Performance Analysis of IEEE 802.15.4 MAC Layer: Prospect for Multi-hop Networks

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***Abstract*—In this paper, we propose and model an enhanced IEEE 802.15.4 MAC for sensor nodes operating in multi-hop scenarios. Existing IEEE 802.15.4 MAC, when adapted to multi-hop networks may not perform efficiently due to lack of knowledge about the instantaneous state of local gateway. We therefore ameliorate the channel access mechanism by introducing a new Active-Tx state, which aids in identifying the state of local gateway along with traditionally existing Sleep and CSMA/CA states. A 3D Markov chain based model is developed for analysing the performance of proposed MAC framework under different configurations of network. Upon considering reliability, energy and delay as the key performance metrics the analysis shows that the model captures behaviour of the sensor node most accurately with 95% confidence level. In addition performance is also analysed using real time deployment and found to be in good accordance with analytical and simulation outcomes.**

***Keywords*-multi-hop network, 3D Markov chain, Analytical models for IEEE 802.15.4 MAC.**

I. Introduction

IEEE 802.15.4 is a proven technology for low power and minimal data rate applications, which has already drawn a significant attention from industry, control, home automation and health care applications [1]–[3]. Primary power conserving strategy for the devices which adopts IEEE 802.15.4 lies in efficient duty cycle management by MAC layer. The standard for MAC layer proposed in [1] is very much suitable for single-hop networks due to their sole dependency on channel. When extended to multi-hop scenarios, the traditional MAC layer may not deliver similar performance as opposed to single-hop cases. To interpret better, consider a multi-hop scenario shown in Fig. 1(a), where the sensor nodes should have to eventually commit the data at gateway using the local gateways (also known as cluster heads). Primary challenge involves detection of local gateways availability to receive the data being transmitted by sensor nodes, which is not the case in single-hop scenario where the gateway will always remain in receiving state. The local gateway has two primary and varied functions to be served of which the first one involves the reception of data from sensor nodes and the latter involves forwarding thus received data to the gateway. Upon using the traditional MAC layer, sensor nodes will not have an accurate knowledge on the operational state of local gateway making the successful transmission arduous. To avert such confrontations, we propose a beacon based handshaking mechanism, where the local gateway transmits a beacon whenever it is available for reception of the data from sensor nodes. Our primary contributions include

- Proposed a new system model by introducing Active state into the sensor node
- Proposed a 3D Markov chain for analytical study
- Development of an accurate mathematical model for studying sensor node behaviour
- Scrutinizing the performance of sensor node under different network conditions
- Development and analysis of real time test-bed deployment

Primary research studies of IEEE 802.15.4 such as [4]–[9] are inspired with the model proposed by Bianchi for analysing IEEE 802.11 MAC protocol [10]. IEEE 802.15.4 MAC, with unsaturated or saturated traffic, acknowledgements, and retransmissions for a star network is analysed in [4] by deriving congestion probabilities in Clear Channel Assessment (CCA) states. In [5], authors discussed Slotted IEEE 802.15.4 for a star topology. The model proposed in [6] consists of IEEE 802.15.4 under non beacon-enabled mode. Slotted IEEE 802.15.4 throughput is analysed under unsaturated conditions for a star network in [7]. In [8], analytical model is used to investigate the impact of the CSMA/CA parameters, the number of contending users, and the data frame size on the network performance in terms of throughput and energy efficiency.

In similar trend many more research studies such as [10]–[13] have analysed the behaviour with respect to reliable and timely data delivery. We can clearly infer from the afore stated literature that many studies constrained themselves to single-hop scenarios and to the best of our knowledge, no study provides a clear analysis of the behaviour in multi-hop scenario. Hence we feel that our study can have great impact on future researches which drive the efficiency of IEEE 802.15.4 MAC based multi-hop networks in IoT scenario. Rest of this manuscript is organized as follows. Section 2 discusses the system model based on a generic 3D Markov chain and Section 3 provides the mathematical formulation of the proposed model. Brief outline of the test bed developed for analysing real time performance is provided in section 4. The performance analysis from the emulations and analytical model is discussed in Section 5 which also includes comparison with the test bed outcomes. Finally, Section 6 concludes

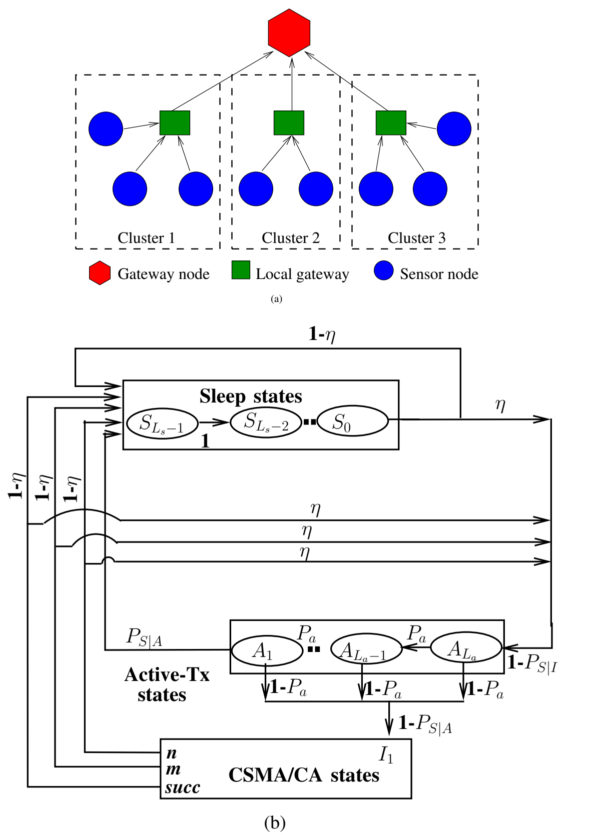

Fig. 1: a) Network model b) State model of a sensor node

this study by discussing the future scope of the work.

II. System Model

Fig. 1(a) shows the system model considered for the proposed model where a single gateway acts as a destination for all the data generated from sensor nodes. Data collected at the sensor nodes has to be routed towards the gateway using local gateways (also known as cluster heads). The behaviour of a sensor node is modelled accurately by considering 3 different states namely Sleep (S_i), Active-Tx (A_i) and CSMA/CA as shown in Fig. 1(b). Primary contribution in this study when compared with the model proposed in [5] is the inclusion of Active state which helps the sensor node in identifying the local gateway when it is in receiving mode. In Sleep state, sensor nodes sleep for an assigned duration of time (L_S) and during the last slot of Sleep state (S_0), the sensor node senses for any available data. If any data needs to be transmitted, then the node successfully transits into Active-Tx state else the node continues in Sleep state for the next L_S slots and follows the practice. In Active-Tx state, the node waits for a beacon from the local gateway and the rate at which local gateway transmits a beacon plays a key role in determining the waiting time of a sensor node in Active-Tx state which is more elaborated in later sections of this manuscript. The sensor nodes after successfully receiving beacon within a maximum of L_a slots of the Active-Tx state, perform handshake with local gateway in order to get access for data transmission to the local gateway. Once the successful handshake is completed with the local gateway, the sensor node follows CSMA/CA flow depicted using a 3D Markov chain shown in Fig. 2 with backoff stages (m), backoff counter (k) and collision retries (n) as the three dimensions. If the node fails in handshaking process, it continues in Active-Tx state and waits for a new beacon subsequently repeating the same process. Such handshaking procedure can evade locus where the sensor nodes transmit into the channel but local gateway is not in receiving state thereby resulting in loss of energy and reliability. For the purpose of modelling, the overhead associated with beacon handshaking process between sensor node and local gateway is negligible and was considered as a realistic assumption in most popular of earlier studies such as [5], [15], [16].

Our primary investigation focuses on the effect of traffic, sleep time of a node, beacon rate and Active state length on the performance of network. Although this study extends models proposed in [4], [14], [15], we still make use of few mathematical formulations present in those studies directly wherever necessary due to space constraints.

III. Mathematical Model

We formulate the proposed model in two stages by starting with derivation of transition probabilities across all states shown in Fig. 1(b). Second phase follows the formulation of CSMA/CA model.

In equation (1), P_S refers to the probability of a node staying in Sleep state at any given random slot and in equation (2), P_{A_0} indicates the probability of a node residing in the first slot of Active-Tx state at any given random slot. Here L_a and L_s indicate length of Active-Tx and Sleep states respectively. Probability of a node successfully completing handshake with local gateway in a given slot of Active-Tx can be obtained from equation (3) with N indicating the total number of sensor nodes within the cluster.

$$P_S = P_{S_{L_0}} L_s \tag{1}$$

$$P_{A_0} = (P_{S_{L_0}} + b_{0,0,0})\eta \tag{2}$$

$$P_a = 1 - \frac{P_b}{1 + (N-1)P_A} \tag{3}$$

Where, P_A is Active state probability given in equation (4) and P_b is the probability of a sensor node to observe a beacon transmitted by local gateway in a given slot of Active-Tx state. $1 - P_a$ is the probability of node for successful handshake in any given random slot of Active-Tx state.

$$P_A = P_{A_0} \frac{1 - P_a^{L_a}}{1 - P_a} \tag{4}$$

$$b_{0,0,0} = P_{S_{L_0}} \eta (1 - P_a^{L_a}) + b_{0,0,0} \eta (1 - P_a^{L_a}) \tag{5}$$

By rearranging the equation (5), we can arrive at a relation between $b_{0,0,0}$ and $P_{S_{L_0}}$ as shown in equation (6). $P_{S_{L_0}}$ indicates the probability of a node to stay in the last sleep slot at any given instant in terms of $b_{0,0,0}$, where as $b_{0,0,0}$ indicates the probability of a node to stay in the first CCA1 slot of the CSMA/CA model.

$$b_{0,0,0} = \frac{P_{S_{L_0}} \eta (1 - P_a^{L_a})}{1 - \eta (1 - P_a^{L_a})} \tag{6}$$

$$\begin{aligned} P_{S|CSMA} = P_{S_{L_s}|CSMA_m} + P_{S_{L_s}|CSMA_n} \\ + P_{S_{L_s}|CSMA_{succ}} = 1 \end{aligned} \tag{7}$$

In equation (7), $P_{S_{L_s}|CSMA_m}$ and $P_{S_{L_s}|CSMA_n}$ are the probabilities to enter into the first slot of Sleep state when the received packet is discarded in CSMA/CA after exceeding maximum number of backoff stages (*m*) and retries (*n*) respectively. $P_{S_{L_s}|CSMA_{succ}}$ is the probability of a node to enter the first slot of Sleep state after the node successfully forwards the packet.

$$\begin{aligned} P_{CSMA} = \sum_{i=0}^{m} \sum_{k=0}^{W_i\text{-}1} \sum_{j=0}^{n} b_{\text{i,k,j}} + \sum_{j=0}^{n} \sum_{i=0}^{m} b_{\text{i,-1,j}} \\ + \sum_{j=0}^{n} \left(\sum_{k=0}^{L_s\text{-}1} b_{\text{-1,k,j}} + \sum_{k=0}^{L_c\text{-}1} b_{\text{-2,k,j}} \right) = Z_1 * b_{0,0,0} \end{aligned} \tag{8}$$

The probability of a node to reside in CSMA/CA state (P_{CSMA}) at a randomly given time slot is the sum of backoff, CCA2, success and failure state probabilities respectively given in equation (8). Z_1 indicates the proportionality factor after expressing all probabilities in equation (8) in terms of $b_{0,0,0}$. In equation (9) P_S, P_A and P_{CSMA} indicate the probabilities for a node to reside in Sleep, Active-Tx and CSMA/CA states respectively in any given random time slot. All probabilities P_S, P_A and P_{CSMA} of Fig. 1(b) can be written in terms of P_{S_0} and $b_{0,0,0}$ as shown in equation (10).

$$P_S + P_A + P_{CSMA} = 1 \tag{9}$$

$$P_{S_{L_0}} * L_s + P_{A_0} * \frac{1 - P_a^L a}{1 - P_a} + Z_1 * b_{0,0,0} = 1 \tag{10}$$

After arriving at the relation for $b_{0,0,0}$, we derive CCA1 busy (α), CCA2 busy (β) and channel sensing probabilities (τ) utilizing $b_{0,0,0}$ in a similar methodology described in [4]. Numerical methods are used to solve highly non linear α, β, τ and $b_{0,0,0}$ to arrive at a definite solution. Following sub section discusses the delay and reliability of the proposed model.

A. Reliability model

The reliability of a sensor node can be determined by deriving the failure probabilities. Failure can occur due to exceeding *m*, *n* and Active-Tx time out. Considering these cases, the reliability of node *k* (R_k) is given by equation (11).

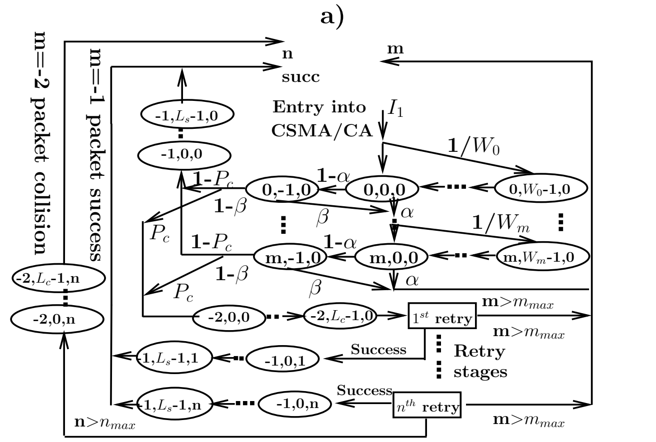

Fig. 2: Three-dimensional Markov model of IEEE 802.15.4 CSMA/CA

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$\widetilde{y}$ indicates the probability of a node transitioning to next retry after successfully sensing the channel from any of the *m* stages shown in Fig. 2.

$$R_k = 1 - \left(x^{\text{m+1}} (1 + \widetilde{y}) - \widetilde{y}^{\text{n+1}} \right) \left(1 - P_a^{L_a} \right) - P_a^{L_a} \tag{11}$$

B. Delay Model

Total delay incurred by an individual node for forwarding a packet successfully is contributed by CSMA/CA delay and active state delay. Delay due to CSMA/CA is given in equation (12).

$$\begin{aligned} D_{\text{csma}} = T_s + D_{\text{avg}} + (T_s + D_{\text{avg}}) \Big[\frac{y}{1-y} \\ - \frac{((n+1) * (y^{(\text{n+1})}))}{1 - y^{\text{n+1}}} \Big] \end{aligned} \tag{12}$$

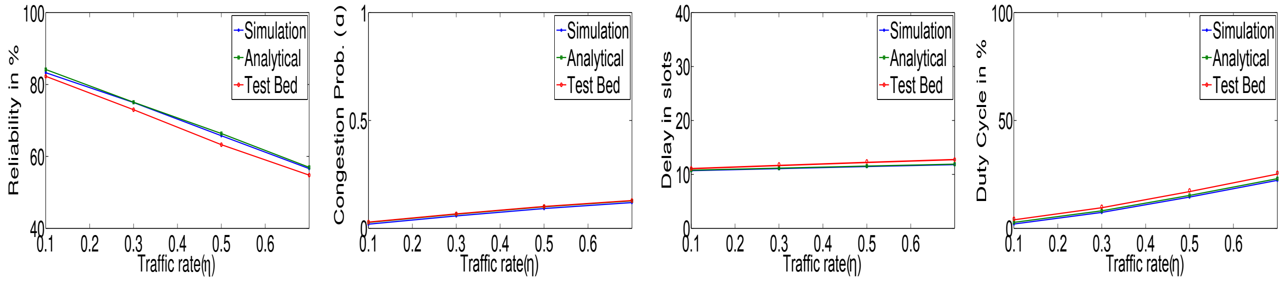
$$\begin{aligned} D_{\text{avg}} = 2S_b \Big[1 + 0.25 \Big\{ \frac{1 - b_l}{1 - b_l^{m+1}} \Big[2W_0 \frac{1 - 2b_l^{m+1}}{1 - 2b_l} \\ - \frac{3(\text{m+1}) b_l^{\text{m+1}}}{1 - b_l} \Big] + \frac{3b_l}{1 - b_l} - (W_0 + 1) \Big\} \Big] \end{aligned} \tag{13}$$

$$P_{(delay=i)|success} = \frac{P_a^{i-1}(1 - P_a)}{(1 - P_a^{L_a})} \tag{14}$$

$$D_{active} = \sum_{i=1}^{L_a} (i) \frac{P_a^{i-1}(1 - P_a)}{(1 - P_a^{L_a})} \tag{15}$$

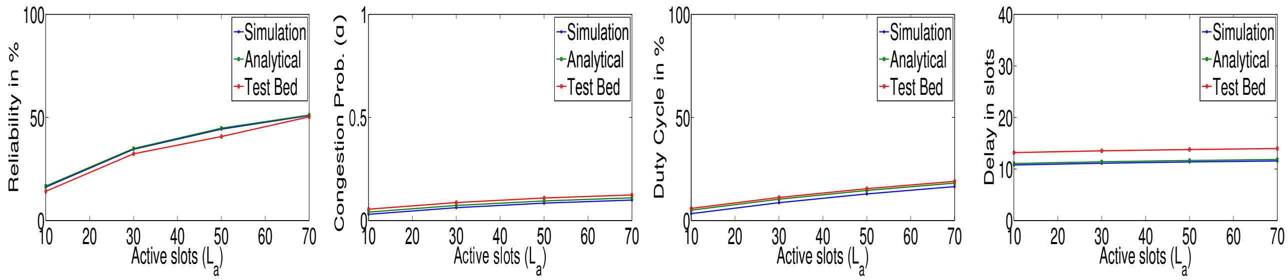
$$D_{\text{total}} = (D_{\text{csma}} + D_{\text{active}} * S_b) \tag{16}$$

In equation (12), D_{avg} indicates the average backoff delay and is derived in equation (13) by taking expectation over *m* stages of CSMA/CA, where D_{csma} of a link can be obtained from computing average probability of success after *j* retries. T_s and S_b are packet transmission time and unit backoff time, b_l is max$\{\alpha,(1\text{-}\alpha)\beta\}$, W_0 indicates minimum backoff window. L_p and L_c are length of time slots required for successful packet transmission and collision respectively and T_c indicates packet collision time. In equation (15), the average number of



(a) (b) (c) (d)

Fig. 3: Fig. 3a and 3b: Reliability and congestion Vs. Traffic; Fig. 3c and 3d: Delay and Duty cycle Vs. Traffic; (Simulation parameters for 3a), 3b), 3c) and 3d) are N = 10, m = 3, n = 1 , L_a = 100, L_s = 300)



(a) (b) (c) (d)

Fig. 4: Fig. 4a and 4b: Reliability and congestion Vs. L_a; Fig. 4c and 4d: Delay and Duty cycle Vs. L_a; (Simulation parameters for 4a), 4b), 4c) and 4d) are N = 10, m = 3, n = 1, L_s = 300, η = 0.1)

active slots (D_{active}) that a node waits before a beacon arrives is obtained. Finally total delay which is the sum of delays incurred by CSMA/CA and Active states is given by equation (16).

IV. Test bed deployment

In order to analyse the performance of network under real time constraints, a hardware prototype of the proposed model is developed at Indian Institute of Technology Hyderabad using the in house developed IEEE 802.15.4 compliant radio namely IITH Mote [17] which is shown in Fig. 5. The IITH Motes are having a wide range of capabilities which can suffice data sensing and are very much tunable to adhere different types of networks such as mesh, star and fully connected topologies etc. They can also support multi-hop and single-hop communications in order to achieve a better network performance within a given range of area and the environment characteristics. Using these IITH motes the system model discussed in section II is implemented with varying number of nodes and the performance is studied. The nodes are deployed in a wide area and all the nodes are placed with a pre-defined clustering thereby making sure that no hidden terminal problems persist. The performance analysis of the hardware deployment is limited to analysis of reliability, delay, CCA1 failure probability and duty cycle with varying parameters of L_a, L_s and N. We have extracted the necessary parameters from thus deployed test bed and compared with the analytical and simulation outcomes.

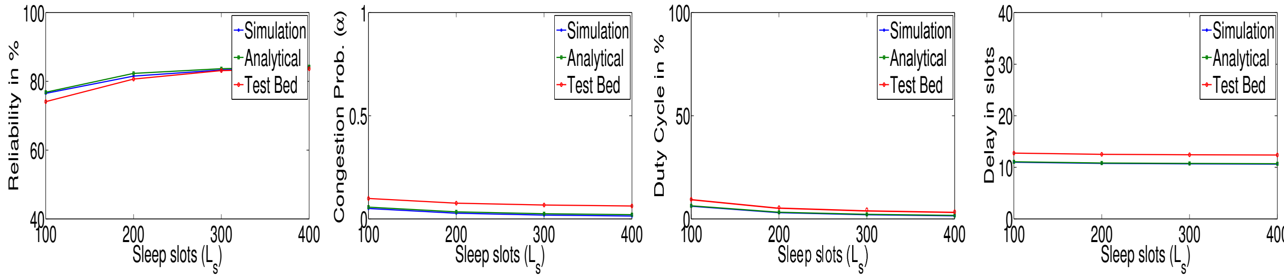
Fig. 5: IITH Mote used for test bed deployment

V. Analytical results

Along with the test bed deployment, the outcomes of analytical model developed is validated by simulating a scenario similar to that shown in Fig. 1(a), which has varying number of nodes ranging from 5 to 20.

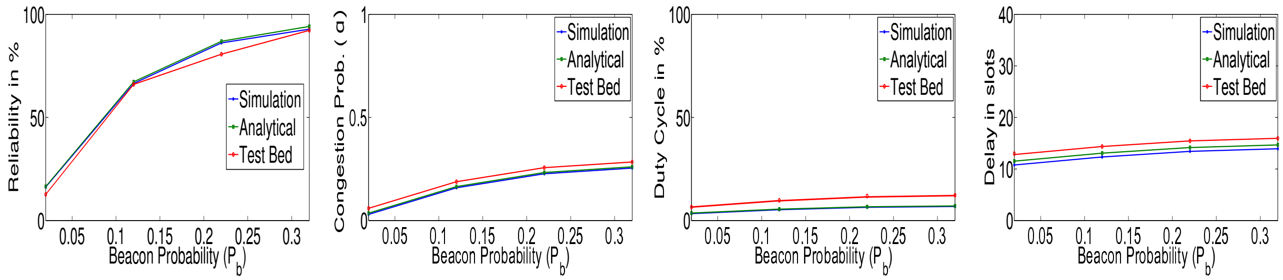
A. Effect of traffic (η)

We first analyse the effect of traffic (η) on R_E, congestion (α), duty cycle and D_{total}. Fig. 3(a) and Fig. 3(b) plots R_E and α versus η respectively. One can observe the degradation in reliability as traffic increases. This is due to the reason that as traffic increases, the channel utilization will be more and congestion increases. The same is reflected in Fig. 3(b)



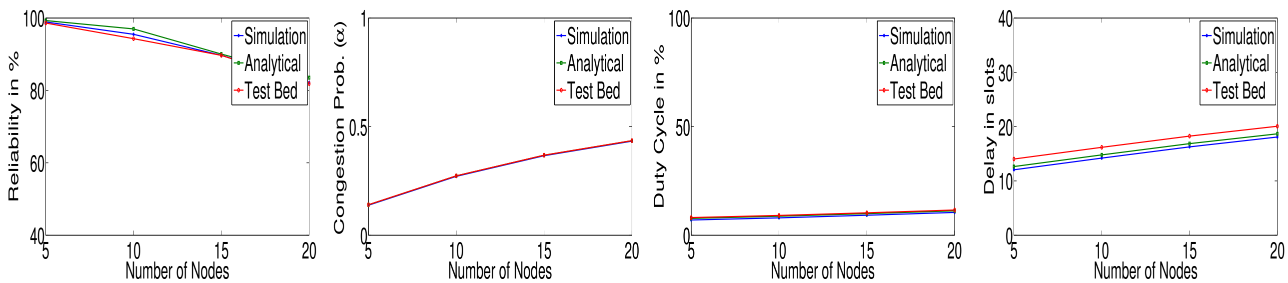
(a) (b) (c) (d)

Fig. 6: Fig. 6a and 6b: Reliability and congestion Vs. L_s; Fig. 6c and 6d: Delay and Duty cycle Vs. L_s; (Simulation parameters for 6a), 6b), 6c) and 6d) are N = 10, m = 3, n = 1, L_a = 100, η = 0.1)



(a) (b) (c) (d)

Fig. 7: Fig. 7a and 7b: Reliability and congestion Vs. P_b; Fig. 7c and 7d: Delay and Duty cycle Vs. L_s; (Simulation parameters for 7a), 7b), 7c) and 7d) are N = 10, m = 3, n = 1, L_a = 100, η = 0.1)



(a) (b) (c) (d)

Fig. 8: Fig. 8a and 8b: Reliability and congestion Vs. N; Fig. 8c and 8d: Delay and Duty cycle Vs. N; (Simulation parameters for 8a), 8b), 8c) and 8d) are m = 3, n = 1, L_a = 100, P_b = 0.22 η = 0.1)

which depicts the increase in congestion as traffic increases. As the congestion increases, a node in order to gain access to the channel should have to wait for a longer time than usual which results in increase of delay for successful packet transmission and duty cycle. Fig. 3(c) and Fig. 3(d) provides the variation in delay and duty cycle respectively with respect to traffic generation where one can observe the increase in duty cycle asexpected.

B. Effect of Active-Tx state length (L_a)

As the number of slots in Active-Tx state increases, the chance of a node receiving a beacon and performing successful handshake increases. Hence the node spends most of it's time in CSMA state which in turn also increases the congestion in channel but improves reliability due to decrease in packet losses in Active-Tx state. The same behaviour can also be observed from the analysis shown in Fig. 4(a) and Fig. 4(b). With respect to delay as congestion increased the node has to wait for a longer time in order to gain access to the channel. Due to this we can observe a slight rise in both delay and duty cycle with the increase in Active-Tx slots as shown in Fig. 4(c) and Fig. 4(d).

C. Effect of Sleep state length (L_s)

The length of Sleep state can be assumed as an inverse of traffic rate in a much broader sense. The backing reason is, as the number of sleep slots increase the node spends most of it's life time in Sleep state due to which the number of packets required to be transmitted will decrease. As the number of packets required to be transmitted decreases, the congestion in the channel falls down and in turn results in increase of reliability. The same behaviour can also be observed from Fig. 6(a) and Fig. 6(b). As the channel congestion decreases, the delay required for a successful packet transmission also decreases. In addition as the node spends most of it's life cycle in sleep state, the duty cycle of the node reduces thereby enhancing the lifetime of battery. Fig. 6(d) and Fig. 6(c) provides the variation of delay and duty cycle with L_s

D. Effect of Beacon transmission probability (L_s)

Impact of increase in transmission of beacons by local gateway can be characterized similar to increase in Active-Tx state length. As the beacon reception probability by a sensor node increases the Active-Tx failure decreases and results in increase of reliability and channel congestion. The same can be observed from Fig. 7(a) and Fig. 7(b). Fig. 7(c) and 7(d) consists of variation in delay and duty cycle with respect to increase in beacon probability. We can observe the rise in delay and duty cycle as in this scenario the node has to spend more time in CSMA due to increased channel congestion.

E. Effect of number of nodes (N)

As number of nodes increase, the channel congestion increases and results in decrease of reliability. In addition delay and duty cycle increases as channel congestion increases. Fig. 8(a) and Fig. 8(b) shows the reduction of reliability and increase in channel congestion with variation of N. Analysis of delay and duty cycle with variation in N can be observed from Fig. 8(c) and Fig. 8(d).

Upon observance, the outcomes from all the analytical model, simulation and real time test bed can be found in good accordance with each other. Although in some cases where delay achieved from test bed deviates from analytical model, the maximum error is found to be limited by 9%. The reason behind this is the presence of delay incurred from handshaking process whereas the overhead due to handshake in analytical model and simulation study is assumed to be accounting negligible amount of delay. The same is also reflected in duty cycle analysis as well. We also analysed the effect of maximum allowable retries and packet length which found to be in good accordance across analytical, simulation and test bed outcomes.

VI. Conclusion

In this paper, state-wise behaviour of sensor node operating in multi-hop scenario is developed with inclusion of 3D Markov chain. Reliability, channel congestion, duty cycle and delay are considered as key performance metrics and the same are analysed with multiple network configurations. The proposed model is validated using both analytical and simulation outcomes which are found to be in good accordance with a confidence level of 95%. In addition, the real-time test bed analysis is also performed for the proposed model and found to be in good accordance with the analytical model by achieving a maximum error of 9%. Increase of error slightly whilst analysing the real time test bed is due to the realistic assumption considered with respect to beacon based handshake mechanism. The proposed model and the analysis can greatly aid in efficient operation of long range dense traffic monitoring applications using IEEE 802.15.4 in the currently enriching IoT scenario. Optimization of the parameters to tune the network performance towards the most efficient operation is the future scope of this work.

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