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Science Letters:

Finite time-horizon Markov model for IEEE 802.11e

Cheng KUAN[†], Kaharudin DIMYATI

(*Department of Electrical and Electronic Engineering, Universiti Malaya, Kuala Lumpur 50603, Malaysia*)

[†]E-mail: cy@royal.net

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Abstract: We model wireless local area network channel utilization over a finite interval through a finite time-horizon Markov (FTHM) model. By accurately capturing time-varying utilization, the FTHM model allows for generally distributed transmission-opportunity (TXOP) duration, which most existing models do not account for. An absorbing state is introduced to limit the lifetime of the counting process, resulting in a non-ergodic Markov chain that is solved via transient analysis. The model predictions for time-varying utilization are validated by simulation with errors of no more than 0.1% after eight beacon intervals. Moreover, we show that the FTHM model prediction error is below 4% for Poisson distributed and uniformly distributed TXOP durations.

Key words: Wireless local area networks (WLANs), Markov, IEEE 802.11, Transient analysis
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INTRODUCTION

Among the various issues under investigation in 802.11 medium access control (MAC) protocol (IEEE Std 802.11, 2007), IEEE Std 802.11-k is the development of accurate and reliable models to determine resource utilization. A failure to anticipate utilization performance over time may result in poor quality of service (QoS) (Garroppo *et al*., 2007; Panaousis *et al*., 2008). Existing models and analyses (Kuan and Dimyati, 2007; Lim *et al*., 2008; Xu *et al*., 2009) are often restricted to steady-state behaviors. However, the steady-state behavior ($t\rightarrow\infty$) does not provide much insight for improving performability (Karagiannis *et al*., 2004). With intermittent changes in MAC parameters, dynamic channel occupancy patterns and interaction of these and possibly other factors, steady-state performance measures might be elusive. It remains unclear whether convergence to a steady state is ever achieved or, perhaps, is achieved so fast that the predicted performance under stationary assumptions is appropriate under such dynamic conditions. The finite time-horizon Markov (FTHM) model in this letter examines the transient behavior through the generalization of existing utilization models to derive time-dependent expressions for channel utilization.

UTILIZATION IN 802.11 WLAN

Utilization information is periodically broadcasted over an 802.11 wireless local area network (WLAN) for various uses such as access point (AP) selection, admission control and QoS management (Panaousis *et al*., 2008). Controlled-contention access is provided by the hybrid coordination function (HCF) channel access (HCCA) entity, while contention-based access is serviced by the enhanced distributed coordinated access (EDCA) entity. The IEEE Std 802.11 has provisions for joint HCCA-EDCA operation to further improve channel utilization (Gozalvez *et al*., 2007). Since 802.11 WLAN uses a single broadcast channel, channel utilization is a system measure (IEEE Std 802.11-k, 2008) and does not necessarily reflect the utilization of any QoS station (QSTA) or flow.

We begin by considering a typical scenario with N QSTAs attached to an AP in an infrastructure based WLAN. Both EDCA and HCCA backoff entities are active in each QSTA. The channel may be seized by either EDCA or HCCA and these events are mutually exclusive. Let τ_E and τ_H denote the successful conditional transmission probabilities of EDCA and HCCA, respectively. Hence, channel utilization is the outcome of one transmission in N Bernoulli trials with success probabilities τ_E and τ_H. In this letter, τ_E and τ_H are assumed constant as long as the number of QSTAs and the MAC parameters are unchanged. Detailed derivations of τ_E (Zhang *et al*., 2007; Hu *et al*., 2008; Lim *et al*., 2008; Lee and Lee, 2009) and τ_H (Sharon and Altman, 2001; Sikdar, 2005; Coenen *et al*., 2008) are reported extensively in the open literature. Once seizing the channel, a backoff entity occupies it for a certain duration governed by the transmission-opportunity (TXOP) duration parameter. The TXOP is a parameter which defines a starting time and a maximum transmission duration.

Finite time-horizon model

We adopt the model in Kuan and Dimyati (2007) and transform it into a finite time-horizon Markov model (Fig.1). Finite time-horizon models consider the problem of estimating performance measures over a finite interval rather than stationary measures derived from typical Markov chains. A successful transmission (due to HCCA or EDCA) advances the Markov chain, while non-transmission events (either collision or idle events) are modeled as a self-transition. A reset state and corresponding reset probabilities are introduced to account for the fact that the total time elapsed since the start of the counting process is not less than T_B, where T_B is the beacon interval. Owing to this modification, the finite time-horizon model proposed in this letter differs from those in Kuan and Dimyati (2007) and existing works in the following aspects:

1. A finite time-horizon model: the FTHM model provides temporal information on performance metrics.

2. Variable TXOP duration: a more realistic model accounts for variable TXOP duration.

3. Performance analysis: transient analysis is used due to non-recurrent chain structure.

Let $i(n)$ and $j(n)$ represent a cumulative counting process of the number of successful transmissions due to HCCA and EDCA on the channel within T_B.

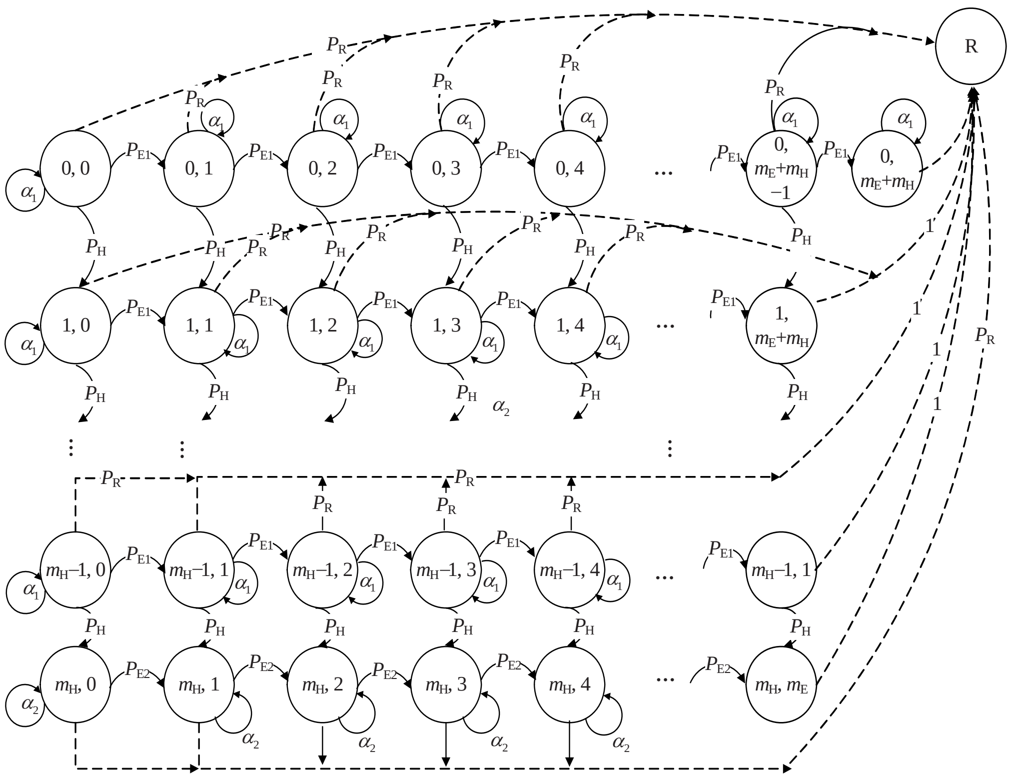

Fig.1 Bi-dimensional finite time-horizon Markov model

A discrete-time variable length epoch (0, 1, …, n) is adopted with a timer keeping track of the total elapsed time in each time epoch. Let the set of positive integers $\{i, j\}$ denote the states of the bi-dimensional Markov chain in Fig.1, while state 'R' is an absorbing state indicating a timer reset to zero and the beginning of a new beacon interval. At time step n, embed the Markov chain in the counting process such that $\{i(n)=i, j(n)=j\}$ $\forall n\le T_B$. Since the counting process counts the number of successful TXOPs within a finite time, the reset state is entered when the total elapsed time first exceeds T_B. Additionally, i and j are bounded by $i\le m_H$ and $j\le m_E$, where m_H is a fixed parameter limiting the number of HCCA accesses (to prevent starvation of EDCA), while m_E may be viewed as a movable boundary denoting the residual TXOPs. The parameters m_E and m_H are hypothetical; however, they may be used to tune the TXOP quota between HCCA and EDCA. In this letter it is assumed that the TXOPs are equally shared between EDCA and HCCA, hence $m_H=m_E=15$.

Furthermore, the minimum EDCA TXOP duration ($T_E^{\min}$) is 3264 μs while the maximum EDCA TXOP duration ($T_E^{\max}$) is 8160 μs; both values are specified in IEEE Std 802.11 for the 802.11b physical layer. Without loss of generality, we assume that $T_H^{\min}=T_E^{\min}$ and $T_H^{\max}=T_E^{\max}$, where $T_H^{\min}$ and $T_H^{\max}$ are the minimum and maximum HCCA TXOP durations, respectively. Hence, the maximum number of TXOPs within a beacon interval generalizes to $m_E+m_H\le\lfloor T_B/\min(T_H^{\min},T_E^{\min})\rfloor$.

FTHM TRANSITION PROBABILITIES

The transition probabilities are modified to accommodate the finite-time characteristics captured by the transformed model. For consistency, the one-step transition probability notations P_{E1}, P_{E2}, P_H, α_1, α_2 and P_R used here are similar to those in Kuan and Dimyati (2007). The transition probabilities for the Markov chain are derived as follows. With N active stations, the probability of a successful EDCA transmission may be expressed as the result of a Bernoulli trial:

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

Similarly, the probability of a successful HCCA transmission is

$$P_H=N\tau_H(1-\tau_H)^{N-1}(1-\tau_E)^N, \tag{2}$$

and no successful transmission occurs with a probability

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

After a maximum number of TXOPs are exhausted by HCCA, no further HCCA transmissions are allowed. Consequently, the channel observes only EDCA backoff entities from N distinct stations attempting to transmit frames, and hence the new probabilities of successful EDCA and HCCA transmissions are

$$P_{E2}=N\tau_E(1-\tau_E)^{N-1},\ P_H=0, \tag{4}$$

while the probability of no successful transmissions is

$$\alpha_2=1-P_{E2}. \tag{5}$$

The channel access probabilities P_{E1}, P_{E2} and P_H are independent of the elapsed time, and hence α_1 and α_2 are also independent of the elapsed time.

However, the reset probability P_R is conditioned on the elapsed time and must be modified. Fortunately, the elapsed time is summarized by the current state. The counting processes in state $\{i, j\}$ must have recorded the total utilized time amounting to $T_{\{i,j\}}^{\text{util}}$, and

$$T_{\{i,j\}}^{\text{util}}=\int_{T_H^{\min}}^{T_H^{\max}}\sum_{w=0}^{i}G_{\{w,j\}}(u)\mathrm{d}u+\int_{T_E^{\min}}^{T_E^{\max}}\sum_{w=0}^{j}G_{\{i,w\}}(u)\mathrm{d}u, \tag{6}$$

where u is a non-negative random variable denoting the TXOP duration and $G_{\{i,j\}}(u)$ is the corresponding distribution function of u in state $\{i, j\}$. Consequently, the probability that the counting process resets to state 'R', given that it is in an arbitrary state $\{i, j\}$, is equivalent to the probability that the chain stays in state $\{i, j\}$ for the remaining time until a reset event occurs. This implies that the sojourn time in state $\{i, j\}$ prior to reset is $T_B-T_{\{i,j\}}^{\text{util}}$. Thus, the reset probability is given by

$$P_{\mathrm{R}} = 1 - G_{\{i,j\}}\left(u \le T_{\mathrm{B}} - T_{\{i,j\}}^{\mathrm{util}}\right). \quad (7)$$

The distribution $G_{\{i,j\}}(u)$ requires additional information that will be defined later. With all the states and transition probabilities defined, the FTHM model is complete.

TRANSIENT ANALYSIS OF THE FTHM MODEL

A point to note here is that, the balance equation approach in Kuan and Dimyati (2007) is not applicable to the FTHM model since the transformed Markov chain is non-recurrent. To analyze the FTHM model, define $p_{\{i,j\}}^{n}$ as the probability that the chain transits from {0, 0} to $\{i, j\}$ in n steps. Thus, the state probabilities of the Markov chain (Fig.1) associated with the counting process are expressed as

$$p_{\{i,j\}}^{n} = \Pr\left(i(n) = i, j(n) = j \,\middle|\, i(n) = 0, j(n) = 0\right). \quad (8)$$

Let the matrix $\boldsymbol{P}$ (see Eq.(9) at the bottom of this page) represent the one-step transition probability matrix for the Markov chain. From the one-step transition probabilities, the state probability at time n is given by

$$\boldsymbol{p}^{n} = \boldsymbol{\pi}_{k}^{0}\boldsymbol{P}^{n}, \quad k = 1, 2, \ldots, N, \quad (10)$$

where $\boldsymbol{p}^{n}$ is a vector denoting the state distribution defined element-wise by Eq.(8) and $\boldsymbol{\pi}_{k}^{0}$ is a row matrix indicating the initial probability that the chain is in state $\{i, j\}$ during the kth beacon interval. With vector $\boldsymbol{p}^{n}$ known, we have a complete description of all state probabilities at step n. In the following section we will derive the channel utilization based on the FTHM model.

PERFORMANCE EVALUATION

The accuracy of the FTHM model was validated with simulations. All simulation results were obtained using ns-2 (version 2.20). The simulator closely followed the details of the 802.11 protocol details and had been used extensively in various studies. The traffic profile of individual stations was simplified to independent and identically distributed traffic inline with the FTHM model assumptions. The traffic source in ns-2 was modeled as an exponential generator and a constant bitrate (CBR) generator, both readily available from the simulator. MAC parameters such as CW (contention window) and AIFS (arbitration interframe space) values were assigned as per IEEE Std 802.11 (2007) using the 802.11b physical layer at 11 Mbps. Each simulation lasting $500T_{\mathrm{B}}$ was repeated with 20 different random seeds for reproducibility. The channel utilization using the FTHM model for the kth beacon interval, $U_{\mathrm{A}}(k)$, was calculated as

$$U_{\mathrm{A}}(k) = \frac{1}{kT_{\mathrm{B}}}\sum_{i}\sum_{j} p_{\{i,j\}}^{n} T_{\{i.j\}}^{\mathrm{util}}, \quad k = 1, 2, \ldots, N, \quad (11)$$

while the channel utilization from simulation, $U_{\mathrm{S}}(k)$, was reckoned as

$$\boldsymbol{P} = \left(\begin{array}{c|cccccccccc}
 & \{0,0\} & \{0,1\} & \{0,2\} & \cdots & \{0, m_{\mathrm{E}}+m_{\mathrm{H}}\} & \{1,0\} & \{1,1\} & \cdots & \{m_{\mathrm{H}},0\} & \cdots & \mathrm{R} \\
\hline
\{0,0\} & \alpha_1 & P_{\mathrm{E1}} & 0 & \cdots & 0 & P_{\mathrm{H}} & 0 & \cdots & 0 & \cdots & P_{\mathrm{R}} \\
\{0,1\} & 0 & \alpha_1 & P_{\mathrm{E1}} & \cdots & 0 & 0 & P_{\mathrm{H}} & \cdots & 0 & \cdots & P_{\mathrm{R}} \\
\{0,2\} & 0 & 0 & \alpha_1 & \cdots & 0 & 0 & 0 & \cdots & 0 & \cdots & P_{\mathrm{R}} \\
\vdots & \vdots & \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\
\{0, m_{\mathrm{E}}+m_{\mathrm{H}}\} & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & \cdots & 1 \\
\{1,0\} & 0 & 0 & 0 & \cdots & \vdots & \alpha_1 & P_{\mathrm{E1}} & \cdots & 0 & \cdots & P_{\mathrm{R}} \\
\{1,1\} & 0 & 0 & 0 & \cdots & \vdots & 0 & \alpha_1 & \cdots & 0 & \cdots & P_{\mathrm{R}} \\
\vdots & \vdots & \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\
\{m_{\mathrm{H}},0\} & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & \alpha_2 & \cdots & P_{\mathrm{R}} \\
\vdots & \vdots & \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\
\mathrm{R} & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & \cdots & 0
\end{array}\right). \quad (9)$$

$$U_S(k)=\frac{T_B^k+T_{idle}^{\sigma}+T_{coll}^{\sigma}}{T_B^k},\quad k=1,2,\ldots,N, \tag{12}$$

where T_{idle}^{σ} is the total idle time, T_{busy}^{σ} is the total collision time, and T_B^k is the beacon interval, all measured within the *k*th beacon interval.

The results of channel utilization predictions using the stationary model in Kuan and Dimyati (2007), the FTHM model and simulation are shown in Fig.2 for N=40 and N=90, where N denotes the number of stations. The TXOP duration is constant and fixed at $G_{\{i,j\}}(u)=T_E^{min}$. At time point T_B, there is a 4% difference in utilization prediction between the stationary model and FTHM model. At time point $6T_B$, the difference reduces to 1% and from $8T_B$ onwards the difference is less than 0.1%. Utilization predictions for remaining time points (not shown for brevity) in Fig.2 have errors of less than 0.1%. It is also apparent from Fig.2 that the convergence between the FTHM predictions, stationary measure and simulation is achieved after $8T_B$.

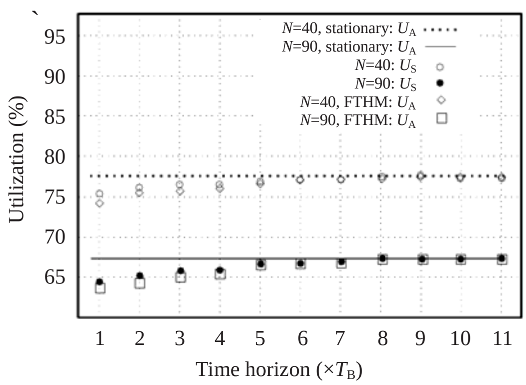

Fig.2 Convergence of FTHM utilization to equilibrium

Fig.3 shows the utilization performance for two different distributions of TXOP duration with an increasing number of stations, N. The TXOP duration is: (1) uniformly distributed between 3264 and 6200 μs; (2) Poisson distributed with an average duration of 4500 μs. FTHM average utilization predictions (drawn as lines) closely track simulation results with errors of no more than 4% at any point in N. In both Figs.2 and 3, the FTHM model slightly underestimates the utilization compared to simulation. This is most likely due to the inconsistent measured values of T_B^k in simulation. While the FTHM assumes fixed intervals, in simulation, beacon interval termination may coincide with the on-going transmission, thus stretching T_B and resulting in higher utilization. Overall, the FTHM model predictions accurately fall within the 95% confidence interval of simulation predictions, validating the FTHM model for Poisson and uniformly distributed TXOP durations.

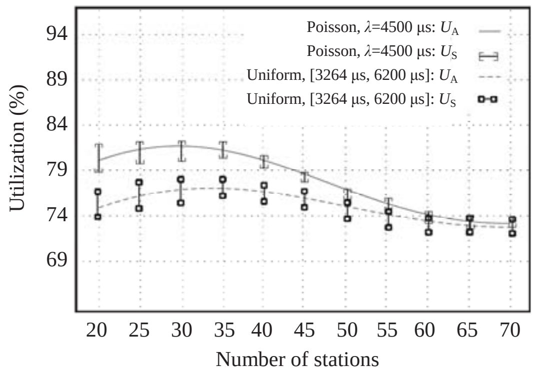

Fig.3 Accuracy of utilization performance with Poisson and uniformly distributed TXOP duration

CONCLUSION

In this letter, we propose the FTHM model that reveals the evolution of channel utilization with time. The model accurately characterizes time-varying channel utilization and correctly captures channel utilization with Poisson and uniformly distributed TXOP duration. Results indicated that stationary performance measures were achieved after $8T_B$ with errors of less than 0.1%. The FTHM model paves the way for further research on temporal stability of WLAN utilization due to random perturbations such as station mobility or re-configuration of contention parameters. Some modeling details such as polling strategies, queue dynamics and so forth have been left out for mathematical tractability and are left open for future work.

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