Adaptive Network Resource Management in IEEE 802.11 Wireless Random Access MAC

Hao Wang, Changcheng Huang, James Yan
Department of Systems and Computer Engineering
Carleton University, Ottawa, ON, Canada

Abstract— **Effective and efficient management of wireless network resources is attracting more and more research attention, due to the rapid growing deployment of wireless mesh and ad hoc networks and to the increasing demand for Quality of Service (QoS) support in these networks. This paper proposes an adaptive network resource management scheme in the popular IEEE 802.11 random access MAC by adaptively adjusting the minimum contention window sizes of traffic flows. First, a novel Generalized Processor Sharing (GPS) model is presented for the IEEE 802.11 random access MAC revealing the relationship between the minimum contention window size of a traffic flow and the amount of network resource this flow can receive. Using this GPS MAC model, a feedback control system model for the proposed adaptive network resource management system is developed, by directly extending our previous work in wireline GPS networks. Based on the feedback control system model, adaptive *P* and adaptive *PI* controllers are designed, and their performances are studied in simulations. Simulation results show that by using the designed controllers, the proposed adaptive network resource management approach is able to provide guaranteed distinct QoS support to traffic flows.**

I. INTRODUCTION

In recent years, Wireless Local Area Networks (WLANs) have become increasingly popular, both as an extension to the existing wireline networks and as stand-alone applications. WLANs are expected to play an important role in future everyday communication providing support for both best effort and quality of service (QoS) sensitive services. In order to provide efficient QoS support, network resources must be effectively managed and allocated to traffic flows.

The medium access control (MAC) manages the network resources in wireless networks. There are usually two types of MAC, i.e. centralized and distributed. Although centrally controlled MAC, such as the PCF in IEEE 802.11, makes it easier to provide QoS support, they are hardly implemented in most existing wireless devices. This is mostly because of their higher complexity, inefficiency for normal data traffic, lack of robustness and assumptions on global synchronization. In addition, such centralized MAC can only work in infrastructure-based wireless LAN, where a central control access point is available, but it cannot be applied in non-infrastructure-based ad hoc networks.

In contrast, the distributed contention-based random access MAC, such as the DCF in IEEE 802.11, received great acceptance among end users, because it is simple, robust, plug and play, and it allows fast installation with minimum network management and maintenance cost. It is very likely that the contention-based random access MAC will remain the dominant wireless MAC in the future. However, in legacy IEEE 802.11 random access MAC, only best-effort type of service is supported. Given the increasing growth of QoS demanding real-time applications, such as voice and video, it is necessary to study how to provide QoS support in such distributed random access MAC.

One approach for providing QoS in distributed random access MAC is measurement-based admission control, such as VMAC [1] and SWAN [2]. However, because the wireless medium is shared among all nodes in the same contention neighborhood, the arrival of a new flow at one node will affect the delay of all other flows on all nodes in its contention neighborhood. Therefore, such admission control based approaches cannot effectively support delay QoS requirement [3].

Another approach is to imitate the centralized scheduling algorithms in wireline networks by exchanging information among nodes in a contention neighborhood [12] [13]. But such approach causes high message overhead. In addition, because the transmission range of a wireless node is usually much smaller than its carrier-sensing range, using this approach, a node may only receive information from a small portion of nodes in its contention neighborhood. Therefore, the effectiveness of this approach is greatly limited.

A third approach explores the fact that the contention window size of a traffic flow in IEEE 802.11 random access MAC determines how much network resource this flow can get in the contention process. IEEE 802.11e [14] implements class-based QoS differentiation, which is similar to DiffServ in wireline IP networks. DWTP [15] and DFS [16] achieve proportional delay differentiation and proportional throughput differentiation respectively. But these methods cannot guarantee satisfying the flow-level QoS requirements.

In [3] and [4], the contention window sizes of the flows are adaptively adjusted in order to achieve guaranteed per-flow QoS requirement. But, the guaranteed QoS in [4] is the maximum packet delay, which is over conservative, since most real-time applications can tolerate a portion of its packets having delay greater than the required delay bound [25]. In [3], the guaranteed QoS is the average contention delay of the packets, which is only part of the entire average packet delay [1]. Although the authors show that the average packet delay is determined by the average contention delay, it

1. The entire average packet delay was decomposed into three components, average queueing delay, average transmission delay and average contention delay.

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is not easy to calculate the proper average contention delay requirement given the requirement on average packet delay. Therefore, it is difficult to apply this method in real networks. In addition, the adaptive contention window adjustment algorithms proposed in [3] and [4] are only heuristic. There is no analytical model proposed for studying the performance of the adaptive contention window adjustment algorithms.

This paper proposes an adaptive network resource management scheme in the popular IEEE 802.11 random access MAC by adaptively adjusting the minimum contention window sizes of traffic flows. There are four major contributions of this paper. First, we present a novel GPS model for the popular IEEE 802.11 random access MAC. Second, we extend our previous work in wireline GPS networks and develop a feedback control system model for the proposed adaptive network resource management system, which is essential for the analytical study of the adaptive contention window adjustment algorithms. Third, different controllers are designed based on the feedback control system model, and their performances are evaluated in simulations. Finally, the QoS requirement used in this paper is given in a statistical form by the packet delay violation ratio (DVR), which is the ratio of packets experiencing delay greater than the required delay bound. By using such a statistical QoS requirement, the network resource needed by a traffic flow is much less than when using a deterministic QoS requirement [26]. Therefore, the efficiency of the networks can be greatly improved.

The remainder of this paper is organized as follows. Section II briefly describes the MAC studied in this paper. Section III introduces the GPS model developed for the IEEE 802.11 random access MAC, revealing the relationship between the minimum contention window size of a traffic flow and the amount of network resource this flow can receive. Using this model and by extending our previous work in wireline GPS networks, a feedback control system model for the proposed adaptive network resource management in IEEE 802.11 wireless random access MAC is presented in section IV. In section V, adaptive *P* and adaptive *PI* controllers are designed, and their performances are studied in simulations in section VI. Due to space constraint, the simulations in this paper are limited to the single hope case. Section VII concludes the paper and discusses future research directions.

II. OVERVIEW OF THE MAC

IEEE 802.11 random access MACs, including DCF and EDCA, are the most popular MACs, and they implement a distributed CSMA/CA contention-based random access network resource management scheme. The IEEE 802.11 random access MAC studied in this paper is not limited by the specifications of any single standardized MAC protocol, but is based on a generalized version of all distributed CSMA/CA contention-based random access MAC, as shown in Fig. 1.

In this MAC, a wireless node can have multiple traffic flows, and each flow has its own queue and its own contention window associated with its queue. Each flow contends individually with all other flows in its contention neighborhood, both inter- and intra-node, for the network resource using the contention window mechanism as if each flow is an individual wireless node in IEEE 802.11 DCF.

In this generalized MAC, if all traffic traversing a wireless node is aggregated and treated as a single flow, this MAC turns into DCF. If traffic is separated into different classes and each class is treated as an individual flow, this MAC becomes EDCA. Traffic flows can also be defined by the source and destination IP and port numbers, as it is done in wireline networks.

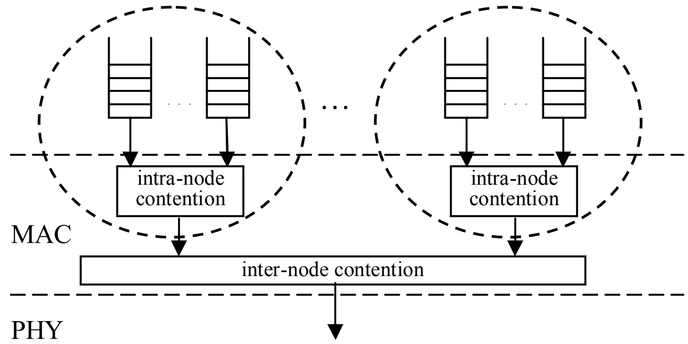

Figure 1 Generalized MAC.

In the next section, we will present a novel GPS model developed for this generalized random access MAC.

III. GPS MODEL OF THE MAC

Existing research on the performance of the IEEE 802.11 MAC has been primarily focused on the packet level network throughput [21][22][24]. But such results are of little help in providing QoS for traffic flows in ad hoc wireless networks.

[23] studies the performance of DCF using the *G/G/1* queueing model and computes the probability distribution function of the flow level packet delay. But it does not support flow level service differentiation. In addition, it is computationally very complex and is of limited help for obtaining deeper understanding of the random access MAC.

[17] and [18] propose to analyze DCF and EDCA using the Processor Sharing (PS) model at the flow level. But because such CSMA/CA based random access MAC is very difficult to analyze, no analytical result on flow queue distribution and packet delay distribution is produced.

Because of the absence of a good analytical model of the wireless MAC, QoS support in wireless ad hoc networks is difficult to quantify and optimize. To help address this problem, in this paper, we propose a GPS model for analyzing the queue tail behavior in IEEE 802.11 random access MAC. The importance of having this model is that it makes extending some of the wireline analytical results into wireless ad hoc networks possible, and such results would be useful in providing QoS support in wireless ad hoc networks

We first start from the network saturation mode. When the wireless network is in the saturation mode, every flow is

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backlogged, which means that there are always packets in the queue of every flow waiting to be transmitted by the MAC layer. Let s_i and s_j represent the *expected service rate* for flow *i* and flow *j* in the same contention neighborhood when the network is in the saturation mode. It is shown in [20] that s_i and s_j have the following relation:

$$\frac{s_i}{s_j} = \frac{E[L_i]/W_i}{E[L_j]/W_j}, \qquad (1)$$

in which, W_i is the minimum contention window size of flow i ; and L_i is the *extended packet size* of flow *i*, which is the channel transmission rate multiplied by the total duration of a successful transmission of a flow *i* packet, including DIFS/AIFS, SIFS, and RTS/CTS/DATA/ACK handshake.

A new feature, called TXOP, is introduced in EDCA, which allows a traffic queue to transmit multiple packets continuously after winning one contention. These continuously transmitted packets can be treated as an aggregated single packet. Therefore, if TXOP is employed, the *extended packet size* of a flow would become adjustable by changing its TXOPlimit value.

However, most actual wireless networks are running in non-saturation mode. Let $S_i(\tau,t)$ and $S_j(\tau,t)$ be the *actual amount of traffic* served for flow *i* and flow *j* in time interval $[\tau, t]$, during which flow *i* is always backlogged. Because accessing the transmission medium is contention-based, the maximum amount of traffic that flow *j* can transmit is achieved only when flow *j* is backlogged all the time during this time interval. Which means that the value of $S_i(\tau,t)/S_j(\tau,t)$ is minimized only when flow *j* is also always backlogged during $[\tau, t]$. When flow *i* and flow *j* are both always backlogged, they can be treated the same as in the saturation mode, therefore equation (1) holds in this time interval $[\tau, t]$.

Because the MAC is CSMA/CA based random access, the amount of traffic served for flow *i* and flow *j* in the time interval $[\tau, t]$ are random numbers. However, when $t >> \tau$, this amount can be approximated by the product of the expected service rate and the service time interval following the Law of Large Numbers. Therefore, we have the following

$$\min\{\frac{S_i(\tau,t)}{S_j(\tau,t)}\} \approx \frac{s_i \cdot (t-\tau)}{s_j \cdot (t-\tau)} = \frac{E[L_i]/W_i}{E[L_j]/W_j}, \ (t >> \tau). \qquad (2)$$

Let $\phi_i = E[L_i]/W_i$ and $\phi_j = E[L_j]/W_j$, then (2) can be rewritten as:

$$\frac{S_i(\tau,t)}{S_j(\tau,t)} \geq \frac{\phi_i}{\phi_j}, (t >> \tau). \qquad (3)$$

From (3), one can show that flow *i* is guaranteed a minimum backlog clearing rate of

$$g_i = \frac{\phi_i}{\sum_{j=1}^{N} \phi_j} \cdot R_i, \qquad (4)$$

in which R_i is the total throughput of the contention neighborhood of flow *i* when the network is in saturation mode.

Note that (3) is in the exact form as a GPS scheduler in wireline networks, which means that when $t >> \tau$, the IEEE 802.11 random access MAC can be modeled as a GPS scheduler, i.e. the queue tail behavior in the IEEE 802.11 MAC should match the queue tail behavior in wireline GPS scheduler. This GPS model for IEEE 802.11 has been verified in simulation. More details can be found in [7].

IV. FEEDBACK CONTROL SYSTEM MODEL

In [8], a feedback control system model was proposed for adaptive bandwidth provisioning in wireline GPS networks. In the previous section, it has been shown that the contention-based IEEE 802.11 random access MAC can be modeled as a GPS scheduler. Thus, this wireline feedback control system model can be directly extended to wireless networks.

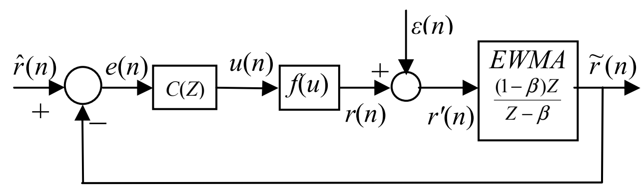

Figure 2 Block diagram of the feedback control system model.

Fig. 2 shows the block diagram of the feedback control system model for adaptive network resource management proposed in this paper, which is almost the same as the one in [8]. The input of the system is $\hat{r}(n)$, which is the desired DVR of the flow. The output of the system is $\tilde{r}(n)$, which is the result of passing $r'(n)$ through an Exponential Weighted Moving Average (EWMA) filter with parameter β. $r'(n)$ is the actual DVR of this flow measured during the time interval [(*n-1*)*T, nT*], in which *T* is the control update interval. This DVR measurement is performed at the receiving end of this flow by counting the total number of packets received and the number of packets that are lost or have packet delay greater than the delay bound. The difference between $\hat{r}(n)$ and $\tilde{r}(n)$, denoted as *e*(*n*), is used as the input to the controller *C*(*Z*). The output of the controller is *u*(*n*) = 1/*w*(*n*), in which *w*(n) is the minimum contention window size of this flow.

The block *f*(*u*) is the mapping between the controller output *u*(*n*) and the resulting DVR experienced by this flow *r*(*n*). It should be pointed out here that *r*(*n*) is the long term steady state DVR of the flow assuming that *u*(*n*) and the characteristics of this flow as well as all other competing flows in the network are kept constant. Therefore the mapping between *u*(*n*) and *r*(*n*) is deterministic, i.e. for every specific value of *u*(*n*), there is a corresponding deterministic specific value of *r*(*n*). However, because of the stochastic nature of the

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networks, as well as the limited finite duration of the control interval, the actual measured DVR of the flow at the end of each control interval, denoted as $r'(n)$, is not deterministic but rather a random process, which can be modeled as the result of combining the deterministic $r(n)$ with a random noise signal $\varepsilon(n)$. The function of the EWMA block after $r'(n)$ is to act as a low pass filter filtering out the random noise $\varepsilon(n)$ within $r'(n)$ and to generate $\tilde{r}(n)$, which is an estimation of $r(n)$.

The tail queue distribution of wireline GPS scheduler was studied in [19], and it is shown that for an exponentially bounded burstiness (EBB) flow i, its tail delay distribution can be bounded in the following form [2],

$$r_i = f_i(d) = \Pr\{D_i \geq d\} \leq \Lambda_i^* \cdot e^{-\gamma_i \phi_i \cdot d}, \tag{5}$$

in which D_i is the packet delay of this flow, ϕ_i is the weight assigned to this flow in the GPS scheduler, and Λ_i^* and γ_i can be calculated using equations given in [19].

As shown in section III, when $t >> \tau$, the IEEE 802.11 random access MAC can be modeled as a GPS scheduler. Therefore, the queue tail behavior in the IEEE 802.11 MAC should match the queue tail behavior in wireline GPS scheduler. Thus, (5) also holds in IEEE 802.11 MAC. Since we have $\phi_i = E[L_i]/W_i$ and $u_i = 1/W_i$ in IEEE 802.11 MAC, as shown in section III, the tail delay distribution in IEEE 802.11 random access MAC can be rewritten from (5) to the following form,

$$r_i = \Pr\{D_i \geq d\} = f(u_i) \leq \Lambda_i^* \cdot e^{-\alpha_i^* d \cdot u_i}, \tag{6}$$

in which r_i is the DVR experienced by this flow i; u_i is the output of the controller, which is the inverse of the flow's contention window size; D_i is the packet delay of this flow; d is the required packet delay bound; and Λ_i^* and α_i^* are constant numbers that can be calculated

By adopting the method used in [8], the feedback control system model is linearized by approximating the mapping function $f(u)$ with a linear function:

$$f(u) \approx -Ku + B, \tag{7}$$

in which $K > 0$, and B is a constant number. The block diagram of the linearized system model is shown in Fig. 3.

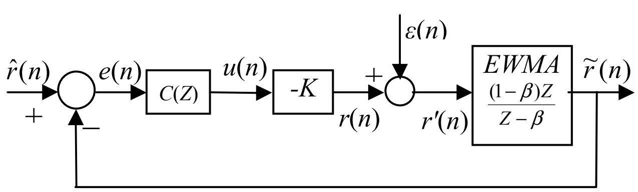

Figure 3 Linearized feedback control system model.

The same as in [8], the specific value of K is still unknown. For different flows in different network conditions, K can have different values. It has been shown in [8] that for such a system, it's very difficult to design a fixed controller that can work well for various flows and network conditions.

Therefore, by following the approach in [8], adaptive P and adaptive PI controllers are designed in the next section.

V. Controller Design

A. Adaptive P Controller

The block diagram of the system with adaptive P controller is shown in Fig. 4, in which $\tilde{K}$ is the estimation of K using the method in [8].

$$\tilde{K}(n) = (1-\beta) \cdot K'(n) + \beta \cdot K'(n-1), \tag{8}$$

$$K'(n) = -\frac{\tilde{r}(n) - \tilde{r}(n-1)}{\tilde{u}(n) - \tilde{u}(n-1)}. \tag{9}$$

This estimation of K is then used to adaptively adjust the parameter K of the P controller using the following rule,

$$K_P(n+1) = G_{ol} / \tilde{K}(n). \tag{10}$$

in which, G_{ol} is the desired open-loop gain of the system, which is determined by how much steady state error is acceptable in the system output.

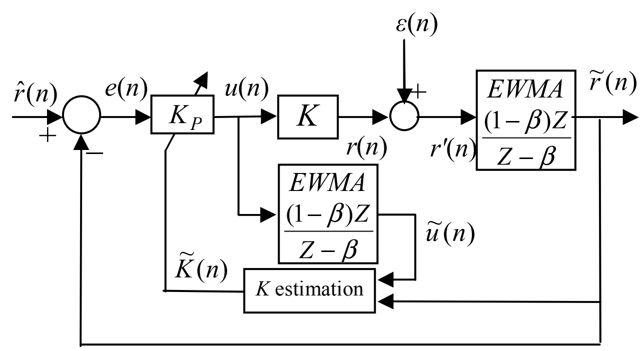

Figure 4 Linearized system block diagram with adaptive P controller.

B. Adaptive PI Controller

Based on the linearized feedback control system model, we can tell that this system is a first order system. From control theory, it is known that using P controllers in this system will result in steady state error in the system output. Simulation results in [8] also confirm this.

In order to eliminate the steady state error in the system output, an adaptive PI controller is designed. The block diagram of the system with adaptive PI controller is the same as the one with adaptive P controller shown in Fig. 4. The only difference is that an integral part is added into the controller so that the transfer function of the controller is changed from K_P to $K_{PI} \cdot [1 + \gamma(Z+1)/(Z-1)]$.

Similar to the adaptive P controller case, the value of K_{PI} is adjusted using the following rule:

$$K_{PI}(n+1) = G_{ol} / \tilde{K}(n). \tag{11}$$

In the next section, the performances of adaptive P and adaptive PI controllers are evaluated in simulations. The

2. The notation here is slightly different from what is used in [19].

controller parameter values used in this paper are the same as those used in [8].

VI. SIMULATIONS

The simulations are implemented in *ns2*. Due to space limit, this paper contains only single hop simulations. In the simulation, there are eight pairs of wireless nodes in a single hop IEEE 802.11 WLAN, which has a transmission rate of 2 Mbps. All wireless nodes are within each other's one-hop transmission range. There are eight traffic flows in this WLAN, five of which are QoS sensitive flows and the rest three of them are best-effort data traffic.

The five QoS flows are simulated voice traffic using exponential on-off sources. During the on period, the sources send out packets at the rate of 64 Kbps, and the size of each packet is 84 Byte. The sources do not send out any packet during the off period. The mean on time and mean off time of the sources are 350 ms and 650 ms respectively.

The three data flows are generated using the well-known BellCore trace [27] and their mean rates are randomly set between 30 Kbps and 100 Kbps.

In this paper, the QoS requirement of traffic flows are given in the form of the required packet delay bound and the maximum acceptable DVR. For the same type of traffic, the end-to-end QoS requirements should be the same. But, since the traffic flows may travel through different number of hops, their per-hop QoS requirement could be different. To consider this effect, in our simulation, the QoS requirements of the five voice flows are randomly selected from the following two, (100 ms, $1.0*10^{-3}$) and (50 ms, $0.5*10^{-3}$).

To evaluate the performance of the controllers designed in section V, three simulation scenarios are implemented. In the first scenario, the feedback adaptive network resource management is not implemented. The MAC parameters are set up using the default 802.11e values. Voice traffic belongs to AC[3], and it has CW_MIN[3] = 7 and AIFS[3] = 2. Best-effort data traffic belongs to AC[0], with CW_MIN[0] = 31 and AIFS[3] = 7.

The second scenario implements the adaptive *P* controller designed in section V. The adaptive network management scheme is applied only on the five voice flows. The initial values of CW_MIN for all five voice flows are set to 31, and the adjustment range of CW_MIN is limited to between 31 and 7. The data flows have fixed CW_MIN = 31. The values of AIFS for the voice flows and data flows are set to 2 and 9 respectively, so that when the voice flows demand more network resource by decreasing their CW_MIN values, the data flows can be blocked from accessing the wireless channel and therefore give more resources to voice flows. When the voice flows have CW_MIN = 7, the data flows can be completed blocked. This is also referred to as QoS protection.

The adaptive *PI* controller is implemented in the third scenario. The setting in this scenario is the same as in scenario 2, except that the control algorithms are different. Fig.5 and Fig. 6 show the simulation results of two voice flows with the QoS requirements of (100 ms, $1.0*10^{-3}$) and (50 ms, $0.5*10^{-3}$) respectively.

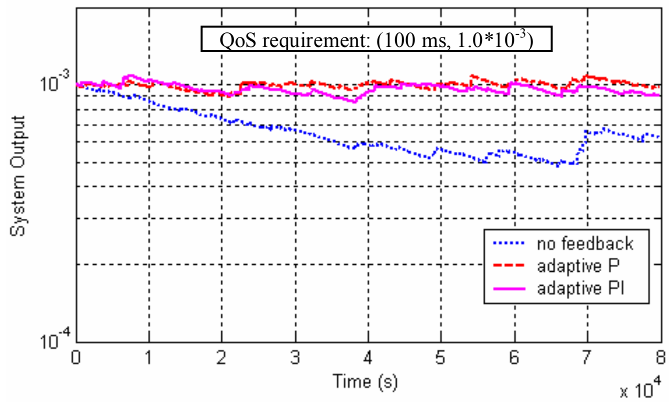

Figure 5 System output for a voice flow using different controllers, with QoS requirement (100 ms, 1.0*10-3).

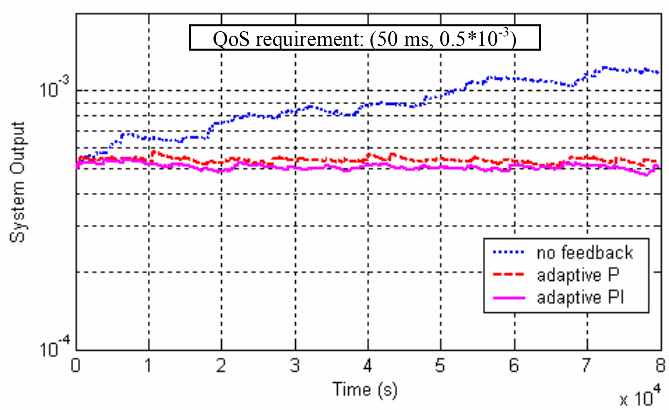

Figure 6 System output for a voice flow using different controllers, with QoS requirement (50 ms, 0.5*10-3).

The simulation results for scenario 1 are shown by the doted lines in these two graphs, labeled as "no feedback". In this scenario, the two voice flows both belong to class AC[3] and are configured using the default 802.11e setting, and there is no feedback adaptive adjustment. It can be seen that the actual QoS experienced by the voice flow in Fig 5 is better than its requirement, which indicates that the amount of network resource obtained by this flow is more than what it actually needs. However, the QoS experienced by the voice flow in Fig.6 does not meet its requirement, which means that not sufficient amount of network resource is acquired by this voice flow. The reason for this is because the voice flow in Fig. 6 has a stricter QoS requirement than the voice flow in Fig. 5, thus it requires more network resource. Therefore, this scenario shows that by using static setting, even with IEEE 802.11e type of QoS support, there is no guarantee on the QoS received by traffic flows. It is very possible that some flows are not getting sufficient network resource while some other flows are over-provisioned.

In Fig. 5 and Fig. 6, the simulation results of scenario 2 and 3, using adaptive *P* controller and adaptive *PI* controller, are shown by the dashed line and solid line respectively. Compared with the results of scenario 1, it can be seen that by using adaptive network resource management, the voice flow in Fig. 5 is no longer over-provisioned, and the voice flow in Fig. 6 can obtain enough network resource to meet its QoS requirement.

In Fig. 6, it can also be observed that when using adaptive *P* controller, there is a steady state error in the system output. This steady state error is removed when adaptive *PI* controller is applied. There is no such observation in Fig. 5, but the reason for this is due to the contention window adjustment range constraint we implemented in these two scenarios.

The simulation results of scenario 2 and 3 match our earlier analysis in this paper, and it is also in accordance with our studies in wireline networks [8].

VII. CONCLUSIONS

This paper studies adaptive network resource management in IEEE 802.11 wireless random access MAC. We propose to adaptively adjust the minimum contention window sizes of traffic flows in order to meet their QoS requirements.

We present a novel GPS model for the popular IEEE 802.11 random access MAC, revealing the relationship between the minimum contention window size of a traffic flow and the amount of network resource this flow can receive.

Using this GPS MAC model, a feedback control system model for the proposed adaptive network resource management system is developed, by directly extending our previous work in wireline GPS networks.

Based on the feedback control system model, adaptive *P* and adaptive *PI* controllers, which are similar to our previously designed controllers in wireline networks, are designed in this paper. Simulation results show that by using the designed controllers, the proposed adaptive network resource management approach can effectively meet the QoS requirements of the traffic flows, and the performances of the controllers also match our analysis.

Further research that are currently being conducted include more extensive studies on the proposed approach and the system model in dealing with more complex traffic and network conditions, such as in multi-hop ad hoc networks. Other important related issues include the effect of the proposed approach on network throughput, the effect of imperfect measurement on the system performance, solutions for the admission control of traffic flows, mobility handling, flow balancing, etc.

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