

# Utilization Model for HCCA EDCA Mixed Mode in IEEE 802.11e

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*ABSTRACT*—This letter proposes an analytical model to characterize medium utilization in IEEE 802.11e operating in HCCA-EDCA mixed mode (HEMM). In contrast to existing works which model the backoff process in individual stations, we consider the channel occupancy pattern. Additionally, our work considers the operation of HEMM, which is not widely documented. We show that the proposed model accurately characterizes medium utilization with no more than 5% error.

*Keywords*—802.11, HEMM, Markov chain, utilization.

## I. Introduction

Channel access for wireless stations in an IEEE 802.11e wireless local area network (WLAN) is governed by the hybrid coordination function (HCF) [1]. The HCF provides contention-based channel access called enhanced distributed coordinated access (EDCA) and controlled-contention channel access called HCF coordinated channel access (HCCA).

In this paper, we develop a model which characterizes medium utilization. Our proposed model furthers our understanding of medium utilization performance and provides insights for further improvement. We apply our model to a saturated single-hop network under ideal channel conditions and validate the proposed model through simulations.

## II. EDCA, HCCA, and HEMM

EDCA mandates a random backoff process governed by two key parameters, the minimum contention window ( $CW_{\min}$ ) and arbitration inter-frame space (AIFS). Various combinations of these parameters regulate the amount of time each access

category (AC) is allowed to transmit on a channel. HCCA on the other hand, relies on a contend-poll mechanism to deliver frames. The HCCA entity gains control of the channel as needed by waiting a shorter time between transmissions than EDCA entities. The duration values used in frame exchange sequences reserve the channel to complete the current frame transfer sequence [1]. Joint operation of HCCA and EDCA within a station is termed HCCA-EDCA mixed mode (HEMM).

## III. Utilization Model for HEMM

We first observe that the channel alternates between successful and unsuccessful states. Successful states are due to either HCCA or EDCA, while unsuccessful states are either collisions or idle events. Based on this observation, we propose a new model describing the transmission opportunity (TXOP) occupancy. A TXOP is an interval of time defined by a starting time and a maximum duration when a transmission occurs on the channel [1].

This model is developed based on the following assumptions.

First, the HCCA access and EDCA access in each station are independent of each other, and the channel probabilities are identical at each point in time. Second, the TXOP duration is constant for HCCA and EDCA (3264  $\mu$ s for 802.11b) [1]. Third, beacon intervals of (0.1 s) have a maximum of thirty TXOP of which ( $m_H$ ) are HCCA-TXOP, while ( $m_E$ ) are EDCA-TXOP, subject to  $m_H + m_E = 30$ .

Let  $i(t)$  and  $j(t)$  represent a cumulative counting process of the number of TXOP occupied by HCCA and EDCA on the channel. A discrete-time scale  $t, (t+1), \dots, (t+n)$  with a duration of one TXOP is adopted.

Then, define  $\pi_{i,j}$  as the stationary distribution of the chain,

$$\pi_{i,j} = \lim_{t \rightarrow \infty} P\{i(t) = i, j(t) = j\}, i \in [0, m_H] \text{ and } j \in [0, m_E].$$

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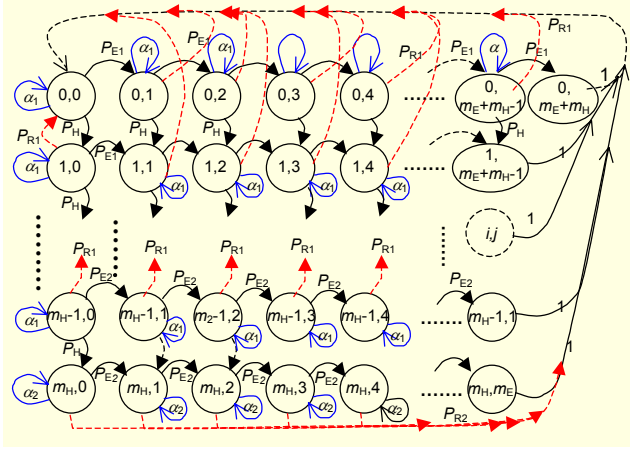


Fig. 1. Proposed Markov model for HEMM utilization.

Using the notation in [2], one-step transition probabilities for the Markov chain in Fig. 1 is one of the following events:

$$\text{EDCA access: } P(i, j | i, j-1) = \begin{cases} P_{E1}, & i < m_H, \\ P_{E2}, & i = m_H, \end{cases}$$

$$\text{HCCA access: } P(i, j | i-1, j) = P_H, \text{ subject to } i < m_H,$$

$$\text{collision or idle: } P(i, j | i, j) = \begin{cases} \alpha_1, & i < m_H, \\ \alpha_2, & i = m_H, \text{ or} \end{cases}$$

$$\text{reset: } P(0, 0 | i, j) = \begin{cases} P_{R1}, & i < m_H, \\ P_{R2}, & i = m_H. \end{cases}$$

#### IV. Channel Probabilities

The model we have just proposed assumes that the conditional transmission probabilities,  $\tau = [\tau_E, \tau_H]$ , regulating a node's operation are readily known. The conditional transmission probabilities required in our model are obtained by numerically solving a system of non-linear equations derived from [3]. With  $N$  active stations in the WLAN, we derive the expressions for the channel probabilities. Although the model in this letter considers a single access category (AC)-3 EDCA entity in each station, it can be easily extended to three ACs with modifications to the channel probabilities.

The probability of a successful EDCA transmission is

$$P_{E1} = N\tau_E(1-\tau_E)^{N-1}(1-\tau_H)^N. \quad (1)$$

The probability of a successful HCCA transmission is

$$P_H = N\tau_H(1-\tau_H)^{N-1}(1-\tau_E)^N. \quad (2)$$

The probability that no successful transmission occurs is

$$\alpha_1 = (1-P_{E1}) \times (1-P_H). \quad (3)$$

The probability that the cycle terminates is

$$P_{R1} = (\alpha_1)^{(m_H+m_E-i-j)}. \quad (4)$$

After a maximum number ( $m_H$ ) of TXOPs are granted to HCCA, no further HCCA TXOPs are available. Consequently, the channel only observes EDCA backoff entities from  $N$  distinct stations attempting to transmit. Hence

$$P_{E2} = N\tau_E(1-\tau_E)^{N-1} \text{ and } P_H = 0. \quad (5)$$

The probability that no successful transmission occurs is

$$\alpha_2 = 1 - P_{E2}. \quad (6)$$

The probability that the cycle terminates is

$$P_{R2} = (\alpha_2)^{(m_E-j)}. \quad (7)$$

With all the channel probabilities known, we proceed to analyze the stationary probabilities ( $\pi_{i,j}$ ) of the proposed Markov chain.

#### V. Analysis of Markov Chain

For the Markov chain in Fig. 1,  $m_T = m_E + m_H$ , the stationary transition probabilities are

$$\pi_{i,0} = \left(\frac{P_H}{1-\alpha_1}\right)^i \pi_{0,0}, 0 < i < m_H, \pi_{0,j} = \left(\frac{P_{E1}}{1-\alpha_1}\right)^j \pi_{0,0}, 0 < j < m_E, \quad (8)$$

$$\pi_{m_H,0} = \left(\frac{P_H}{1-\alpha_1}\right)^{m_H-1} \left(\frac{1}{1-\alpha_2}\right) \pi_{0,0}, \pi_{0,m_T} = \frac{(P_{E1})^{m_T}}{(1-\alpha_1)^{m_T-1}} \pi_{0,0}, \quad (9)$$

$$\pi_{i,j} = \binom{i}{j} \times \frac{(P_{E1})^j (P_H)^i}{(1-\alpha_1)^{i+j}} \pi_{0,0}, 0 < j < m_T, 0 < i < m_H. \quad (10)$$

For  $i = m_H$  and  $j < m_E$ , the state probabilities are

$$\pi_{m_H,j} = \left(\frac{P_H}{1-\alpha_1}\right)^{m_H} \times \left\{ 1 + \sum_{k=1}^{j-1} \binom{m_H-1+k}{k} \times \left( \frac{(P_{E1})^k}{P_{E2} \times (1-\alpha_2)^{k-1}} \right) \right\} \pi_{0,0} \quad (11)$$

and

$$\pi_{i,j} = \begin{cases} \binom{i}{j} \times \frac{(P_{E1})^j (P_H)^{i-1}}{(1-\alpha_1)^{i+j}} \pi_{0,0}, & \text{if } 0 < i < m_H \text{ and } i+j = m_T, \\ \left(\frac{P_H}{1-\alpha_1}\right)^{m_H} \times \left\{ 1 + \sum_{k=1}^{j-1} \binom{m_H-1+k}{k} \times \left( \frac{(P_{E1})^k}{P_{E2} \times (1-\alpha_2)^{k-1}} \right) \right\} \pi_{0,0}, & \text{if } i = m_H \text{ and } j = m_T. \end{cases} \quad (12)$$

Imposing the normalization condition yields

$$\sum_{i=0}^{m_1} \sum_{j=0}^{m_2} \pi_{i,j} = 1. \quad (13)$$

Finally, by solving (13), all state probabilities in the Markov chain can be expressed in terms of  $\pi_{0,0}$ .

## VI. Model Validation

In this section, we evaluate the accuracy of our model in predicting the medium utilization. For this purpose, we use *ns-2.20* to run simulations with various HEMM parameter settings. In the simulation, each station generates identical traffic. The payload and MAC overhead fits exactly in a TXOP, and  $CW_{\min}$  and AIFS values are assigned as in [1]. Each experiment lasting 500 s is repeated with 20 different random seeds. For the proposed Markov model, the medium utilization ( $U_A$ ) is calculated as

$$U_A = \frac{\left\{ \sum_{i=0}^{m_E} \sum_{j=0, \text{except } i=j=0}^{m_H} (i+j) \pi_{i,j} \right\}}{m_H + m_E}. \quad (14)$$

From simulation, the medium utilization ( $U_S$ ) is calculated as

$$U_S = \frac{\text{Total transmit time} - \text{Total idle time} - \text{Total collision time}}{\text{Total transmit time}}. \quad (15)$$

To validate the accuracy of our proposed model, we compared the prediction based on our proposed analytical model with simulation. Figure 2 shows how the medium utilization varies with  $N$  in a WLAN. For illustrative purposes, the analytical results are linearly interpolated with integer resolution. The model predicts the utilization with good accuracy and captures the non-monotonic characteristics typical of carrier sense multiple access (CSMA) protocols. As shown in Figs. 2 and 3, errors of no more than five percent were recorded between the simulation ( $U_S$ ) and the proposed Markov model ( $U_A$ ), while the average error for each plot is around three percent.

Figure 3 shows the impact of  $m_H$  on the medium utilization. As

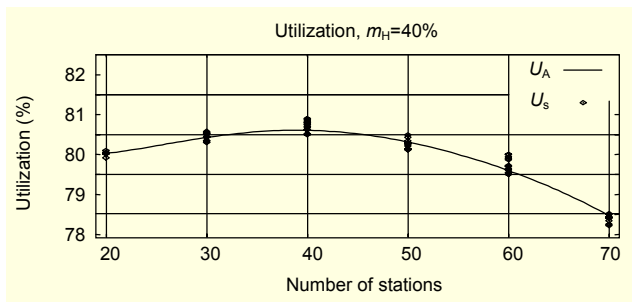


Fig. 2. Comparison of analytical and *ns-2* simulation (with 95% confidence interval, 40% HCCA limit).

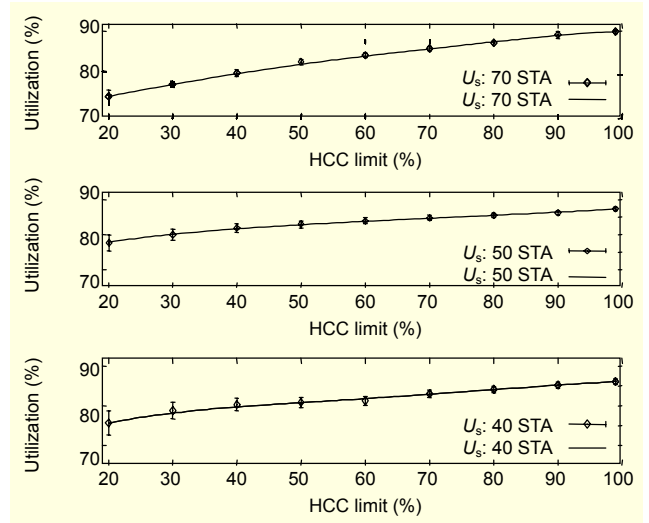


Fig. 3. Channel utilization for 40, 50, and 70 STA with increasing HCCA limit ( $m_H$ ).

expected, a higher HCCA limit improves the medium utilization due to more determinism in the medium access. The proposed model correctly captures this. Increasing accuracy for large  $N$  is attributed to improved estimation in channel probabilities due to [3]. As evidenced in Fig. 3, increased  $m_H$  increases the medium utilization for larger WLANs in saturation conditions.

Despite some simplifying assumptions on the modeled TXOP and independence supposition among system variables in the mathematical development, the results obtained are in very good agreement with simulations.

## VII. Conclusion

This letter presents a new model for characterizing HEMM medium utilization. In addition to giving insight into the protocol behavior, the model may be used for optimization purposes especially for admission control processes and service level agreements.

## References

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