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Cross-Layer Optimization on Different Data Rates for Efficient Performance in Wireless Sensor Network

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Abstract: The traditional protocols used in wireless sensor networks adhere to stringent layering approaches, which decreases the performance of the quality of service (Quality of Service) metrics. As per specifications 802.15.4, wireless sensor networks are inexpensive and energy efficient. It is essential for evaluating the performance of WSNs. Researchers have looked into the fundamental aspects of a single physical layer and the medium access control (MAC) layer protocol using methodologies calculated using several mathematical models or experimental approaches, respectively. In this research, we offer an improved cross-layer analytical model that utilises a thorough combining and interacting of a Markov chain model of the MAC layer's propagation with a model of the PHY layer's propagation. This combination and interaction are described in detail. Various Quality of Service (quality of service) statistics are presented and evaluated, and a cross-layer effectiveness degradation study is conducted under different inputs of multi-parameter vectors. Other parameters, such as Average Wait Time, Reliability, Failure Probability, and Throughput, have been estimated from the simulation results and contrasted with standardised models. The cross-layer model provides a more thorough performance study with various cross-layer parameter sets, some of which comprise distance, power transmission, and offered loads, among other things.

Keywords— WSN, IEEE 802.15.4, CSMA/CA, Cross-layer, Markov chain model, Reliability, Throughput, etc.

I. Introduction

Wireless Sensor Networks (WSN) have a greater capacity since they enhance a person's ability to communicate with the actual world while in another location. In addition to this, the WSN do not require any established infrastructure, and the nodes are dispersed haphazardly over the sensing region. The collection and transmission of the sensed data to the MS is the responsibility of these distant nodes (Master Station). However, when the nodes are placed in a hostile environment, there is a chance that they will perish or sustain physical damage (i.e. the nodes become weak due to the scarcity of energy, power, computational resources, and so on). These constraints led the way for developing WSN protocols that are straightforward, energy efficient, and capable of withstanding specific environmental changes and situations [1-2][21][31].

The cross-layer design of the network protocols is the only challenging technique that can increase the applications of WSNs. Because only so many resources are available, it is necessary to use the information inside the various OSI layers efficiently. These statistics may be employed to enhance the ultimate performance of the network efficiently. In addition, using cross-layer techniques makes it possible to improve energy efficiency while enhancing the interaction between different communication layers to come to more informed decisions. In a more significant development, protocol design incorporating the cross-layer technique enables information to be exchanged from one layer to the protocols at other layers.

Figure 1 presents a representation of a typical configuration for a WSN. According to the figure, the sensor and autonomous nodes are configured in a certain way depending on the area of interest, like a forest to a hospital to a civil infrastructure to industry to a battlefield. These nodes are configured to monitor the environment in which they are placed and gather information about it, such as information regarding pressure, sound, vibration, motion, temperature, and humidity, among other things [3][22].

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After that, all of this information about the environment that was gathered is sent to the MS. In most implementations, the MS will consist of a wireless transceiver that has the capacity to both store data and receive it from the nodes.
On the other hand, the end user is the one who retrieves the sensor data while using these networks. Compared with the MS, a sensor node essentially consists of the bare minimum regarding communication capabilities, wireless bandwidth, energy, storage, and computational capacity. In other words, the MS has superior capabilities in terms of communication, energy, storage, and processing resources, among other things [4].

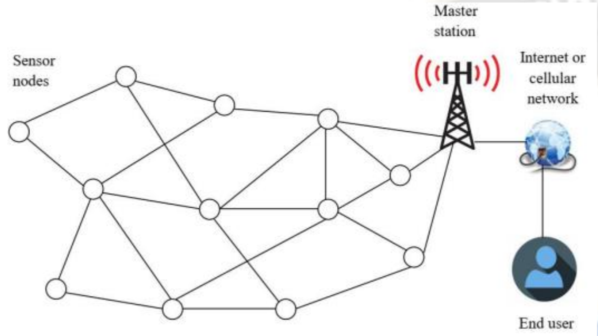

Figure 1: A typical WSN configuration

Because only so many resources are available, it is necessary to use the information inside the various OSI layers efficiently. This information may be utilised to enhance the actual effectiveness of the network efficiently. The sharing of information between different cross-layers is illustrated in Figure 2.
Making decisions is the responsibility of the Physical layer regarding the frequency selection and power selection that are necessary for a particular application. The physical layer must also choose suitable modulation and data encryption techniques, as this layer is also accountable for making this decision. The radio transceiver needs to have a sensing module and a processing unit designed, in addition to reducing the amount of power it uses as much as possible. The logical link control (LLC) sublayer and the medium access control (MAC) sublayer are the two sublayers that make up the data link layer. The multiplexing of data streams, detection of data frames, and control of access to the media are all provided by it. The Media Access Control (MAC) layer manages errors and access, creates network links, and effectively shares limited resources. LLC is utilised within a WSN to provide a consistent interface to the network link layer concerning the various access control types. The MAC layer discusses low energy consumption and self-organisation, which refers to the network constructing itself without an access point or base station. These are two of the essential issues [5][25][26].

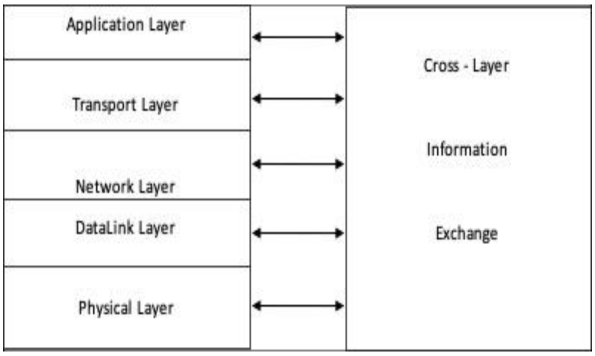

Figure 2: The Information exchanges across cross-layer

Cross-Layer Design

Because it enables one layer to access the information of another layer, the cross layer makes it possible for layers to communicate with one another and, as a result, improves the quality of service characteristics of the network.
Concerning wireless networks, the functionality of each layer and the requirements for those layers are determined by the specific application. The functionality of all of the layers will be optional for many of the apps. It is possible to combine the functions of multiple layers to make the implementation of the system more energy efficient. According to the findings, applying cross-layer synthesis and design methodologies in WSNs significantly improves views of the networks' energy utilisation [6-7][23][24].
The focus of the study on cross-layer plans has been on specific issues and facets associated with wireless communication. Several studies have summarised the current technology in cross-layer plan procedures and sorted out the cross-layer approach.
In the current cross-layer design research, the illustrations in Figure 3 (a-d) concentrate on the primary classes of how the accepted layered OSI correspondence framework model is changed. The core concept that underlies them is best explained as follows [8-9]:

1. **Creation of new interfaces**: To facilitate information exchange during runtime, new interfaces are developed between nearby and non-adjacent layers. This makes it possible to optimise the running of algorithms and take advantage of the information at higher and lower layers.
2. **Merging of adjacent layers**: Two or more layers are mixed to form a single, indistinguishable super layer. This super layer then executes an enhancement methodology and jointly manages all the responsibilities previously handled by the merged layers.
3. **Vertical calibration across all layers**: All layers share the same reading and editing capabilities for layer-specific parameters.

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4. Completely new abstractions: Some authors propose abandoning the layer paradigm, represented in a simplified form by a graph with links that can go in either way rather than layers.

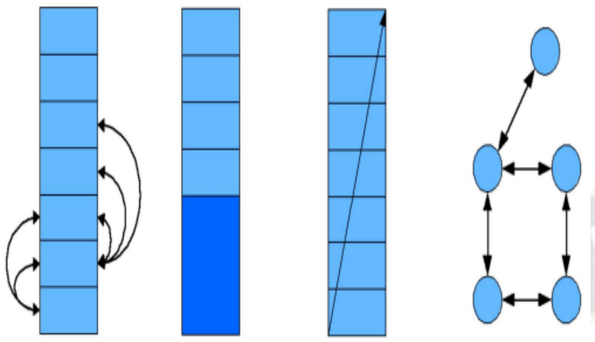

Figure 3: Classification of Cross-layer Design (a) Creation of new interfaces (b) Merging of adjacent layers (c) vertical calibration (d) Completely new abstractions

Importance of Cross-layer Design

The traditional model has a problem with transfer overhead because it must maintain incompatibility as a system. CL protocols may offer a preferable substitute to this problem to overcome it and may also improve the information accessibility shared between layers. The list of parameters, Network Lifetime, Quality of Service (quality of service), and Security, have been optimised in multiple works [10-11].

II. Literature Review

A body of research was done on cross-layer structure and adapting methods of data collecting in WSNs. This paragraph provides a brief overview of the work that is connected.

The IEEE-802.11 and IEEE-802.15.4 protocols use the CSMA-CA method to control how competing nodes can acquire the wireless channel. CSMA-CA utilises the Binary Exponential Backoff (BEB) technique to lessen the likelihood of collisions of packets on the communication channel. But BEB needs to be fairer and have better channel usage since it frequently rewards the ending node that successfully captured the method used to transmit its packets. Additionally, BEB changes the contention window's size predictably without considering the frequency of channel collisions. The latter component directly affects channel use; therefore, considering it when specifying the contention window's dimensions can improve the backoff algorithm's overall performance. They provide a brand-new adaptive backoff algorithm that improves BEB's drawbacks and surpasses it gave channel usage, power efficiency, and dependability while maintaining node fairness. We use a Markov chain to simulate our technique and run numerous simulations to test and validate our system. Our results indicate that an effective backoff algorithm will perform well [12][27][28].

This article proposes a new medium access control (MAC) protocol for sensor devices with less power that is appropriate for Internet of Things (IoT) systems. Although the IEEE-802.15.4 standard is suitable for energy-efficient wireless personal area networks (WPAN), it doesn't meet the data throughput and stability criteria for Internet of Things systems when utilised in 5G wireless networks. During the process of data transmission, we noticed that a redundant packet drop occurs as a result of beacon superframe broadcasting. This is the fundamental cause of the deficiency in datarate and dependability that the standard possesses.

This issue illustrates a scenario in which data transmission occurs despite insufficient time available for data transmission during that superframe. To fill this gap, we have incorporated a freezing technique for backoff, which causes the backoff counter to freeze whenever the amount of time available for data transmission in that superframe's duration is inadequate. A unique sleep routine is being developed to reduce power usage during sleep and idle phases. The suggested MAC protocol has been modelled as a three-dimensional Markov chain for an analytical performance evaluation. The findings of the simulation are utilised to ensure the quantitative results. The proposed MAC with the sleep protocol performs noticeably better than the state-of-the-art procedures that are currently in use [13][29].

Traditional protocols used in wireless sensor networks adhere to stringent layering approaches, which decreases the effectiveness of the quality of service (Quality of Service) factors. To accomplish what has to be done with a wireless sensor network (WSN), battery-operated sensor nodes that are very small and have limited energy resources and a guaranteed amount of time require communication protocols that are both efficient and inventive. In particular, these standards become increasingly demanding as new applications that are based on WSN become available in the market. A method that considers multiple layers at once and makes it possible for them to collaborate, synchronise, and communicate with one another is the most suitable way to find an optimal answer to this problem. To improve even better quality of service parameters of the Energy Efficient Inter-Cluster Coordination Protocol (EEICCP) that has already been developed at the Network layer level, a feasible cross-layer protocol was developed and discussed in this paper. This protocol takes into consideration both the MAC layer and the Physical layer [14].

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III. System Model: The IEEE 802.15.4 Backstory

The following paragraphs offer a brief explanation of the IEEE-802.15.4 beacon-enabled mode. In this mode, a coordinator will initiate a superframe by sending out a beacon frame at regular intervals, measured by the Beacon Interval (BI = BaseSuperFrameDuration*2^{BO}).

During the Contention Access Period (CAP), nodes affiliated with the coordinator employ the slotted CSMA/CA mechanism to compete for a transmission. Additionally, these nodes may retain a Guaranteed-Time-Slot (GTS) for real-time traffic periodically.

The awake portion of the superframe continues for the amount of time denoted by the Superframe Duration (SD; SD = BaseSuperFrameDuration*2^{SO}), and nodes are free to enter a sleep state after sending data until the next beacon is sent. At a minimum, the coordinator needs to maintain their wakefulness during the entire active duration [15].

Identifying the following backoff boundary and selecting a random backoff within the contention window between 0 and (2^{BE}-1)*UnitBackoffPeriod are the two steps that make up the slotted CSMA/CA technique. During the backoff, a node will go to sleep, and once it wakes up, it will carry out two Clear Channel Assessments (CCA) to determine whether or not there is an occurring transmission taking place on the channel. The node will carry out an exponential backoff if it detects the channel is busy while carrying out a CCA.

It will select a new backoff in an increasing interval between 0 and (2^{BE+1}-1)*UnitBackoffPeriod. The node will drop the frame if the macMaxFrameRetrie threshold is exceeded without receiving an ACK. The node will also decrease the edge if the macMaxCSMABackoff threshold is exceeded without the free channel.

MAC Parameters Selection

Wireless Sensor Networks need low energy consumption, and nodes could attain minimal duty cycles (the percentage of time spent awake and asleep) by either increasing the length of their sleeping intervals or decreasing the size of their active breaks. For example, when the beacon parameters are set to SO=BO-10, the duty cycle for the coordinator can be as low as 0.1% (2^{-10}); however, the duty cycle can be a level of magnitude less for the devices that only have to wake up for frame transmission, beacon reception, and perhaps a CCA. The coordinator must be awake throughout the active period. Therefore this is essential.

Initially, using a straightforward simulation setup, we investigated the influence that a variety of MAC parameters had on the effectiveness of IEEE-802.15.4 [16]:

- macMaxFrameRetrie: number of attempts to send a frame again because it did not receive an acknowledgement before giving up and dropping it,
- macMaxCSMABackoff: number of failed channel detecting cracks that must occur before discarding a frame,

BE (backoff exponent) is responsible for determining the dimensions of the contention window that a node uses to select the random backoff period value before sensing the channel.

We have used WsNet, an event-driven simulator for large-scale wireless sensor networks, and a freely available implementation of IEEE-802.15.4 for WsNet. (It employs beacon-enabled mode and the Beacon-Only Period). We are working under the assumption that every node will always keep a packet handy ready to deliver at the start of every superframe. The simulation's data are listed in Table 1 below.

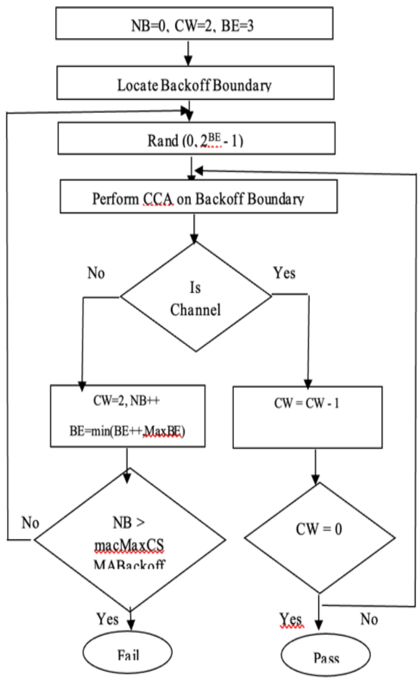

Figure 4: IEEE 802.15.4 Slotted CSMA/CA

Markov Chain Model: An Overview

The situation in which N stations or nodes attempt to communicate with a sink is taken as the starting point for the model. The parameters τ, α and β describe the probability that a node will attempt a first carrier sensing for frame transmission, that a node will observe the activity of busy channels throughout CCA1 and CCA2, respectively, and that a node will find the track busy during CCA2. Seeing the steady state probabilities of a form of the IEEE-802.15.4 Markov Chain Model yields a system of three nonlinear

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mathematical equations related to these three probabilities. These three likelihoods are associated with a system of three nonlinear mathematical equations.
When a node tries to transmit a frame, its backoff counter has already reached 0, and it is necessarily not idle (It needs to send a structure). Because of this, the likelihood that a node will try to transmit a frame using first carrier sensing is calculated using the product (1- p0)τ, rather than, where p0 represents the probability that a station is idle.

Probability of Assessing Channel Busy During CCA1: Having waited for random back-off, the nodes will sense the carrier's status and determine whether it is active or inactive. To compute the probability, one must follow the general model of the Markov Chain presented. Following is an explanation of how we arrived at the busy channel probability. Since

$$\alpha = \alpha 1 + \alpha 2$$

Where α1 is the likelihood of locating a busy channel throughout CCA1 owing to data transfer,

$$\alpha 1 = L(1-(1-\tau)N-1)(1-\alpha)(1-\beta)$$

During CCA1, the probability that the channel will be busy due to ACK transmission is denoted by α2, and this probability is equal to

$$\alpha 2 = \frac{(L_{ack}\tau\big((1-\tau).N-1\big).(1-(1-\tau).N-1).(1-\alpha).(1-\beta)}{1-(1-\tau).N}$$

Where
Lack = Length of Acknowledgement frame
α = likelihood of a busy channel throughout CCA1
L = Data frame length in slots
τ = node attempting to sense carrier during CCA1

The word Pc denotes the likelihood that one or more of the N -1 nodes will occur that are still operational will transmit during the same time slot. If every node has a transmission probability of τ, then the critical path length, Pc = 1 - (1- τ) N – 1, where N is the total number of nodes [18][30].

Table 1: Simulation Parameters for Mac Layer

Parameters	Value
Number of nodes	50
Backoff window size	8
Frame-size	51
Min Backoff Exponent	3
Max Backoff Exponent	5
Max CSMA Backoff	4
Max Frame Retry	3
Data Rates	20 Kbps, 40 kbps, 250 kbps
Payload	968 bits
Overhead bits	48 bits
ACK Frame size	88
Mean Propagation Delay	222e-9 seconds
Backoff Time Period	1000e-6, 500e-6, 320e-6
ACK wait time	6000e-6, 3000e-6, 1920e-6
Max Turnaround Time	600e-6, 300e-6, 192e-6
Sensing Time	400e-6, 200e-6, 128e-6
Tolerance	1.00E-10

Probability of Assessing Channel Busy During CCA 2: After the node has successfully sensed the channel idle for the first time, it feels the track for a second time in the same manner detailed in earlier sections. The formula for calculating the likelihood of sensing CCA2 is as follows:
Finally,

$$\beta = \frac{(1-(1-\tau).N-1+N\tau(1-\tau).N-1)}{2-(1-\tau).N+N\tau(1-\tau).N-1}$$

Here, β is the likelihood of a busy channel throughout CCA2.

Channel Access Failure Probability: When a node can locate the channel inactive twice in a row while still within its maximum allowable backoff stages (max csma backoff), this is considered a failed attempt to access the channel [19]. The following formula can be used to determine it:

$$x = \alpha + (1-\alpha)\beta \qquad y = P_{fail}(1-x^{(m+1)})$$

Where m = macMaxCSMABackoff

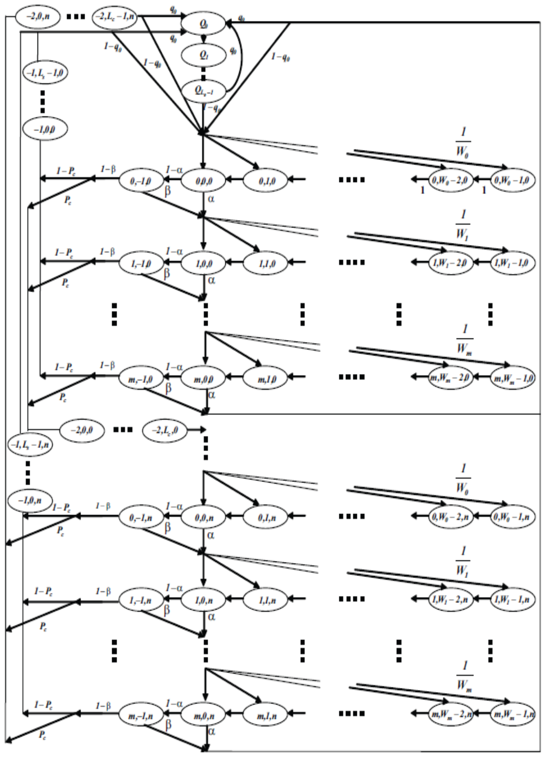

Figure 5: Markov chain model for IEEE-802.15.4's CSMA/CA mechanism

The technique that computes these probabilities allows for the determination of the possibility of collision (Pcol), the

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likelihood of loss owing to channel and radio settings (Pe), and the probability of a transmission failing (Pfail), among other possibilities. Only the collisions themselves were considered as potential causes of loss [20].

$$P_{col} = 1 - (1 - (1 - p0) * \tau)^{.(N-1)}$$
$$P_{fail} = 1 - (1 - P_e) * (1 - P_{col})$$

The probability that the packet will be thrown away because of a failed channel access is denoted by the symbol Pcf.

$$Pcf = \frac{x^{m+1}(1 - y^{n+1})}{1 - y}$$

The reliability is given by:

$$R = 1 - Pcf - Pcr$$

Simulation parameters

Table 2: Simulation Parameters for Physical Layer

Parameters	Value
Bandwidth	30 KHz
Path Loss Exponent	4
Noise Figure	23 dB
Standard Deviation	4
Transmission Power	5 dB
Wavelength	0.125 meters
Min node distance	1
Max node distance	20
Temperature	300^0 k
Boltzmann Constant	1.38e-23
Preamble Length	40 bits
Frame Length	808 bits

IV. Results and Discussion

The performance of CSMA/CA is evaluated in this result analysis when it is being operated under various frequency channels. The comparison considers reliability, the throughput analysis, the likelihood of transmission failure, and the risk of loss of channel access.

Additionally, during CCA1 and CCA2 operations, it considers the chance of sensing that the access channels are congested and the average wait time of the node before it transmits a frame. The behaviour is studied by applying an increasing load across various frequency bands while maintaining the default settings for the parameters.

To determine the outcomes, the simulation tool MATLAB is utilised.

The following performance parameters are often used to assess cross-layer optimisation in WSN protocols:

- Average Wait Time vs Offered-Load.
- Reliability vs Offered-Load.
- Alpha vs Offered-Load
- Throught vs Offered-Load
- Pcf vs Offered-Load

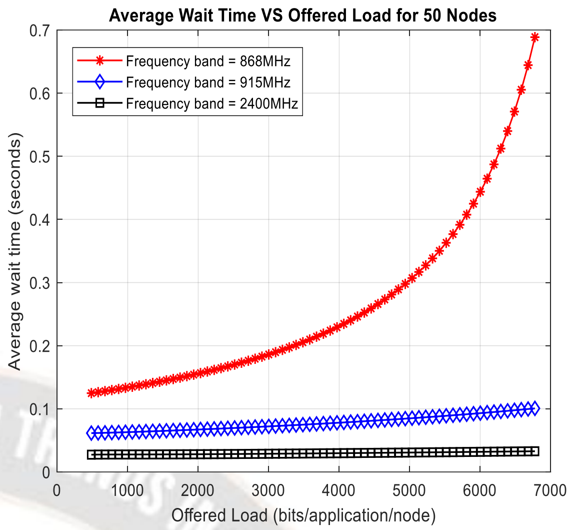

Figure 6: Average Wait Time vs Offered-Load

Figure 6 defines the system average wait time when the offered load variation happens from 484 bits/application/node to 6776 bits/application/node at various frequency bands ranging from 868 to 2400 MHz for 50 nodes. The average time a network's nodes have to wait before they can begin transmitting data packets because of a busy channel is the network's average wait time. It should be noticed that the waiting time of a node increases when the duration of the backoff period increases, as demonstrated in this picture. This is as a result of the fact that nodes are required to wait for a more extended amount of time as a result of the more considerable backoff duration in comparison to the shorter backoff duration length. We observe that at 2400 MHz, it outshines other advanced MAC protocols with a minimum average wait time.

Figure 7 defines the system reliability when the offered load variation happens from 484 bits/application/node to 6776 bits/application/node at various frequency bands ranging from 868 to 2400 MHz for 50 nodes. The reliability of a network is determined by the amount of successfully transferred data packets from their origin to their destination. Failure of a data packet can occur for one of two reasons. (i) A node could not send its data packet because the medium remained busy for such a long period that it exceeded the Mac max csma backoff threshold. (ii) If an acknowledgement frame is not received, a node will continue to send the data packet until the retry limitations (Pcr) have been exceeded and the most significant number of allowed retries is reached. According to the findings presented in this figure, the network's reliability improves when its load is decreased and reduces when it is increased. The increased reliability of successful transmission is directly correlated to the duration of the Backoff Period. We observe that at 2400 MHz, it outperforms other advanced

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MAC protocols. The likelihood of a packet failing can be used to explain this observation is less for 2400 MHz.

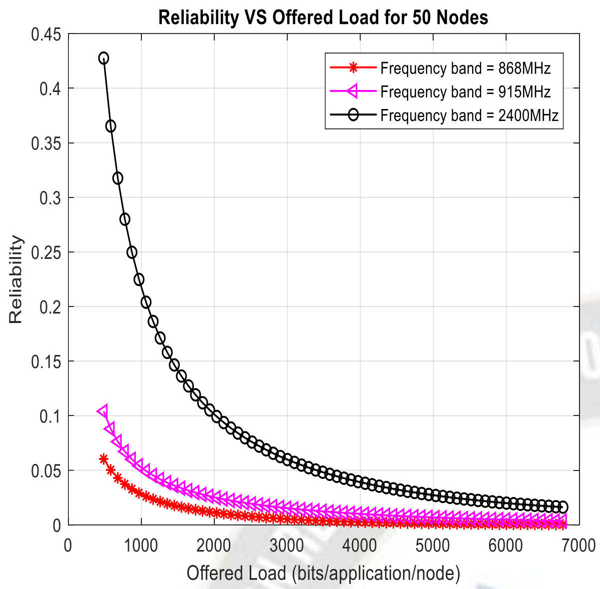

Figure 7: Reliability vs Offered Load

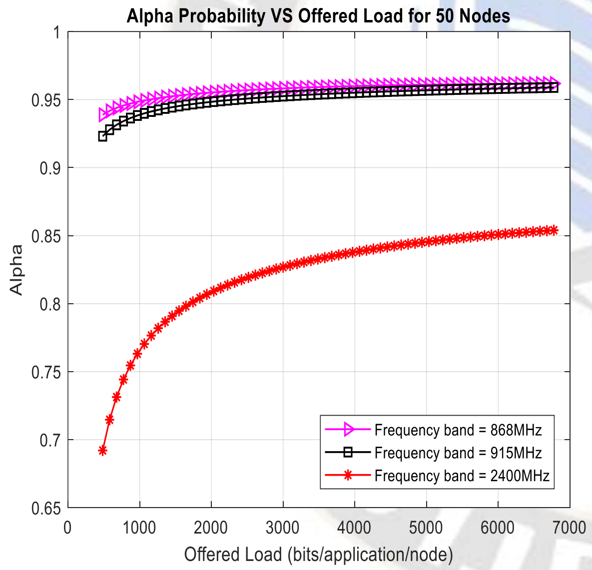

Figure 8: Alpha vs Offered Load

Figure 8 defines the system a maximum number of frame transmission retries (alpha probability) when the offered load variation happens from 484 bits/application/node to 6776 bits/application/node for various frequency bands ranging from 868 to 2400 MHz for 50 nodes. The proportion of frames that the MAC layer of the device has lost due to the CSMA/CA algorithm failing because the most significant number of frame transmission retries was reached or exceeded. This percentage relates to the overall, various data frames that the MAC layers of the device try to send. The findings in this figure suggest that an increase in traffic load positively impacts the alpha probability. This is due to the channel being busy for most of the time. The findings also indicate that a shorter backoff period duration results in a higher likelihood of a dynamic channel throughout CCA-1 and that the opposite is also true.

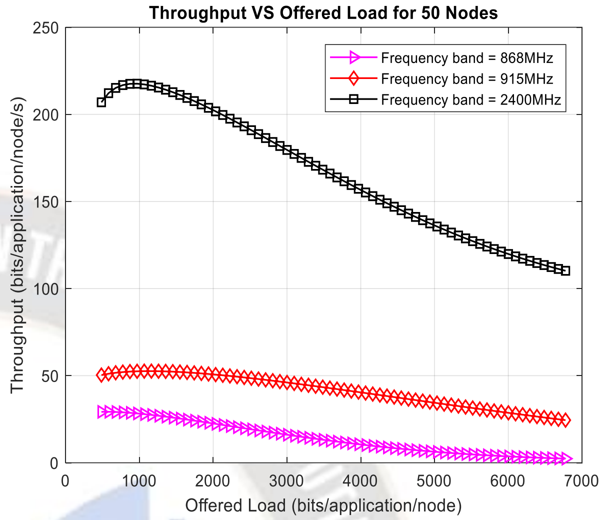

Figure 9: Throughput vs Offered-Load

Figure 9 defines the system throughput when the offered load variation happens from 484 bits/application/node to 6776 bits/application/node for various frequency bands ranging from 868 to 2400 MHz for 50 nodes. The number of successful data transfers divided by the time spent moving across a medium defines "average throughput." Using the Shannon-Hartley theorem, a correlation was found between the throughput of a set of 50 nodes and the load being provided by those nodes. Saturation occurs at a throughput of 3.0 kbps when the throughput has decreased linearly in proportion to the load.

This figure demonstrates that a more extended backoff period can yield a higher throughput than a shorter one. The most excellent throughput may be achieved over a frequency band of 2400 MHz.

Figure 10 defines the system Channel access failure probability (Pcf) when the offered load variation happens from 484 bits/application/node to 6776 bits/application/node for a frequency band ranging from 868 to 2400 MHz for 50 nodes. Failure to gain access to a channel is recorded as a failure when the hub is unable to find the channel active for two consecutive occasions while remaining within its maximum permissible backoff stages (max csma backoff), as shown in section II.

The values of and macMaxcsmabackoff are the two most important factors that determine the channel access failure probability. The higher the probability that a carrier perceives that it is busy, the higher the probability that an attempt to access the channel will fail. A similar pattern of

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behaviour can be seen repeated here as the load continues to increase: these values go up as the pack does. This graphic presents the results, which verify the statement.

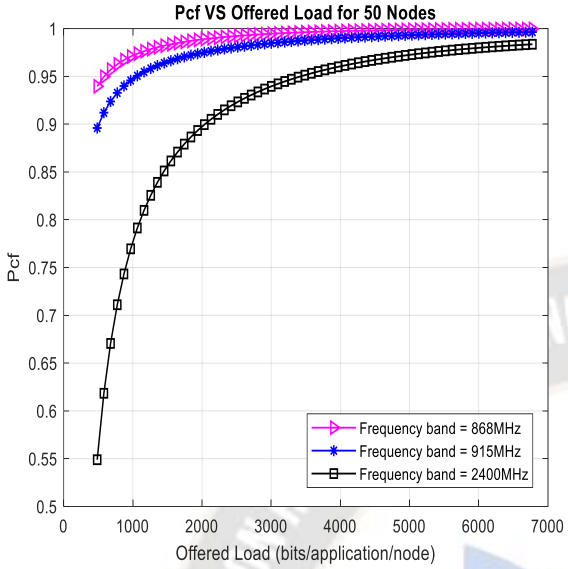

Figure 10: PCF vs Offered-Load

Table 3: Throughput comparison at various frequency bands

S. No	Offered Load	868 MHz	915 MHz	24 MHz
1	1000	28.32	52.51	271.6
2	2000	22.34	50.61	201.7
3	3000	16.09	46.08	179.6
4	4000	10.64	40.59	157.3
5	5000	6.21	34.26	135.6
6	6000	3.64	28.66	119.8

V. Conclusion

This article presents a cross-layer model for complete performance analysis of IEEE-802.15.4 networks. The model is focused on the joint layer model and includes static PHY layer computation. A Markov chain MAC layer model is combined with the physical channel model. This model is then assessed with multivariate parameter inputs. The network's performance is investigated based on the dynamic interaction derived from single-sublayer models and the environment characterised by multi-dimensional characteristics. The simulation findings prove that using a multivariate model helps obtain a more thorough analysis of quality of service performance and, in particular, enables us to reproduce realistic performance tracking while working with several parameters.

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