OSDBS performs noticeably better than the current schemes in terms of throughput.

In prior art, in paper [15], the scheme for improving channel contention efficiency (ECCE) has been proposed to maximize the Channel Contention Efficiency (CCE) so that higher throughput and smaller delay could be obtained. To conclude, the presented ECCE might enhance throughput and delay in the MAC layer of the IEEE 802.15.4 standard by adjusting the three targeted parameters, macMaxCsmaBackoffs, macMinBe, and macMaxBe on the CSMA/CA mechanism opportuned at the MAC layer of the IEEE 802.15.4 standard with their optimal values calibration, respectively.

CSMA/CA has been used instead of TDMA in most works. Although the CSMA/CA is very power-consuming and has been widely used in scalable, dynamic networks, WBANs are not dynamic. Hence, it is not suitable for WBANs.

2.1. Motivation and Modeling Rationale

In applications such as Wireless Sensor Networks (WSN) and Wireless Body Area Networks (WBAN), the sensor nodes are power-limited with limited battery capacity, and energy-efficient data delivery is an important design consideration. Serving as the cornerstone part of these networks, throughput optimization cannot be accomplished through a series of parameter tuning individually because, in practice, certain MAC-layer parameters interactively affect not only channel access behavior but also duty cycle and packet delivery probability.

IEEE 802.15.4 MAC protocol provides a number of tunable attributes such as the beacon order, superframe order, guaranteed time slots, packet size, packet arrival rate, and number of active nodes.

Although individual studies have investigated subsets of these parameters, the collective impact on throughput is not easily quantified through a one-factor-at-a-time approach. This justifies the implementation of a structured multi-factor experimental design that can account for interactions, while avoiding undesirable degrees of complexity.

As such, a fractional factorial design of experiments is used in this study to effectively consider the multi-dimensional parameter space. The throughput model is expressed as a function of SO–BO ratio, packet size, aggregate traffic load (i.e., product of packet rate and number of nodes), and GTS allocation ratio. This model allows for systematic exploration of the impact of parameter interactions on throughput and is a foundation for making a rational choice of MAC parameters under various traffic and network scenarios.

2.2. IEEE 802.15.4e MAC Enhancements (TSCH and DSME)

In recent efforts, researchers have focused on the IEEE 802.15.4e MAC improvements, such as Time-Slotted Channel Hopping (TSCH) and Deterministic and Synchronous Multichannel Extension (DSME), to enhance the reliability, determinism, and robustness of LPWNs. Contrary to the simulation-heavy analysis that preceded us, experimental and testbed-based research has shown that real-world deployments can induce performance discrepancies beyond what is accounted for by the idealized environment of simulation. Mantilla Gonzalez et al. performed extensive performance evaluation of TSCH scheduling functions in a physical testbed, and demonstrated the effect of different scheduling decisions on packet throughput, latency, and reliability in real-world conditions [16].

Meanwhile, the DSME-based works have been polished to support the characteristics of high-quality-of-service requirements, such as those of industrial and mission-critical applications. Ray and Moulik introduced an industrial-based DSME variant to enhance goodput, delay, and reliability with the help of an advanced resource allocation scheme acceptable in a smart factory automation [17].

Other studies have further considered the effectiveness of channel hopping and interference mitigation in TSCH networks, suggesting that real-world throughput and reliability benefits are heavily affected by environmental conditions and traffic patterns [18]. These works together demonstrate that IEEE 802.15.4e is a significant improvement over the legacy MAC, but certain parameters and scheduling configurations are critical to ensure its robustness.

2.3. Cross-Layer Optimization Trends

In addition to MAC-layer enhancements, recent research is focused on cross-layer optimization frameworks that jointly optimize scheduling, routing, and flow control for overall improved network efficiency. In 6TiSCH-like stacks, which combine TSCH scheduling with IPv6 routing, Hannachi et al. presented an energy-efficient cross-layer solution to joint scheduling and routing decisions that minimizes the joining latency and delay while en route packets in various densities of networks for different loads [19].

These cross-layer methodologies show that throughput and energy are not always dependent on isolated decisions at the MAC-level parameters but rather on a set of interdependent decisions among all protocol layers, further emphasizing the need for holistic performance modeling.

2.4. Adaptive and Learning-Based MAC Control

Moreover, the recent literature explores adaptive and learning-based MAC control schemes to combat dynamic traffic bursts, variability in interference sources, and network dimension. Reinforcement learning has been extensively employed in TSCH networks to facilitate parent selection, channel allocation, and schedule adaptation, resulting in an increase in end-to-end operational efficiency and high packet reception rates under varying network conditions. Also, researchers investigate more advanced deep reinforcement learning-based approaches to optimize interfering scheduling policies and packet reception rates where interference arises due to dense and harsh industrial environments. Despite the significant benefits of the aforementioned adaptive schemes, they introduce additional computational overhead, training overhead, and convergence issues, making it unfeasible to deploy them in WBAN, where system resources are limited.

2.5. Limitations of Existing Approaches and Motivation for DoE-Based Modeling

However, despite the progress made possible by IEEE 802.15.4e enhancements, cross-layer designs, and adaptive MAC protocols, some shortcomings still exist in the current literature. First, the current literature still focuses on single-parameter optimization or incremental protocol design, such as adaptive superframe parameters or dynamic beacon interval changes, which fail to model the combined impact of important parameters such as the SO-BO ratio, packet rate, packet size, node density, and GTS allocation on throughput [22, 23]. Second, while interaction effects among parameters are recognized, they are still qualitatively discussed and remain poorly quantified, with little attention to modeling higher-order interactions. Third, the current The literature lacks design-space exploration models that would allow network designers to predict the achievable throughput for a set of combined parameter settings without needing exhaustive experimentation. These shortcomings justify the need for a systematic design of experiments approach, where controlled multi-factor experimentation and interaction modeling can help develop an interpretable throughput model for beacon-enabled IEEE 802.15.4 networks

3. Experimental Setups

In our investigation, Castalia and OMNET++ were used. A fractional factorial strategy was used to identify how various parameters affected the IEEE 802.15.4 MAC. Each input parameter or factor is given one of three levels ('Low, Medium, and High') in a three-level fractional factorial design [3].

3.1. Design of Experiments

Among the crucial variables we examine are the packet size, packet rate, Beacon Order (BO), number of nodes, Guaranteed Time Slot (GTS), and Superframe Order (SO). To account for this, the input parameters listed below were modified: The acronyms for the same idea are BO (or SOBO), packet rate, packet size, number of nodes, and GTS. The remaining low, medium, and high nodes were 2, 31, and 60, respectively. The following are the low and high values for the various constraints: The three different packet sizes are 37, 82, and 127 bytes. There are three unique packet rates: 10, 55, and 100 pps. A GTS exists that has 1,4,7 and 2,31,60 nodes. For each of the five qualities, we developed 27 scenarios utilising three layers and a packet size of 37 bytes (35-2).

The architecture for generating trials using a fractional factorial design is shown in Figure 2. The metrics for the output were bits per Second (per node) throughput, uninterrupted packet reception, failed packet reception, and unsuccessful packet reception with escalating interference. The throughput, which was measured in bits per node, was the primary concern of this effort. Overall, there were 25110 rows of data.

The SOBO metric is the ratio of SO to BO. This is significant since SO Equals BO, and other combinations of BO and SO also break the norm. To put it another way, SOBO = 0.071 if BO = 14 and SO = 1. The mean level for SOBO is 0.5 at SO=7 and BO=14. The SOBO level is at its highest point of 1 when SO=BO=14.

Additionally, the packet size is continuously maintained (37 bytes). In both the transmit and receive directions, only one device is permitted to submit a single GTS request. The GTS lower value was consequently set to 1. The upper GTS value was set to 7, as each Superframe can support up to that many GTSs.

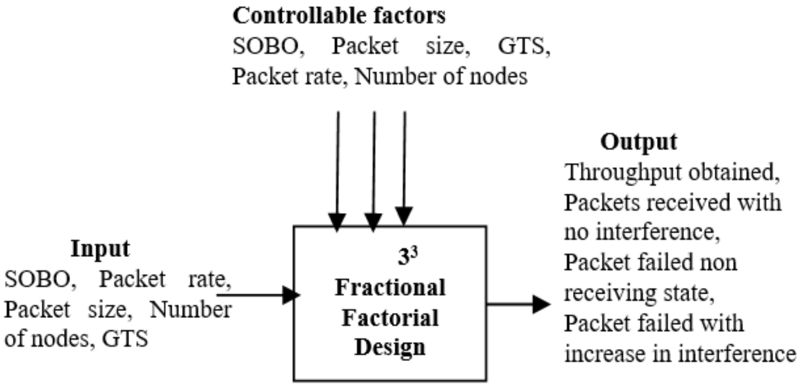

Fig. 2 A fractional factorial design is used in the experiment design

We have determined a customized throughput model for the ZigbeeMAC protocol that takes into consideration the packet size, packet rate, SO (Superframe Order), number of nodes, number of GTSs, and BO (Beacon Order). Based on statistically relevant parameters considering the following: superframe order, beacon order, packet rate, packet size, number of nodes, Guaranteed Time Slots (GTSs), and path loss, we have developed novel throughput models for the IEEE 802.15.4 protocol in the context of WBAN.

There were two, thirty-one, and sixty as low, medium, and high nodes. The low and high values for the different limitations are as follows: There are three distinct sizes of packets: 37, 82, and 127 bytes. The packet speeds are 10, 55, and 100 pps, respectively. There is a GTS with 1,4,7, and 2,31,60 nodes. We used three layers and a 37-byte packet size to create 27 scenarios for each of the five attributes (35-2).

The ratio of SO to BO is known as the SOBO measure. This is noteworthy because different combinations of BO and SO also break the rule, because SO equals BO. Stated otherwise, if BO = 14 and SO = 1, then SOBO = 0.071. The average SOBO level for SO=7 and BO=14 is 0.5. When SO=BO=14, the SOBO level is at its maximum of 1.

3.2. Justification of Fractional Factorial Experimental Design

The IEEE 802.15.4 MAC protocol exposes several tunable parameters that have a non-linear and interaction-based combined impact on the throughput. The values of interest in this work are beacon order, superframe order, guaranteed time slots, packet size, and number of nodes – all assumed to take several active states. Consequently, a full factorial experimental plan accounting for all combinations of parameters would need an impossibly high number of simulation runs and would hardly be practical. In order to solve this problem, a fractional factorial design-of-experiments approach is used. Fractional factorial designs allow the efficient exploration of high-dimensional design spaces in which a subset of experiments is selected systematically in order to retain the capacity to estimate main and strong interaction effects while drastically, at the same time, the number of all runs. This strategy is very well suited for the analysis of communication protocols: instead of checking all possible configurations, we are looking for important parameters and interactions. In the current design of experiments, all selected factors are tested at three levels (low, medium, and high), resulting in the linearity or non-linearity nature to be determined. The fractional factorial design is selected in order to keep a resolution that allows us to determine statistically significant main effects and second-order interactions, which we anticipate would dominate throughput behavior in beacon-enabled IEEE 802.15.4 networks. Higher-order interactions are presumed to be relatively small and are not explicitly resolved, a common, well-accepted assumption in multi-factor experimental analysis. The study strikes a balance between experimental accessibility and analytical depth by using a fractional factorial design. This approach allows for the systematic examination of parameter conjunctions, facilitates further analysis of variance for purposes of significance testing, and forms a solid foundation upon which to build an interpretable secondary throughput model. Therefore, the proposed design-of-experiments framework allows for informed analysis of throughput behavior without suffering from the one-factor-at-a-time pitfalls and zero simulation overhead.

4. Results and Discussions

4.1. Assessment for Other Nodes using Fractional Factorial Design

For our data analysis, R [3] was utilised. We first determine if the data are spread evenly. Then, we do a variance analysis to identify the key variables (ANOVA). The throughput model is built using these factors. The sink node is not included because it is constantly operational and connected to a power source. The data regions (Sample

Quantiles) are shown in Figure 3(a) adjacent to a fictional normal distribution (Theoretical Quantiles). The quantile is the percentage or collection of points that fall below the specified value. Due to the data's regular distribution, the image shows a very straight line. The boxplot of the throughput for other nodes is displayed in the Figure 3(b). The whole impact of all the factors on throughput is displayed in this boxplot. The average (middle value) throughput (per node), excluding sink nodes, was 30.37 bits per Second. The resulting throughput histogram is displayed in Figure 3(c). A large part of Othernodes have a throughput of 5000 bits per Second, as seen by the histogram (per node). Analysis of variance (ANOVA), which is used because the data are normally distributed, is used to select the best model.

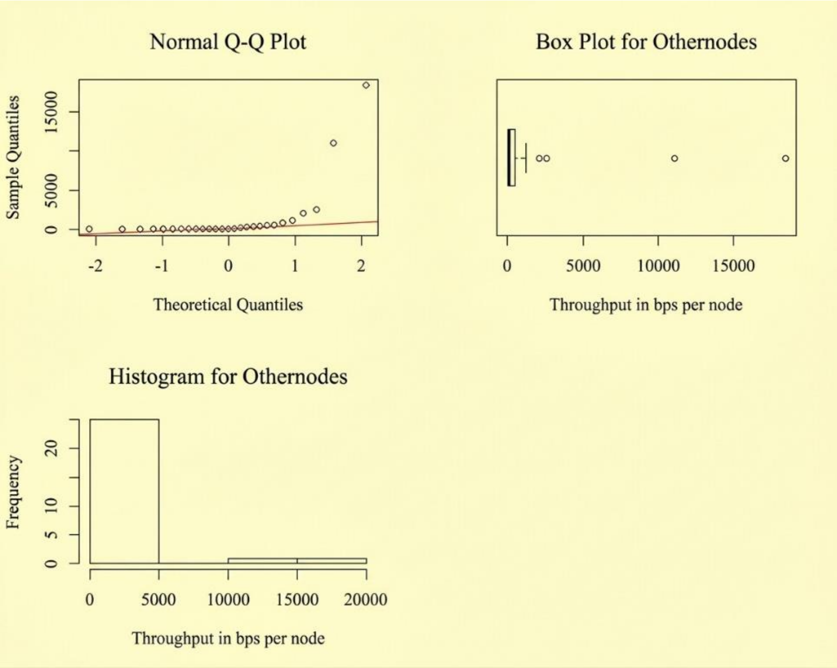

Fig. 3 (a) Normal Q-Q Plot, (b) Boxplot, and (c) Histogram for other nodes (excluding sink).

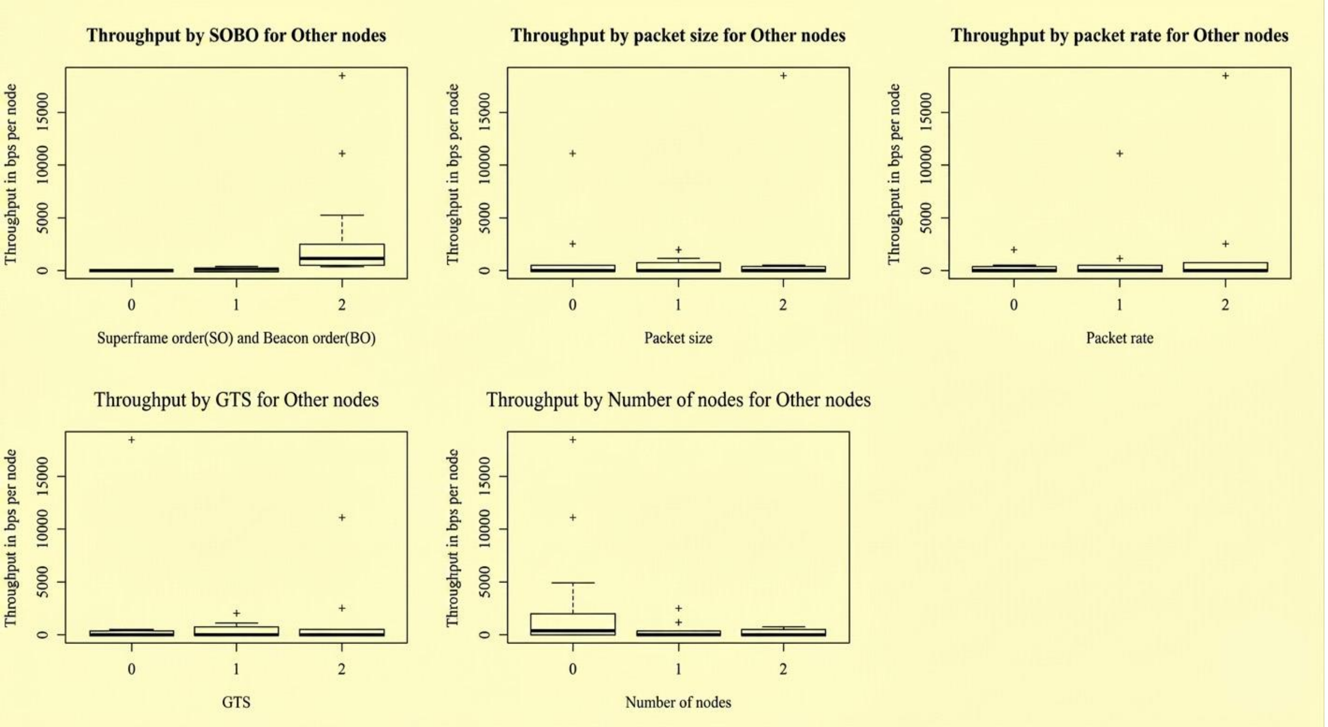

Fig. 4 Throughput for Other nodes (excluding sink) (a) SOBO, (b) Packet size, (c) Packet rate, (d) GTS, and (e) Number of nodes.

As the sink node is not considered, Figure 4 represents boxplots of throughput for the (y-axis shows Throughput) vs SOBO, Packet size, Packet rate, number of nodes for other, and GTS. Low and medium SOBO levels in Figure. 4 showed no effect on throughput (a). Higher SOBO values (such as SOBO=2) boost throughput since the Superframe does not experience any downtime. Large amounts of packets may be sent thanks to the faster packet transmission rate. The SOBO ratio determines how long the operation sleeps. Therefore, SOBO has a bigger effect on throughput. Figures 4(b), 4(c), 4(d), and 4(e) for Packet size, Packet rate, GTS, and Number of nodes show that none of these factors has an impact on the median throughput for other nodes.

First, we fit a model (for throughput) using analysis of variance up to third-order interactions (ANNOVA) The keywords are presented in Table 1. The following variables, as shown in Table 1, are significant at the selected alpha level: There are additional factors to take into account, the packet rate, including the number of nodes, the SOBO (SO: BO Ratio), the combined effects of the SOBO:pktr and SOBO:nn, the combined effects of the pkts:pktr and pkts:nn, the combined effects of the pkts:GTS, and the combined effects of the pktr:pkt (0.05). A higher-order throughput model is fitted with the relevant terms. The model information is displayed in Table 2.

Table 1. Important terms for node throughput (excluding sink node)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)[1]
SOBO	1	77112497	77112497	127.830	9.46e-05***
pktr	1	19764206	19764206	32.763	0.002277**
nn	1	52629378	52629378	87.244	0.000237***
SOBO:pktr	1	29249748	29249748	48.487	0.000939***
SOBO: nn	1	73910886	73910886	122.522	0.000105***
pkts: pktr	1	46418819	46418819	76.949	0.000319***
pkts: nn	1	12631952	12631952	20.940	0.005969**
pkts: GTS	1	58639546	58639546	97.207	0.000183***
pktr: nn	1	9254496	9254496	15.341	0.011218*
nn: GTS	1	12906823	12906823	21.396	0.005707**
SOBO: pkts: pktr	1	7645175	7645175	12.673	0.016215*
pkts: pktr: GTS	1	9370755	9370755	15.534	0.010946*

1Df: Degree of freedom, Mean Sq: Mean square, Pr (>F): p-value (Probability value), F value: F value, Sum Sq: Sum of squares.

Table 2. Higher order model details for other nodes for throughput per node (excluding sink node)

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	2.6349	0.3526	7.473	3.29e-07***
SOBO(X1)	2.6810	0.2737	9.797	4.46e-09***
nn(X2)	-0.8208	0.2404	-3.415	0.00274**
SOBO: pktr(X3)	0.4317	0.1689	2.556	0.01884*
nn: pkts(X4)	-0.2068	0.1068	-1.936	0.06713

*Signif. codes: 0 ‘***’ 0.001 ’**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1*

From Table 2, we get our higher-order model as shown below,

$$Throughput = 2.6349 + 2.6810 \times SOBO - 0.8208 \times nn + 0.4317 \times SOBO : pktr - 0.2068 \times nn \times pkts + 2880 \quad (1)$$

The SOBO row's beta coefficient for X1 is 2.6810, the nn row's beta coefficient is -0.8208, the SOBO:pktr row's beta coefficient is 0.4317, and the nn:pkts row's beta coefficient is -0.2068. These values are the expected values for the intercept row.

The first throughput statistics obtained from our experimental data and those anticipated by the aforementioned model agree. If, for illustration, we alter X1 (SO: BO ratio), X2 (nn), X3 (SOBO: packet), and X4 (nn: packets) with 2*37, the model forecasts a throughput of 2866 bits per node. (A node's data value is 70 bits.) The model's throughput is determined to be 2344 bits per node with X1(SO: BO) = 0.5, X2(nn) = 31, and X3(SOBO:pktr) with 0.5*55. (Data value per node: 317 bits.) The model predicts a throughput of 1303 bits per node with X1(SO: BO) = 1, X2(nn) = 60, and X3(SOBO:pktr) = 1*100. (Data value per node: 1298 bits).

By choosing the ideal combination of SOBO, nn, SOBO: pktr, and nn: pkts, one may use this architecture to maximise throughput in bits per node for a particular situation. Throughput models can be used to determine the appropriate parameter values in IEEE 802.15.4 WBANs to lower energy consumption and increase throughput. An optimized choice of different parameters minimize the energy consumed and maximizes throughput (i.e., improved energy efficiency) in

WBAN, which in turn could prolong the sensor node's battery life. For the parameter settings to control energy consumption or throughput, one of our models could be used or a mix of both, while an average of them is sufficient when the accuracy level is considered for application cases.

Existing work [4-9] do not develop a high-order throughput model for the IEEE 802.15.4 MAC protocol in order to improve throughput and energy consumption of a Wireless Body Area Network (WBAN). The interplay of the multiple parameters to build linear models for WBANs energy consumption and throughput has not drawn attention from the author. Present methodologies do not have the formulas for linear first-order models and higher models with respect to energy consumption and throughput in terms of parameters, Send Only (SO), Beacon Only (BO), packet rate, packet size, required Growth Time Slot (GTS), nodes, and path loss.

The optimum working point, i.e., the best that realizes the minimum total energy consumption and throughput capacity, cannot be explicitly identified by all existing methods. It has not been known what the optimal values for 802.15.4's variables can be with respect to a response variable in any given scenario.

Using our models, one may optimize throughput and lower energy consumption in IEEE 802.15.4 WBANs by configuring the parameters correctly. Through the use of ideal values for different parameters, we may maximize throughput and minimize energy consumption (i.e., enhanced energy efficiency) of a node in WBAN, which may contribute to a node's longer battery life. A combination of our models could be used to control energy usage or throughput, or both, depending on the level of accuracy needed for the application case.

4.2. Comparison with IEEE 802.15.4e MAC Enhancements

The recent developments in low-power wireless networking have included extensions to IEEE 802.15.4 MAC, such as TSCH and DSME [16-18], which focus on improving the reliability, determinism, and resilience against interferers thanks to concepts of synchronized and time-based operation. They are based on time synchronization, multichannel scheduling, and strict slot allocation, which makes them extremely attractive for industrial and dynamic network environments. However, the basic IEEE 802.15.4 MAC is still commonly used in WBANs and low-complexity sensor networks for lower implementation overhead (and thus cost), less demand on synchronization, and greater compatibility with resource-limited nodes.

Rather than suggesting a new protocol, we are going to work inside the IEEE 802.15.4 standard MAC, proposing mechanisms designed to enhance throughput performance by improving parameter interaction analysis for tuning the system parameters among different approaches in order to further the studies reported in the literature.

Although TSCH and DSME provide high reliability and predictability, the performance improvements are at the expense of increased control overheads, scheduling, and memory requirements. The higher-layer throughput model presented in this paper completes these approaches by allowing the choice of MAC parameter values for IEEE 802.15.4 deployments targeting simplicity, energy saving, and configuration flexibility rather than deterministic behavior. The model offers an effective solution to optimize throughput without involving additional protocol layers or synchronization mechanisms by revealing key parameters and interaction effects.

Hence, the contribution of this work is considered to be neither directly competitive with IEEE 802.15.4e amendments nor serve as an alternative to the latter; it is a configuration-level optimization framework that can ameliorate throughput within the traditional model of IEEE 802.15.4 MAC specification. This placement closely matches use cases in which the use of TSCH or DSME is delicate (low, average) or impossible (middle), e.g., due to complexity reasons/limitation of hardware capabilities.

4.3. Limitations and Robustness of the Proposed Model

The proposed higher-order throughput model sheds light on the interaction between important parameters in IEEE 802.15.4 MAC. There are some drawbacks still to be aware of.

The analysis is first performed for beacon-enabled networks working in star topology, a scenario mostly observed in many WBAN applications; however, do not model the intricacies of mesh or multi-hop topologies. As a result, the obtained model may need to be recalibrated when incorporated into more elaborate network configurations.

Second, performance evaluations are carried out by simulated experiments over controlled traffic models and channel characteristics. While parameter combinations can be systematically searched, it must be noted that real deployments typically may suffer from further uncertainty as a result of environmental interferences, differences in the hardware, and time-varying traffic load. Such effects may affect absolute throughput numbers; however, trends in the parameters and interaction terms identified shall be qualitatively appropriate.

Third, the proposed model is centred on the throughput optimization and does not take into account potential secondary effects such as security, fault tolerance, or mobility, which might be even more important in particular applications.

In future work, experimental testbed verification could be included along with other comparisons on different performance metrics and possibly some adaptive mechanisms as well to verify further robustness in dynamic operation conditions. Despite these assumptions, the design-of-experiments-based the framework still provides a scalable and understandable method to study MAC parameter interactions. Taking full consideration of this diminishing return nature, the model could serve as a useful foundation to select throughput-oriented configuration in resource-limited IEEE 802.15.4 deployment without relying on cumbersome try-and-fail experiments.

5. Conclusion

A fast-developing technology for the deployment of both medical and non-medical applications is the Wireless Body Area Network (WBAN). An analysis of a higher-order throughput model has not been done. In this paper, we established a new higher-order model for throughput attained per node for the 802.15.4 MAC protocol based on simulations utilising a star topology. The SO, packet rate, BO, GTS, packet size, and node count of the 802.15.4 MAC protocol were changed during our research. The relevant keywords were discovered using ANOVA. A higher-level model was used to match the important terms. Our findings show how the packet rate, SO: BO ratio, packet size, node count, and GTS are crucial factors in influencing throughput. To maximise throughput, our model may be used to forecast the ideal packet rate, SO: BO ratio, number of nodes, packet size, and GTS. In this paper, a high-order throughput model using a fractional factorial design for the IEEE 802.15.4 MAC in beacon-enabled mode with star topology is proposed. By accounting for the interaction between important MAC parameters in a systematic way, we show that knowing how to tune these properly can have a significant impact on the throughput behavior without changing any protocols. As the analysis is restricted to simulation-based validation and certain network models, the proposed method offers a pragmatic and intelligible solution for throughput-oriented MAC parameter selection in energy-limited sensor (or body) area networks.

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