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Design of Medium Access Control Protocol for IEEE 802.15.4 Based WSNS to Reduce Collisions and Prevent Simultaneous Data Transmission by Nodes

Sumit Saha[1*], Ankur Dumka[2], Priti Dimri[3]

[1]Uttarakhand Technical University, Dehradun, Uttarakhand, India
[2]Graphic Era University, Dehradun, Uttarakhand, India
[3]G.B. Pant Engineering College, Pauri, Uttarakhand, India

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Abstract- Collisions which occur in a channel during data transmissions result in re-transmissions and this causes energy dissipation. In order to reduce this effect, a new Medium Access Control (MAC) Protocol is designed.

In this paper, the existing and current mechanisms of WSNs have been studied and their shortcomings identified. Accordingly the design parameters of IEEE 802.15.4 CSMA/CA based WSNS hse been extended and a new design parameter has been evolved which reduces the collisions and prevents simultaneous data transmission by nodes.

This paper suggests minor modifications to the current mechanism of IEEE 802.15.4 CSMA/CA by incorporating re-transmission limits of the nodes with packet collision probability.

Keywords- WSN, IEEE 802.15, Medium access control (MAC), Received signal strength indicator (RSSI), Clear channel assessment (CCA), Number of backoffs (NB), Backoff exponent (BE), Contention Window (CW), Guaranteed time slots (GTS), Contention access period (CAP), Deterministic synchronous multi-channel extension (DSME), Personal area Network (PAN), Carrier sense multiple access/collision avoidance (CSMA)/CA, Peer to peer (P2P), Number of retries (NRT)

I. INTRODUCTION

Wireless sensors have invaded the civil and defence communication sectors in a big way. This technology has replaced the erstwhile twisted pair shielded cables or multidrop Ethernet buses which were used earlier by various applications.

IEEE 802.15.4 [1] Medium Access Control (MAC) Protocol enabled Wireless Sensors are used in wide variety of industrial applications. These WSNS can be either Star or Peer to Peer (P2P) configuration based on the requirements of the applications or job profile.

In Star topology configuration, a Personal Area Network (PAN) coordinator in a WSN acts as a single central coordinator between source and destination nodes in a star topology. A sender has to send data to the receiver with the help of PAN Coordinator. Media access is Contention based in star topology.

In P2P, however, the connection is between a pair of nodes which are one hop away and are within the range of communication, thus no intermediary is required.

One of the channel access mechanisms for effective communication includes the Beacon enabled slotted CSMA/CA.

IEEE 802.15.4 has been adapted by incorporating additional functionality to provide IEEE 802.15.4 MAC [2] which is further amended by IEEE 802.15.4 e [3] standard that adds more functionality and support to the former ones and thus gives better support. While keeping the superframe structure of low latency wireless devices and basic channel access mechanisms of IEEE 802.15.4 unchanged in [2] the modified standard suggests three possible superframe structures similar to [1] along with a Deterministic Synchronous Multichannel extension (DSME) which is a multi-frame structure having an enhanced Beacon with an information element. The standard described in [2] specifies the optimal use of any superframe structure. In [3] the data transfer model is similar to [1] and [2].

A device listens to the Network beacon if it wants to transfer data to a PAN Coordinator. It synchronizes to the Super Frame Structure if the beacon is formed and then transmits data frame to the PAN Coordinator in its assigned time slots.

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This paper brings out a course of action to mitigate use of excess energy by carrying out an analysis of the concurrent problems faced by WSNS.

A few Analytical Models functioning on IEEE 802.15.4 protocol have been developed and performance analysis of these prototypes has been carried out to assess changes in throughput and energy consumption.
The concluding sections bring out the findings that it is possible to incorporate minor modification to the existing IEEE 802.15.4 base standard which proposes to introduce the limit to the number of transmissions which make a WSN more suitable to low data rate transmission rather than the higher data rates.

II. RELATED WORKS / STUDY OF PUBLISHED WORK

Discreet time Markov chains have been used to analyze performance of an IEEE 802.15.4 compliant network which operate in beacon enabled mode with both download and uplink traffic.
Sensor – MAC (S-MAC) protocol has been proposed by Misic et al., in [4] in which the protocol can locally manage the synchronization and thereby the periodic sleep – listen schedules. However, they have not analyzed the performance of the protocol based on its energy consumption and throughput.

The TDMA based algorithm proposed in [5] by W.Ye et al.,has been rendered energy efficient by increasing the utilization of the classical TDMA. However, the authors have not considered the effects of collisions on energy consumption and throughput.
The CSMA/p* proposed in [6] by Rajendran et al.,achieves low latency in traffic conditions but the idle listening to all slots, before sending the data results in higher energy consumption.
Energy consumption in slotted CSMA/CA algorithm of IEEE 802.15.4 MAC during idle and backoff periods, is evaluated in [7] by Tay et al., but the Paper does not take into consideration the collisions which take place and thereby affect energy consumption.

An analytical model has been developed by Rasheed et al.,in [8] to study performance of Guaranteed Time Slots (GTS) in IEEE 802.15.4 Networks. However, authors have not taken into account the effect on energy consumption and throughput due to collisions and data retransmissions in Contention Access Period (CAP).
In [9] authors Mehta et al., design performance models for slotted CSMA/CA under saturated and unsaturated periodic traffic conditions in which each device’s carrier sensing probability is assumed to be independent. In [10] Polin et al.,have studied the Sensor node density, data transmission rate and communication duration which directly affect performance of a network. However, effects of collisions on performance metrics have not been analyzed or taken into consideration.

Authors in H. Zhao et al., in [11] propose a collision avoidance MAC for WSNs in which each transmitter has to adjust its next transmission time. The algorithm is designed simply to reduce the number of collisions without analyzing the energy consumption and throughput.
Chen et al., in [12] have carried out a performance analysisand audit of wireless sensor networksusing time frequency analysis and neural networks.
In [13] Faridi et al.,describes the behavior of a Node in a wireless PAN in ACK mode using a Markov chain model. Saturated traffic conditions are created for nodes which induce re-transmissions. Similarly in [14] PK Sahoo et al., describes another re-transmission while considering saturated traffic conditions for nodes. A delay sensitive slotted contention-based MAC protocol [15] by Dodou et al., is proposed for WSNs in which several MAC protocols which affect the transmission delay are analyzed. However, no performance analysis model is presented by the authors.

Authors Lee. H et al.,in [16] develop an energy efficient MAC protocol based on a receiver initiated asynchronous duty cycling and analyze it using Markov chain with a finite number of states that represent a queue length at the wake up of nodes. However, the effect of re-transmission, Back off mechanism and contention window is not modeled to analyze the energy consumption and throughput.

In [17] authors Alvi A.N et al., analyse the performance of nodes based on reliability and transmission failure probability in a wireless PAN during CAP taking slotted CSMA/CA algorithm into account. However, the efficiency of the WSN which is affected by/ due to re-transmission of packets in an unsaturated traffic condition is not analyzed. In [18] author P. Park proposed a Markov chain to minimize the power consumption of nodes in IEEE 802.15.4 WSN with re-transmissions and acknowledgements. However, the authors have missed out analyzing the reliability of data transmissions.

A Sampling frequency of sensor nodes and rate of packets lost during data transmission in an IEEE 802.15.4 based WSN based on quality of information received by Cluster Head (CH) during transmissions and periodic sampled date forwarded to the Sink is proposed by the authors Ning Weng et al.,in [19]. The proposal however falls short in not being able to design a theoretical model to study the performance of the proposed WSN in terms of information sensing and forwarding of periodic sampled data to the sink.

III. PROBLEM ANALYSIS

In a WSN based on Star Topology using a single channel, a PAN coordinator is attached to several wireless nodes. The communication between nodes is managed by CSMA/CA mechanisms based on IEEE 802.15.4. Each node has to compete with others to access the channel before transmitting data in order to commence communication with the Coordinator.

A clear picture of how Carrier Sensing mechanism in IEEE 802.15.4 works will enable a better understanding of problem areas.

Functioning of IEEE 802.15.4 MAC Standard

In the slotted CSMA/CS IEEE 802.15.4 the MAC sublayer in the beginning initializes three (03) variables; Number of Back Offs (NB), Contention Window (CW) and Back Off Exponent (BE). It then attempts to identify the boundary of the next Back Off period.

Fig 1 depicts stepwise progression of the mechanism.

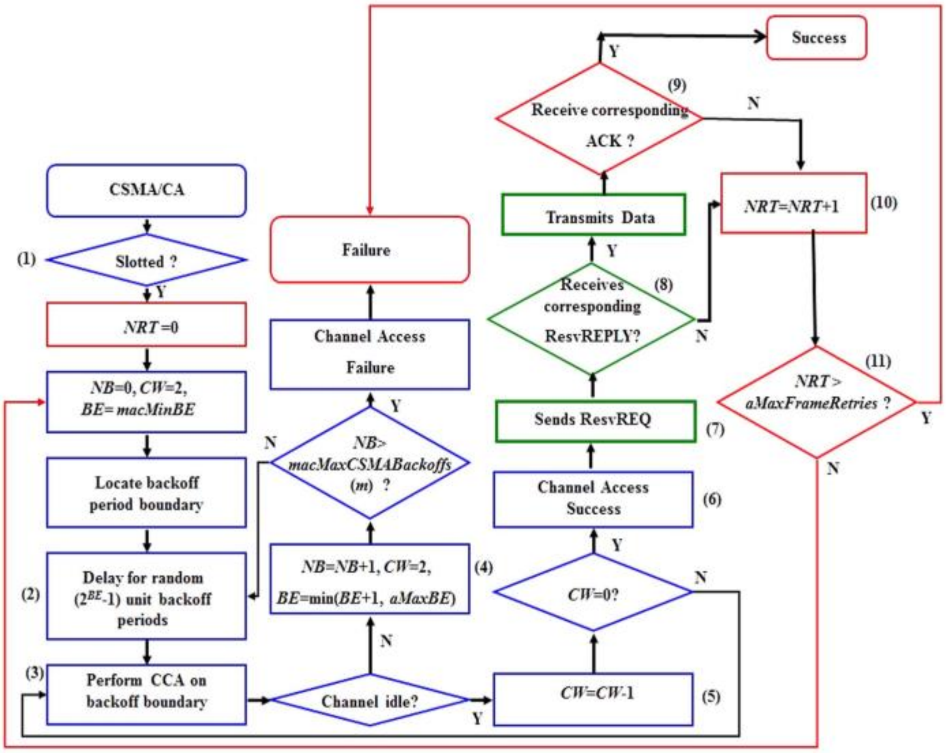

Fig 1. Proposed IEEE 802.15.4CSMA/CA mechanism to avoid unnecessary CCAs but with retry limits

The variable MacMinBE means the minimum value of the Back Off exponent (BE) in CSMA/CA algorithm which can be 0 through 3.

The value of BE cannot be more than a MaxBE and its value can be taken upto 5 as per the standard. Collision avoidance is disabled during the first iteration of the algorithm when NB=0.

In Step 1, BE could either initialized to the value of MacMinBE or to a value lesser than 2 and MacMinBE. The variable MacMinBE means the minimum value of BE in CSMA/CA algorithm and this value can be from 0 to 3.

Also note that the value of BE cannot be more than the value of aMaxBE, which can be taken upto 5 as per the standard for CSMA/CA algorithm.
Collision avoidance is disabled, when during First iteration of the algorithm when the value is set to 0
In Step 2, MAC sublayer resets CW=2 and goes for back Off delay for a random number of back Off periods in the range of 0 to (2^{BE} -1) units Fig 1.
In Step 3, a node performs its Clear Channel Assessment (CCA)on a back off period boundary. The Contention Window (CW) needs to have expired before commencing any transmission. Once the CCA is done, and channel is assessed to be idle during the first CCA and the MAC Sub-layer ensures the Contention Window has expired before the transmission is commenced.
In order to commence transmission, the MAC Sub-layer decrements the value of CW by 1 in Step 5 and this results in value of CW = CW – 1.

In Step 4, After performing the first CCA, the MAC layer increments the value of both NB and BF by 1, if the channel is assessed busy. Thus value of NB is less than or equal to the variable Mac Max CSMA Backoffs, the CSMA/CA algorithm returns to Step 2. Fig1.

In Step 5, Mac Sublayer therefore decreases the value of CW by one. If value is not equal to zero, the second CCA is performed. If the value of CW is 0, then it is a successful channel access and it starts transmitting the frame of the boundary of the next Backoff period. This constitutes a successful packet txn.

The Variable macMax CSMA Backoffs represents the No of times the CSMA/CA algorithm is required to backoff while attempting the current transmission and its value can be taken upto 3 as defined in the standard.
When the value of NB becomes greater or exceeds the value of macMaxCSMAbACKOFFS, Channel Access Failure takes place and CSMA/CA algorithm terminates. The Failure Status is notified to the next higher level and the procedure is terminated.

IV. LIMITATIONS

A Node performs its first Clear Channel Assessment (CCA) in Step 3 as shown in Fig1. In a slotted CSMA/CA system, the CCA starts on a Backoff period boundary. Before actual transmission of any data, a node has to do a CCA twice.
There could be various combinations, which could emerge as a result of CCA1 and CCA2. Lets take the first scenario,
In the existing IEEE 802.15.4 MAC, the node assumes that the medium is busy when it receives a Received Signal Strength Indicator (RSSI) value which is higher than a prefixed threshold.

If the Nodes' first CCA1 is successful, whereas CCA 2 is a failure, it is possible that either another node in the system is transmitting data to the Coordinator or the Coordinator is exchanging Acknowledgement with the Sender.
After the failure of any CCA, a node has to switch to the Backoff delay and returns to re-attempt a CCA.

As per the standard, a Node goes into Backoff delay when its CCA1 or CCA2 is unsuccessful. During this Backoff delay period, it continually senses the channel until the value of BE and NB crosses the maximum prescribed value; which for BE is (aMax BE) = 5 and for Number of Backoffs NB is (macMaxCSMABackoffs) = 4

This brings out the fact that a Node has to perform CCA1 or CCA2 maximum up to 5 times if either of the Clear Channel Assessments ends up as unsuccessful.
Similarly, in the second scenario, consider a WSN which uses hidden terminals. Two nodes may access the channel at the same time and can transmit data if both their CCAs are successful.
However, on the flipside, both their data collides as a result of simultaneous transmission by both nodes.

Identification and Definition of Problem Area

In the first scenario, in order to avoid the CCAs, it can be safely presumed that once a Node senses the channel busy, the Node should avoid performing its second CCA (CCA2) as either data or ACK transmission is going on by other Nodes in the channel.

In the second scenario, which involves hidden terminals in a WSN, Collision due to hidden terminals should be avoided, as repetition of CCAs and retransmission of data due to collision must affect the performance of the network in terms of energy and throughput.

Goal

In order to mitigate the effects of multiple Clear channel Assessments (CCAs) which affects the performance matrix by increasing dissipation of energy while also affecting the throughput, a new Medium Access Control (MAC) mechanism for IEEE 802.15.4 enabled WSNS is proposed which can be implemented within the Contention Access Period (CAP) of the Superframe of a Node without any additional overload on the existing Superframe Structure. The proposed communication mechanism can prevent nodes to transmit their data simultaneously. All hidden terminals get information about the competing nodes in advance and no retransmission of data is required as the network will be free from collisions.

In view of channel interference, noise and other factors associated within the network, a failure in receiving the ACK may take place. Thus, a node may not receive an ACK even when there are no collisions in the network. If a node fails to receive ACK, it can repeat transmission to a maximum No of retry limits (NRT) and finally the packet may be rejected once the value of NRT exceeds the limit.

In order to mitigate the effects of the performance of a network due to this problem, a 3-Dimensional Markov Chain model has been developed.

Comparative Study of Existing Protocols and Summarization of the Suggested Protocol

Based on detailed study of some of the existing protocols, their limitations have been identified and a new protocol is suggested. A new CSMA/CA mechanism is proposed to avoid collision due to hidden terminals and to reduce the number of CCAs.

A 3D Markov chain Model has been designed to analyze the energy consumption and throughput of WSN under unsaturated traffic conditions. The main findings are summarized in Table 1

Table 1. Comparison and contributions

Features	TRAMA [Rajendran et al. 2003]	CSMA/ p* [Tay et al., 2004]	S-MAC [Ye et al. 2004]	Mehta et al., 2009	Rasheed et al., 2014	Our Protocol
Analytical models	No	No	No	No	No	Yes
Retransmission	No	No	No	No	No	Yes
ACK Consideration	No	No	No	No	No	Yes
Collision mitigation	No	No	No	No	No	Yes
Two CCAs	Yes	Yes	Yes	Yes	Yes	No
No. of backoffs (NB)	No	No	No	No	No	Yes
Contention Window length (CW)	No	No	No	No	No	Yes
Channel usage duration	No	No	No	No	No	Yes

V. SYSTEM MODEL

In the WSN model suggested by us, the data flows from ordinary sensors to the co-ordinators. The device periodically listens to the network beacon in order to commence the process of uplink data transfer in a beacon enabled slotted CSMA/CA WSN network.

Each node usually generates a data packet of uniform length of L units and which it sends to the Co-Ordinator. In this System model we propose two types of data transmission modes:

(a) Collision free MAC without re-transmission
(b) MAC mechanism with Retransmission.

Collision free MAC without Retransmission

This MAC mechanism proposes to reduce the number of CCA and avoid collisions due to hidden terminals. According to this protocol, during CAP of superframe, a node is required to broadcast a reservation request (ResvREQ) packet. After a successful channel access and before sending a ResvREQ packet, a node goes into a short random Back off period. The ResvREQ packet indicates a channel usage duration of L units of data slots. A (ResvREQ) packet is broadcast by a coordinator which signifies a channel occupancy of L + 3 slots. Thus, signaling to all the other nodes trying to access the channel or channel is already successful to stop sending the data packets to avoid collision and resultant re-transmissions.

[tACK]= 1 Slot and [LACK]=2 slots,
And thus L + 3 indicates Channel occupancy
On receiving the ResvREPLY packet a sender must transmit its data to the Coordinator and request is confirmed after getting the ACK. Within the CAP of the superframe, each node competes to get the channel by performing CCA1 and CCA2 before sending any data. When both CCAs of a node are successful, it sends the resvREQ packet to the Co-Ordinator as shown in Step 7 of the Figure 1.

At this stage there may be two possibilities which are tabulated below.

Possibility	Status of CCA	ResvREQ pkt	ResvREPLY pkt	Result
Case 1	Both CCA are successful	Packet is sent by Node	Packet is sent by Co-Ordinator	Data is transmitted by Node to Co-Ordinator
Case 2	-do-	-do-	Packet is Not received by Node	1. Collision is assumed in NW 2. Node goes in for Re-transmission

The L + 3 Slots can be incorporated into a new handshaking procedure in certain mini slots following CCA2 of a Node. Figure 2 depicts a proposed communication model to avoid un-necessary carrier sensing.

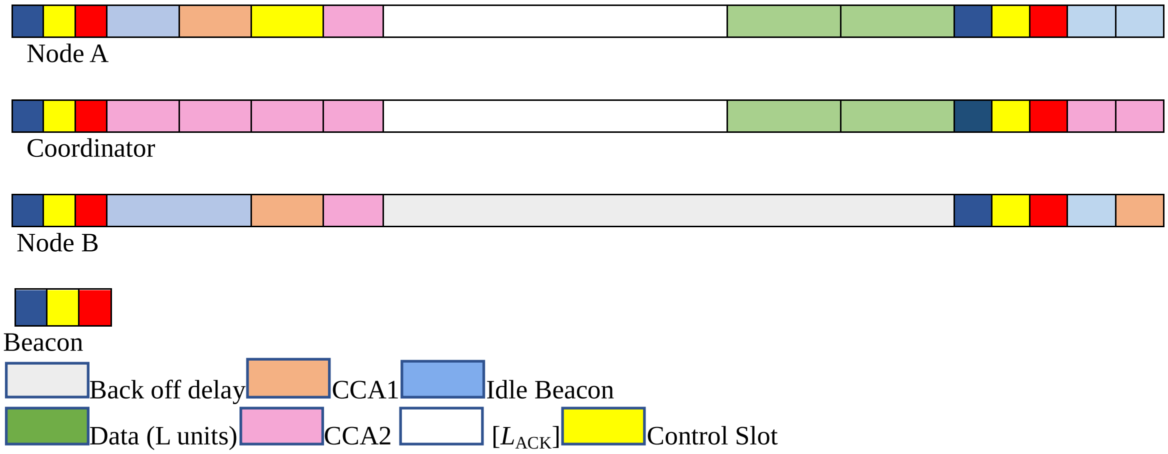

Fig 2. Proposed Communication Model to avoid unnecessary carrier Sensing

The proposed communication mechanism is being executed within the CAP, which lies within the Beacon period of a Superframe. In this process a node should sense the channel busy during the exchange of ResvREQ and ResvREPLY packets. The duration of each such packet can be one mini slot. Thus, if a Node senses Channel busy during CCA1, it should listen to the channel immediately in the next mini slot instead of going for Back off delay.

The possibilities that can emerge out of this system are tabulated.

CAP	**Action**	**Denotes**		
CCA1	Node receives ResvREPLY msg from Coordinator	Implies that Node gets Channel busy information		
CCA1	Node does not receive the resvREPLY message	Node concludes that CCA1 was done during the idle slot **t**$_{ACK}$of another node	Node should go for Random Back off since listening to channel will be of no use	So no transmission takes place and No collision is there
CCA2	Node senses Channel busy	Proposed that Node should listen to the		

<table>
<tr><td></td><td></td><td>immediately in the next slot instead of going back off delay and then performing CCA1 subsequently</td><td></td><td></td></tr>
<tr><td>CCA2</td><td colspan="4">However, if the Node does not receive the ResvREPLY message in this slot Infer that its CCA1 has performed during the idle slot $\mathbf{t}_{ACK}$of another node and its CCA2 has failed as the exchange of ACK is going on.
Then this node may go in for Back Off delay and starts performing CCA1 as per the existing standard.
Hence No transmission and no collision takes place.</td></tr>
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Proposed MAC mechanism with re-transmission

Since no two nodes can transmit data at the same time collision is avoided in the medium. A sender may however fail to receive the ACK due to interference or noise. In such an eventuality it may go for re-transmission.

As per the existing standard if a single transmission is unsuccessful for not receiving the ACK, the Device repeats the process of re-transmission and waits for the ACK up to a max number of”aMAXFrameRetries” times (As per standard value of aMaxFrameRetries = 3).

If ACK is still not received after maximum number of re-transmissions tries (NRT, max Sublayer Assumes that transmission has failed. Even though in a slotted CSMA/CA functioning on IEEE 802.15.4 standard a CSMA/CA algorithm may terminate with a channel access success status, data transmission is not considered a success unless the sender receives the ACK.

Accordingly, in the proposed re-transmission-based channel access mechanism, a sender goes to Step 9 of Figure 1 to check if corresponding ACK is received on time or not.

Only if ACK is received, Packet transmission is considered successful, otherwise value of NRT is incremented by 1 as shown in Step 10 of Fig 1.

If the value of NRT is less than MaxFrameRetries it goes to Step 1 of Fig 1, and if it exceeds the value of MaxFRameRetries then it is a failure.

Thus, our proposed format is similar to the existing mechanism.

VI. ANALYTICAL MODELS

In the analytical model proposed here, the assumption is that N number of Nodes are attached to a coordinator. Transmission from any node to the coordinator is allowed. Here the performance of only uplink traffic is analyzed.

Proposed Markov Chain Model

The proposal of discrete time 3-dimensional Markov Chain model as depicted in Fig 3 is put forward to analyze the efficiency of the Packet transmission probability of IEEE 802.15.4 based Wireless sensor networks. For a given node, the stochastic processes are defined. Given below are definitions of the associated variables which are taken into account.

s(t) represents the Back off stage for the first random variable NB.

c(t) represents the Back off counter for the second random variable CW.

r(t) represents the retransmission counter for a given value of NRT which varies between 0 and 3.

The processes s(t), c(t) and r(t) that define the state of a device at the back of unit boundaries are shown in Fig 3.

$$Sj,x,k = \lim_{t\to\infty} P\ \{s(t) = j,\qquad c(t) = x,\qquad r(t) = k\}^n$$

Where, $j\ \epsilon\ \{0,\ 1,\ \ldots.,\ m\}$, $x\ \epsilon$ {-2, -1, ….,W_j-1}, k ϵ {0,1, ….*aMaxframeRetries*}, where m represents the *macMaxCSMABackoffs* and $Wj = 2^{\min(j+macMinBE,aMaxBE)}$ .The time t corresponds to beginning of the slot time and is directly related to the system time.After the Backoff counter is decremented to zero, $S\ j,0,k$ and $S\ j,-1,k$ represent the states corresponding to the first CCA and the second CCA respectively; and $S\ j,-2,k$ represents the transmission state.

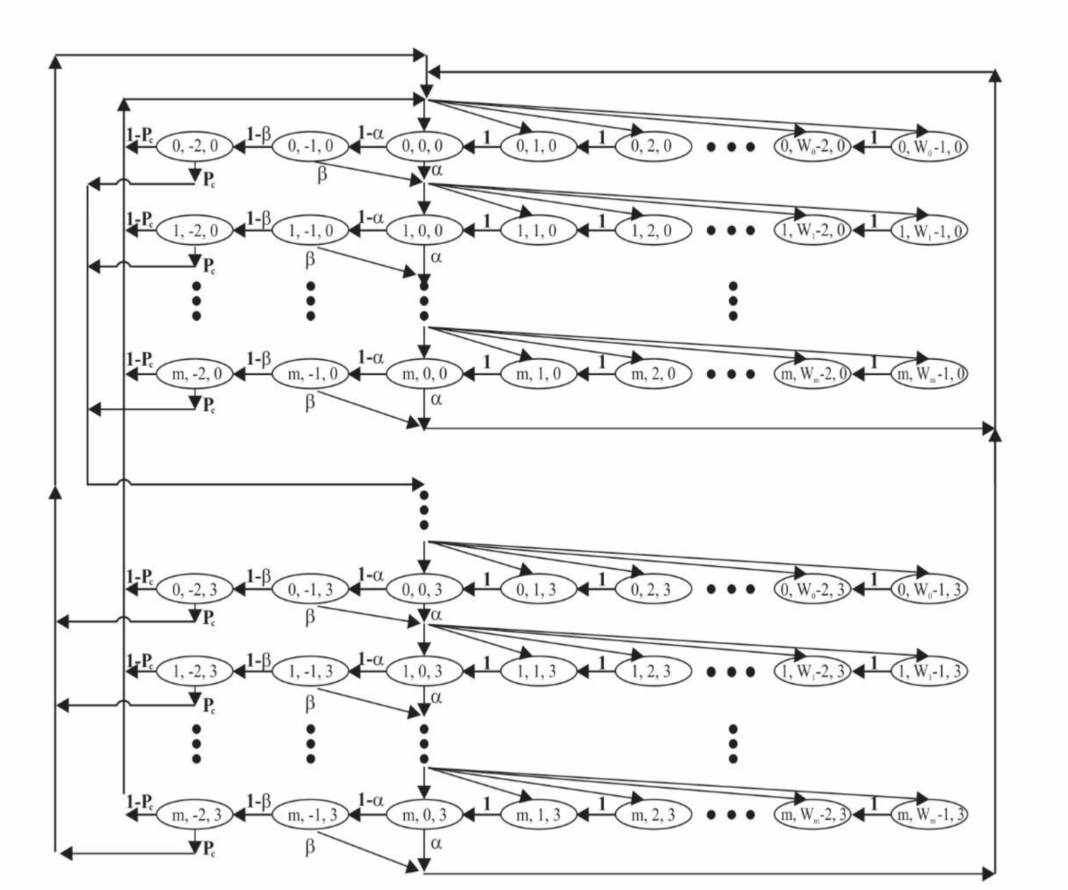

Figure 3: Our Markoy chain model based on retransmission policy of IEEE 802.15.4

The probability of assessing channel busy during the first CCA i.e., (CCA_1) is represented by α and β is the probability of assessing channel busy during the second CCA i.e., (CCA_2) given that the channel was idle in CCA_1. A node goes totransmission state, if the channel is idle in both of the CCAs and attempts totransmit data. It is to be noted that till date in all of the works, it is assumed that the node enters into the transmission state after both CCA_1 and CCA_2 are successful. However, in our model, a node is considered to be in transmission state $S_{j,\ -2,k}$, only if it receives the acknowledgement successfully, which may happen due to absence of collision in the channel. In our model, if channel is idle during both CCAs, but collision occurs during the transmission attempts, a node increases the value of its NRT and again goes to the channel assess procedure.

VII. CHANNEL ASSESS PROBABILITY

For a given station, c(t) is the stochastic process representing the back-off counter. A discrete and integer time scale t and t +1 corresponds to the beginning of two consecutive slot times, and the backoff time counter of each station decrements at the beginning of each slot time. The stochastic process s(t) represents the backoff stage and s(t) = 0 at time t. We assume that the probability to start sensing the channel is constant and independent of all other nodes. The stochastic process r(t), representing the retransmission counter at the beginning of the first transmission, is set to 0 at time t and for each retransmission is incremented by 1. A three-dimensional Markov chain, as shown in Fig. 3 is formulated using the assumptions given for s(t), c(t), and r(t) and the corresponding transition probabilities can be expressed as follows:

$$P(j, x-1, k \mid j, x, k) = 1,$$

$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs \\ 1 \le x \le W_j - 1;\ 0 \le aMaxFrameRetries \end{cases} \quad (1)$$

$$P(j, -1, k \mid j, 0, k) = 1 - \alpha,$$

$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs \\ 1 \le k \le aMaxFrameRetries \end{cases} \quad (2)$$

$$P(j+1, x, k \mid j, 0, k) = \frac{\alpha}{W_{j+1}},$$

$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs - 1 \\ 0 \le x \le W_{j+1} - 1; 0 \le k \le aMaxFrameRetries \end{cases} \qquad (3)$$

$$P(0, x, 0|macMaxCSMA\ Backoff, 0, k) = \frac{\alpha}{W_0},$$

$$for \begin{cases} 0 \le x \le W_0 - 1 \\ 0 \le k \le aMaxFrameRetries \end{cases} \qquad (4)$$

Equation 1 is the condition to decrease the backoff counter until it reaches the state (0, 0, 0). At the state (0, 0, 0), a node performs its first clear channel assessment (CCA_1) and the corresponding transition probabilities are givenin equations 2 and 3. Equation 2 accounts for the fact that the node goes to the second channel assessment CCA_2 following the successful first channelassessment. Equation 3 accounts for the unsuccessful CCA_1. In particular,as considered in equation 3, when an unsuccessful CCA_1occurs with probability α, the backoff stage increases and the new initial backoff value is randomly chosen in the range (0,W_{j+1}−1), for the given value of j. Equation 4, models the scenario, once the backoff stage reaches at the value of *macMaxCSMABackoffs*, it is not increased in subsequent packet transmissions.

$$P(j, -2, k|j, -1, k) = 1 - \beta,$$

$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs \\ 0 \le k \le aMaxFrameRetries \end{cases} \qquad (5)$$

$$P(j + 1, x, k|j, -1, k) = \frac{\beta}{W_{j+1}},$$

$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs - 1 \\ 0 \le x \le W_{j+1} - 1; 0 \le k \le aMaxFrameRetries \end{cases} \qquad (6)$$

$$P(0, x, 0|macMaxCSMABackoff, -1, k) = \frac{\beta}{W_0},$$

$$for \begin{cases} 0 \le x \le W_0 - 1 \\ 0 \le k \le aMaxFrameRetries \end{cases} \qquad (7)$$

Equation 5 and 6 explains the scenario to model the probability of successful and unsuccessful second clear channel assessment (CCA_2), respectively. Equation 5 models the fact that a node goes to the packet transmission state following a successful CCA_2. Equation 6 models the system after an unsuccessful CCA_2, in whicha node goes to next backoff stage and stays within a randomly chosen backoffcounter. Similarly, equation 7 gives the probability that there is failure in both sensing slots, i.e. in CCA_1 and $CCA_2$and also fails up to the last backoff stages i.e. if the failure in both CCAs occurs and it continues till macMaxCSMABackoff becomes 0.

Probability of retransmission of Packets

If acknowledgement of a transmission is not received on time, possibly due to interference or noise in the medium then it results in a packet retransmission as described earlier. And as per the standard, if a single transmission attempt is failed for not receiving the acknowledgement, the the device shall repeat the process of transmission and wait for the acknowledgement upto a maximum of *aMaxFrameRetries*. In this case, a node restarts the channel assessment until the value of the retransmission counter is greater than *aMaxFrameRetries*. Accordingly, equation 8 and 9 model the system for receiving the successful and unsuccessful acknowledgements, respectively. As given in equation 8, the transition probability forthe successful packet transmission is presented, whereas the transition probability of unsuccessful transmission of packet due to collision in the mediumis given in equation 9. Equation 10, models the system for the unsuccessful retransmission of packet, when a node crosses all of its limits such as the value of backoff counter (CW), backoff stages (NB) and retransmission counter (NRT). However, equations 8 through 10 are replaced by the collision probability $p_c = 0$, if the MAC mechanism without retransmission is considered. (If the node receives the corresponding *ResvREPLY* packet from the coordinator, it transmits the the data as shown in Step 8 of the fig 1. However if it does not receive *ResvREPLY* packet, it assumes collision in the channel.) In the proposed model the communication mechanism can be executed within the CAP, which lies in the beacon period of a superframe.

$$P(0, x, 0|j, -2, k) = \frac{1 - p_c}{W_0},$$

$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs \\ 0 \le x \le W_0 - 1; 0 \le k \le aMaxFrameRetries \end{cases} \qquad (8)$$

$$P(0, x, k + 1|j, -2, k) = \frac{p_c}{W_0},$$

$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs \\ 0 \le x \le W_0 - 1;\ 0 \le k \le aMaxFrameRetries - 1 \end{cases} \tag{9}$$

$$P(0, x, 0 | j, -2, aMaxFrameRetries) = \frac{p_c}{W_0},$$

$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs \\ 0 \le x \le W_0 - 1 \end{cases} \tag{10}$$

$$where, W_j = 2^{\min(j+macMinBE, aMaxBE)}, j \in \{0,1,\dots,m\}$$

Conditional channel access probability

Let, $M_i(s)=-1$ be the event that there is at least one transmission in the medium by another node in slot i and $M_i(c)=-1$ be the event that some node start sensing the medium during slot i. On the contrary, $M_i(s) \ge 0$ denotes the event that no station in the medium is transmitting in slot iand $M_i(c) \ge 0$ denotes the event that no station starts sensing during slot i,where slot i could be any time slot, e.g. slot CCA_1, slot CCA_2, slot 1 andso on. Then, the probability that a station is performing first CCA can be estimated as given in equation 11.

$$\tau = \sum_{j=0}^{macMaxCSMABackoffs} \sum_{k=0}^{aMaxFrameRetries} S_{j,0,k} \tag{11}$$

If $[T_L]$ and $[T_{ACK}]$ denotes time duration in the number of slots fortransmitting an L-slot packet and receiving an acknowledgement, respectively,probability of first channel assessment is busy can be given as follows:

$$\alpha = \{(1 - p_c)([T_L] + [T_{ACK}]) + p_c[T_L]\}(1 - \beta) \times [1 - [1 - \tau(1 - p_0)]^{N-1}\}(1 - \alpha) \tag{12}$$

Where $p_0$is the probability that a node is not in one of the state $S_{j,x,k}$,which reflects the unsaturated traffic conditions of the network. The devicewill sense busy in slot CCA_2, if another device is going to transmit at thesame slot, which has already started sensing the channel in slot 1 i.e. $M_1(s)=-1$ and the channel was then idle i.e. $M_1(s)\ge 0$. Hence, β = P (MCCA2(s) = - 1 | MCCA1 (s) ≥ 0).

$$= \left[\frac{\frac{\{1-[1-\tau(1-p_0)]^N\}(1-\alpha)(1-\beta)}{1-[1-\tau(1-p_0)]^N}}{\{1 - [1 - \tau(1 - p_0)]^{N-1}\}(1 - \alpha)(1 - \beta) + \frac{\{1-[1-\tau(1-p_0)]^N\}(1-\alpha)(1-\beta)}{1-[1-\tau(1-p_0)]^N}} \right] \times \{1 - [1 - \tau(1 - p_0)]^{N-1}\} \tag{13}$$

Other than the transition probabilities, the Markov chain steady state probabilities can be abbreviated, as follows:

$$D_1 = (1 - \alpha)(1 - \beta) \cdot p_c \tag{14}$$

$$D_2 = (1 - \alpha)\beta + \alpha \tag{15}$$

However, if our proposed protocol of MAC mechanism without retransmission is considered, equations 12 and 14 will be replaced by p_c =0asnocollision in the medium is taken into account.

Steady state probability

It is to be noted that the network parameters j ∈{0, 1, ..., m}, $x\in\{-2, -1, \dots, W-1\}$, k ∈{0, 1, ..., aMaxFrameRetries}, affect performance of the network, where m represents the macMaxCSMABackoffs and $W_j = 2^{\min(j+macMinBE,aMaxBE)}$. Hence, the closed-form solution for the steady-state probabilities based on our Markov chain model are given as follows:

$$S_{0,0,k} = \left[\frac{D_1(1 - D_2^{m+1})}{1 - D_2}\right]^k S_{0,0,0,}$$

$$for\ 0 \le k \le aMaxFrameRetries \tag{16}$$

$$S_{j,0,k} = D_2^j S_{0,0,k,}\ for \begin{cases} 0 \le j \le macMaxCSMABackoffs \\ 0 \le k \le aMaxFrameRetries \end{cases} \tag{17}$$

$$S_{0,x,0} = \frac{W_\alpha - x}{W_\alpha}\{ \sum_{j=0}^{macMaxCSMABackoffs} (S_j, -2, aMaxFrameRetries \cdot p_c) + \sum_{k=0}^{aMaxFrameRetries} \sum_{j=0}^{macMaxCSMABackoffs} [S_{j,} - 2, k \cdot p_c)]$$

$$+ \sum_{k=0}^{aMaxFrameRetries} S_{macMaxCSMABackoffs,0,k} \cdot \alpha$$

$$+ \sum_{k=0}^{aMaxFrameRetries} S_{macMaxCSMABackoffs,-1,k} \cdot \beta\}, for\ 0 \leq x \leq W_0 - 1$$

$$S_{j,-1,k} = (1-\alpha) \cdot S_{j,o,k,} \tag{18}$$

$$for \begin{cases} 0 \leq j \leq macMaxCSMABackoffs \\ 0 \leq k \leq aMaxFrameRetries \end{cases} \tag{19}$$

$$S_{j,-2,k} = (1-\alpha)(1-\beta) \cdot S_{j,o,k,}$$

$$for \begin{cases} 0 \leq j \leq macMaxCSMABackoffs \\ 0 \leq k \leq aMaxFrameRetries \end{cases} \tag{20}$$

$$S_{j,x,k} = \frac{W_{j-x}}{W_j S_{j,0,k}}$$

$$for \begin{cases} 0 \leq j \leq macMaxCSMABackoffs \\ 0 \leq x \leq W_j - 1; 0 \leq k \leq aMaxFrameRetries \end{cases} \tag{21}$$

Since, sum of the probabilities must be 1, we get

$$1 = \sum_{j=0}^{macMaxCSMABackoffs} \sum_{x=0}^{W_2-1} \sum_{k=0}^{aMaxFrameRetries} S_{j,x,k} \tag{22}$$

$$+ \sum_{j=0}^{macMaxCSMABackoffs} \sum_{k=0}^{aMaxFrameRetries} S_{j,-2,k}$$

$$+ \sum_{j=0}^{macMaxCSMABackoffs} \sum_{k=0}^{aMaxFrameRetries} S_{j,-1,k}$$

However, by considering our proposed MAC mechanism without retransmission,equation 18 can be replaced with $p_c = 0$

Performance analysis

In this section we use our analytical models to study the throughput andenergy consumption issues of sensors under unsaturated traffic condition bytaking a fixed delay of 100 slots before going into the first delay stage andafter sending the previous packet.

Throughput analysis

Let S be the system throughput and p_{tr}be the probability that there isat least one transmission in the considered slot time. Since, N number ofnodes are associated to a coordinator, τ be the probability that the station isperforming first CCA and p_0 be the unsaturated probability, the transmissionprobability is given as follows:

$$p_{tr} = (1-\alpha)(1-\beta)\{1 - [1 - (1 - p_a)\tau]^N\} \tag{23}$$

The probability $p_s$that a transmission occurring in the channel is successfulis given by the probability that exactly one node transmits on the channel,given that at least one node transmits. Hence,

$$p_s = \frac{(1-\alpha)(1-\beta)N \times (1-p_0)\tau[1-(1-p_0\tau]^{N-1})}{p_{tr}} \tag{24}$$

The unsaturated throughput S, defined as the fraction of time the channel isused to successfully transmit the payload bits in unit time can be estimated as follows.

$$S = \frac{p_s p_{tr} T_{pl}}{(1-p_{tr})\alpha + p_{tr} p_s T_s + p_{tr}(1-p_s)T_c} \tag{25}$$

where, T_{pl} be the payload length in number of slots, T_s be the duration ofthe slot time for a successful transmission, and T_c be the time spent during a collision. Here σ is the duration of an empty slot time and the values T_{pl}, T_s, T_c, and σ must be expressed with the same unit. The number of occupiedslots for the successful transmission, and collision are given in equations 26 and 27, respectively.

$$T_s = 2\lceil T_{CCA}\rceil + \lceil T_L\rceil + \lfloor \delta \rfloor + \lceil T_{ACK}\rceil \tag{26}$$
$$T_c = 2\lceil T_{CCA}\rceil + \lceil T_L\rceil + \lfloor \delta_{max} \rfloor \tag{27}$$

Where, T_{CCA}, T_L, δ and T_{ACK} be the time durations (in number of slots) for performing a CCA, for transmitting L-slot packet, for waiting for an ACKand for receiving an ACK, respectively. Note that, in IEEE 802.15.4, a devicewaits for an ACK during *macAckWaitDuration* (equal to 2.7 slots in 2.4GHz channel). However, we assume that the waiting duration is two slots after thelast transmission slot. In addition, we also assume that the backoff procedure starts at the first ACK waiting slot, as given in our Markov chain model.

Energy consumption analysis

An analysis of the normalized energy consumption,which is the average energy consumption to transmit one slot amount of payload has been done in this section. The duration of each successful channel assessment (T_{CCA})and the packet turnaround time has been considered for each successful transmission or reception of a packet. Considering P_s to be the probability of successful transmission occurring in the channel, and T_L being the time duration for transmitting an L-slot packet, consumption of total energy per node can be represented in equation 28.

$$E = \frac{\tau\alpha T_{CCA}P_{RX} + \tau(1-\alpha)\beta \times 2T_{CCA}P_{RX}}{\tau(1-\alpha)(1-\beta)p_s T_{pl}} + \frac{\tau(1-\alpha(1-\beta[(1-p_s)E_c + p_s E_s]}{\tau(1-\alpha)(1-\beta)p_s T_{pl}} \tag{28}$$

where, P_{RX} be the energy consumption to receive and P_{TX} be the energyconsumption to transmit a packet. T_{ta} be the turnaround time i.e time taken during each RX-to-TX or TX-to-RX, and P_{ta} be the turnaround power, which is taken as $\frac{P_{TX}+P_{RX}}{2}$. δ_{max} be the maximum time to wait for an acknowledgment frame to arrive, following a transmitted data frame. The energy consumption for each successful transmission i.e. E_s and each collision i.e. E_c can be estimated as given in equation 29 and 30, respectively.

$$E_s = 2T_{CCA}P_{RX} + T_{ta}P_{ta} + T_L P_{TX} + T_{ta}P_{ta} + \delta_{max}P_{RX} \tag{29}$$

$$E_c = 2T_{CCA}P_{RX} + T_{ta}P_{ta} + T_L P_{TX} + T_{ta}P_{ta} + (\delta - T_{ta} + T_{ACK})P_{RX} \tag{30}$$

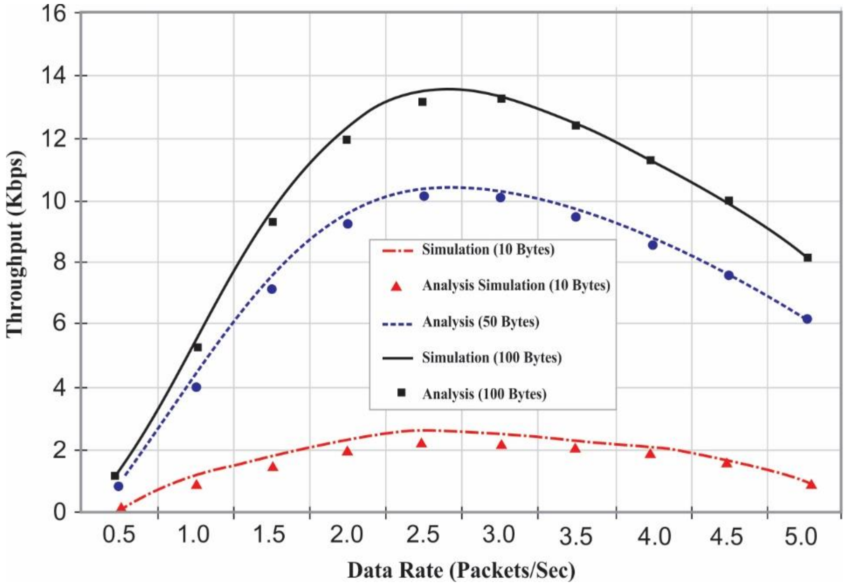

Figure 4: Validation of throughput for different data rates.

Performance evaluation

In this section, we validate our models by comparing the analytical results with the simulation one. Our simulation is performed using NS-2, in which all nodes form a star topology with a radius of 3 meters with one coordinator at the center and other nodes are evenly distributed around it. The transmission range of the transceiver is taken to be 7 meters. The packet size is assumed to be 10, 50 or 100 bytes excluding the routing, MAC and PHY layer headers.The maximum PHY sublayer service data unit (PSDU) size that the node shall be able to receive is considered to be 127 bytes.

Model validation

In order to validate our model, we consider the beacon frames as the control frames to keep the network working. We use the default parameter values such as 3, 5, 4 and 3 for *macMinBE*, *aMaxBE*, *macMaxCSMABackoff* and *aMaxframeRetries*, respectively as defined in 2.4GHz frequency channels. Fixed number of nodes are attached to the coordinator and a node transmits fixed size of packets of 10, 50 or 100 bytes each time. Thus, to validate our model, we have compared the simulation and analytical results for differentdata rates, as shown in Fig. 4, Fig. 5 and Fig. 6. As shown in Fig. 4, the throughput is evaluated for different data rates and it is found that the analytical result quite matches with the simulated one. As shown in Fig.5, validation of analytical and simulation results for energy consumption is presented. It is observed that the energy consumption gradually reaches to a saturated value with increase in the data rates as capacity of the network islimited.

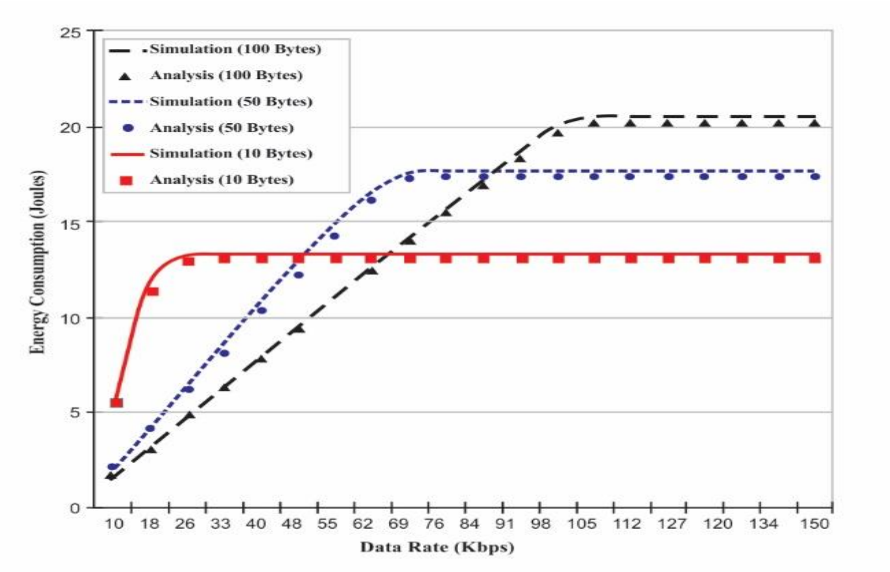

Figure 5: Validation of energy consumption for different data rates.

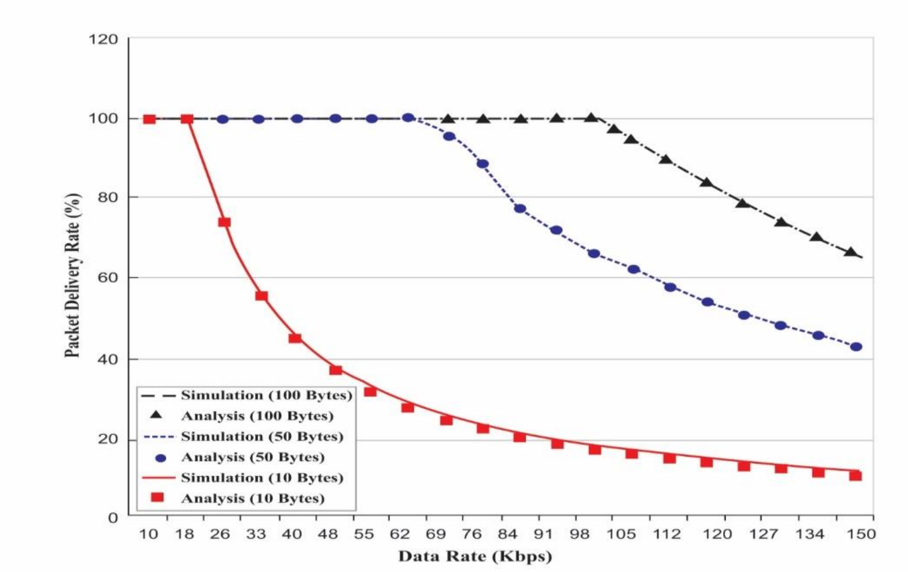

Figure 6: Validation of packet delivery ratio for different data rates.

The packet delivery ratio that is defined as the percentageof the ratio of the number received packets to the number of thesent packets is validated as shown in Fig. 7. The packet deliveryratio is validated for the analytical with our simulation results fordifferent data rates taking different size of the data packets. Asshown in the figure, our analytical results very well match withthe simulation.

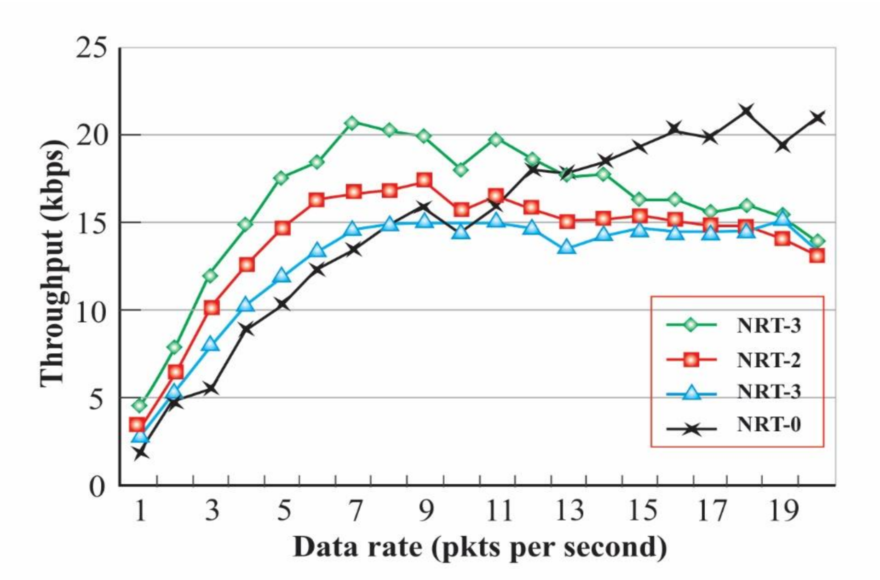

Figure 7: Throughput for different values of NRT.

Evaluation of our protocol

Unsaturated traffic conditions are used to evaluate the proposed protocol and the results are compared with event based simulation. The unsaturated traffic conditions case in our model, comprises a setting with periodic monitoring intervals. In this scenario, all nodes do not generate packets at the same time and thereby do not have packets to transmit. In order to simulate our protocol in an environment with or without collision, different values are used for the number of retransmissions (NRT). A node does not need to retransmit the packet if there is no collision in the system, as the packet transmission is to be successful. Accordingly, the value of NRT=0 in our simulation, if there is no collision in the system. However, the value of NRT is taken to be 1, 2 or 3 in case of a collision detected in the network. A node has to retransmit a packet due to collision and a node has to retransmit the packet twice or thrice that corresponds to the value of NRT=2 or NRT=3, if the retransmission consecutively failed due to repetition of collision. It is to be noted that in our simulation also, the maximum value of NRT=3 according to IEEE 802.15.4 MAC mechanism.

As the number of retransmissions is the new concept introduced in our models, we have evaluated the throughput, energy consumption and packet delivery ratio for different values of NRT as shown in Fig. 7, Fig.8 and Fig. 9, respectively for different data rates (packets/sec).

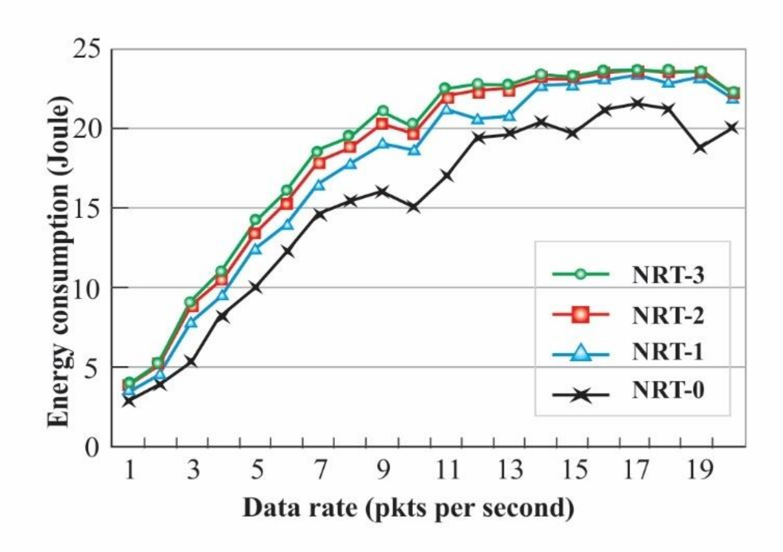

Figure 8: Energy consumption for different values of NRT.

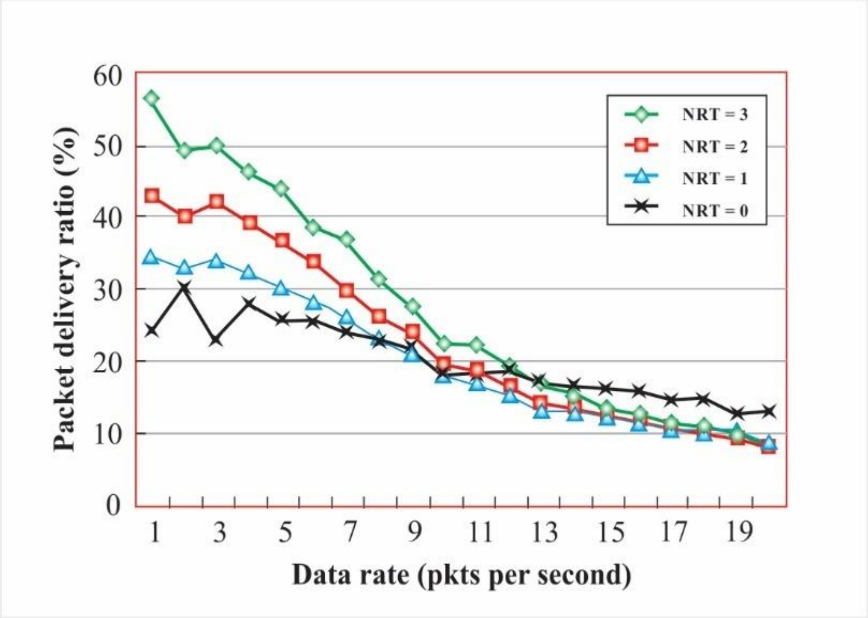

Figure 9: Packet delivery ratio for different values of NRT.

From Fig. 7, it is observed that the throughput withNRT value equal to 3 is higher than others when the data rate is less than 13 pps (packets per second). Once the data rate exceeds13 pps, the throughput with NRT equal 0 is higher than others.When data rate is lower (less than 13 pps) and collision occurs, the retransmissions of the collided packets actually increase the datarate. However, when data rate is higher (more than 13 pps) andcollision occurs, the retransmission of the collided packets becomesa heavy burden on the network. The energy consumption for NRTequals to 0 is always less than that for the NRT equals to 1, 2, and3, as shown in Fig. 8.

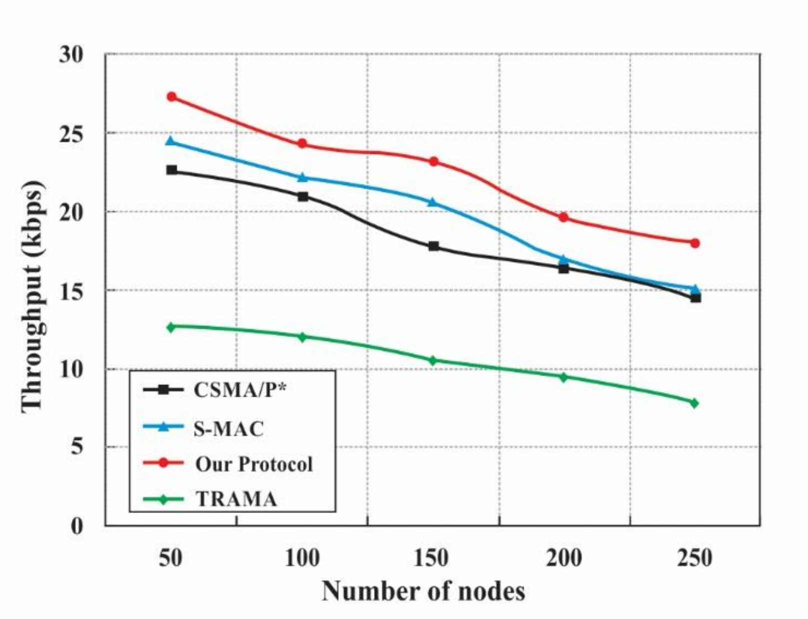

Figure 10: Comparison of throughput for different number of nodes.

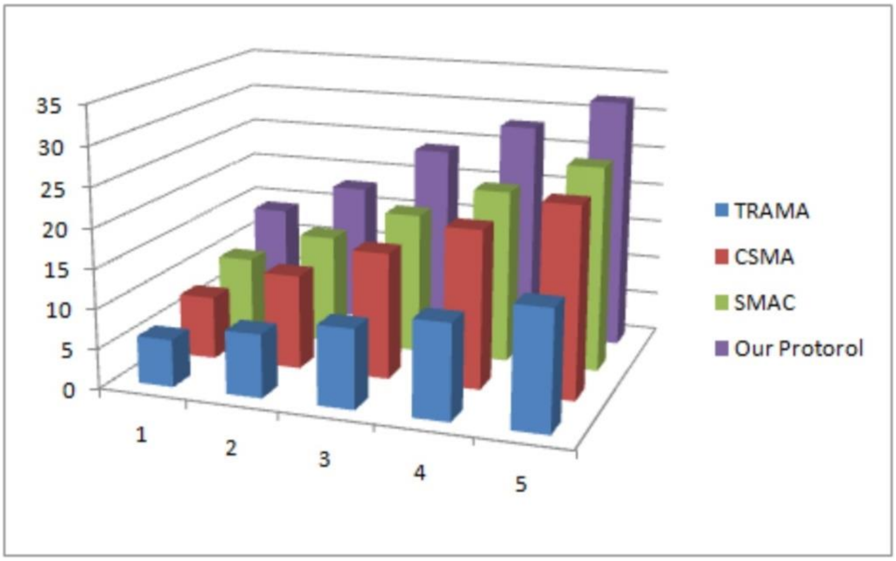

Figure 11: Comparison of throughput for different data rates.

Energy consumption corresponding to thevalue of NRT=0 is comparatively less than other NRT values, asthe packet is rejected, if acknowledgement is not received due tocollision in the medium. In Fig. 10, we can see that the packetdelivery ratio decreases dramatically for NRT equal to 1, 2 or 3.The dropped packets will not be retransmitted while NRT is equalto 0. For this reason, when the data rate is lower (less than 13pps), the packet delivery ratio is lower for NRT equal to 0. Theretransmission makes the data rate increasing.

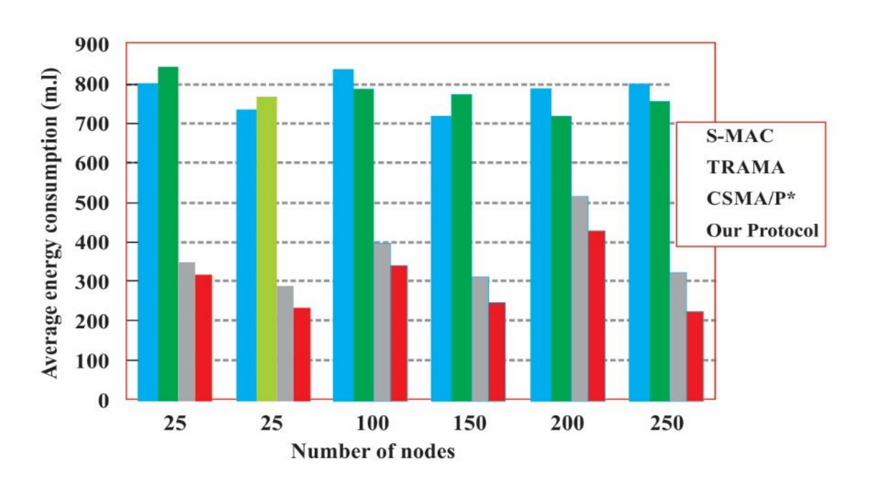

Figure 12: Comparison of energy consumption for different number of nodes.

Comparison of our protocol

In order to compare the performance of our protocol with similar protocols, we have simulated our protocol, S-MAC [5], TRAMA[6] and CSMA/p∗[7] in terms of throughput, average energy consumptionand packet delivery ratio for different number of nodesand data rates as shown in Fig. 10 through Fig. 15. We have comparedour protocol with S-MAC [5] as it is a well known medium access control protocol for the sensor networks. Since, TRAMA[6] is an energy efficient collision free MAC protocol for the WSNand our protocol analyzes the energy consumption with or withoutcollision in the medium, we have compared our protocol with it.We have considered CSMA/p∗[7] to compare with our protocol asthey propose to reduce the collision and thereby to improve theenergy consumption and throughput.

The throughput for different number of nodes is simulated as shown in Fig. 10. It is observed that our protocol out performs over other protocols though it decreases with increase in the number of nodes. Since, our CSMA/CA protocol can avoid the collisions, its performance is better as compared to others. As shown in Fig. 11, throughput of all protocol is increased with increase in the data rates. The throughput of S-MAC is better than other protocols as the time synchronization overhead is prevented with sleep schedule announcements, which enables the smooth transmission of data.However, our protocol gives better performance over others as itcan reduce the number of collisions due to our proposed backoff mechanism.

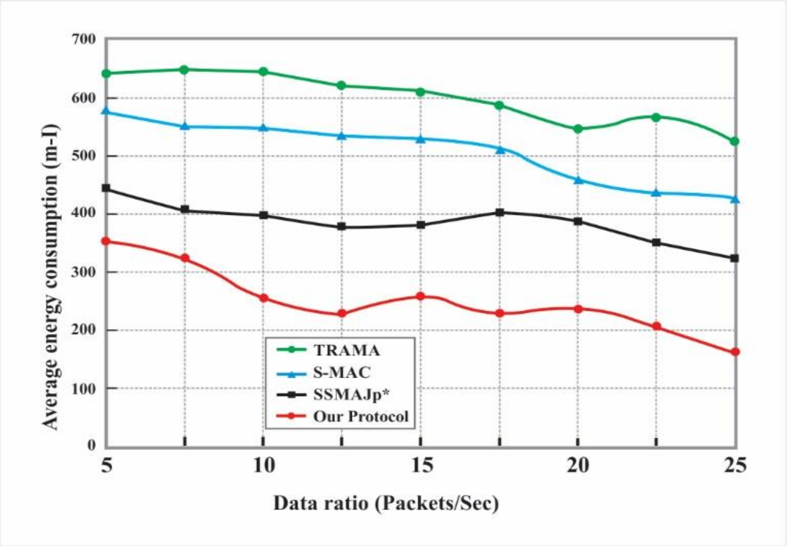

Figure 13: Comparison of energy consumption for different data rates.

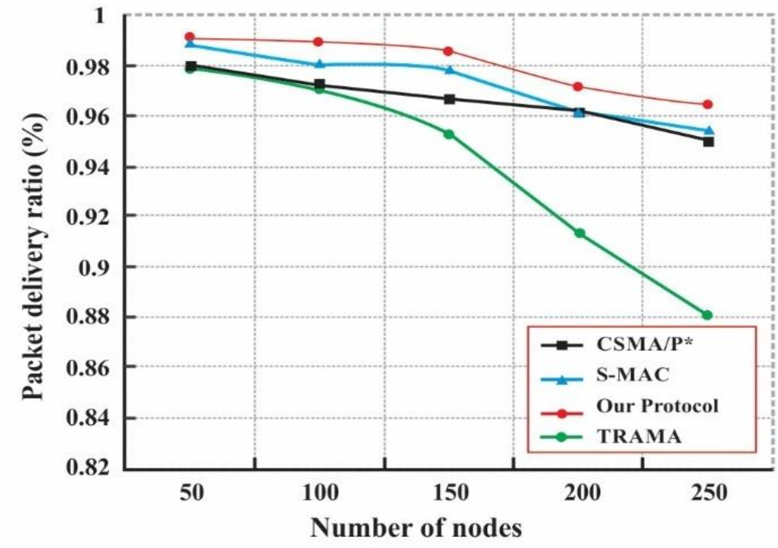

Figure 14: Comparison of packet delivery ratio for different number of nodes.

The average energy consumption of our protocol for different number of nodes is compared with others as shown in Fig. 12. Though energy consumption of our protocol is lowest as compared to others due to minimum number over hearings,TRAMA performs the worst as compared to S-MAC and CSMA/p* as it is not energy efficient.

Average energy consumption for different data rates is simulated as shown in Fig. 13. Average energy consumption of CSMA/p* is better than S-MAC and TRAMA as it can achieve very low latency for different data rates.

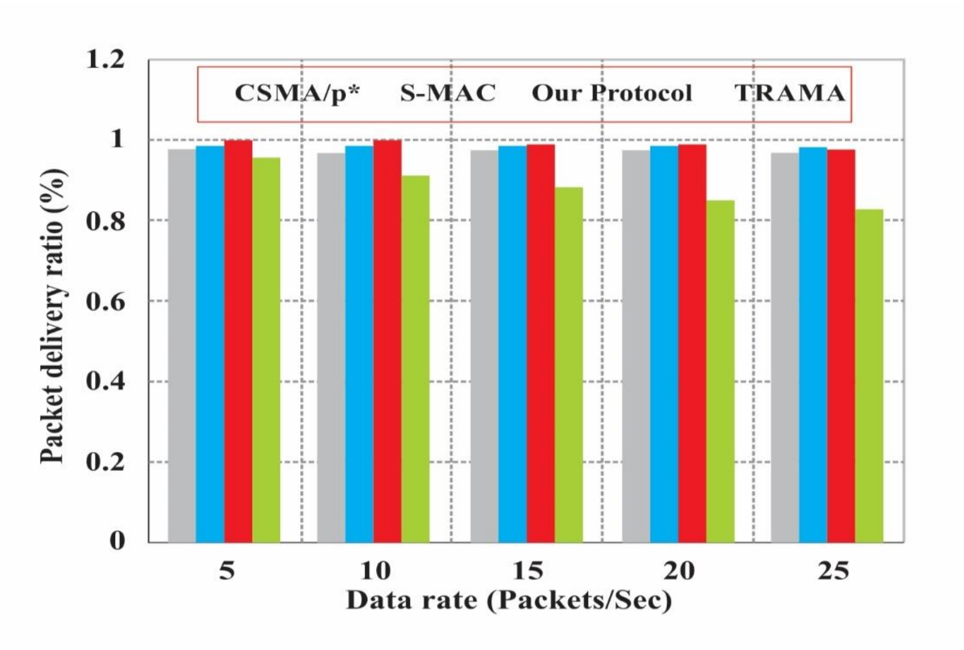

Figure 15: Comparison of packet delivery ratio for different data rates.

But, our protocol shows the best performance as idle listening caused by listening to all slots before sending data is minimized. Moreover, numbers of CCAs in our protocol are less than all other protocols, which is another reasonfor the minimum energy consumption. As shown in Fig. 14, packet delivery ratio in TRAMA drastically decreases with increase in the number of nodes, which is due to the long waiting time becauseof the longer duty cycle. However, our protocol can outperform over all other protocols since there are less numbers or no collision at all, along with considerations of shortest duty cycle. The packet delivery ratio in CSMA/p∗ and S-MAC is almost same as depicted in Fig.15, since both of them maintain similar form of collision avoidance mechanism. However, packet delivery ratio of our protocol is better than the rest protocols though it remains almost same even if there is an increase in data rate is. It could be due to few collisions in the system that reduces the packet delivery ratio in spite of increase in data rates.

VIII. CONCLUSION

In this paper, a beacon-enabled slotted CSMA/CA with acknowledgement of IEEE 802.15.4 based Wireless Sensor Network is considered. Analytical models are developed to study the throughput and energy consumption of the network under unsaturated traffic condition. In order to reduce the number of clear channel assessments, a new communication model is proposed. An extension to the existing CSMA/CA mechanism with number of retransmission limits is proposed and a three-dimensional Markov chain model is developed. Simulation results show that the standard is suitable for the low data rate transmission rather than higher data rates. It is observed that we should make the payload size as large as possible in order to get better throughput. Since throughput of the network is reduced for several retransmissions with higher data rates, it is concluded that retransmission ofcollided packets could be considered for the network of lower data rate such as wireless sensor networks.

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