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Performance Analysis of CSMA/CA and PCA for Time Critical Industrial IoT Applications

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***Abstract*—Recently proposed IEEE 802.15.4-2015 MAC introduced a new Prioritized Contention Access (PCA) for transfer of time-critical packets with lower channel access latency compared to CSMA/CA. In this paper, we first propose a novel Markov chain based analytical model for unslotted CSMA/CA and PCA for industrial applications. The unslotted model is further extended to derive the analytical model for slotted CSMA/CA and PCA. Primary emphasis is laid on understanding the performance of PCA compared to CSMA/CA for different traffic classes in industrial applications. The performance analysis shows the slotted PCA achieves a reduction of 63.3% and 97% in delay and power consumption respectively compared to slotted CSMA/CA, whereas unslotted PCA achieves a delay reduction of 53.3% and reduction of power consumption by 96% compared to unslotted CSMA/CA without any significant loss of reliability. The proposed analytical models for both slotted and unslotted IEEE 802.15.4-2015 MAC offer satisfactory performance with less than 5% error when validated using Monte Carlo simulations. Also, the performance is verified using real-time testbed.**

***Index Terms*—Industrial Internet of Things, IEEE 802.15.4, CSMA/CA, Prioritized Contention Access, Markov chain**

I. Introduction

In recent years, industrial applications such as monitoring, controlling, automation, etc., have witnessed a significant increase in usage of the Internet of Things (IoT) technologies for communication [1]–[3], especially IEEE 802.15.4 [4], [5]. Also, a new Prioritized Contention Access (PCA) is introduced in IEEE 802.15.4-2015 MAC to provide service differentiation in IoT applications [6]. Transfer of prioritized or critical data with low latency plays a crucial role in industrial monitoring and automation applications [7], [8]. The existing IEEE 802.15.4e supports time-slotted channel hopping (TSCH) where the assigned time slots are used for communication between the nodes, and frequency hopping is used to mitigate the effects of fading [9]. Traditional CSMA/CA suffers from increased channel access delay with an increase in traffic or number of nodes. Unlike CSMA/CA, PCA offers faster channel access without any significant loss of reliability. Hence, a time-critical packet uses PCA and CSMA/CA for normal packet transmission. In this paper, using Markov chains, we model the CSMA/CA and PCA in both beacon-enabled and nonbeacon-enabled personal area network (PAN) and derive the performance metrics (reliability, delay, and power consumption). Our primary contributions in this paper include:

- Mathematical formulation for analyzing the performance of unslotted PCA and CSMA/CA in a nonbeacon-enabled PAN.
- Mathematical formulation for analyzing the performance of slotted PCA and CSMA/CA in a beacon-enabled PAN.
- Validation of proposed analytical models for both slotted and unslotted channel access using a real-time testbed and Monte Carlo simulations.
- Performance comparison of PCA and CSMA/CA in both beacon-enabled and nonbeacon-enabled PAN.

Rest of this paper is organized as follows. Sections II discusses the existing studies, and Section III provides the brief description of contention based random channel access schemes in IEEE 802.15.4-2015 standard respectively. Section IV provides the mathematical formulation for nonbeacon-enabled PAN, and mathematical formulation for beacon-enabled PAN is discussed in Section V. Performance and validation of proposed analytical models using Monte Carlo simulations and real-time testbed are provided in Section VI. Finally, section VII concludes the paper by discussing the future scope of this work.

II. Related Work

Accurate analytical models of this kind aid in understanding the performance and suitability of channel access mechanisms and aid in optimizing the operational parameters leading to efficient network operation. Many studies to analyze the performance of IEEE 802.15.4 CSMA/CA exist [10]–[18] and very few studies analyzed the performance of PCA. Authors in [10] and [11] used event chains and Markov models respectively to analyze slotted CSMA/CA but the performance of PCA is not considered. In [12], authors analyzed the performance of dense traffic multi-hop networks. In [13], Pollin *et al.* considered star topology under saturated and unsaturated traffic conditions without retransmissions. The models proposed in [14]–[16] analyzed the impact of CSMA/CA parameters, the number of nodes, and data frame size on the network throughput and energy efficiency, but do not discuss the performance of PCA. Although in this study we did not consider throughput as a performance metric, one can refer to [15] to extend this model to derive the throughput. In [17], [18], authors analyzed the performance of IEEE 802.15.4 MAC considering the effects of noisy environments and channel fading but do not consider PCA.

Gebremedhin *et al.* in [19] analyzed the performance of PCA using only simulation model and no analytical model is considered. In [20] and [21], the authors investigated the

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TABLE I: Summary of primary notations used for modeling

Parameter	Description
η	Probability of at least one packet availability in the queue
h_p	Probability of the available packet being time critical
L_c	Packet collision duration
L_s	Successful packet duration
L_p	Packet duration
L_{ack}	Acknowledgment duration
n	Max. no. of retries
m	No. of backoff stages
$macMinBE$	Min. backoff exponent
$macMaxBE$	Max. backoff exponent
α	CCA1 busy probability
β	CCA2 busy probability
P_c	Probability for collision
τ	Probability of a node in CCA1
N	No. of nodes in the network
P_Q	Probability of the node residing in Idle state
$b_{0,0}$	Probability of node residing in the state (0,0) of unslotted CSMA/CA
$b_{i,k}$	Probability of unslotted CSMA/CA states
$b_{i,k,j}$	Probability of slotted CSMA/CA states
$p_{i,k}$	Probability of PCA states
τ	Probability of node attempting CCA1 in an arbitrary time
R^U_{CSMA}	Reliability of unslotted CSMA/CA
R^S_{CSMA}	Reliability of slotted CSMA/CA
D^U_{CSMA}	Delay of successfully transmitted packet using unslotted CSMA/CA
D^S_{CSMA}	Delay of successfully transmitted packet using slotted CSMA/CA
P^U_{CSMA}	Power consumption of unslotted CSMA/CA
P^S_{CSMA}	Power consumption of slotted CSMA/CA
P_{fr}	Probability of normal packet discard due to exceeded retransmissions
P_{fc}	Probability of normal packet discard due to channel access failure
P_{de}	Probability of packet being discarded due to delay expiry in PCA
P_{dc}	Probability of packet being discarded due to collision in PCA

performance of frame slotted aloha for low energy critical infrastructure monitoring (LECIM) applications. Hence to the best of our knowledge, this is the first study which provides the theoretical model for the behavior of PCA along with CSMA/CA in both beacon-enabled and nonbeacon-enabled PAN.

III. Contention based random channel access mechanisms in IEEE 802.15.4-2015 standard

The Personal Area Network (PAN) using IEEE 802.15.4-2015 MAC supports both beacon-enabled and nonbeacon-enabled operation. In a beacon-enabled PAN, the node waits for a periodic beacon from the coordinator and synchronizes to the superframe structure after which it employs either slotted CSMA/CA or slotted PCA for the channel access. Slotted PCA is chosen whenever a time-critical packet needs to be transmitted. Whereas in the nonbeacon-enabled PAN, the coordinator does not transmit any beacon and the nodes use unslotted CSMA/CA or unslotted PCA for transmission depending on the packet criticality.

A. Prioritized Contention Access Mechanism (PCA)

Fig. 1 describes the channel access flow using both slotted and unslotted PCA. Initially, a delay counter is started on the arrival of a time-critical packet which updates after every Clear Channel Assessment (CCA) performed. $critDelay$ is the maximum delay specified by the application within which the time critical data needs to be transmitted after which

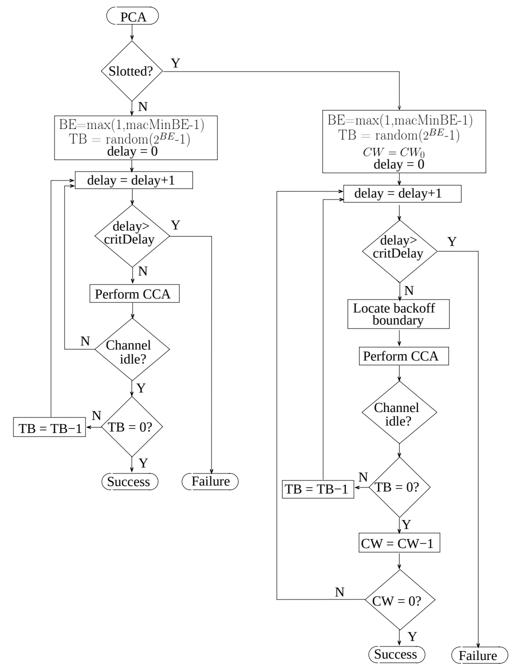

Fig. 1: Operation of slotted and unslotted PCA

the validity of data expires. Then the node selects a back-off waiting time (TB) randomly chosen from $[0, 2^{BE} - 1]$ where $BE = max(1, macMinBE - 1)$ and *macMinBE* is the minimum backoff exponent. A backoff period in IEEE 802.15.4 lasts for a duration of 20 symbols ($i.e.$, $320\mu s$). The node continuously monitors the channel and decrements TB by one only if the channel is free. After every channel sensing, the node updates the delay and discards the packet if the node does not get channel access before the specified $critDelay$. This process continues until the node gets access to the channel after $TB = 0$.

In slotted PCA, the backoff boundaries of all the nodes are aligned with the start of the periodic superframe, and channel sensing is performed at the beginning of a backoff boundary. Also, slotted PCA uses Contention Width (CW) equals to CW_0 where the node performs CCA successively and transmits the packet only if the channel is free during the entire period of the CW. Usually CW_0 is two backoff periods, and once the node finishes backoff waiting ($TB = 0$), the node performs CCA and decrements *CW* if the channel is clear, and proceeds to transmission if *CW=0*. If the channel is found busy during the CW, *CW* is reset to CW_0, and the node repeats the same process. The slotted PCA uses acknowledgments received from coordinator to make sure the packet is transmitted successfully.

B. Carrier Sense Multiple Access - Collision Avoidance (CSMA/CA)

At the beginning of the unslotted CSMA/CA, TB is initialized to a value randomly chosen from $[0, W_0)$ where $W_0 = 2^{macMinBE}$. After the backoff waiting, the node performs CCA and starts transmission if the channel is free else it increments the BE (BE=BE+1) and selects a random backoff from

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$[0, W_1)$, where $W_1 = 2^{min(macMaxBE,BE)}$ and $macMaxBE$ is maximum backoff exponent. The node repeats the same process until the number of backoff stages (NB) exceeds the specified maximum backoff stages ($macMaxBackoffs$) after which the packet is discarded. Similar to unslotted PCA, unslotted CSMA/CA employs no acknowledgment (NACK), whereas the slotted CSMA/CA relies on acknowledgment (ACK). Also, slotted CSMA/CA employs contention width $CW = CW_0$. As CSMA/CA is well studied in the literature, we advise the readers to refer [6], for a more detailed operation of CSMA/CA.

While the nonbeacon-enabled channel access is decentralized, improves throughput, and reduces the delay, the beacon-enabled channel access is complex as the nodes require tight synchronization with the beacon superframe. The channel access in slotted mode requires performing CCA for a CW of 2 which helps in the detection of ACK transmission by the gateway. Whereas in the case of unslotted channel access the CCA is performed only once which increases collisions if ACK is employed. Also, usage of ACK leads to increased energy consumption [14], [22]. Hence, in this study, unslotted channel access is used with no acknowledgments (NACK), meaning that if a collision occurs, the transmitting node still proceeds to serve a new packet. For the mathematical formulation, we consider below acceptable assumptions which are in agreement with the existing popular studies in the literature. [11].

1) We assume the traffic overhead due to periodic beacon frame communication from the gateway is negligible.
2) Ideal channel conditions are considered.

IV. Mathematical formulation for leaf node operating in nonbeacon-enabled PAN (Using unslotted PCA and unslotted CSMA/CA)

Fig. 2 shows the developed Markov chain model for unslotted CSMA/CA with the node in the Idle state (Q) during the absence of packets. Each state in the Markov chain corresponds to a unit backoff period duration (20 symbols). η and h_p represent the packet generation probability and the probability of the available packet being time-critical respectively. Upon the availability of a normal packet with probability $\eta(1 - h_p)$, the node uses unslotted CSMA/CA and selects a random backoff waiting time. These backoff waiting periods are represented using states (i, k), $\forall i \in [0, m],\ k \in [0, W_0)$ in the Markov chain. The states $(i, 0)$, $\forall i \in [0, m]$ represent the CCA. P_c and α indicate the probability of collision and channel being busy during the CCA respectively with L_s and L_c indicating the successful and collision packet lengths in terms of unit backoff periods. The states $(-2, k)$ and $(-3, k)$ represent packet collision and successful transmission states, whereas m represents the maximum backoff stages after which the packet is discarded due to channel access failure.

Fig. 3 shows the Markov chain of PCA used for time-critical packets with probability ηh_p. The states are guided by a two-dimensional stochastic process $(c(t), d(t))$ where $c(t)$ represents the backoff waiting counter and $d(t)$ represents the delay incurred by the packet in terms of unit backoff period.

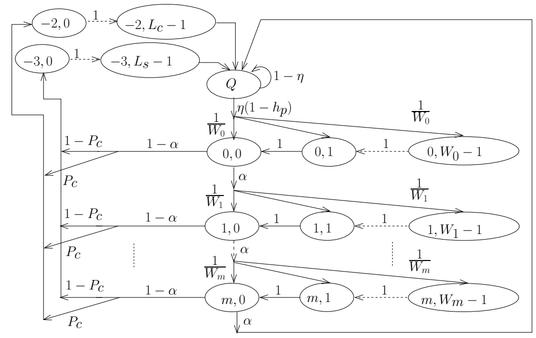

Fig. 2: Markov chain model for unslotted CSMA/CA

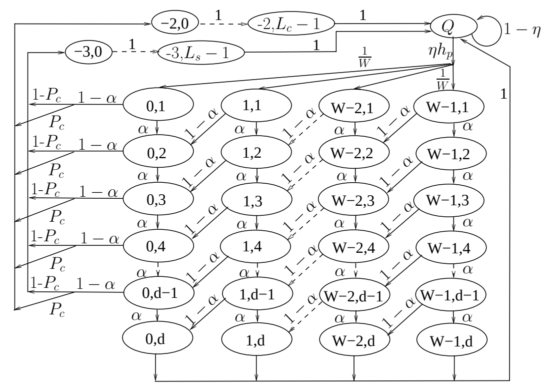

Fig. 3: Markov chain model for unslotted PCA

Hence, at the beginning of PCA, the initial states that can be chosen, will all have the second dimension set to 1. Supposing the node chooses backoff waiting time i, then it transits from the Idle state to $(i, 1)$. After performing CCA, if the channel is found free the node transits from $(i, 1)$ to $(i - 1, 2)$ else it transits to $(i, 2)$. In both the transitions, the second dimension is incremented as the node will have incurred with one backoff period delay in the previous state while performing CCA. This procedure continues until the node gets channel access within $critDelay$ number of backoff periods and if the node incurs a delay equal to $critDelay$ before accessing the channel, the packet is discarded. In the Markov chain, we represented the $critDelay$ as d. Therefore, if the node reaches any of the states (i, d), the packet will be discarded, and the node transits to the Idle state. If the node gets channel access before $critDelay$, the node proceeds to transmission and the corresponding states are represented using $(-3, k)$ and $(-2, k)$ for both successful and collision respectively. One thing to note here is the state Q is common for both the Markov chains (unslotted CSMA/CA in Fig. 2 and unslotted PCA in Fig. 3).

For clear discrimination between the states of CSMA/CA and PCA, we represent the CSMA/CA state probabilities using $b_{i,k}$ and those of PCA using $p_{i,k}$. Table I summarizes the primary notations used for mathematical formulation. As Q is common for both unslotted PCA and unslotted CSMA/CA, P_Q represents the probability of node residing in Q. From Fig. 2, the below transition probabilities can be formulated.

$$P(i, k|i, k + 1) = 1, \qquad \forall i \in [0, m],\ k \in [0, W_i - 1), \qquad (1)$$

$$P(i,k|i-1,k) = \tfrac{\alpha}{W}, \qquad \forall i \in (0,m], \tag{2}$$

$$P(Q|m,0) = \alpha, \tag{3}$$

$$P(0,k|Q) = \tfrac{\eta(1-h_p)}{W_0}, \qquad \forall k \in [0,W_0), \tag{4}$$

$$P(-3,k+1|-3,k) = 1, \qquad \forall k \in [0,L_s-1), \tag{5}$$

$$P(-2,k+1|-2,k) = 1, \qquad \forall k \in [0,L_c-1), \tag{6}$$

$$P(-3,0|i,0) = (1-\alpha)(1-P_c), \qquad \forall i \in [0,m] \tag{7}$$

$$P(-2,0|i,0) = (1-\alpha)(1-P_c), \qquad \forall i \in [0,m], \tag{8}$$

$$P(Q|-3,L_s-1) = P(Q|-3,L_c-1) = 1. \tag{9}$$

Eq. (1) represents the probability of backoff counter decrement within the same backoff stage and (2) represents the probability of node proceeding to next backoff stage after the channel is sensed busy. Eq. (3) represents the node transiting to Idle state after the backoff expiry and (4) gives the probability of transition from Idle to CSMA/CA and choosing the backoff waiting time k in the first backoff stage. Eqs. (5) and (6) express the probability of transition across the successful transmission and collision states respectively. Eqs. (7) and (8) represent the probability of node entering into successful and collision states from the last backoff period of backoff stage i respectively. Eq. (9) represents the probability of node transiting to Idle after both successful or collision transmission. Similarly, using Fig. 3, transition probabilities for unslotted PCA can be computed as shown in (10)-(15).

$$P(i,k|i,k-1) = \alpha, \qquad \forall i \in [0,W), k \in (1,d], \tag{10}$$

$$P(i-1,k|i,k-1) = 1-\alpha, \qquad \forall i \in (0,W), k \in (1,d], \tag{11}$$

$$P(i,0|Q) = \tfrac{\eta h_p}{W}, \qquad \forall i \in [0,W), \tag{12}$$

$$P(-3,0|0,k) = (1-\alpha)(1-P_c), \qquad \forall k \in [0,d), \tag{13}$$

$$P(-2,0|0,k) = (1-\alpha)P_c, \qquad \forall k \in [0,d), \tag{14}$$

$$P(Q|i,d) = 1, \qquad \forall i \in [0,W). \tag{15}$$

Eq. (10) represents the probability of an increase in delay within the same backoff counter which can only happen if the channel is busy due to which the delay increments without a change in the backoff counter. Eq. (11) gives the probability of decrement in backoff counter which happens when CCA in the state (i,k) is free and (12) gives the probability of time-critical packet arrival in Idle state and node selecting a random backoff slot in PCA. Eqs. (13) and (14) represent the probability of node entering into successful and collision states from the last backoff period respectively. Eq. (15) represents the probability of node transiting to Idle after the critical delay expiry. Using these transition probabilities, we will now derive the individual state probabilities. (16) expresses the state probability $b_{i,k}$ in terms of $b_{0,0}$ and the probability $b_{0,0}$ can be expressed in terms of P_Q as shown in (17). Now combining (16) and (17), any CSMA/CA backoff state probability can be expressed in terms of P_Q as shown in (18).

$$b_{i,k} = \tfrac{W_i-k}{W_i} b_{i,0} = \tfrac{W_i-k}{W_i}\alpha^i b_{0,0}, \tag{16}$$

$$b_{0,0} = P_Q\eta(1-h_p), \tag{17}$$

$$b_{i,k} = \tfrac{W_i-k}{W_i}\alpha^i\eta(1-h_p)P_Q. \tag{18}$$

Now considering the CSMA/CA transmission probabilities, the successful transmission state probability ($b_{-3,0}$) can be expressed as.

$$\begin{aligned} b_{-3,0} &= (1-\alpha)(1-P_c)\sum_{i=0}^{m} b_{i,0} = (1-\alpha)(1-P_c)\sum_{i=0}^{m}\alpha^i\eta(1-h_p)P_Q \\ &= (1-P_c)(1-\alpha^{m+1})P_Q\eta(1-h_p). \end{aligned} \tag{19}$$

Similarly, the collision state probability can be given as.

$$\begin{aligned} b_{-2,0} &= (1-\alpha)P_c\sum_{i=0}^{m} b_{i,0} = (1-\alpha)P_c\sum_{i=0}^{m}\alpha^i\eta(1-h_p)P_Q \\ &= P_c(1-\alpha^{m+1})P_Q\eta(1-h_p). \end{aligned} \tag{20}$$

We now derive the rest of the state probabilities of PCA from the Markov chain shown in Fig. 3, and the state probability $p_{i,k}$ can be expressed as

$$p_{i,k} = \begin{cases} (1-\alpha)p_{i+1,k-1} + \alpha p_{i,k-1}, & \text{if } i \in [0,W-1), k \in (1,d] \\ \alpha p_{i,k-1}, & \text{if } i = W-1, k \in (1,d]. \end{cases} \tag{21}$$

The probability of a node selecting any of the random backoff states after a time-critical packet arrives can be given as

$$p_{i,1} = \tfrac{P_Q\eta h_p}{W}, \qquad \forall i \in [0,W-1]. \tag{22}$$

By making use of (21), (22) and exploiting the recursiveness, probability of any backoff state in PCA can be formulated as below.

$$p_{i,k} = \sum_{j=0}^{min(W-1-i,k-1)} {}^{k-1}C_j(1-\alpha)^j\alpha^{k-j-1}\tfrac{P_Q\eta h_p}{W}. \tag{23}$$

Using (23), the successful transmission probability ($p_{-3,0}$) can be expressed as below.

$$\begin{aligned} p_{-3,0} &= (1-P_c)(1-\alpha)\sum_{k=1}^{d-1} p_{0,k} \\ &= (1-P_c)(1-\alpha)\sum_{k=1}^{d-1}\sum_{j=0}^{min(W-1,k-1)} {}^{k-1}C_j(1-\alpha)^j\alpha^{k-j-1}\tfrac{P_Q\eta h_p}{W}. \end{aligned} \tag{24}$$

Considering Fig. 2 and 3, by owing to chain regularities, the normalization criteria of this Markov chain can be given as

$$\begin{aligned} P_Q &+ \sum_{i=0}^{m}\sum_{k=0}^{W_i-1} b_{i,k} + \sum_{k=0}^{L_s-1} b_{-3,k} + \sum_{k=0}^{L_c} b_{-2,k} \\ &+ \sum_{k=0}^{L_s-1} p_{-3,k} + \sum_{k=0}^{L_c} p_{-2,k} + \sum_{i=0}^{W-1}\sum_{k=1}^{d} p_{i,k} = 1. \end{aligned} \tag{25}$$

Evaluating each summation term, the first summation term using (18) can be expressed as

$$\sum_{i=0}^{m}\sum_{k=0}^{W_i-1} b_{i,k} = \tfrac{P_Q\eta(1-h_p)}{2}\left[\tfrac{1-(2\alpha)^{m+1}}{1-2\alpha}W_0 + \tfrac{1-\alpha^{m+1}}{1-\alpha}\right]. \tag{26}$$

Considering the second summation term in (25) and by making use of (5) and (19), the simplified expression can be realized as below.

$$\sum_{k=0}^{L_s-1} b_{-3,k} = L_s(1-P_c)(1-\alpha^{m+1})P_Q\eta(1-h_p). \tag{27}$$

With the similar hypothesis used in deriving (27), we can

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simplify the third summation term as below.

$$\sum_{k=0}^{L_c-1} b_{-2,k} = L_c P_c (1-\alpha^{m+1}) P_Q \eta (1-h_p). \tag{28}$$

The transmission probabilities for PCA can be expressed as in (29) and (30).

$$\sum_{k=0}^{L_s-1} p_{-3,k} = L_s(1-P_c)(1-\alpha)\sum_{k=1}^{d-1} \sum_{j=0}^{min(W-1,k-1)} {}^{k-1}C_j (1-\alpha)^j \alpha^{k-j-1} \frac{P_Q \eta h_p}{W}, \tag{29}$$

$$\sum_{k=0}^{L_c-1} p_{-2,k} = L_c P_c (1-\alpha) \sum_{k=1}^{d-1} p_{0,k} = L_c P_c (1-\alpha) \sum_{k=1}^{d-1} \sum_{j=0}^{min(W-1,k-1)} {}^{k-1}C_j (1-\alpha)^j \alpha^{k-j-1} \frac{P_Q \eta h_p}{W}. \tag{30}$$

Finally, the sixth summation term is given by (31)

$$\sum_{i=0}^{W-1} \sum_{k=1}^{d} p_{i,k} = \sum_{i=0}^{W-1} \sum_{k=1}^{d} \sum_{j=0}^{min(W-1-i,k-1)} {}^{k-1}C_j (1-\alpha)^j \alpha^{k-j-1} \frac{P_Q \eta h_p}{W}. \tag{31}$$

By making use of (26)-(31) and the normalization criteria given by (25), P_Q can be derived as below.

$$P_Q = \Bigg\{ 1 + \frac{\eta(1-h_p)}{2}\left[\frac{1-(2\alpha)^{m+1}}{1-2\alpha} W_0 + \frac{1-\alpha^{m+1}}{1-\alpha}\right] + \eta(1-h_p)(L_s(1-P_c)+L_c P_c)(1-\alpha^{m+1}) + \frac{\eta h_p}{W} L_s (1-P_c)(1-\alpha) \sum_{k=1}^{d-1} \sum_{j=0}^{min(W-1,k-1)} {}^{k-1}C_j (1-\alpha)^j \alpha^{k-j-1} + \frac{\eta h_p}{W} L_c P_c (1-\alpha) \sum_{k=1}^{d-1} \sum_{j=0}^{min(W-1,k-1)} {}^{k-1}C_j (1-\alpha)^j \alpha^{k-j-1} + \frac{\eta h_p}{W} \sum_{i=0}^{W-1} \sum_{k=1}^{d} \sum_{j=0}^{min(W-1-i,k-1)} {}^{k-1}C_j (1-\alpha)^j \alpha^{k-j-1} \Bigg\}^{-1}. \tag{32}$$

The probability τ of a node attempting CCA in CSMA/CA or attempting CCA in state *(i,0)* of the PCA mechanism can be given as

$$\tau = \sum_{i=0}^{m} b_{i,0} + \sum_{k=1}^{d-1} p_{0,k}. \tag{33}$$

Using (33), the channel busy probability α can be given by (34). Equation (35) formulates the collision probability P_c that at least one of the other $(N-1)$ nodes transmit the packet at the same time.

$$\alpha = (1-(1-\tau)^{N-1})(1-\alpha)(L_s(1-P_c)+L_c P_c) = \frac{(1-(1-\tau)^{N-1})(L_s(1-P_c)+L_c P_c)}{1+(1-(1-\tau)^{N-1})(L_s(1-P_c)+L_c P_c)}, \tag{34}$$

$$P_c = (1-(1-\tau)^{N-1}). \tag{35}$$

A. Reliability Model

The reliability of a node in a nonbeacon-enabled PAN is defined as the fraction of generated packets that are successfully transmitted to the gateway. Eq. (36) gives the reliability of unslotted CSMA/CA (R^U_{CSMA}) where P_{fr} and P_{fc} indicate the packet failure due to collision and channel access failure within $m+1$ backoff stages respectively. P_{fr} in (37) gives the probability of a node getting the channel access but suffers due to collision and P_{fc} in (38) gives the probability of a node not getting the channel access within the $m+1$ backoff stages.

$$R^U_{CSMA} = 1 - P_{fc} - P_{fr}, \tag{36}$$

$$P_{fr} = P_c(1-\alpha^{m+1}), \tag{37}$$

$$P_{fc} = \alpha^{m+1}. \tag{38}$$

Reliability of unslotted PCA (R^U_{PCA}) is given by (39) where P_{de} and P_{dc} indicate the probability of a time-critical packet being discarded due to delay exceeding beyond $critDelay$ and packet lost due to collision respectively.

$$R^U_{PCA} = 1 - P_{de} - P_{dc}(1-P_{de}). \tag{39}$$

The probability P_{de} can be found using (40), where A_g indicates the event that a time-critical packet was generated and event A_d indicates that thus generated packet is discarded due to delay expiry. Probability P_{dc} which indicates the probability of collision is given by (41).

$$P_{de} = P(A_d|A_g) = \frac{P(A_d \cap A_g)}{P(A_g)} = \frac{\sum_{i=0}^{W-1} p_{i,d}}{P_Q \eta h_p} = \frac{\sum_{i=0}^{W-1} \sum_{j=0}^{min(W-1-i,d-1)} {}^{d-1}C_j (1-\alpha)^j \alpha^{d-1-j}}{W}, \tag{40}$$

$$P_{dc} = (1-(1-\tau)^{N-1}). \tag{41}$$

B. Delay Model

The delay incurred for a successful packet transmission using unslotted CSMA/CA or unslotted PCA includes the delay for channel access and packet transmission time to the gateway. Equation (42) gives the average delay incurred in any given backoff stage i. The delay incurred by a successfully transmitted packet using CSMA/CA in seconds (D^U_{CSMA}) can be expressed as (43), where T_b indicates the duration of a unit backoff period (320μs) and T_{SC} indicates the duration for sensing which is 1 backoff period in unslotted CSMA/CA. T_s indicates the time taken for successful transmission ($T_b L_s$).

$$D_{CSMA,i} = \sum_{k=0}^{W_i-1} \frac{k}{W_i}, \tag{42}$$

$$D^U_{CSMA} = T_s + T_b \sum_{i=0}^{m} \frac{\alpha^i(1-\alpha)}{1-\alpha^{m+1}} \Big[(i+1)T_{SC} + \sum_{j=0}^{i} D_{CSMA,j}\Big], \tag{43}$$

Considering the PCA mechanism, delay incurred for the successful packet transmission in seconds can be expressed as below.

$$D^U_{PCA} = T_s + T_b \frac{\sum_{k=1}^{d-1} k p_{0,k}}{\sum_{k=1}^{d-1} p_{0,k}}. \tag{44}$$

C. Power Consumption Model

The power consumption of the node modeled here comprises the power consumption of the radio in the Idle state, during channel access, and packet transmission, but do not consider the power consumed by the microcontroller. We considered three power consuming states, idle during backoff waiting and in the Idle state (P_i), sensing during CCA (P_{sense}) and packet transmission (P_{tx}). Considering these three states, we express the total power consumption (P) of the node using (45) and the power consumed in CSMA/CA (P^U_{CSMA}) and PCA (P^U_{PCA}) are given in (46) and (47) respectively.

$$P^U = P_i P_Q + P^U_{CSMA} + P^U_{PCA}, \quad (45)$$

$$P^U_{CSMA} = P_{tx}\Big[\sum_{k=0}^{L_s-1} b_{-3,k} + \sum_{k=0}^{L_c-1} b_{-2,k}\Big] + P_i \sum_{i=0}^{m}\sum_{k=1}^{W_i-1} b_{i,k} + P_i \sum_{i=0}^{m}\sum_{k=1}^{W_i-1} b_{i,k} + P_{sense}\sum_{i=0}^{m} b_{i,0}, \quad (46)$$

$$P^U_{PCA} = P_{tx}\Big[\sum_{k=0}^{L_s-1} p_{-3,k} + \sum_{k=0}^{L_c-1} p_{-2,k}\Big] + P_{sense}\sum_{i=0}^{W-1}\sum_{k=1}^{d} p_{i,k}. \quad (47)$$

V. Mathematical formulation for leaf node operating in beacon-enabled PAN (Using slotted PCA and slotted CSMA/CA)

Fig. 4 provides the developed Markov chain model for a node using slotted PCA and slotted CSMA/CA where with a probability ηh_p the node enters into PCA and with probability $\eta(1-h_p)$ chooses slotted CSMA/CA. Each state in the developed Markov chain corresponds to a unit backoff slot duration (20 symbols). As the node enters into CSMA/CA, the node selects a random backoff waiting time represented using states $(i,k,j),\ \forall i \in [0,m],\ j \in [0,n],\ k \in [0,W_i)$. Upon the completion of backoff waiting, the node proceeds for Clear Channel Assessment 1 (CCA1, state $(i,0,j)$) and if the channel is free, the node proceeds to CCA2 (state $(i,-1,j)$) and proceeds to transmission if free. α and β represent the probability of channel busy in CCA1 and CCA2 respectively. If CCA1 or CCA2 is busy in current backoff stage $i-1$, the node increments the backoff exponent and generates a backoff waiting time randomly chosen from $[0, W_i - 1]$. This process is continued until the total backoff stages exceed the maximum backoff stages ($m+1$) after which the packet is discarded due to channel access failure. States $(-2,k,j)$, $\forall k \in [0,L_c),\ j \in [0,n]$ and $(-3,k,j)\ \forall k \in [0,L_s),\ j \in [0,n]$ represent the collision and successful transmission. L_s and L_c represent the successful packet transmission length (packet length (L_p) + Inter Frame Spacing (IFS) + ACK (L_{ack})) and collision length (L_p + IFS + ACK time-out duration). After collision, the node proceeds for retransmission and n represents the maximum allowed retransmissions beyond which node discards the packet. After a packet service, node checks for packet availability and if available chooses the appropriate channel mechanism else transits to Idle state. While the states $(0,k),\ k \in [1,d]$ and $(-1,k),\ k \in [1,d)$ represent CCA1 and CCA2, the states $(-3,k),\ k \in [0, L_s-1]$ and $(-2,k)$, $k \in [0, L_c-1]$ represent successful and collision slots of PCA. Eqs. (48) and (49) represent the transition probabilities from CCA1 of CSMA/CA to successful and collision slots respectively, whereas (50) and (51) represent the transition probabilities from CCA1 of PCA to successful and collision slots respectively.

$$P(-3,0,j|i,0,j) = (1-\alpha)(1-\beta)(1-P_c),\ \forall i \in [0,m],\ j \in [0,n] \quad (48)$$

$$P(-2,0,j|i,0,j) = (1-\alpha)(1-\beta)P_c,\ \forall i \in [0,m],\ j \in [0,n] \quad (49)$$

$$P(-3,0|0,k) = (1-\alpha)(1-\beta)(1-P_c), \qquad \forall k \in [1,d) \quad (50)$$

$$P(-2,0|0,k) = (1-\alpha)(1-\beta)P_c, \qquad \forall k \in [1,d) \quad (51)$$

Here, we define a virtual state V which occurs after service completion by PCA and CSMA/CA for ease of mathematical formulation. From Fig. 4, the below transition probabilities can be inferred. From Fig. 4, the virtual state probability (P_V) can be expressed as

$$P_V = \beta p_{-1,d} + \sum_{i=0}^{W-1} p_{i,d} + p_{-3,L_s-1} + p_{-2,L_c-1} + b_{-2,L_c-1,n} + \sum_{j=0}^{n} b_{-3,L_s-1,j} + \sum_{j=0}^{n} b_{m,0,j}(\alpha + (1-\alpha)\beta). \quad (52)$$

The Idle state probability (P_Q) can be expressed as

$$P_Q = P_Q(1-\eta) + P_V(1-\eta) = P_V\tfrac{1-\eta}{\eta}. \quad (53)$$

The probability $p_{i,1}$ in terms of P_V can be formulated as

$$p_{i,1} = P_V\tfrac{\eta h_p}{W} + P_Q\tfrac{\eta h_p}{W} = P_V\tfrac{h_p}{W}, \quad (54)$$

where $i \in [0, W-1]$. With similar hypothesis, the probability $P_{i,2}$ can be given as

$$p_{i,2} = \begin{cases} \alpha p_{i,1} + (1-\alpha)p_{i+1,1}, & \text{if } i \in [0, W-2] \\ \alpha p_{i,1}, & \text{if } i = W-1. \end{cases} \quad (55)$$

Upon generalizing, the probability $p_{i,k}$ can be given by

$$p_{i,k} = \sum_{j=0}^{min(W-1-i,k-1)} {}^{k-1}C_j (1-\alpha)^j \alpha^{k-j-1}\tfrac{P_V h_p}{W}, \quad \forall i \in [1, W-1],\ j \in [1,d]. \quad (56)$$

Similarly, $p_{0,3}$ in terms of P_V can be expressed as

$$p_{0,3} = \beta p_{-1,2} + (1-\alpha)p_{1,2} + \alpha p_{0,2} = (1-\alpha)\beta p_{0,1} + (1-\alpha)(\alpha p_{1,1} + (1-\alpha)p_{2,1}) + \alpha(\alpha p_{0,1} + (1-\alpha)p_{1,1}) = (1-\alpha)\beta\tfrac{P_V h_p}{W} = F_{0,3}(\alpha,\beta)\tfrac{P_V h_p}{W}, \quad (57)$$

where $F_{0,3}$ is function of α and β. In similar way the probabilities $p_{0,k}$ for $k \in [1,d]$ and $p_{-1,k}$ for $k \in [2,d]$ can be expressed as below

$$p_{0,k} = F_{0,k}(\alpha,\beta)\tfrac{P_V h_p}{W}, \qquad \forall k \in [1,d], \quad (58)$$

$$p_{-1,k} = (1-\alpha)p_{0,k-1}, \qquad k \in [2,d]. \quad (59)$$

Now, the success and collision probabilities of PCA are

$$p_{-3,0} = (1-\beta)(1-P_c)\sum_{k=2}^{d} p_{-1,k}, \quad (60)$$

$$p_{-2,0} = (1-\beta)P_c\sum_{k=2}^{d} p_{-1,k}. \quad (61)$$

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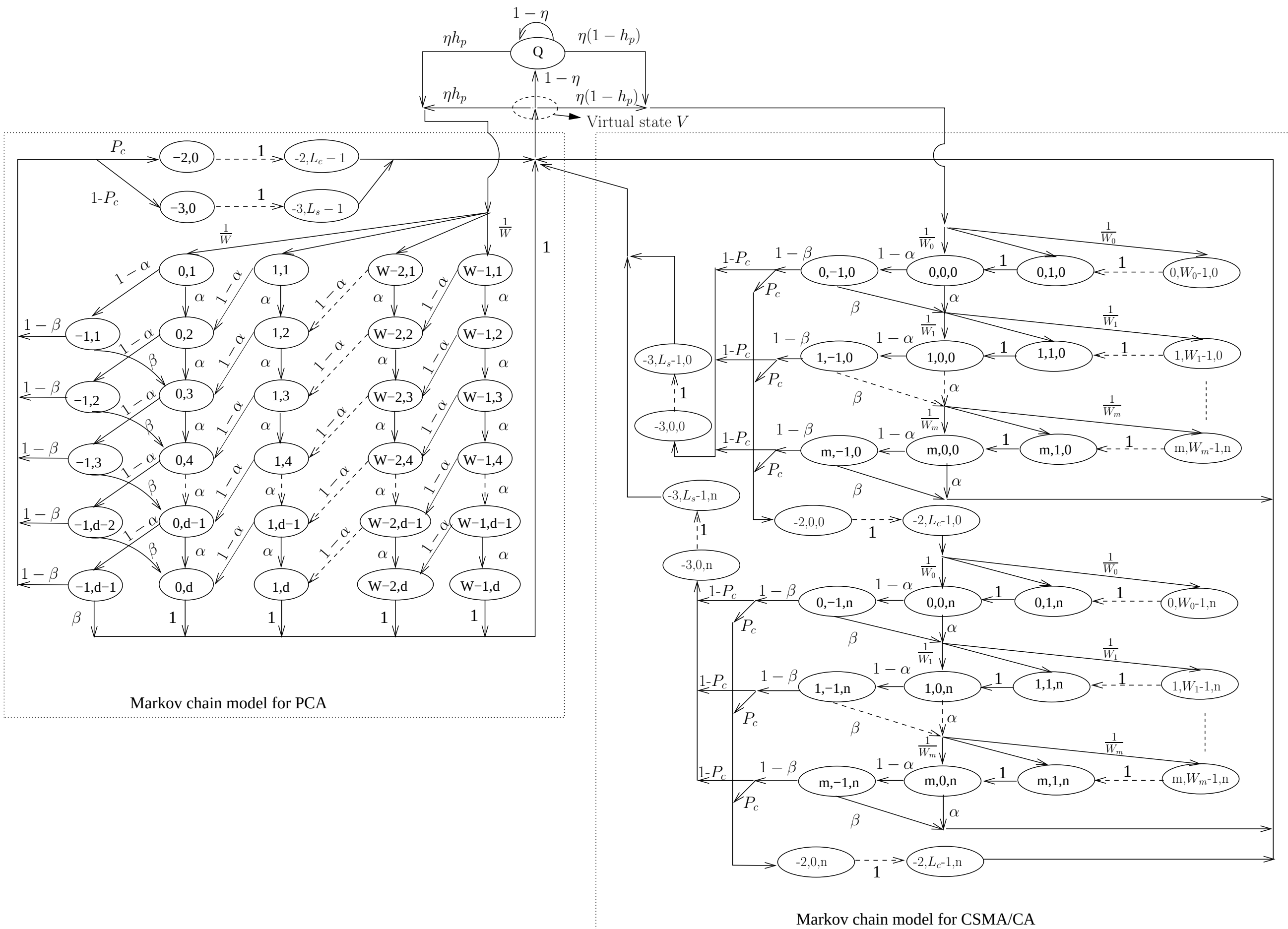

Fig. 4: Proposed Markov chain model for slotted CSMA/CA and PCA channel access mechanisms of IEEE 802.15.4-2015

Considering the CSMA/CA Markov chain, the probability of a node residing in state $(0, 0, 0)$ can be expressed as

$$b_{0,0,0} = \eta(1-h_p)P_V + \eta(1-h_p)P_Q = (1-h_p)P_V. \tag{62}$$

Using (62), the probability of i consecutive channel access failure can be found using (63)

$$b_{i,0,0} = (\alpha + (1-\alpha)\beta)^i b_{0,0,0} = x^i b_{0,0,0}, \tag{63}$$

where $x = (\alpha+(1-\alpha)\beta)$ represents the channel access failure probability in any backoff stage. Similarly the probability for a node to retransmit can be given as

$$b_{0,0,j} = (P_c(1-x^{m+1}))^j b_{0,0,0} = y^j b_{0,0,0}, \quad \forall\ j \in [0, n], \tag{64}$$

where $y = P_c(1 - x^{m+1})$ indicates the probability for node getting channel access within m backoff stages and occurrence of a collision. The successful and collision state probabilities in CSMA/CA can be given as in (65) and (66) respectively.

$$b_{-3,0,j} = (1-P_c)(1-x^{m+1})b_{0,0,j}, \qquad \forall j \in [0, n], \tag{65}$$

$$b_{-2,0,j} = P_c(1-x^{m+1})b_{0,0,j}, \qquad \forall j \in [0, n]. \tag{66}$$

The normalization property can now be expressed as

$$P_Q + \sum_{i=0}^{W-1}\sum_{k=1}^{d} p_{i,k} + \sum_{k=2}^{d} p_{-1,k} + \sum_{k=0}^{L_s-1} p_{-3,k} + \sum_{k=0}^{L_c-1} p_{-2,k} + \sum_{i=0}^{m}\sum_{j=0}^{n}\sum_{k=-1}^{W_i-1} b_{i,k,j} + \sum_{j=0}^{n}\Big(\sum_{k=0}^{L_s-1} b_{-3,k,j} + \sum_{k=0}^{L_c-1} b_{-2,k,j}\Big) = 1. \tag{67}$$

Using (56) and (58), the first summation term in terms of P_V can be written as

$$\sum_{i=0}^{W-1}\sum_{k=1}^{d} p_{i,k} = \sum_{k=1}^{d} F_{0,k}(\alpha,\beta)\tfrac{P_V h_p}{W} + \sum_{i=1}^{W-1}\sum_{k=1}^{d}\sum_{j=0}^{min(W-1-i,k-1)} {}^{k-1}C_j (1-\alpha)^j \alpha^{k-j-1}\tfrac{P_V h_p}{W} = S_1 P_V, \tag{68}$$

and using (59), the second summation term can be given as

$$\sum_{k=2}^{d} p_{-1,k} = (1-\alpha)\sum_{k=2}^{d} F_{0,k-1}(\alpha,\beta)\tfrac{P_V h_p}{W} = S_2 P_V. \tag{69}$$

Using (60) and (61), the third and fourth summation terms can be expressed as (70) and (71) respectively.

$$\sum_{k=0}^{L_s-1} p_{-3,k} = L_s(1-\alpha)(1-\beta)(1-P_c)\sum_{l=2}^{d} F_{0,l-1}(\alpha,\beta)\tfrac{P_V h_p}{W} = S_3 P_V, \tag{70}$$

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$$\sum_{k=0}^{L_c-1} p_{-2,k} = L_c(1-\alpha)(1-\beta)P_c \sum_{l=2}^{d} F_{0,l-1}(\alpha,\beta)\frac{P_V h_p}{W} = S_4 P_V. \quad (71)$$

Considering the fifth summation term, using (62), (63) and (64) it can be expressed as

$$\sum_{i=0}^{m}\sum_{j=0}^{n}\sum_{k=-1}^{W_i-1} b_{i,k,j} = \sum_{i=0}^{m}\sum_{j=0}^{n}\sum_{k=0}^{W_i-1} b_{i,k,j} + \sum_{i=0}^{m}\sum_{j=0}^{n} b_{i,-1,j}$$
$$= \frac{P_V(1-h_p)}{2}\left(\frac{1-(2x)^{m+1}}{1-2x}W_0 + \frac{1-x^{m+1}}{1-x}\right)\frac{1-y^{n+1}}{1-y}$$
$$+(1-\alpha)\frac{1-x^{m+1}}{1-x}\frac{1-y^{n+1}}{1-y}(1-h_p)P_V = S_5 P_V. \quad (72)$$

Finally, by using (65) and (66) the sixth summation can be formulated as

$$\sum_{j=0}^{n}\Big(\sum_{k=0}^{L_s-1} b_{-3,k,j} + \sum_{k=0}^{L_c-1} b_{-2,k,j}\Big) =$$
$$(L_s(1-P_c)+L_cP_c)(1-x^{m+1})\frac{1-y^{n+1}}{1-y}(1-h_p)P_V = S_6 P_V. \quad (73)$$

By substituting (68) - (73) in (67), P_V can be derived as

$$P_V = \left(\frac{1-\eta}{\eta} + S_1 + S_2 + S_3 + S_4 + S_5 + S_6\right)^{-1}. \quad (74)$$

Probability of a node attempting CCA1 in any given random time (τ) can be given as

$$\tau = \sum_{i=0}^{m}\sum_{j=0}^{n} b_{i,0,j} + \sum_{k=1}^{d} b_{0,k}. \quad (75)$$

Using (75), the probability of collision is

$$P_c = 1-(1-\tau)^{N-1}. \quad (76)$$

α as given by (77), comprises of channel busy due to packet transmission (α_1) and due to acknowledgment (α_2) which are expressed in (78) and (79).

$$\alpha = \alpha_1 + \alpha_2, \quad (77)$$

$$\alpha_1 = L_p(1-(1-\tau)^{N-1})(1-\alpha)(1-\beta), \quad (78)$$

$$\alpha_2 = L_{ack}\frac{N\tau(1-\tau)^{N-1}}{1-(1-\tau)^N}(1-(1-\tau)^{N-1})(1-\alpha)(1-\beta). \quad (79)$$

Similarly β can be derived as (80) and for more detailed derivation of β, one can refer to [11].

$$\beta = \frac{1-(1-\tau)^{N-1}+N\tau(1-\tau)^{N-1}}{2-(1-\tau)^N+N\tau(1-\tau)^{N-1}}. \quad (80)$$

A. Reliability Model

The reliability of a node in a beacon-enabled PAN is defined as the fraction of generated packets that received the acknowledgment successfully. Reliability of slotted PCA (R^S_{PCA}) is given in Eq. (81), where P_{de} and P_{dc} indicate the probability of a time-critical packet being discarded due to delay exceeding beyond d and packet loss due to collision respectively.

$$R^S_{PCA} = 1 - P_{de} - P_{dc}(1-P_{de}). \quad (81)$$

The probability P_{de} can be found using Eq. (82), where A_g indicates the event that a time-critical packet was generated and event A_d indicates the generated packet is discarded due to delay expiry. Probability P_{dc} which indicates the probability of collision is given by Eq. (83)

$$P_{de} = P(A_d|A_g) = \frac{P(A_d \cap A_g)}{P(A_g)} = \frac{\beta p_{-1,d} + \sum_{i=0}^{W-1} p_{i,d}}{P_Q \eta h_p}$$
$$= \frac{\sum_{i=0}^{W}\sum_{k=0}^{min(W-1-i,d-1)} {}^{d-1}C_k(1-\alpha)^k\alpha^{d-1-k}}{W}, \quad (82)$$

$$P_{dc} = (1-(1-\tau)^{N-1}). \quad (83)$$

Packet losses in CSMA/CA occur due to exceeded retransmissions and packet discard due to the exceeded maximum number of backoff stages. Hence the reliability of slotted CSMA/CA (R^S_{CSMA}) can be expressed as (84) where P_{fc} and P_{fr} indicate the packet failure due to channel access failure within $m+1$ backoff stages and exceeded retransmissions respectively.

$$R^S_{CSMA} = 1 - P_{fc} - P_{fr}, \quad (84)$$

$$P_{fc} = \frac{x^{m+1}(1-y^{n+1})}{1-y}, \quad (85)$$

$$P_{fr} = y^{n+1}. \quad (86)$$

B. Delay Model

The delay incurred for a successful packet transmission using slotted CSMA/CA or slotted PCA includes the delay for channel access, packet transmission time to the gateway and time taken for the reception of acknowledgment from the gateway. Delay incurred for a successful packet transmission using PCA can be expressed as below.

$$D^S_{PCA} = T_s + T_b\frac{\sum_{k=1}^{d} kp_{0,k}(1-\alpha)}{\sum_{k=1}^{d} p_{0,k}(1-\alpha)}, \quad (87)$$

where T_b is the length of a unit backoff period which is $320\mu s$ and T_s indicates the time taken for successful transmission (T_bL_s). We make use of delay incurred for a successful transmission using CSMA/CA in [11] and is given by (88)

$$D^S_{CSMA} = T_s + E[\tilde{T_h}] + \left(\frac{y}{1-y} - \frac{(n+1)y^{n+1}}{1-y^{n+1}}\right)(T_c + E[\tilde{T_h}]). \quad (88)$$

where $E[\tilde{T_h}]$ indicates the approximate backoff delay given by (89), T_c indicates the time taken for successful transmission (T_bL_c) and $\gamma = max(\alpha, (1-\alpha)\beta)$. As deriving (88) and (89) is not our primary contribution in this paper, we advise the readers to refer [11] for more insights.

$$E[\tilde{T_h}] = 2T_b\Bigg(1 + \frac{1}{4}\Bigg(\frac{1-\gamma}{1-\gamma^{m+1}}\Bigg(2W_0\frac{1-(2\gamma)^{m+1}}{1-2\gamma} -$$
$$\frac{3(m+1)\gamma^{m+1}}{1-\gamma}\Bigg) + \frac{3\gamma}{1-\gamma} - (W_0+1)\Bigg), \quad (89)$$

C. Power Consumption Model

The power consumption of the node modeled here comprises the power consumption of the radio in the Idle state,

TABLE II: Average power consumption of node in different states considered for analysis

State	*Avg. Power Consumption* (μW)
P_i	160
P_{tx}	160
P_{rx}	170
P_{sense}	170

during channel access, packet transmission, and acknowledgment reception, but do not consider the power consumed by the microcontroller. Assuming P_i, P_{tx}, P_{rx} and P_{sense} indicate the power consumption of the node in idle mode, transmit, receiving and sensing mode respectively, total power consumed (P^S_{tot}) comprises of power consumption while node spends in Idle state, during PCA mechanism (P^S_{PCA}) and CSMA/CA (P^S_{CSMA}).

$$P^S_{tot} = P_i P_Q + P^S_{PCA} + P^S_{CSMA}, \tag{90}$$

The power consumed in PCA states can be calculated as below

$$P^S_{PCA} = P_{sense}\Big(\sum_{i=0}^{W-1}\sum_{k=1}^{d} p_{i,k} + \sum_{k=2}^{d} p_{-1,k}\Big) + P_{tx}\sum_{i=-3}^{-2}\sum_{k=0}^{L_p-1} p_{i,k} + P_i \sum_{i=-3}^{-2} p_{i,L_p} + \sum_{k=L_p+1}^{L_p+L_{ack}+1}(P_{rx}p_{-3,k} + P_i p_{-2,k}), \tag{91}$$

and power consumed in CSMA/CA states can be found using (92)

$$P^S_{CSMA} = P_i \sum_{i=0}^{m}\sum_{k=1}^{W_i-1}\sum_{j=0}^{n} b_{i,k,j} + P_{sense}\sum_{i=0}^{m}\sum_{j=0}^{n}(b_{i,0,j} + b_{i,-1,j}) + P_{tx}\sum_{i=-3}^{-2}\sum_{k=0}^{L_p-1}\sum_{j=0}^{n} b_{i,k,j} + P_i \sum_{i=-3}^{-2}\sum_{j=0}^{n} b_{i,L_p,j} + \sum_{j=0}^{n}\sum_{k=L_p+1}^{L_p+L_{ack}+1}(P_{rx}b_{-3,k,j} + P_i b_{-2,k,j}). \tag{92}$$

VI. Performance Analysis

For the performance analysis, a star topology with N nodes and a gateway is considered. Authors in [23], proposed a simplistic Monte Carlo simulation model with ideal channel conditions using C, for analyzing the performance of MAC layer. We extended the simulation model proposed in [23] to analyze the performance of PCA in co-existence with CSMA/CA. Primary assumptions in the simulation framework developed include:

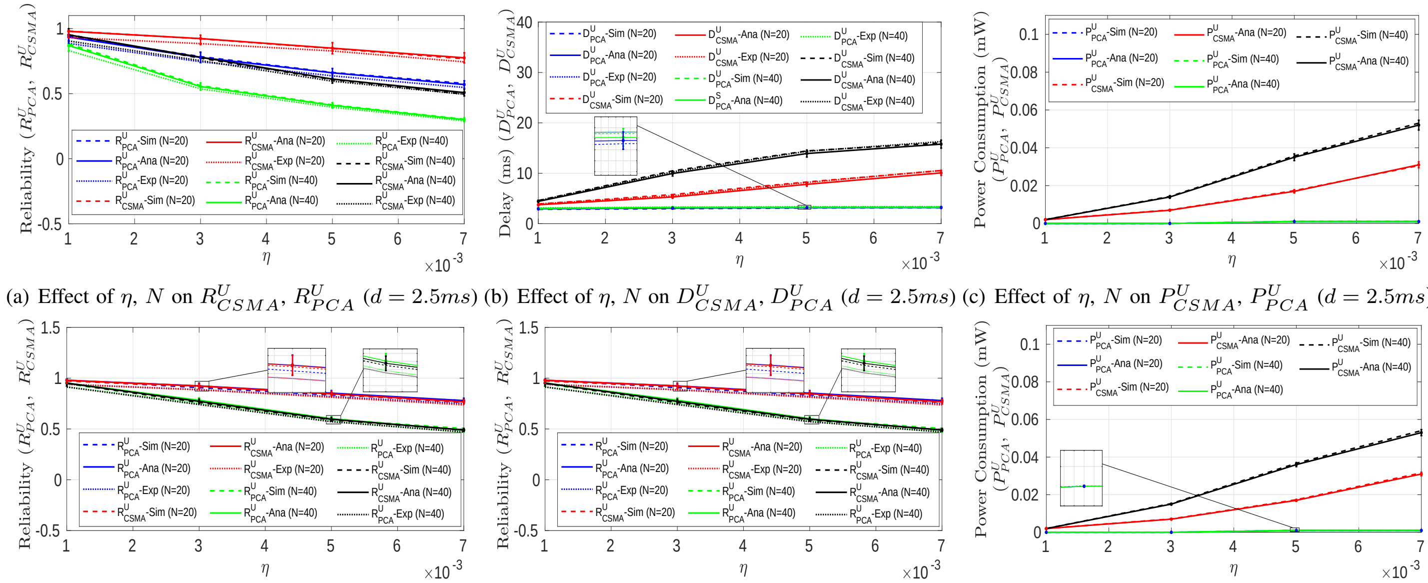
- Traffic due to periodic beacon frame communication is negligible.
- Ideal channel conditions are considered.

Also, we developed a real-time testbed for analyzing the real-time performance of the proposed models. We made use of commercially available IITH Motes which support Contiki 3.0 for the development of the testbed [24]. Each experiment comprises a fixed number of N nodes deployed within line of sight range in a star topology inside a room of dimensions 7.5m x 10m. In [17], authors analyzed the effects of channel fading on the performance of IEEE 802.15.4 MAC and claims the negative effect of fading on the reliability when the distance between the nodes increase beyond 10m. As the proposed analytical models aims at analyzing the performance of MAC layer under ideal channel conditions, we have closely deployed the nodes thereby minimizing the effects of channel conditions such as fading. Also, for validating with the experimental outcomes, we consider reliability, delay and ignore the power consumption because the power consumption of the mote includes the power consumed by the microcontroller and the radio. Whereas when comparing with the simulation outcomes, we considered all the three parameters reliability, delay and power consumption. Each experiment is conducted for 30 minutes, and the performance measures provided in this paper are average taken over measurements acquired from the randomly selected leaf node every 20 seconds. We have considered two different classes of prioritized data in industrial applications with critical delays of 2.5ms and 5ms each [25] and TABLE II gives the power consumption of node in different states considered for analyzing the performance [24].

A. Performance of nonbeacon-enabled PAN (Uses unslotted PCA and CSMA/CA)

Fig. 5(a) plots R^U_{PCA} and R^U_{CSMA} versus η for $N = 20$ and 40 with $d = 8$ backoff periods (2.5ms). With an increase in η, traffic and channel congestion in the PAN increases. It also increases the chances for the delay in accessing the channel to exceed d leading to a dominant loss of time-critical packets and increases number of packet collisions. Hence, unslotted CSMA/CA offers better reliability compared to unslotted PCA. By increasing from $N = 20$ to 40 the traffic further increases resulting in more loss of packets due to channel access failure leading to further degradation in reliability of CSMA/CA and PCA. Fig. 5(b) plots the D^U_{CSMA} and D^U_{PCA} for $d = 8$, and one can observe the significant difference between delay offered by CSMA/CA and PCA. PCA offers a very lower delay compared to CSMA/CA as the channel access is faster. Also, the maximum delay for channel access of a node using PCA will be d. With an increase of η, the latency incurred for channel access increases and the same behavior will incur by increasing N. Fig. 5(c) plots the power consumption of PCA and CSMA/CA where the power consumed by PCA for both $N = 20$ and $N = 40$ are very lower compared to CSMA/CA. As the number of nodes increase, the latency incurred for channel access increases due to which the power consumed by CSMA/CA is less for $N = 20$ compared to the $N = 40$ scenario.

As we increase the d, chances for channel access using PCA increases thereby increasing R^U_{PCA} and the same can be seen from Fig. 5(d) for $d = 16$ backoff periods (5ms). The reliability offered by PCA is almost identical to that of CSMA/CA for both $N = 20$ and $N = 40$. With the identical reliability of PCA and CSMA/CA, major advantage of using PCA can be observed from delay and power consumption as shown in Fig. 5(e) and 5(f) respectively. Fig. 5(e) plots D^U_{CSMA} and D^U_{PCA} for $d = 16$ where the D^U_{PCA} is very lower compared to CSMA/CA. Similarly, the power consumption of PCA and CSMA/CA for $d = 16$ is shown in Fig. 5(f) where P^U_{PCA} is negligible when compared to P^U_{CSMA}. Also,



(a) Effect of η, N on R^U_{CSMA}, R^U_{PCA} $(d = 2.5ms)$ (b) Effect of η, N on D^U_{CSMA}, D^U_{PCA} $(d = 2.5ms)$ (c) Effect of η, N on P^U_{CSMA}, P^U_{PCA} $(d = 2.5ms)$

(d) Effect of η, N on R^U_{CSMA}, R^U_{PCA} $(d = 5ms)$ (e) Effect of η, N on D^U_{CSMA}, D^U_{PCA} $(d = 5ms)$ (f) Effect of η, N on P^U_{CSMA}, P^U_{PCA} $(d = 5ms)$

Fig. 5: Effect of η and N on R^U_{CSMA}, R^U_{PCA}, D^U_{CSMA}, D^U_{PCA}, P^U_{CSMA} and P^U_{PCA}. Model parameters: $L_p = L_s = L_c = 6\ backoff\ periods\ (60\ bytes)$, $h_p = 0.1$, $macMinBE = 3$, $m = 5$, $macMaxBE = 8$

when compared to $d = 8$, in the case of $d = 16$, as more packets are being transmitted using PCA the node performs CCA for more times due to which there is a little increase in delay for packet transmission and power consumption. In the case of CSMA/CA, since the generation traffic remained same, R^U_{CSMA}, D^U_{CSMA} and P^U_{CSMA} remained almost the same although d is increased. From the performance analysis, it is observed that unslotted PCA achieves average delay reduction of 53.3% and an average reduction in power consumption by 96% compared to unslotted CSMA/CA.

B. Performance of beacon-enabled PAN (Uses slotted PCA and CSMA/CA)

Fig. 6(a) plots R^S_{PCA} and R^S_{CSMA} versus η for $N = 20$ and $N = 40$ with a d of 8 backoff slots (2.5ms). Similar to the case of nonbeacon-enabled as η increases, the traffic and channel congestion in the PAN increases.It also increases the chances for the delay in accessing the channel to exceed d leading to a dominant loss of time-critical packets. Hence slotted CSMA/CA offers significantly better reliability compared to slotted PCA. When compared to the reliability of unslotted PCA, as the node using slotted PCA needs to perform CCA for $CW = 2$ consecutively, the opportunities for accessing channel further reduces compared to unslotted PCA leading to significant increase in packet failure due to delay expiry. By increasing from $N = 20$ to $N = 40$ the traffic further increases resulting in more loss of packets due to channel access failure leading to further degradation of reliability for both CSMA/CA and PCA. Fig. 6(b) plots the D^S_{CSMA} and D^S_{PCA} for $d = 8$ and one can observe the significant difference between delay offered by CSMA/CA and PCA. Similar to unslotted scenario, slotted PCA offers a very lower delay compared to slotted CSMA/CA as the channel access is faster and the maximum delay for channel access of a node using PCA will be d. With increase in η, the channel congestion increases and hence the latency incurred for channel access increases and the same behavior will incur with increase in N. Fig. 6(c) plots the power consumption of PCA and CSMA/CA where the power consumed by PCA for both $N = 20$ and $N = 40$ are very lower compared to the power consumed by CSMA/CA. As number of nodes increase, the latency incurred for channel increases due to which the power consumed by CSMA/CA for $N = 20$ compared to $N = 40$ scenario. Although the node performs channel assessment for CW period before accessing the channel, it can at maximum perform 8 CCAs before accessing the channel in both slotted and unslotted PCA for $d = 8$, due to which the power consumption and delay are nearly identical. One can also observe the same from Fig. 6(b) and 6(c) with delay and power consumption of slotted PCA respectively which are identical to that of unslotted PCA.

As we increase the d, opportunities for the node to access the channel using PCA increases thereby increasing R^S_{PCA} and the same behavior can be seen from Fig. 6(d) for $d = 16$ backoff slots (5ms). With $d = 16$ the reliability offered by PCA is slightly lesser than that of CSMA/CA for both $N = 20$ and $N = 40$ due to the fact that CSMA/CA has feasibility for 1 additional retransmission ($n = 1$). Regarding delay and power consumption PCA still outperforms CSMA/CA as shown in fig. 6(e) and 6(f) respectively. Fig. 6(e) plots the D^S_{CSMA} and D^S_{PCA} for $d = 8$ where the D^S_{PCA} is very lower compared to CSMA/CA. Similarly, the power consumption of PCA and CSMA/CA for $d = 16$ is shown in Fig. 6(f) and the power consumed by PCA is negligible when compared with CSMA/CA. Also, when compared to $d = 8$, in the case of $d = 16$, as more packets are being transmitted using PCA the node performs CCA for more times due to which there is a little increase in delay for packet transmission and power consumption. In the case of CSMA/CA, since

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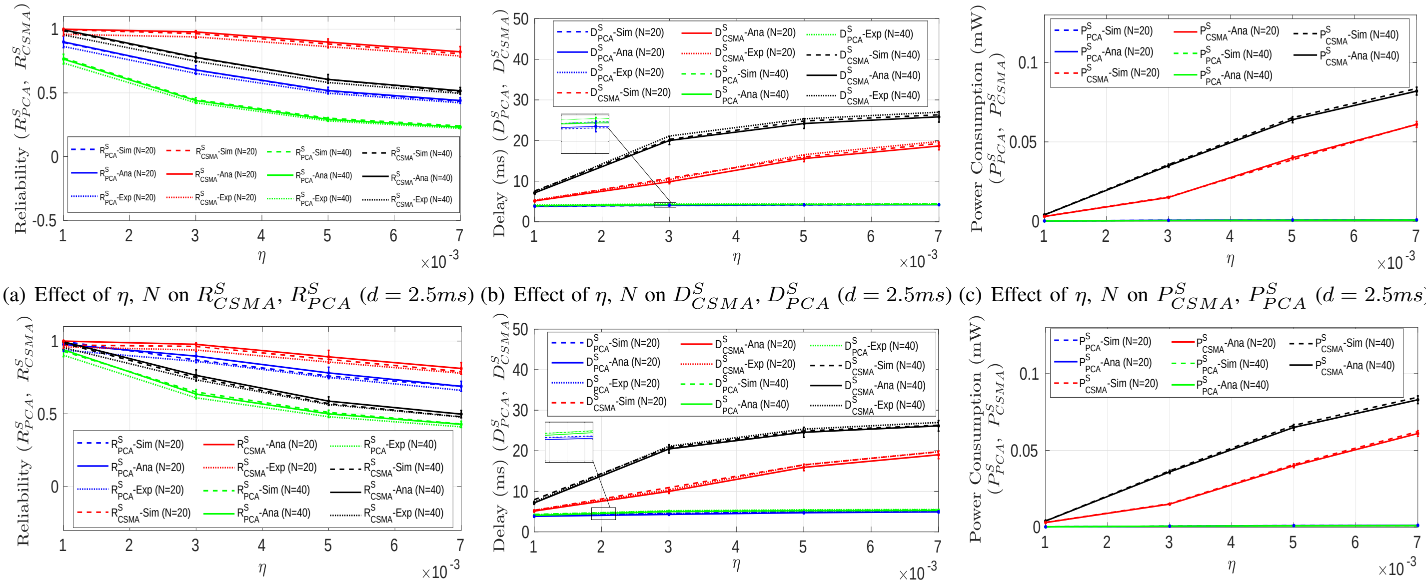

(a) Effect of η, N on R^S_{CSMA}, R^S_{PCA} ($d = 2.5ms$) (b) Effect of η, N on D^S_{CSMA}, D^S_{PCA} ($d = 2.5ms$) (c) Effect of η, N on P^S_{CSMA}, P^S_{PCA} ($d = 2.5ms$)

(d) Effect of η, N on R^S_{CSMA}, R^S_{PCA} ($d = 5ms$) (e) Effect of η, N on D^S_{CSMA}, D^S_{PCA} ($d = 5ms$) (f) Effect of η, N on P^S_{CSMA}, P^S_{PCA} ($d = 5ms$)

Fig. 6: Effect of η and N on R^S_{CSMA}, R^S_{PCA}, $D^S_{CSMA/CA}$, D^S_{PCA}, P^S_{CSMA} and P^S_{PCA}. Model parameters: $L_p = 6\ backoff\ periods\ (60\ bytes)$, $L_{ack} = 1\ backoff\ period\ (10\ bytes)$, $L_s = L_c = 8\ backoff\ periods$, $h_p = 0.1$, $macMinBE = 3$, $m = 5$, $macMaxBE = 8$, $n = 1$

the generation traffic remained same, R^S_{CSMA}, D^S_{CSMA} and P^S_{CSMA} remained almost the same although d is increased.

Table III shows the performance with variation in h_p for both beacon-enabled and nonbeacon-enabled PAN using the proposed analytical models. Although h_p varies, the underlying amount of traffic generated (η) is kept unchanged due to which one can observe a very little degradation in R^S_{PCA}, R^S_{CSMA}, D^S_{PCA}, D^S_{CSMA}, R^U_{PCA}, R^U_{CSMA}, D^U_{PCA} and D^U_{CSMA}. Whereas P^S_{CSMA}, P^U_{CSMA} decrease and P^S_{PCA}, P^S_{PCA} increase as more packets use PCA compared to CSMA/CA. From the performance analysis, it is observed that slotted PCA achieves average delay reduction of 63.3% and average reduction in power consumption by 97% when compared to slotted CSMA/CA.

Each simulation outcome is the average taken over 100 realizations with each realization having a simulation length of 1280 seconds. We have also indicated the 95% confidence intervals, and the analysis shows that the proposed Markov chain and mathematical formulation models the IEEE 802.15.4-2015 MAC layer accurately by achieving less than 5% error when compared with both the experimental and simulation outcomes.

VII. Conclusion

In this paper, we proposed a novel analytical model to analyze the performance of IEEE 802.15.4-2015 MAC layer for both beacon-enabled and nonbeacon-enabled PAN. We developed a Markov chain and mathematical formulation of reliability, delay for successful packet transmission and power consumption of the node when using unslotted PCA, slotted PCA, unslotted CSMA/CA and slotted CSMA/CA. Also, a real-time testbed using commercially available IITH Motes with Contiki 3.0 is developed for analyzing the performance of the proposed analytical models. Validation of the proposed models using both the Monte Carlo simulations and real-time testbed shows that the proposed models analyze the performance of the network accurately by achieving less than 5% error. Also, the service differentiation offered by PCA mechanism when used for transmission of time-critical packets is emphasized. It is observed that PCA achieves average delay reduction of 63.3% and 53.3% compared to CSMA/CA in beacon-enabled and nonbeacon-enabled PAN respectively without any significant loss of reliability. PCA also achieves an average reduction in power consumption by 97% and 96% compared to CSMA/CA in beacon-enabled and nonbeacon-enabled PAN respectively. To the best of our knowledge, this is the first study which analyzes the performance of PCA when operated simultaneously along with CSMA/CA in both beacon-enabled and nonbeacon-enabled using an accurate analytical model. We are convinced that the model can significantly aid in the development of optimization techniques to improve the network operational efficiency. As a future scope of this work, we would like to develop and model an efficient MAC protocol mainly for industrial applications which supports multiple classes of prioritized data with different critical delay requirements considering the channel conditions.

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TABLE III: Performance analysis of beacon-enabled and nonbeacon-enabled PAN with variation in h_p. Model parameters: $L_p = 6\ backoff\ periods\ (60\ bytes)$, $L_{ack} = 1\ backoff\ period\ (10\ bytes)$, $L_s = L_c = 8\ backoff\ periods$, $n = 1$, $macMinBE = 3$, $m = 5$, $macMaxBE = 8$, $\eta = 0.003$, $N = 40$, $d = 5ms$

h_p	R^S_{PCA}	R^S_{CSMA}	D^S_{PCA}	D^S_{CSMA}	P^S_{PCA} (μW)	P^S_{CSMA} (μW)	R^U_{PCA}	R^U_{CSMA}	D^U_{PCA}	D^U_{CSMA}	P^U_{PCA} (μW)	P^U_{CSMA} (μW)
0.4	0.647684	0.755278	5.01	20.70	2.71	26	0.772668	0.761107	3.67	10.47	2	11
0.7	0.636854	0.743998	5.03	21.01	5.07	14	0.761152	0.749335	3.70	10.79	4	6
1	0.622869	0.729335	5.05	21.40	7.84	0	0.747416	0.735434	3.73	11.15	5	0

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