Analytical Model of Relay Node Integrating IEEE 802.15.4 MAC and Energy Conserving State Behaviour

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***Abstract*—Accurate relay node model for a generic topology of multi-hop networks is still unsolved problem in the Wireless Sensor Networks (WSN) arena. Even though there are lot of multi-hop models in the literature, there is still a lot of scope for improvement in these relay node models to achieve end-to-end reliability and delay optimizing energy. In this paper a state behavioural relay node model is developed integrating IEEE 802.5.4 MAC and energy conserving states like Sleep, Idle-Listen and Active-Tx using three dimensional Markov chain framework. Novel window of reference is introduced into relay nodes to decide the wake up strategies and to improve performance of the network. Hence developed model is a combination of asynchronous and periodic protocols which is first in it's kind of nature. Developed emulation model of the MAC confirms the performance improvement with 95% confidence level. Analysis proves that random anycast routing with proposed duty cycle model extends network lifetime with efficient load sharing among all relay nodes and reduce overall active duration of a node.**

***Keywords*-Anycast clustered multi-hop network, 3D Markov chain, Analytical model of IEEE 802.15.4 MAC.**

I. INTRODUCTION

Multi-hop communication is essential for real time applications like IoT, Cyber Physical Systems (CPS) and Smart grid applications which are distributed over large area. Most of the IEEE 802.15.4 analytical models are based on 3D Markov chains. Single-hop IEEE 802.15.4 networks has been thoroughly investigated, but analytical model that can mimic multi-hop networks is still under active research.

IEEE 802.15.4 multi-hop models are inspired by IEEE 802.11 multi-hop networks in [1], [2] and [3]. Multi-hop communication is modelled for IEEE 802.11 networks for single traffic flow in [1]. Work in [1] has been extended to multiple non saturated flows in [2]. A model for saturated traffic flows in IEEE 802.11 networks is presented in [3]. However, we note that these models cannot be directly applied to IEEE 802.15.4 networks due to the different access mechanisms of IEEE 802.11 and IEEE 802.15.4. Analytical modelling of IEEE 802.15.4 multi-hop network is discussed in [4] considering heterogeneous traffic and hidden node terminal problem. Model presented in [4] analysed multi-hop considering different topologies. Even though model captured multi-hop behaviour for particular topologies due to route layer dependencies analysing a larger network without a generalized model becomes complex. Reliable and timely communication for sensors to sink is discussed in [5] with anycast multi-hop routing between relay clusters. Reliability, delay and energy of overall network are analysed with cumulative exponential wake up rate, traffic rate and number of relay clusters. Model in [5] proposed different states like sleep, idle, active and CSMA/CA for relay nodes but analytical model has fixed backoff window and lacks many network parameters.

Carrier sense multiple access with collision avoidance (CSMA/CA) scheme MultiCSMA for multi-hop WSNs is proposed in [6]. A Markov chain based analytical model for multi-hop networks is analysed with variation in traffic rate, node density, packet length, number of MAC backoff stages and retries are considered for the analysis. An analytical model for evaluating the performance of IEEE 802.15.4 multi-hop networks based on beacon-less CSMA/CA is discussed in [7]. Multi-hop tree network with sensors and relay nodes (relay node can be sensors as well) considering with and without hidden node problem was analysed in [7]. Though model in [7] captured tree multi-hop network behaviour but nodes nearer to sink have higher congestion leading to failure of nodes as well as network failure. Most of the above mentioned models could not capture multi-hop behaviour in the aspects like relay hot spots and failed to obtain generalized analytical model with network parameters like wake up rate, packet rate, packet length and node density. Above mentioned problems are answered in this paper proposing a route independent anycast routing based modified IEEE 802.15.4 analytical model. Beacon enabled slotted IEEE 802.15.4 standard is modified to model a generalized relay node in a cluster between a sensor/source node to central sink node. Relay node is modelled with three dimensional Markov chain with states like sleep, idle, active and IEEE CSMA/CA states to obtain tradeoff between application performance and energy savings.

The remainder of this paper is as follows. In Section II, proposed system model is described. Mathematical model of the proposed system is given in detail in Section III. Analytical and simulation results of proposed system is discussed in section IV. Finally, Section V concludes the paper with future scope of research.

II. SYSTEM MODEL

We consider a generic network scenario of central sink with sensor and relay clusters shown in the Fig. 1. Sensors are distributed across large area, where data from them is forwarded using relay cluster nodes. Relay nodes in each cluster can accept data from any node and any direction in the neighborhood and forwards to it's nearest neighbor cluster which is well known as anycast routing. Relay node behaviour is captured accurately in 4 different states namely, Sleep (S_i), Idle-Listen (I_i), Active-Tx (A_i) and CSMA/CA as shown in Fig. 2. Relay node state behavioural model is briefly described as below.

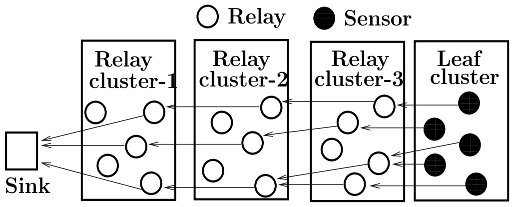

Fig. 1: Example network scenario of the proposed system

Relay node after every S_0 slot moves to Idle-Listen state with P_w probability or rolls back to Sleep state shown in the Fig. 2. Relay node after successful transition to Idle-Listen state with probability P_w waits for LI_{avg} slots to observe a packet from preceding cluster. Time intervals between beacons observed by a relay in Active-Tx are poisson distributed which determine the average waiting time LA_{avg} slots in Active-Tx state. Relay node which is successful in receiving a beacon within maximum L_a slots of Active-Tx state follows CSMA/CA flow depicted using a 3D Markov chain shown in Fig. 3 with backoff stages (*m*), backoff counter (*k*) and collision retries (*n*) as the three dimensions. Relay node spends an average LC_{avg} slots in CSMA/CA state. Finally node spends $L_{S|CSMA}$ slots in Sleep which are the remaining slots left after Idle-Listen, Active-Tx and CSMA/CA states.

Total number of slots that a relay node takes to complete all states is fixed as L_{DC}, which we termed as Duty cycle window or frame of reference window. It is assumed that only one wake-up can happen with a P_w probability, where P_w is the provability of a node to have a wake-up in first slot of L_{DC} from $1/L_{DC}$ poisson distributed wake-ups in a second. Relay node cannot wake-up in between L_{DC} slots and transmit beacon. It is also evident from above assumption that relay node can only service one packet in L_{DC} slots. The maximum capacity of a relay cluster *C* is $\frac{N}{L_{DC}}$. If number of packets to the relay cluster is more than capacity of network, then network performance surely degrade.

III. MATHEMATICAL MODEL

We first define the required terminologies for the mathematical model and then follows the formulation of CSMA/CA model. In the rest of our discussion μ_w indicates average wake up rate per node in a cluster consisting of *N* nodes, L_a and L_i are length of active and idle slots respectively.

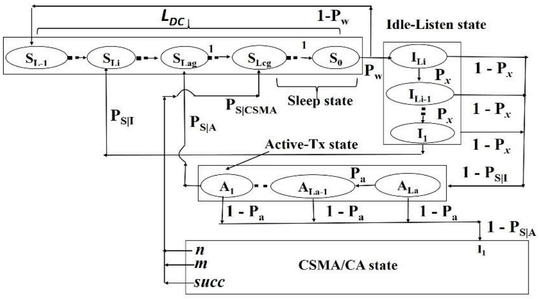

Fig. 2: Relay node model with Duty cycle frame work

In Eq. 2 , P_x gives the transition probability of a relay node to move into next Idle-Listen slot from the current, when there is no packet arrival at a given slot with an average of λ poisson arrivals and P_a in Eq. 4 indicates the transition probability of a relay node to move into next Active-Tx slot from the current, when there is no beacon arrival at a given slot with an average of λ_a poisson arrivals. The probability of a node transiting to Sleep state from last slot of Idle-Listen ($P_{S|I}$), Active-Tx ($P_{S|A}$) and CSMA/CA ($P_{S|CSMA}$) states can be obtained as shown in Eq. 13, 14 and 12 respectively.

$$\lambda_a = \mu_w * L_{DC} \tag{1}$$

$$P_x = \exp(-\lambda) \tag{2}$$

$$P_w = 1 - \exp(-\lambda_a) \tag{3}$$

$$P_a = (1 - \frac{P_w}{L_{DC}})^N \tag{4}$$

$$LA_{avg} = \sum_{i=1}^{L_a} (i) \frac{P_a^{i-1}(1 - P_a)}{(1 - P_a^{L_a})} \tag{5}$$

$$LI_{avg} = \sum_{i=1}^{L_i} (i) \frac{P_x^{i-1}(1 - P_x)}{(1 - P_x^{L_i})} \tag{6}$$

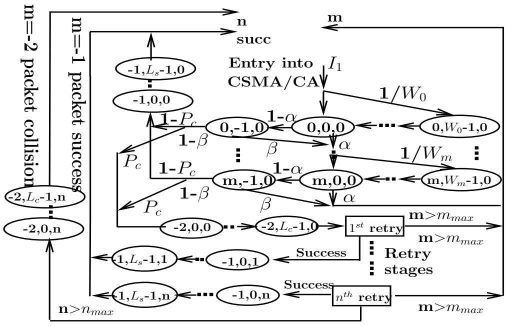

Fig. 3: 3D Markov model of IEEE 802.15.4 CSMA/CA

Relay node with proposed cyclic state framework is shown in Fig. 2. Relay node state transition starts from last slot S_{L_0} and moves to Idle-Listen state with P_w probability or rolls back to Sleep state with 1-P_w probability. P_w is the probability of a node to have a wake-up at the first slot of L_{DC} window, where wake-up of a node is assumed Poisson process with mean μ. Relay node wake-up at first slot is considered because node is assumed to complete all its states with in L_{DC} slots and no wake-up is possible after first slot of L_{DC} window. Relay node which is wake-up at first slot follows similar Idle-Listen, Active-Tx and CSMA/CA state behaviour in the model already described. If a relay node is unsuccessful in receiving a packet it spends its rest of time in Sleep state shown in Eq. 7. Relay node after successfully receiving a packet and failing to receive a beacon in Active-Tx spends rest of time in Sleep state shown in Eq. 8. Relay node which is successful in Idle-Listen and Active-Tx states completes its CSMA/CA state in LC_{avg} which is shown in Eq. 10 and the time it spends in Sleep state after CSMA/CA is shown in Eq. 9. LC_{avg} is the average number of slots a node spends in CSMA/CA assuming CSMA/CA as gaussian distribution.

$$L_{S|I} = L_{DC} - L_i \tag{7}$$

$$L_{S|A} = L_{DC} - LI_{Avg} - L_a \tag{8}$$

$$L_{S|CSMA} = L_{DC} - LI_{Avg} - LA_{avg} - LC_{avg} \tag{9}$$

$$LC_{avg} = \frac{(n+1)(m+1)W_0}{2} \tag{10}$$

where, W_0 is the minimum backoff window (2^{m_0}), *m* is the maximum backoff stages and *n* is the maximum collision retries. It is observed that from the above expressions that relay node spends remaining time in Sleep state after it completes Idle-Listen, Active-Tx and CSMA/CA states. It is also evident that $L_{S|CSMA}$ should not exceed L_{DC} as the window size is fixed. In order to conserve energy, node should spend more time in Sleep state by adjusting other state parameters LI_{avg}, LA_{avg} and LC_{avg} considering given constraints. State probabilities and state transition probabilities of relay node with proposed framework is given in detail as below.

State transition probabilities are derived observing state behaviour model of relay node with framework shown in Fig. 2. $P_{S_{L_{DC}}}$ is the probability of a node to be in first slot of duty cycle window. $P_{S|I}$, $P_{S|A}$, $P_{S|CSMA}$ and $P_{S|L_{DC}}$ are the probabilities of a node to enter Sleep state from Idle-Listen, Active-Tx, CSMA/CA and last slot of Sleep state respectively. Expressions inter relating these probabilities are given below. P_{S_0} is the probability to enter in last slot of Sleep state.

$$P_{S_0} = P_{S|CSMA} \tag{11}$$

$$P_{S|CSMA} = P_{S|A} + b_{0,0,0} \tag{12}$$

$$P_{S|A} = P_{S|I} + P_a^{L_a} P_{A_0} \tag{13}$$

$$P_{S|I} = P_{S|L_{DC}} + P_i^{L_i} P_{I_0} \tag{14}$$

$$P_{S|L_{DC}} = (1 - P_w) P_{S_0} \tag{15}$$

$$\begin{split} P_{S_0} = (1 - P_w) P_{S_0} + P_x^{L_i} P_w * P_{S_0} + \\ P_a^{L_a} (1 - P_i^{L_i}) P_w * P_{S_0} + Z_0 * b^f_{0,0,0} \end{split} \tag{16}$$

Rearranging the Eq. 16, we arrive at an expression relating P_{S_0} and $b^f_{0,0,0}$. P_x and P_a are failure probabilities to receive a packet and beacon in any slot of Idle-Listen and Active-Tx states respectively from their neighbor cluster nodes. State provability equations for Sleep, Idle-Listen, Active-Tx and CSMA/CA are given in Eq. 17, 18, 19 and 20 respectively.

$$L_i * P_{S|L_{DC}} + L_a * P_{S|I} + L_c * P_{S|A} + L_{S|CSMA} P_{S|CSMA} = P_S \tag{17}$$

$$P_I = \frac{P_w * P_{S_0} * (1 - P_x^{L_i})}{1 - P_x} \tag{18}$$

$$P_A = \frac{P_w * P_{S_0} * (1 - P_x^{L_i})(1 - P_a^{L_a})}{1 - P_a} \tag{19}$$

$$P_{CSMA} = b^f_{0,0,0} * Z_1 \tag{20}$$

After substituting the above state probabilities in normalization property of Markov chain shown in Eq. 21, we can arrive at essential Markov probability $b^f_{0,0,0}$.

$$P_S + P_I + P_A + P_{CSMA} = 1 \tag{21}$$

In this paper busy channel probabilities α and β in Clear Channel Assessment (CCA1 and CCA2) states and channel sensing probability τ shown in Fig. 3 are derived considering the effect of Cyclic states Sleep, Idle-Listen and Active-Tx state probabilities along with CSMA/CA model. With basic understanding of busy probabilities in [8], [9], [10] and [11] one can derive easily $b^f_{0,0,0}$ and thereby α, β and τ using numerical methods. End-to-end Reliability, delay and energy of the proposed multi-hop model for dense traffic applications are derived in next section using mathematical expressions in previous section.

A. End-to-end Reliability Model

Performance metrics for leaf to relay cluster and end cluster to gateway cluster differ from relay to relay cluster link. All these three different links are modeled separately as follows.

$$P_f^A = \frac{P_w * (1 - P_x^{L_i}) * (1 - P_a^{L_a}) * P_{S_0}}{1 - P_a} \tag{22}$$

$$P_f^a = P_a^{L_a} \quad , P_f^m = x^{\mathrm{m+1}}(1 + \widetilde{y}) \quad , P_f^n = \widetilde{y}^{\mathrm{n+1}} \tag{23}$$

Reliability of leaf to relay link is given in Eq. 24. Reliability is derived by deriving failure probabilities of this link. Failure can happen due to channel access failure and collisions in CSMA/CA state. Packet is also discarded when leaf node cannot find a beacon in L_a slots.

$$R_S = 1 - \left(P_f^m + P_f^n + P_f^a + P_f^A\right) \tag{24}$$

$$R_k = 1 - \left(P_f^m + P_f^n + P_f^a\right) \tag{25}$$

Reliability of link between end and gateway node is shown in Eq. 26. Reliability of this link is obtained by considering CSMA/CA failure probabilities. End node doesn't have Active-Tx state due to which failure is only due to CSMA/CA is shown in the Eq. 26.

$$R_G = 1 - \left(P_f^m + P_f^n\right) \tag{26}$$

Above three links are assumed independent as shown in

Eq. 27 to obtain end-to-end performance metrics. 3D Markov modeling is used to model all three different state models.

$$R_E = R_L * \prod_{k=1}^{h} R_k * R_G \tag{27}$$

B. Delay model

End-to-end delay of the proposed model is summation of delay incurred at three types of links, shown in Eq. 28.

$$D_T = D_{SR} + \sum_{i=0}^{h} D_R(i) + D_{EG} \tag{28}$$

where D_{SR} is the delay of link between sensor and first relay cluster, $D_R(i)$ is the delay of a link between two relay nodes, D_{EG} is the delay of the link between end node and gateway/sink node. Delay models for each link are expressed in mathematical expressions and finally an end-to-end delay of the network is derived in following section.

1) Delay between Sensor and Relay: Delay of this link is composed of CSMA/CA delay and Active-Tx state delay. CSMA/CA delay of a link with *N* nodes in a cluster is similar to [11] shown in Eq. 29. Active-Tx state delay of the link is given in Eq. 30.

$$D_{\text{csma}} = (Ts + Delay_{\text{avg}}) \left(1 + \frac{y}{1-y} - \frac{(n+1) * y^{\text{n+1}}}{1 - y^{\text{n+1}}}\right) \tag{29}$$

Sensor node in Active-Tx state waits for L_a consecutive slots to observe a beacon from next cluster. Sensor node may not wait for all L_a slots every time it enters Active-Tx state. Average number of slots a relay node waits to receive a beacon is the delay incurred in Active-Tx state. Broadcast of beacons from relay nodes in next cluster are Poisson distributed with mean λ_a. Active-Tx state delay D_{active} is shown in Eq. 30. Finally End-to-end delay (D_T) is sum of D_{csma} and D_{active} shown in Eq. 32. D_{SR} is shown in Eq. 31.

$$D_{active} = \sum_{i=1}^{L_a} (i) \frac{P_a^{i-1}}{\sum\limits_{k=0}^{L_a} P_a^k} \tag{30}$$

$$D_{SR} = D_{\text{csma}} + D_{\text{active}} * S_b \tag{31}$$

D_{csma} shown in Eq. 29 is similar for relay-relay and end-gateway links. Relay-relay node link experience Active-Tx state delay as sensor node, but end-gateway link doesn't have Active-Tx state delay because gateway nodes in gateway cluster are always on to receive a packet. Relay node experience *h* number of Active-Tx state delays assuming node distribution in each relay cluster is same. End-to-end delay of the multi-hop network is shown in Eq. 32.

$$D_T = (h+2) D_{csma} + D_{active}(h+1) \tag{32}$$

C. Energy model

Energy of leaf, end and relay node models differ according to the state behaviour explained above. Energy of each node is derived from its state probabilities. State energies of leaf, end and relay nodes are calculated by accounting state transitions of each node. E_i, E_a, E_{CCA}, E_w, E_t and E_r are energy consumption in Idle-Listen, Active-Tx, CSMA/CA sensing, wake-up, transmit and receive state respectively.

1) Energy model - Leaf node: Energy spent by a leaf node can be derived considering state behaviour. Leaf node doesn't have Idle-Listen and receive states. Total energy of leaf node E_{leaf} is given in Eq. 33.

$$E_{leaf} = (E_a + E_w) + E_{\text{CCA}} + E_t \tag{33}$$

2) Energy model - End node: Energy spent by a end node is in Idle-Listen, CSMA/CA sensing, transmit and receive energies. End node Active-Tx energy is negligible as the gateway node is continuously on to receive a packet from end node. Total energy of end node E_{end} is given in Eq. 34.

$$E_{end} = (E_i + E_w) + E_{\text{CCA}} + E_t + E_r \tag{34}$$

3) Energy model - Relay node: Energy spent by a relay node can be derived by observing its state behaviour. Relay node state probabilities are derived in previous section. Total energy of leaf node E_{relay} is given in Eq. 35. Finally total energy is summation of all above node energies.

$$E_{relay} = (E_i + E_a + E_w) + E_{CCA} + E_t + E_r \tag{35}$$

IV. ANALYTICAL RESULTS

End-to-end reliability, delay and energy versus λ_g is plotted in Fig. 4(a), 4(b) and 4(c) respectively. λ_g is varied from 0.04 to 0.1 packets per slot probability. Reliability is also observed with variation in two different number of nodes in each cluster. Reliability is observed decreasing with traffic density and after certain increase in traffic variation, it decreases marginally. Increase in number of nodes from *N*=20 to 30 reduces reliability from 0.73 to 0.62 is shown in Fig. 4(a). Delay is increased marginally from 89 to 94 milliseconds with λ_g, when number of nodes are twenty. Increase in delay is justified by the fact that number of nodes increase the number of contending nodes for the channel resulting in increase in channel access delay of CSMA/CA. Energy increases with increase in λ_g due to increase in active time of relay nodes. Increase in number of nodes also increases energy as number of nodes participate in forwarding the traffic increases. Observing the plots Fig. 4(a), 4(b) and 4(c), it is observed that reliability, delay and energy respond to λ upto some extent and saturates to a value. This is due to same reason that after certain traffic levels reliability, delay and energy of networks doesn't change because the number of packets that receives with change in λ_g freezes to a value. Simulation and analytical results are in agreement with less than 4% mean error.

Congestion probability α, $b_{0,0,0}$ and Active state failure probability are observed with variation in λ_g and number of nodes in Fig. 4(d), 4(e) and 4(f) respectively. Increase in packet arrivals results in increase in α and $b_{0,0,0}$. Active state failure probability is nearly a constant value with increase in λ_g but when the number of nodes increased from 20 to 30, active failure probability reduces due to increase in number

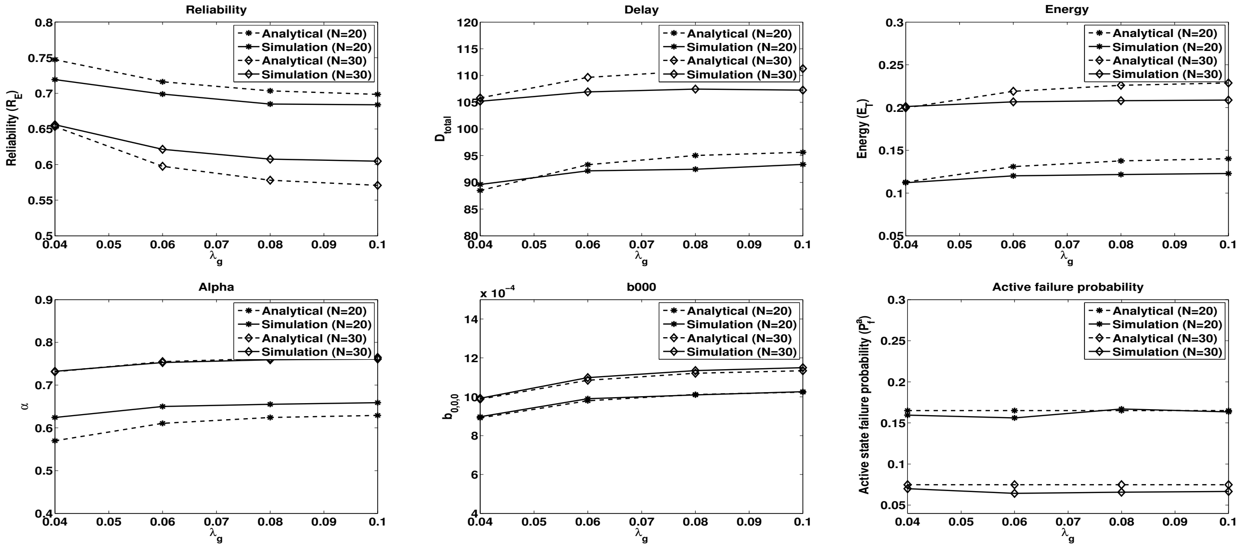

Fig. 4: Different performance metrics like R_E, D_T, E, α, $b_{0,0,0}$ and P_f^A variation with respect to λ_g and N; Fixed MAC and network parameters m_0 = 3, m = 4, L_{DC} = 500, μ_w = 6, n = 1, L_a = 70, N=[20 30], λ =[0.04 0.1], L_p = 30, L_i=100.

of beacons in L_a slots. In order to improve the performance metrics either N or μ of each relay node should be increased.

Energy of a relay node is also observed in terms of active duty cycle of relay node. Active states of a relay node are Idle-Listen, Active-Tx, CSMA/CA channel sensing, transmit and receive states. Proposed model active duty cycle is compared with existing multi-hop protocol in [5]. Results of comparison is given in Fig. 5. Parameters considered for the simulation are μ =4, N=15, m_0=3, m = 4 and n=3, L_i = 50 backoff slots, L_a = 70 backoff slots and each iteration is $4*10^5$ backoff slots. It is observed that proposed framework reduces duty cycle of nodes to 1.4%. It is observed that duty cycle of relay node is 60% lower on an average compared to the existing Breath model. Increase in energy savings is due to accurate state behaviour and anycast routing.

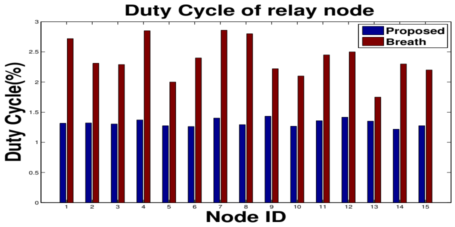

Fig. 5: Comparison of proposed and Breath models relay node duty cycle: N = 15, λ = 15 pks/sec, L_{DC} =700 slots, μ = 4

V. CONCLUSION

Three dimensional Markov model based analytical model for a relay node in a dense wireless multi-hop network is developed that can be part of IoT applications. Energy conserving state behaviour and generic anycast routing is integrated to IEEE 802.15.4 MAC. Results of the developed analytical and simulation models agree with each other with an accuracy of 5%. Active duty cycle of relay node is found 1.4% which is 60% less than existing models. Optimization framework at sink considering MAC and network parameters is the future scope of this work.

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