Distributed Optimal TXOP Control for Throughput Requirements in IEEE 802.11e Wireless LAN

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***Abstract*—This paper designs a distributed Transmission Opportunity (TXOP) adaptation algorithm for IEEE802.11e Enhanced Distributed Channel Access (EDCA). Each node measures its throughput in a window and compares it with a target value. If the measured throughput is higher than the target value, the node reduces its TXOP, otherwise if the measured value is less than the target throughput, the node increases its TXOP. We show that the target throughput can be achieved in a globally stable manner.**

***Index Terms*—IEEE 802.11e, EDCA, WLAN, TXOP, Distributed parameter control, Lyapunov stability**

I. Introduction

The IEEE 802.11e Enhanced Distributed Channel Access (EDCA) protocol [1] defines multiple queues, denoted by access categories (ACs), per each node and sets the corresponding control parameters such as the Arbitraion Interframe Space (AIFS), the Contention Window (CW) and the Transmission Opportunity (TXOP), per each queue in order to provide Quality-of-Service (QoS) differentiation. TXOP as our research target allows a station to transmit multiple frames consecutively when getting the channel without exceeding the specific TXOP limit duration. Among the three main medium access control (MAC) parameters in wireless LAN, TXOP is the most impacting one [2, 3] because TXOP can provide multiple contention-free transmissions even in high contention periods, while CW and AIFS cannot limit the collision rates. As a result, much attention has been given for designing TXOP adaptation algorithms [3–6]. Unfortunately, most of the reported work in the literature is intuitive without rigorous analysis. Hence, it is not yet clear how TXOP should be adapted in a distributed fashion to provide a target QoS, identified for instance by the throughput requirement for each queue in an IEEE 802.11e network.

In this paper, we propose an algorithm to set TXOP for given throughput requirement. The proposed solution is a distributed mechanism for TXOP adaptation with minimal control overhead. In the proposed algorithm, each node independently measures its throughput and compares it with a target value. TXOP is then adapted using the result of this comparison; that is, TXOP is increased if the measured throughput is less than the target value, and it is decreased if the measured throughput is more than the target throughput. We show that the throughput converges to the target throughput in a globally and geometrically stable manner. Our stability analysis provides a basis for optimal control of individual TXOP values of the corresponding AC queues with different throughput requirements in IEEE 802.11e-based wireless networks.

II. TXOP Solution for Throughput Requirements

We assume that there are n queues and denote the set of queues as $\mathcal{N} = \{1, 2, \dots, n\}$. We also assume that all the traffic classes use the same AIFS which is equal to distributed inter-frame space (DIFS) in order to extract TXOP effect only. Hence, the QoS in each queue can only be differentiated by CW_{min} and TXOP. Let τ_i be the probability that the i-th queue transmits during a generic timeslot. Let p_b denote the probability that the channel is busy. Then,

$$p_b = 1 - \prod_{i \in \mathcal{N}} (1 - \tau_i). \tag{1}$$

Let $p_{s,i}$ denote the probability that a successful transmission occurs in a timeslot for the i-th queue, and p_s the probability that a successful transmission occurs in a timeslot. Then, we can obtain the following [7]:

$$p_{s,i} = \tau_i \prod_{j \neq i, j \in \mathcal{N}} (1 - \tau_j) \quad \text{for } i \in \mathcal{N}, \tag{2}$$

$$p_s = \sum_{i \in \mathcal{N}} p_{s,i}. \tag{3}$$

Let S_i be the throughput of the i-th queue. Let δ, x_i, T_s and T_c denote the duration of an empty timeslot, TXOP of the i-th queue, the average time that the channel is sensed busy because of a successful transmission, and the average time that the channel has a collision, respectively. Based on the previous analysis [7, 8], we can derive the saturation throughput of the i-th queue as

$$\begin{aligned} S_i &= \frac{E[\text{payload size in a timeslot for the } i\text{-th queue}]}{E[\text{length of a timeslot}]} \\ &= \frac{p_{s,i} x_i R_i}{(1 - p_b)\delta + p_s T_s + (p_b - p_s) T_c} \end{aligned} \tag{4}$$

where R_i is the channel capacity of the i-th queue. We assume that RTS/CTS exchange is adopted. Let T_{RTS} and T_{CTS} denote the time to transmit an RTS frame and a CTS frame, respectively. Let T_H, T_{ACK}, and $SIFS$ denote the time to transmit the header (including MAC header, physical layer header, and/or trailer), an ACK, and short inter-frame spacing, respectively. Then, T_s and T_c can be expressed as

$$T_s = \sum_{i\in\mathcal{N}} \frac{p_{s,i}}{p_s} x_i + o_s \tag{5}$$

$$T_c = T_{RTS} + SIFS + T_{ACK} + DIFS \tag{6}$$

where o_s is defined as

$$o_s = T_{RTS} + 3*SIFS + T_{CTS} + T_H + T_{ACK} + DIFS. \tag{7}$$

The throughput of the i-th queue, S_i in (4) is a function of $\boldsymbol{\tau} = (\tau_1, \tau_2, \ldots, \tau_n)$ and $\boldsymbol{x} = (x_1, x_2, ..., x_n)$. The vector $\boldsymbol{\tau}$ is determined by CW_{min} of all queues and is not affected by the variation of the vector $\boldsymbol{x}$ [7]. In this paper, we assume that CW_{min} are fixed for each queue although each queue can have different CW_{min} values. Then, S_i is a function of $\boldsymbol{x}$.

Let s_i be the normalized saturation throughput, which is defined as

$$s_i = \frac{S_i}{R_i}. \tag{8}$$

Using (1) – (8), s_i can be expressed as

$$s_i(\boldsymbol{x}) = \frac{\beta_i x_i}{\sum_{j\in\mathcal{N}} \beta_j x_j + O_T} \tag{9}$$

where

$$\beta_i = \frac{\tau_i}{1-\tau_i} > 0, \tag{10}$$

$$O_T = \delta + \sum_{i\in\mathcal{N}} \beta_i (o_s - T_c) + \left(\prod_{i\in\mathcal{N}} (1+\beta_i) - 1\right) T_c > 0. \tag{11}$$

To calculate τ_i in (10), we use Wu's model [11] which is a modification of Bianchi's model [8] with the frame retry limit.

Our objective is to find the TXOP values, $\boldsymbol{x}$, in a distributed manner such that

$$s_i(\boldsymbol{x}) = s_i^* \quad \text{for } i \in \mathcal{N}, \tag{12}$$

where s_i^* is the target normalized throughput of the i-th queue. Note that (12) builds a set of n linear equations in variables $\boldsymbol{x}$ as follows:

$$\beta_i(1-s_i^*)x_i - \sum_{j\neq i, j\in\mathcal{N}} (\beta_j s_i^*) x_j = s_i^* O_T \quad \text{for } i \in \mathcal{N}. \tag{13}$$

Proposition 1: If the following condition holds:

$$\sum_{i\in\mathcal{N}} s_i^* < 1, \tag{14}$$

then the solution for the problem (12), $\boldsymbol{x}^* = (x_1^*, x_2^*, ...x_n^*)$, exists uniquely as

$$x_i^* = \frac{O_T}{\beta_i} \frac{s_i^*}{1 - \sum_{j\in\mathcal{N}} s_j^*} \quad \text{for } i \in \mathcal{N}. \tag{15}$$

The condition (14) creates a stable system. This is indeed the feasibility condition. That is, the target throughputs should be achievable and hence should create a feasible system. We will discuss shortly that if the system is not feasible then, the nodes extend their TXOP to the maximum value and still cannot achieve the target throughput. This is of course an anomaly where no any other distributed scheduler can satisfy the target throughputs.

III. TXOP Adaptation and Stability Analysis

If there is a centralized coordinator, the TXOP values can be selected as in (15). However, the users may not know other users' parameters including throughput requirements. We propose a TXOP adaptation algorithm with which the solution (15) can be reached in a distributed manner.

We define two sets, $\mathcal{A}(t)$ and $\mathcal{B}(t)$ for time $t \geq 0$:

$$\mathcal{A}(t) = \{i | s_i(t) \geq s_i^*,\ i \in \mathcal{N}\}, \tag{16}$$

$$\mathcal{B}(t) = \{i | s_i(t) < s_i^*,\ i \in \mathcal{N}\}. \tag{17}$$

Assume that each queue independently measures its throughput and selects its TXOP using the following control system for $t \geq 0$:

$$\frac{d}{dt} x_i(t) = \begin{cases} -x_i(t) & \text{if } i \in \mathcal{A}(t), \\ x_i(t) & \text{if } i \in \mathcal{B}(t). \end{cases} \tag{18}$$

Therefore, we can conclude that if a node has the measured throughput larger than the target throughput, it decreases its TXOP, and if it has a throughput smaller than the target value, it increases its TXOP. Since the variation of TXOP is directly related to the throughput, we speculate that (18) adjusts the throughput so that it gets closer to the target throughput. We prove this claim by showing that if $i \in \mathcal{A}(t)$, then $\frac{ds_i(t)}{dt} < 0$ and if $i \in \mathcal{B}(t)$, then $\frac{ds_i(t)}{dt} > 0$.

From (9), the partial derivatives for $\boldsymbol{s}(x)$ are given for $i, j \in \mathcal{N}$, as

$$\frac{\partial s_i}{\partial x_j} = \begin{cases} (s_i - s_i^2)/x_i & \text{if } i = j, \\ -s_i s_j / x_j & \text{if } i \neq j. \end{cases} \tag{19}$$

If $i \in \mathcal{A}(t)$,

$$\begin{aligned} \frac{ds_i}{dt} &= \sum_{j\in\mathcal{N}} \frac{\partial s_i}{\partial x_j} \frac{dx_j}{dt} \\ &= \frac{s_i - s_i^2}{x_i}(-x_i) + \sum_{j\in\mathcal{A}(t), j\neq i} \left(-\frac{s_i s_j}{x_j}\right)(-x_j) \\ &\quad + \sum_{j\in\mathcal{B}(t)} \left(-\frac{s_i s_j}{x_j}\right) x_j \\ &= -s_i \left(1 - \sum_{j\in\mathcal{A}} s_j + \sum_{j\in\mathcal{B}} s_j\right) \\ &= -s_i \left(\frac{2\sum_{j\in\mathcal{B}(t)} \beta_j x_j(t) + O_T}{\sum_{j\in\mathcal{N}} \beta_j x_j(t) + O_T}\right) < 0. \end{aligned} \tag{20}$$

On the other hand, if $i \in \mathcal{B}(t)$,

$$\frac{ds_i}{dt} = s_i \left(\frac{2\sum_{j\in\mathcal{A}(t)} \beta_j x_j(t) + O_T}{\sum_{j\in\mathcal{N}} \beta_j x_j(t) + O_T}\right) > 0. \tag{21}$$

Now, we investigate whether we can reach the point $\boldsymbol{s}^* = (s_1^*, s_2^*, \dots, s_n^*)$ with the dynamics (18). The global stability of the algorithm can be studied by the application of the Lyapunov function. Let us introduce the following Lyapunov function:

$$V(\boldsymbol{s}) = \frac{1}{n}\sum_{i\in\mathcal{N}}\left(\frac{s_i}{s_i^*} - 1\right)^2. \tag{22}$$

Note that $V(\boldsymbol{s}^*) = 0$, and $V(\boldsymbol{s}) > 0$ if $\boldsymbol{s} \neq \boldsymbol{s}^*$. On the other hand, from (20) and (21),

$$\frac{dV}{dt} = \frac{2}{n}\sum_{i\in\mathcal{N}}\frac{1}{s_i^*}\left(\frac{s_i}{s_i^*} - 1\right)\frac{ds_i}{dt} < 0. \tag{23}$$

Therefore, the solution $\boldsymbol{s} = \boldsymbol{s}^*$ is globally asymptotically stable [9], which implies that

$$\lim_{t\to\infty}\boldsymbol{s}(t) = \boldsymbol{s}^*. \tag{24}$$

Therefore,

$$\lim_{t\to\infty} x_i(t) = \lim_{t\to\infty}\frac{O_T}{\beta_i}\frac{s_i(t)}{1 - \sum_{j\in\mathcal{N}} s_j(t)} = x_i^* \quad \text{for } i\in\mathcal{N}, \tag{25}$$

and the solution $\boldsymbol{x} = \boldsymbol{x}^*$ is globally asymptotically stable.

A. Practical Considerations

In practice, we should measure the throughput in each measurement interval. Let $s_i(k)$ be the estimated normalized throughput of user i in $[kT, (k+1)T)$, $i \in \mathcal{N}$, $k = 0, 1, 2, \dots$. Let $x_i(k)$ be TXOP of user i during $[kT, (k+1)T)$. We define two sets, $\mathcal{A}(k)$ and $\mathcal{B}(k)$ as follows:

$$\mathcal{A}(k) = \{i | s_i(k) \geq s_i^*,\ i\in\mathcal{N}\}, \tag{26}$$

$$\mathcal{B}(k) = \{i | s_i(k) < s_i^*,\ i\in\mathcal{N}\}. \tag{27}$$

We consider the following discrete-time nonlinear dynamical system for $k = 0, 1, 2, \dots$

$$x_i(k+1) = \begin{cases} (1-\eta_k)x_i(k) & \text{if } i\in\mathcal{A}(k) \\ (1+\eta_k)x_i(k) & \text{if } i\in\mathcal{B}(k), \end{cases} \tag{28}$$

which is the discrete-time version of (18). Then, we can reach $\boldsymbol{x}^*$ using the dynamics (28) if the following conditions hold [10]:

$$\sum_{k=1}^{\infty}\eta_k = \infty \quad \text{and} \quad \lim_{k\to\infty}\eta_k = 0. \tag{29}$$

In a distributed control environment, it is difficult to adapt a variable step size η_k. Thus, we assume that $\eta_k, k = 1, 2, ...$ are fixed at η, which is a small positive constant.

Now, we investigate the convergence speed. Let $y_i(k) = \beta_i x_i(k),\ i\in\mathcal{N},\ k = 0, 1, 2, \dots$. Suppose that $i \in \mathcal{A}(k)$. Then,

$$\begin{aligned} s_i(k+1) &= \frac{y_i(k+1)}{\sum_{j\in\mathcal{N}} y_j(k+1) + O_T} \\ &= \frac{y_i(k)(1-\eta)}{\sum_{j\in\mathcal{A}(k)} y_j(k)(1-\eta) + \sum_{j\in\mathcal{B}(k)} y_j(k)(1+\eta) + O_T} \\ &= \frac{y_i(k)}{\sum_{j\in\mathcal{N}} y_j(k) + O_T} \\ &\quad \left[\frac{1-\eta}{1 + \left(\frac{\sum_{j\in\mathcal{B}(k)} y_j(k)}{\sum_{j\in\mathcal{N}} y_j(k) + O_T} - \frac{\sum_{j\in\mathcal{A}(k)} y_j(k)}{\sum_{j\in\mathcal{N}} y_j(k) + O_T}\right)\eta}\right]. \end{aligned} \tag{30}$$

Therefore, the Taylor series for $s_i(k+1)$ at $\eta = 0$ can be expressed for $i \in \mathcal{A}(k)$ as

$$s_i(k+1) = s_i(k)\left(1 - \frac{2\sum_{j\in B(k)} y_j(k) + O_T}{\sum_{j\in\mathcal{N}} y_j(k) + O_T}\eta + \mathcal{O}(\eta^2)\right), \tag{31}$$

where $\lim_{\eta\to 0}\mathcal{O}(\eta^2)/\eta^2$ is a constant. On the other hand, if $i \in \mathcal{B}(k)$,

$$s_i(k+1) = s_i(k)\left(1 + \frac{2\sum_{j\in A(k)} y_j(k) + O_T}{\sum_{j\in\mathcal{N}} y_j(k) + O_T}\eta + \mathcal{O}(\eta^2)\right). \tag{32}$$

We adopt the Lyapunov function in (22) as follows:

$$V(k+1) = \frac{1}{n}\sum_{i\in\mathcal{N}}\left(\frac{s_i(k+1)}{s_i^*} - 1\right)^2. \tag{33}$$

Applying (31) and (32) in (33), gives

$$\begin{aligned} V(k+1) &= \sum_{i\in\mathcal{N}}\frac{1}{n}\left(\frac{s_i(k)}{s_i^*} - 1\right)^2 \\ &- \sum_{i\in\mathcal{A}(k)}\frac{2\eta}{n}\frac{s_i(k)}{s_i^*}\left|\frac{s_i(k)}{s_i^*} - 1\right|\left(\frac{2\sum_{j\in\mathcal{B}(k)} y_j(k) + O_T}{\sum_{j\in\mathcal{N}} y_j(k) + O_T}\right) \\ &- \sum_{i\in\mathcal{B}(k)}\frac{2\eta}{n}\frac{s_i(k)}{s_i^*}\left|\frac{s_i(k)}{s_i^*} - 1\right|\left(\frac{2\sum_{j\in\mathcal{A}(k)} y_j(k) + O_T}{\sum_{j\in\mathcal{N}} y_j(k) + O_T}\right) + \mathcal{O}(\eta^2) \\ &\leq \sum_{i\in\mathcal{N}}\frac{1}{n}\left(\frac{s_i(k)}{s_i^*} - 1\right)^2 \\ &\quad - \sum_{i\in\mathcal{N}}\frac{2\eta}{n}\frac{s_i(k)}{s_i^*}\left|\frac{s_i(k)}{s_i^*} - 1\right|\left(\frac{O_T}{\sum_{j\in\mathcal{N}} y_j(k) + O_T}\right) + \mathcal{O}(\eta^2) \\ &\leq \sum_{i\in\mathcal{N}}\frac{1}{n}\left(\frac{s_i(k)}{s_i^*} - 1\right)^2\left(1 - 2\eta\frac{O_T}{\sum_{j\in\mathcal{N}} y_j(k) + O_T}\right) + \mathcal{O}(\eta^2) \\ &= V(k)\left(1 - 2\eta\frac{O_T}{\sum_{j\in\mathcal{N}} y_j(k) + O_T} + \mathcal{O}(\eta^2)\right). \end{aligned} \tag{34}$$

Suppose that TXOP is bounded as

$$x_i(k) \leq x_{i,max}, \quad \text{for } i\in\mathcal{N},\ k = 0, 1, 2, ... \tag{35}$$

If η is sufficiently small, we can ignore $\mathcal{O}(\eta^2)$ in (34). Then,

$$V(k+1) \leq \rho V(k) \tag{36}$$

where

$$\rho = 1 - 2\eta \frac{O_T}{\sum_{j\in\mathcal{N}} \beta_j x_{j,max} + O_T}. \tag{37}$$

Moreover,

$$\alpha_{min}\|\boldsymbol{s} - \boldsymbol{s}^*\|^2 \le V(\boldsymbol{s}) \le \alpha_{max}\|\boldsymbol{s} - \boldsymbol{s}^*\|^2 \tag{38}$$

where

$$\alpha_{min} = \frac{1}{n(\max_{i\in\mathcal{N}} s_i^*)^2}, \quad \alpha_{max} = \frac{1}{n(\min_{i\in\mathcal{N}} s_i^*)^2}. \tag{39}$$

Since $\rho < 1$, the system is globally geometrically stable at $\boldsymbol{s} = \boldsymbol{s}^*$ [9]. If ρ approaches 0, the convergence speed is high. On the other hand, if ρ is close to 1, the system converges to the solution slowly. From (36) and (37), the convergence speed is affected by the parameter η. As η increases, ρ decreases and the optimal solution can be reached faster.

We define the overall normalized throughput as $s = \sum_{i\in\mathcal{N}} s_i$. Then, from (9) and (19), for $i \in \mathcal{N}$,

$$\frac{\partial s}{\partial x_i} = \sum_{j\in\mathcal{N}} \frac{\partial s_j}{\partial x_i} = \frac{s_i}{x_i}(1 - \sum_{j\in\mathcal{N}} s_j) = \frac{s_i}{x_i}\frac{O_T}{\sum_{j\in\mathcal{N}} \beta_j x_j + O_T} > 0. \tag{40}$$

Therefore, the maximum throughput can be achieved when all users set TXOP to the maximum value, that is, $x_i = x_{i,max}, i \in \mathcal{N}$. Now suppose that the sum of all throughput requirements is greater than the system capacity. Then, unsatisfied users will increase TXOP to the maximum value. If all users set TXOP value to the maximum value, then the throughput requirements cannot be enhanced and guaranteed. This is an unfeasible case in which the target throughputs are so high that they cannot be achieved even with the TXOP set at the maximum.

IV. Numerical Results

In this section, we present simulation results to validate our algorithm. We consider four flows established over four pairs of source-destination nodes. We assume that each node has one active queue and the buffer size is infinite. The channel capacity is 11 $Mbps$. The RTS/CTS signalling is applied. First, we evaluate TXOP settings for throughput requirements in IEEE 802.11e WLAN with system parameters shown in Table I. The target throughput for flows is given by the vector $(2.4, 1.8, 1.2, 0.6)$ $Mbps$. Since the channel capacity is $R_i = 11Mbps$, $i = 1, 2, 3, 4$, the required normalized saturation throughput is $\boldsymbol{s}^* = (0.22, 0.16, 0.11, 0.05)$. From (15), the analytical value of TXOP is $\boldsymbol{x}^* = (2.71, 2.03, 1.35, 0.68)msec$.

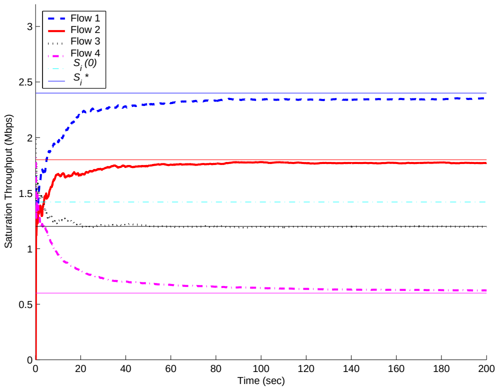
Next, we investigate the proposed distributed algorithm in (28). The length of measurement interval is set to T = 100 $msec$. We measure the throughput of each flow i as $S_i(k)$ in $[kT,(k+1)T)$. By using $S_i(k)$ and $x_i(k)$ in $[kT,(k+1)T)$, we adapt the payload size of TXOP for each flow i, $x_i(k+1)$, at each interval of length T according to (28). Fig. 1 (a) shows the saturation throughput variation of each flow with η = 0.01. If T is sufficiently large, the measurement error becomes small. In Fig. 1 (a), the saturation throughput of flow i at time t is depicted using the average throughput during $[0, t)$, $\bar{S}_i(k) = \sum_{j=1}^{k} S_i(j)/k$. The initial payload size of each flow $x_i(0)$ is 1.504 $msec$ (= 2068 $bytes$) [1] [1]. Then, the initial saturation throughput of each flow $S_i(0)$ is calculated as 1.4194 $Mbps$ according to (4)–(7). Since there exists the measurement error including the randomness of the backoff window of flow i, measured throughput of flow i at $k = 0$, $\bar{S}_i(0)$ in Fig. 1 (a), may be different from 1.4194 $Mbps$. We observe that the measured throughput of each flow i, $\bar{S}_i(k)$ converges to the required throughput of each flow i, S_i^* as time increases. Fig. 1 (b) shows the payload size of TXOP for each flow with η = 0.01. The target TXOP is $\boldsymbol{x}^* = (2.71, 2.03, 1.35, 0.68)msec$. We observe that the size of TXOP for each flow i, $x_i(k)$ fluctuates about the target size of TXOP for each flow i, x_i^*, as time increases.

TABLE I
System Parameters

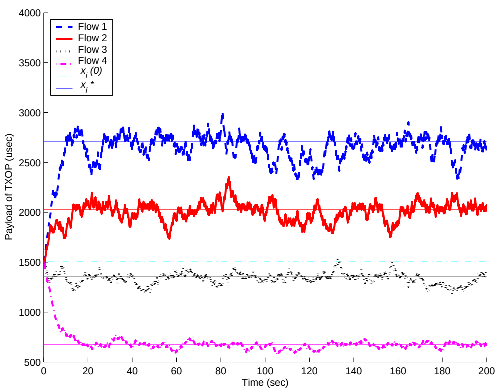
Common Parameters	Values
Payload (M_P)	2068 $bytes$ (initial value)
MAC header (M_H)	272 $bits$
PHY header length (T_P)	192 μs
Data Rate (R_D)	11 $Mbps$
Control Rate (R_C)	1 $Mbps$
DATA length	$(M_P + M_H)/R_D$ + T_P
RTS length	160 $bits/R_C$ + T_P
CTS length	112 $bits/R_C$ + T_P
ACK length	112 $bits/R_C$ + T_P
CW_{min}	32
CW_{max}	1024
Retry Limit	7
Propagation Delay	1 μs
SIFS	10 μs
Slot Time	20 μs
DIFS	50 μs

Now we examine the convergence speed according to the control parameter η. As a convergence criterion, we use the Lyapunov function $V(k)$ defined in (33). In Fig. 2 (a), $V(k)$ decreases as k increases, which implies that the measured throughput approaches the target throughput. As noticed in the figure, $V(k)$ decreases fast with time as η increases, that is, the convergence speed for each flow increases as η increases. However, $V(k)$ does not approach zero although time increases. This is because η is a fixed parameter independent of k. We define the convergence time as kT such that $V(k) = 0.01$. If the throughput of every flow i, $\bar{S}_i(k)$ is $0.9S_i^* \le \bar{S}_i(k) \le 1.1S_i^*$, then $V(k) \le 0.01$. Note that ρ defined in (37) is the upperbound of decreasing ratio of $V(k)$. Accordingly, we define the cutoff time as kT such that $\rho^k = 1/2$. Fig. 2 (b) shows the convergence time and the cutoff time for the saturation throughput with varying η. We observe that as η increases, the convergence time and cutoff time for saturation throughput are reduced.

[1] In the IEEE 802.11e standard [1], the default value of TXOP limit for AC_VO is set to 3.264 ms or 1.504 ms according to different physical layers. For AC_VI, the default value of TXOP limit is set to 6.016 ms or 3.008 ms according to different physical layers.

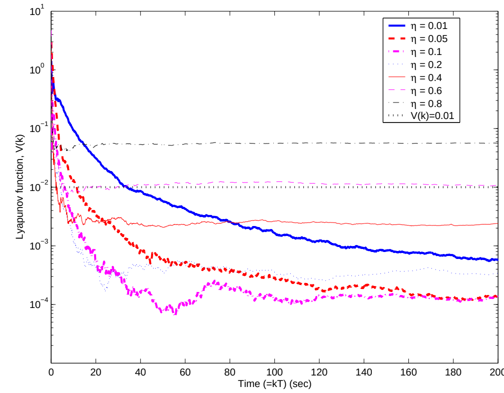


(a) Saturation throughput for each flow.

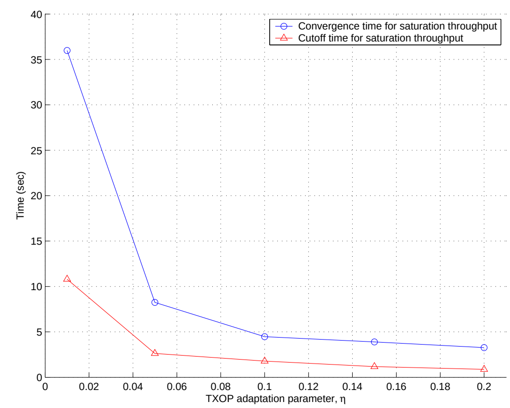


(b) Payload size of TXOP for each flow.

Fig. 1. Throughput and TXOP for each flow with η = 0.01.



(a) Lyapunov function for saturation throughput with varying η.



(b) Convergence time and cutoff time for saturation throughput

Fig. 2. Lyapunov function and convergence time for saturation throughput.

V. Conclusion

This paper derives a closed-form solution of TXOP settings and proposes a distributed TXOP adaptation algorithm to satisfy target throughputs for IEEE 802.11e users in a distributed manner. Each node measures its throughput in a window and compares it with the target throughput. If the measured throughput is higher than the target value, the node reduces its TXOP; otherwise if the measured value is lower than the target throughput, the node increases its TXOP. We show that if the optimal solution of setting a TXOP for throughput requirements exists, then the target throughputs can be reached in a globally and geometrically stable manner.

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