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APPLE: Providing Absolute and Proportional Throughput Guarantees in Wireless LANs

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Abstract—This paper proposes an APPLE scheme that aims at providing absolute and proportional throughput guarantees, and maximizing system throughput simultaneously for wireless LANs with homogeneous and heterogenous traffic. We formulate our objectives as an optimization problem, present its exact and approximate solutions, and prove the existence and uniqueness of the approximate solution. Simulations validate that APPLE scheme is accurate, and the approximate solution can well achieve the desired objectives already.

Keywords—IEEE 802.11e, throughput guarantee, priority.

I. Introduction

IEEE 802.11e EDCA [1] can provide differentiated services when a variety of applications coexist. However, it is more desirable to provide different levels of guaranteed services simultaneously for many multimedia applications.

In our APPLE scheme, we consider an EDCA network with one high-priority (HP) class and one low-priority (LP) class. By setting different contention windows (CWs), APPLE aims at achieving three objectives simultaneously: providing an absolute (or a fixed) throughput guarantee for HP nodes, and a proportional throughput guarantee for LP nodes (where all LP nodes share the available bandwidth according to the desired ratios), and maximizing the system throughput. We present the exact and approximate solutions to the optimal CWs, and prove the existence and uniqueness of the approximate solution. Our experiment verifies that the approximate solution can well achieve the desired objectives already.

A distinct difference between our APPLE scheme and the related schemes is that we can achieve the above three objectives simultaneously in the general network (i.e. each node may have an arbitrary packet size), while the others just provide one or two of them under the assumption that all nodes have the same packet size. For example, the scheme in [2] just provided absolute throughput guarantee, not considering proportional throughput guarantee. The scheme in [3] only provided a weighted bandwidth allocation, not considering the absolute throughput guarantee. The scheme in [4] focused on supporting absolute and proportional priorities, rather than absolute and proportional throughput guarantees. Supporting absolute priority means that absolute-priority nodes will always benefit from all available throughput even if some non-absolute-priority nodes exist already, consequently lowering the bandwidth utilization because they may acquire more bandwidth than the required one. In contrast, supporting absolute throughput guarantee in APPLE scheme means that HP nodes are guaranteed to acquire the bandwidth for providing the required throughput only, rather than occupy more bandwidth. Another significant difference is that most of the related papers did not discuss the existence and uniqueness of the solutions.

The rest of this paper is organized as follows. Section II introduces model assumptions and the problem formulation. Section III specifies the optimal attempt rate. Section IV verifies the accuracy of our model. Finally, Section V concludes this paper.

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II. Model Assumptions and Problem Formulation

In APPLE scheme, we consider a one-hop wireless LAN with two classes: HP class and LP class. The HP (LP) class has n (m) nodes and therefore the total node number is $N = n + m$. Each node i, $1 \leq i \leq N$, always generates a random backoff count uniformly distributed in $[0, CW_i]$ for each new transmission or retransmission, where $CW_i > 1$. All nodes send data to the AP (access point), while the AP only acts as a receiver. We assume that 1) all nodes can hear each other and run in the basic mode; 2) ideal channel conditions (i.e., the transmission errors are a result of packet collision only); and 3) all nodes are in saturated operation (i.e., each node always has packets to transmit) and have arbitrary packet size.

We now formulate our problem. Let $\beta \triangleq (\beta_1, \beta_2, ..., \beta_N)$, where β_i represents the attempt rate of node i per slot (namely, the mean number that node i attempts to transmit a packet in a slot). In saturated operation, β_i is calculated by CW_i as [5],

$$\beta_i = \frac{2}{CW_i + 1}. \tag{1}$$

Then, finding the optimal $(CW_1, CW_2, ..., CW_N)$ boils down to finding the optimal β.

Let $\Gamma_i \triangleq \Gamma_i(\beta)$, $1 \leq i \leq N$, be the throughput of node i. Let a_i, $1 \leq i \leq n$, represent the fixed throughput required by each HP node i. Let r_i, $1 \leq i \leq m$, represent the proportional throughput ratio between LP nodes $n + i$ and $n + 1$. In the considered wireless LAN, APPLE desires to find the optimal β, so as to guarantee each HP node's fixed throughput requirement a_i, each LP node's proportional throughput requirement r_i, and at the same time maximize the system throughput $\Sigma_{i=1}^{N}\Gamma_i$. That is,

$$\text{the optimal } \beta = \arg\max_{\beta} \sum\nolimits_{i=1}^{N} \Gamma_i \tag{2}$$

$$\text{over } \Gamma_i = a_i, 1 \le i \le n, \quad (3)$$

$$\frac{\Gamma_{n+i}}{\Gamma_{n+1}} = r_i, 1 \le i \le m. \quad (4)$$

In the next section, we will express the throughput Γ_i and find the optimal β.

III. The Optimal Attempt Rate

This section first expresses the per-node throughput Γ_i, and then calculates the exact and approximate solutions to the optimal β.

A. Per-node Throughput

Denote P_e as the probability that a slot is idle. We have

$$P_e = \Pi_{i=1}^{N}(1-\beta_i). \quad (5)$$

Let Ω be the mean time that elapses for one decrement of the back-off counter. Note that the back-off counter decreases by one for each idle slot and is suspended when the channel is busy. For the general network with arbitrary packet size, the successful transmission time of each node depends on it's packet size only. If multiple nodes are in collision, however, the collision time should be calculated based on the larger or the largest packet size. Assume that the packet size of each node is L_i, $L_1 \le L_2 \le ... \le L_N$, then Ω can be expressed by

$$\Omega = \begin{cases} \sigma, & P_e \\ T_o^i, & \beta_i \prod_{j=i+1}^{N}(1-\beta_j),\ 1 \le i \le N-1, \\ T_o^N, & \beta_N \end{cases} \quad (6)$$

where σ is the duration of one time slot; $T_o^i \gg \sigma$ is the time that the channel is occupied by node i, and T_o^i is given in Table I. So the mean value of Ω is

$$\overline{\Omega} = \sigma\Pi_{i=1}^{N}(1-\beta_i) + \sum_{i=1}^{N-1} T_o^i \beta_i \prod_{j=i+1}^{N}(1-\beta_j) + T_o^N \beta_N. \quad (7)$$

The throughput of node i, Γ_i, $1 \le i \le N$, is defined as the number of bits that node i successfully transmits in a time duration of $\overline{\Omega}$. We have

$$\Gamma_i = \frac{L_i P_s^i}{\overline{\Omega}}, \quad (8)$$

where P_s^i is the successful transmission probability of node $i, 1 \le i \le N$, where

$$P_s^i = \beta_i \Pi_{j \ne i}^{N}(1-\beta_j) \quad (9)$$

B. Exact Solution to the Optimal β

The exact solution to the optimal β can be found in the following five steps.

Step 1: Express $\beta_{n+i}, 1 \le i \le m$, in terms of β_{n+1}. From (4), (9) and (8), we have

$$r_i = \frac{\Gamma_{n+i}}{\Gamma_{n+1}} = \frac{\beta_{n+i}(1-\beta_{n+1})L_{n+i}}{\beta_{n+1}(1-\beta_{n+i})L_{n+1}}. \quad (10)$$

Then β_{n+i} can be expressed in terms of β_{n+1}, namely

$$\beta_{n+i} = \frac{r_i \beta_{n+1} L_{n+1}}{(1-\beta_{n+1})L_{n+i} + r_i \beta_{n+1} L_{n+1}}, 1 \le i \le m. \quad (11)$$

Step 2: Express $\beta_i, 1 \le i \le n$, in terms of β_1. Note $\frac{\Gamma_i}{\Gamma_1} = \frac{a_i}{a_1}$ and regard $\frac{a_i}{a_1}$ as the throughput ratio between nodes i and 1. From (11), we have

$$\beta_i = \frac{\frac{a_i}{a_1}\beta_1 L_1}{(1-\beta_1)L_i + \frac{a_i}{a_1}\beta_1 L_1}, 1 \le i \le n. \quad (12)$$

Step 3: Setup a relationship between β_{n+1} and β_1. After substituting (9), (5) and (7) into (8), we rewrite $\Gamma_1 = a_1$ as

$$a_1 = \frac{L_1\beta_1\Pi_{i=2}^{n}(1-\beta_i)\Pi_{i=1}^{m}(1-\beta_{n+i})}{\sigma\Pi_{i=1}^{N}(1-\beta_i) + \sum_{i=1}^{N-1} T_o^i \beta_i \prod_{j=i+1}^{N}(1-\beta_j) + T_o^N \beta_N}. \quad (13)$$

Further, substituting (11) and (12) into (13), we obtain an implicit relationship between β_{n+1} and β_1.

Step 4: Express $\Sigma_{i=1}^{N}\Gamma_i$ in terms of β_{n+1} and β_1. With (3) and (4), the system throughput $\Sigma_{i=1}^{N}\Gamma_i$ is written as

$$\Sigma_{i=1}^{N}\Gamma_i = \Sigma_{i=1}^{n} a_i + \Gamma_{n+1}\Sigma_{i=1}^{m} r_i \quad (14)$$

$$= \Sigma_{i=1}^{n} a_i + \frac{\beta_{n+1}(1-\beta_1)L_{n+1}}{\beta_1(1-\beta_{n+1})L_1} a_1 \Sigma_{i=1}^{m} r_i, \quad (15)$$

where from (14) to (15), we use the expression of $\frac{\Gamma_{n+1}}{\Gamma_1}$, which can be obtained according to (9) and (8).

Step 5: Find the optimal β. We first search all pairs of β_{n+1} and β_1 that satisfy (13), then choose their optimal values maximizing (15), and finally calculate other β_is by (11) and (12).

In general, it is not easy to know whether the exact solution exits and is unique. We therefore seek the approximate solution in the next subsection and prove that the solution is uniquely exist.

C. Approximate Solution to the Optimal β

In this section, we first specify the method to calculate the approximate solution to the optimal β, and then we prove the existence and uniqueness of the approximate solution.

1) Calculation of the Optimal β: In order to find the approximate solution to the optimal β, we first adopt a key approximation, $\beta_i \ll 1$, which is widely used in the related literatures such as [4]. The approximation holds true since β_i represents the per-node attempt rate in a very short slot and therefore it is generally much small. And then, we repeat and modify five calculation steps in Section III-B as:

Step 1: Express $\beta_{n+i}, 1 \le i \le m$, in terms of β_{n+1}. Based on the approximation, $\beta_i \ll 1$, (10) reduces to $r_i = \frac{\beta_{n+i}L_{n+i}}{\beta_{n+1}L_{n+1}}$, so we have

$$\beta_{n+i} = \frac{r_i \beta_{n+1} L_{n+1}}{L_{n+i}}, 1 \le i \le m. \quad (16)$$

Step 2: Express $\beta_i, 1 \le i \le n$, in terms of β_1. According to (16), (12) reduces to

$$\beta_i = \frac{a_i \beta_1 L_1}{a_1 L_i}, 1 \le i \le n. \quad (17)$$

TABLE I
PARAMETERS FOR 802.11 B

m/M	5/7	Header	228 µs	= Mheader + Pheader
σ	20 µs	T_o		= Header + L_{tm} + SIFS + ACK + DIFS
SIFS	10 µs	L_{tm}		= L_i bytes @ R_{data}
DIFS	50 µs	ACK	304 µs	= 24 bytes @ R_{basic} + 14 bytes @ R_{basic}
R_{data}	11 Mbps	Mheader	20 µs	= 24 bytes @ R_{data} + 4 bytes @ R_{data}
R_{basic}	1 Mbps	Pheader	208 µs	= 26 bytes @ R_{basic}

Step 3: Setup a relationship between β_{n+1} and β_1. We can obtain the relationship between β_{n+1} and β_1 by substituting (16) and (17) into (13).

Step 4: Express $\Sigma_{i=1}^{N}\Gamma_i$ in terms of β_{n+1} and β_1. From the derivation of (14) and (15), (15) can be re-written as

$$\Sigma_{i=1}^{N}\Gamma_i = \Sigma_{i=1}^{n} a_i + \frac{\beta_{n+1}L_{n+1}}{\beta_1 L_1} a_1 \Sigma_{i=1}^{m} r_i. \qquad (18)$$

Step 5: Find the optimal β as like in Section III-B.

2) The Existence and Uniqueness of the Approximate Solution: In the following, we only consider a simple case of $n = 1$ and $m \geq 1$, and prove that the approximate solution is uniquely exist. From the case of $n = 1$ and $m \geq 1$, we have an insight into the existence and uniqueness of the general case of $n > 1$ and $m \geq 1$.

With the approximation $\beta_i \ll 1$, we can calculate the per-node attempt rate β_i by

$$\beta_i = \begin{cases} \dfrac{\sigma + \beta_2 L_2 \sum\limits_{i=1}^{N-1} \omega_i e^{\lambda}}{\varphi}, & i = 1 \\ \dfrac{r_{i-1}\beta_2 L_2}{L_i}, & i = 2, ..., N \end{cases}, \qquad (19)$$

where $\varphi = \frac{L_1}{a_1} + \sigma - T_o^1$, $\omega_i = \frac{r_i T_o^{i+1}}{L_{i+1}}$, and $\lambda = \beta_2 L_2 \sum\limits_{j=1}^{i} \frac{r_j}{L_{j+1}}$ are constants when the total node number N, the packet size L_j and the throughput ratio r_j are given; β_2 is the unique solution to the function $h(\beta_2) = 0$, where $h(\beta_2) = \sigma - \beta_2 L_2 \sum\limits_{i=1}^{N-1} \omega_i \lambda e^{\lambda}$.

Proof: Please refer to the Appendix.

IV. MODEL VERIFICATION

In this section, we demonstrate the efficiency of our proposed APPLE scheme for wireless LANs. We use the 802.11e EDCA simulator [6] in NS2 version 2.28 [7] as a validation tool. In simulation, we differentiate CW parameter only, so we set $AIFS = DIFS$, $TXOP = 0$, and $CW_{\min} = CW_{\max} = CW_i$ for node i. The other protocol parameter values are listed in Table I and are set by IEEE 802.11b. Each simulation run lasts 200 seconds.

In our experiment, the HP class has $n = 2$ nodes with the fixed throughput requirements: $a_1 = 0.5$ Mbps and $a_2 = 1$ Mbps. The LP class has m nodes with the proportional throughput ratios: $r_i = 1$, $(1 \leq i \leq \frac{m}{2})$ and $r_i = 2, (\frac{m}{2} + 1 \leq i \leq m)$, where $m = 4, 6, ..., 20$. We set the packet size of two HP nodes to $L_1 = L_2 = 500$ bytes, and set the packet size of all LP nodes to $L_3 = ... = L_N = 1500$ bytes. We set $CW_i = \frac{2}{\beta_i} - 1$ by (1) in simulation, where the exact and

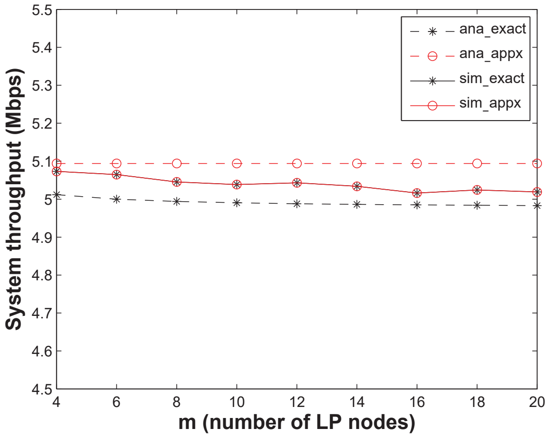

Fig. 1 System throughput vs. the number of LP nodes, where $n = 2$ and $m = 4, 6, 8, ..., 20$

approximate solutions to β_i can be calculated in Section III-B and III-C, respectively. Table II shows the obtained values of CW_is and the theoretical system throughput.

We now explain that the derived CW_is can maximize the system throughput (as shown in Fig. 1), guarantee the fixed throughput requirement of HP nodes (as shown in Fig. 2), and guarantee the proportional throughput ratios of LP nodes (as shown in Fig. 3). In Figs. 1-3, the labels "ana_exact" and "ana_appx" denote the theoretical exact throughput and approximate throughput, respectively; the labels "sim_exact" and "sim_appx" denote the simulation results based on the exact and approximate solutions, respectively.

Fig. 1 plots the system throughput vs. the number of LP nodes. From Fig. 1, we can see that 1) the sim_exact and sim_appx simulation curves closely match the ana_exact theoretical curve which plots the maximum system throughput limit, and 2) the ana_appx theoretical curve matches the ana_exact theoretical curve well with the nodes number increasing. This manifests that the proposed APPLE scheme can maximize the system throughput. In addition, the simulation shows that the maximum system throughput is a quasi constant regardless of how the node number varies.

Fig. 2 plots the per-node throughput of HP class vs. the number of LP nodes. There are 2 nodes in HP class. The fixed throughput requirements of nodes 1 and 2 are $a_1 = 0.5$ Mbps and $a_2 = 1$ Mbps, respectively. From Fig. 2, we can see that 1) the sim_appx simulation curves closely match the corresponding sim_exact simulation curves, respectively, and 2) each simulation value is almost equal to the corresponding target value, which is either $a_1 = 0.5$ Mbps or $a_2 = 1$ Mbps. This manifests that the proposed APPLE scheme can guarantee the fixed throughput requirements of HP class.

Fig. 3 plots the per-node throughput of LP class vs. the number of LP nodes. There are m nodes in LP class, where m varies from 4 to 20. The required throughput ratio between the first and later $\frac{m}{2}$ nodes is 1:2. From Fig. 3, we can see that 1) the sim_appx simulation curves almost overlap with the corresponding sim_exact simulation curves, respectively, and 2) with the number of LP nodes increasing, the simulated throughput ratio between the first and later $\frac{m}{2}$ nodes is still

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TABLE II
EXACT AND APPROXIMATE SOLUTIONS TO CW_kS AND SYSTEM THROUGHPUT

m (n=2)	Exact solution					Appxoximate solution				
	CW_1	CW_2	CW_i (i=3,...2+m/2)	CW_i (i=3+m/2,...2+m)	system throughput [unit: Mbps]	CW_1	CW_2	CW_i (i=3,...2+m/2)	CW_i (i=3+m/2,...2+m)	system throughput [unit: Mbps]
4	61	31	155	78	5.0120	56	28	142	70	5.0940
6	62	32	238	120	5.0000	56	28	213	106	5.0940
8	63	32	319	160	4.9939	56	28	284	142	5.0940
10	63	32	400	201	4.9903	56	28	356	177	5.0940
12	63	32	482	242	4.9879	56	28	427	213	5.0940
14	63	32	563	282	4.9861	56	28	499	249	5.0940
16	63	32	645	323	4.9849	56	28	570	284	5.0940
18	63	32	726	364	4.9839	56	28	641	320	5.0940
20	63	32	808	405	4.9831	56	28	713	356	5.0940

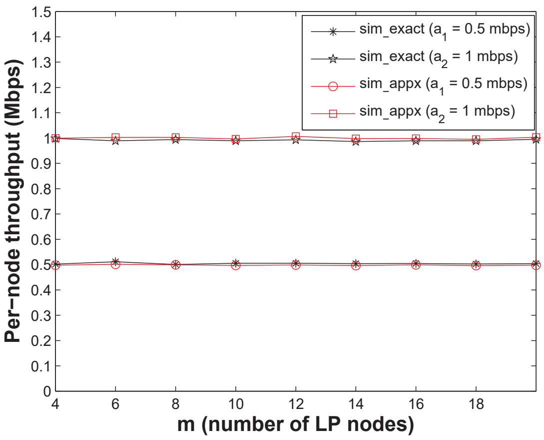

Fig. 2 Per-node throughput for HP class vs. the number of LP nodes, where the HP class has $n = 2$ nodes with the fixed throughput requirements: $a_1 = 0.5$ Mbps and $a_2 = 1$ Mbps

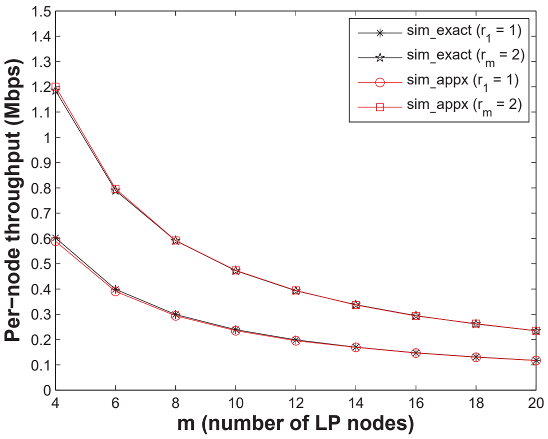

Fig. 3 Per-node throughput for LP class vs. the number of LP nodes, where LP class has m nodes, and the required throughput ratio between the first and later $\frac{m}{2}$ nodes is 1:2

about 1:2. This manifests that the proposed APPLE scheme can guarantee the proportional throughput requirements of LP class.

V. CONCLUSION

In wireless LANs, it is desirable to provide different levels of guaranteed services simultaneously for applications with different requirements. This paper proposes an APPLE scheme, which considers providing the absolute throughput guarantee for HP nodes, providing the proportional throughput guarantee for LP nodes, and at the same time maximizing the bandwidth utilization. We formulate the optimization problem, investigate the existence and uniqueness of the solutions. Simulations validate that the proposed APPLE scheme is very accurate.

APPENDIX

In this appendix, we prove (19) and the approximate solution to the case of $n = 1$ and $m \geq 1$ is uniquely exist.

Proof: We prove (19) and the approximate solution in three steps below.

Step 1: Express $\beta_{i+1}, 1 \leq i \leq m$, in terms of β_2. From (16), we have

$$\beta_{i+1} = \frac{r_i \beta_2 L_2}{L_{i+1}}, 1 \leq i \leq m. \tag{20}$$

Step 2: Express β_1 in terms of β_2. After substitute (20) into (13) and apply the approximation, $(1-x)^y \approx e^{-xy}$ for $x \ll y$, we have

$$\beta_1 = \frac{\sigma + \beta_2 L_2 \sum_{i=1}^{N-1} \omega_i e^{\lambda}}{\varphi}, \tag{21}$$

where $\omega_i = \frac{r_i T_o^{i+1}}{L_{i+1}}$, $\varphi = \frac{L_1}{a_1} + \sigma - T_o^1$ and $\lambda = \beta_2 L_2 \sum_{j=1}^{i} \frac{r_j}{L_{j+1}}$ are constants when the total node number N, the packet size L_j and the throughput ratio r_j are given. Hence, we get (19).

Step 3: Prove that β exists and is unique. First, we can express the system throughput $\Sigma_{i=1}^{N} \Gamma_i$ in terms of β_2. Then, (18) reduces to

$$\Sigma_{i=1}^{N} \Gamma_i = a_1 + \frac{L_2 \beta_2}{L_1 \beta_1} a_1 \Sigma_{i=1}^{m} r_i. \tag{22}$$

Substitute (21) into (22), then $\Sigma_{i=1}^{N} \Gamma_i$ is the function of β_2. So the optimal value for β_2 can be derived through setting the first-order derivative of $\Sigma_{i=1}^{N} \Gamma_i$ to zero, we get $h(\beta_2) = 0$. Due to the reasons that (i) $h'(\beta_2) < 0$, (ii) $h(0) > 0$ and $h(1) < 0$. the solution to β_2 must exist uniquely in domain $(0, 1)$. Further, the solution to β must exist uniquely. ■

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