A Cross-Layer Control Based on Fuzzy Automata for Ad-Hoc WLAN QoS

Chao-Lieh Chen, Hsin-Long Yang, and Yao-De Huang

Department of Electronic Engineering
Kun-Shan University
Yung-Kang, Tainan County, TAIWAN
frederic@ieee.org

Abstract

This paper proposes a new interface model for cross-layer designs using generalized fuzzy automata (GFA) and fuzzy control. When using the proposed model, an upper layer is reduced to an adaptive and cognitive controller and the lower layers act as hierarchical plants. In this paper, we utilize the model in wireless LAN Quality of Service (QoS). The fuzzy controller allocates bandwidths for different traffics, detects saturation of performances, and criticizes satisfaction of traffic specifications (TSPECs). The distributed fuzzy controller adaptively tunes its fuzzy sets according to both the TSPECs and the network states. According to the realization theory and the experiments, the adaptive QoS controller fulfills TSPECs no matter what dynamics of the TSPECs and the network environment are.

Keywords: wireless ad-hoc networks, cross-layer design, fuzzy control, generalized fuzzy automata, IEEE 802.11e.

1. Introduction

The uncertain dynamics such as mobility, link capacity, and many other resources along with diverse QoS requirements in different applications make protocol designs significant challenges [1]. Scientists found that cross-layer designs are useful to tackle some of the challenges and will be essential for wireless networks. However, there are still many open challenges such as interface standardization, physical layer signal processing, co-existence problems, cost-effectiveness assessments, and network states measurements [2]. This paper proposes a novel cross-layer interface model that provides certain levels of solutions to these challenges. As in Fig. 1, each of the lower layers interprets a control vector from upper layers as part of the dynamic command of its internal control system. Thus, the controller in a lower layer is transparent to an upper layer. The control system performances and costs can be analyzed in each logical layer by fuzzy feedback control theories.

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Different from the abstractions investigated in [2], our cross-layer proposal uses fuzzy automata and control to deal with the challenges respectively as follows. First, the proposed fuzzy control hierarchy does not violate the classical layered architecture but does promote efficiency and standardize the interactions between layers. Second, the interface model does not change the physical layer and the signal processing is as was in the classical OSI model. Third, since the layering abstraction is not completely destroyed, logical links between the same layer of different nodes are maintained. Therefore, the traditional and other cross-layer designs are able to communicate the proposed design. Moreover, costs and performances are easily assessed using control theories. We can thus perform cross-layer optimization using optimal fuzzy control. Finally, fuzzy automata theory is very useful in modeling and operating uncertain concepts. Uncertain states in the control system hierarchy are easily handled.

The utilization of the cross-layer model in WLAN QoS is as follows. The media access control (MAC) layer is based on the IEEE 802.11e standard [8], which receives dynamic TSPECs as commands from upper layer. In mobile ad-hoc networks, the TSPECs dynamically change due to flow control, traffic re-shaping, or the mobile nodes recasting new roles in applications of scenarios. Moreover, a QoS algorithm requires the capabilities of determining resource availability on neighboring links and resource reservation functions at nodes [3]. Measurements at lower layers assure these capabilities. Therefore, the QoS work does not merely rely on a single layer but rather on all layers. How to accomplish the QoS is a typical example utilizing cross-layer designs and nodes' cooperation.

In the IEEE 802.11e MAC layer QoS standard [8], the Enhanced Distributed Channel Access Function (EDCAF) and the Hybrid Coordination Function (HCF) are alternatives to access the wireless channel. In this paper, we choose EDCAF as the plant in the fuzzy control system. Prioritized QoS is done by assigning of the parameters different values in different traffic categories. The parameters are the contention window (CW), persistence factor (PF), and arbitration interframe space (AIFS). The EDCAF function provides coordination for QoS enhancement. However, we suffer the following problems:

P1. Uncertainties and dynamics of network states: The measurement of network states is very difficult since there are too many affecting factors, which are unknown and dynamic.

P2. Dynamic TSPECs: Dynamic network state results in requirement of dynamic TSPEC. In the IEEE 802.11e standard, there is no definition of ways to realize dynamic TSPEC. In the MAC layer, we need to accurately fulfill or criticize both static and dynamic TSPECs requested by upper layers. Therefore, a cross-layer interface is required.

In this paper, we propose the cross-layer fuzzy control architecture to solve these problems. Many other recent studies on the QoS extension of wireless LAN can be found in [9-14]. These studies can be classified into two major categories. The first category papers focus on performance evaluation and analysis [9-10], where sophisticated stochastic models are used for dealing with the nonlinearities and uncertainty and the other is about control and enhancement of the IEEE 802.11e standard [11-14]. In the second category of studies, article [12] made the modification to acknowledgement (ACK) scheme of the original standard while some incorporated applications are proposed in [11-13]. In [13], we have developed the QoS control for legacy IEEE 802.11 to meet the node level dynamic TSPEC. In this paper, to support QoS required in different layers, we extend the controller into hierarchical and vectored fashion and prove its feasibility according to the realization theory. Instead of stochastic computing, we develop the soft computing model for the IEEE 802.11e EDCAF fuzzy control by generalized fuzzy automata theory and prove that the controller can be very simple, effective, and easy to realize. The remainder of this paper is organized as follows. Section II describes how the whole fuzzy controller is constructed based on GFA theory. In Section III, we give MPEG4 streaming simulations. In Section IV, we give conclusions and discussions.

2. Realization of the Fuzzy Controller

In this paper, we do not apply analytical procedure to find out exact probability model of IEEE 802.11e EDCAF functions in a cell. Instead, we apply fuzzy control to take care of uncertainties and non-linearity in wireless networks where states change quickly. According to the standard [8], a frame transmission in a channel will require the following time duration.

$$d = t_{defer} + t_{RTS} + t_{CTS} + t_{frame} + t_{ACK} + 3t_{SIFS} + 3\tau_p, \qquad (1)$$

where $t_{RTS} + t_{CTS} + t_{ACK}$ can be regarded as constant, t_{defer} is the deferred time according to the specification of DCF, t_{frame} is concerned with length of the frame, and τ_p is the maximum possible propagation delay. At MAC layer, the value of t_{frame} is based on frame length and the data rate. To compatible with the standard, $t_{RTS} + t_{CTS} + t_{ACK} + 3t_{SIFS}$ is a constant. Therefore, the only adaptable parameter is t_{defer}, which is obtained by the back-off procedure defined in the standard. If the defer time of a traffic in a mobile node is effectively controlled, any dynamic TSPEC can be realized.

2.1. Automaton for the Adaptive Controller

The control system architecture is shown as Fig. 2. Suppose there are n nodes each of which at most has m traffic categories. Every node i has basic rate B_i and the total network capacity is B. The distributed controller has two sets of inputs – TSPEC and the observed system state. One element of the TSPEC input set is the goal delay matrix $[D_{gi}]$ where each D_{gi} is a row vector of m goal delays d_{ij}'s for traffic categories j's of node i. Each goal delay d_{ij} is related with the packet size l_{ij} and the desired bandwidth b_{ij}. Thus we have

$$B = \sum_{i=0}^{n-1} B_i = \sum_{i=0}^{n-1}\sum_{j=0}^{m-1} b_{ij}$$
$$d_{gij} = \frac{l_{ij}}{b_{ij}}, j > 0;\ d_{gi0} = \frac{l_{i0}}{B_i - \sum_{j=1}^{m-1} b_{ij}} \qquad (2)$$

The traffic category (j = 1) with lowest priority uses the remaining bandwidth for transmission. The TSPEC includes the tolerable delay variation matrix $[E_i]$ where each E_i is a row vector of m desired tolerable delay variations ε_{ij}'s for traffic categories j's of node i. In the network, the delay vector D_{gi} and the tolerable delay variation E_i are dependent.

To model the control system with the generalized fuzzy automata (GFA) [4, 14], we regard the level-2 fuzzification Q of the observed network states ξ_{mn}'s as the state universe of the automaton while the adaptive distributed controller becomes the output function that gives the actions $U_{mn} = [CWmin_{ij}]_{m\times n}$. Let F: TSPEC→ $[D_{gi}]$ be the transformation as equation (2), $\xi_0 = \xi_{mn}(0)$ be the initial state, Σ be the range of $CWmin_{ij}$ parameter, and T be the set of fuzzy time durations $\{dT_r | r \in \mathbb{N}\}$ that the state transition $\delta = \{\delta(u_r(t), \xi_r(t), dT_r) | r \in \mathbb{N}\}$ requires for changing from one fuzzy state to another. Then, we have $m\times n$ distributed GFA's $\boldsymbol{M_{mn}}=\{\boldsymbol{M_{ij}}(\delta, \Sigma, Q, \xi_0, F, T) \mid 0< i \le n, 0< j \le n$ and $i, j \in \mathbb{N}\}$ realizing the control system if the transition rule base δ can be found. Unfortunately, since the whole system is dynamic and uncertain, it is impossible to find out exact δ via classical system identification approaches. Moreover, even some very accurate system models of the EDCAF function can be found by delicacy analyses [9-10], as [11] mentioned it is still very difficult to have the sophisticated probability model of the whole system behavior without specific assumptions. The system behavior can be only be described by observations. Defining ξ_{ij} as the error between the desired and measured MAC access delays, by using the observer in Fig. 2, we only know that by giving $CWmin_{ij}$ = *Small (S)*, *Medium (M)*, or *Large (L)* the observed maximum and minimum state (delay) changing rates r_{ij} and l_{ij} in either directions of state axis can be found as follows.

$CWmin_{ij} = Small$, $-r_{ij} < d\xi_{ij}/dt < -l_{ij} < 0$

$CWmin_{ij} = Medium$, $d\xi_{ij}/dt \approx 0$

$CWmin_{ij} = Large$, $0 < l_{ij} < d\xi_{ij}/dt < r_{ij}$

This is a simple input-state observation and therefore the observation is achievable [5]. We obtain the state and its changing rates r_{ij} and l_{ij} by the observer in Fig. 2 that performs simple histogram analysis – averaging packet delays during a time window. Thus, the state transition δ is an input-state homomorphism of the above vague information [5, 14]. To attain the goal, we design the feedback controller for the automaton $\boldsymbol{M_{ij}}$ is as Fig. 3. The fuzzy sets P and N represent fuzzy concepts "Positive" and "Negative" error values respectively while P' and N' represent fuzzy concepts "Positive" and "Negative" error changing rates respectively. The domains of base variables *error* (denoted e), $\Delta error/\Delta t$ (denoted e'), and $CWmin_{ij}$ are $[Q_1(t), Q_2(t)]$, $[dQ_1(t), dQ_2(t)]$, and $[\Sigma_1(t), \Sigma_2(t)]$ respectively. The conclusion parts of the four rules use singletons representing *Small (S)*, *Medium (M)*, or *Large (L)* quantity of $CWmin_{ij}$. In Fig. 3, the value of the base variable *error* is the error between the desired delay and the system output. It is obtained by subtracting the desired delay d_{gij} from the observed control system output $\boldsymbol{O}(\xi_{ij}(t))$. The membership functions of the fuzzy sets of the controller are time-variant and they are on-line tuned according to network status.

2.2. Controller Adaptation and Cross-Layer Signaling

The membership functions of the controller rule base are specified in terms of the TSPEC including goal delay, tolerable delay variation while the upper layers determine the TSPEC according to the measured MAC access delay and loss rate. The membership functions are as follows, where the symbol $\ominus$represents the bounded difference operations.

$$\mu_S(CWmin_{ij}, t) = \begin{cases} 1, & CWmin_{ij} = d_{gij}(t) - \varepsilon_{ij}(t) \\ 0, & \text{otherwise} \end{cases}$$

$$\mu_M(CWmin_{ij}, t) = \begin{cases} 1, & CWmin_{ij} = d_{gij}(t) \\ 0, & \text{otherwise} \end{cases}$$

$$\mu_L(CWmin_{ij}, t) = \begin{cases} 1, & CWmin_{ij} = d_{gij}(t) + \varepsilon_{ij}(t) \\ 0, & \text{otherwise} \end{cases}$$

$$\mu_{P\cup N}(e,t) = 1 \ominus \frac{CWmax_{ij}(t) - |e|}{CWmax_{ij}(t)}$$

$$\mu_{P'\cup N'}(e',t) = 1 \ominus \frac{CWmax_{ij}(t) - |e'|}{2CWmax_{ij}(t)}$$

For the feedback signaling to upper layers, the measured loss rate and delay are used to estimate the noise and background traffic and then the sending rate, compression factors, and packet size are adapted. Furthermore, they are also useful in the modulation scheme selection of the physical layer. When measuring the delay, we perform the weighted moving average [13] of all frame delays in a sliding window. The losses of packets are found if the number of retries to access the channel exceeds the retry limits $RetryLimit_{ij}$ as defined in the standard.

3. MPEG4 Streaming Simulations

At time 0, the MPEG4 streaming with packet size 1024 bytes is from node 0 to node 2 where there is also accompanied a background traffic 300kbps at packet size 1k bytes. There are four pairs of nodes and each pair is also generating background 300kbps at packet size 1k bytes. The AIFS are all 50 slots and each slot is 20μs. The other parameters are as Table. 1. Fig. 4 shows the throughput where the fairness among the nodes is preserved. From Fig. 5, 6, and Table 2, we can compare the video results via both human visual feeling and the PSNR curves. We use the NS2 simulator for the network and protocol stacks environment. We use MATLAB and FPGA hardware for the fuzzy controller. These two tools pass data via sockets in the personal computer.

4. Conclusions

This paper proposes a new cross layer model which utilizes fuzzy control and generalized fuzzy automata theory to successfully tackle the uncertainty and dynamic problems in ad-hoc wireless networks. The QoS control based on the proposed approaches features better video streaming quality and at the same time preserves the fairness.

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Table 1. Parameters for EDCAF and proposed fuzzy control.

	AIFS	CWmin	CWmax	Retry limit	Pkt. Size Bytes	Data rate kbps
MPEG4(TC2)	50	Fuzzy Control		8	Max1028	Mean400
Bkground(TC1)	50	31	1023	4	1000	300

Table 2. Losses and PSNR comparisons.

	Skipped frames	Lost packets	Video PSNR
EDCA	190	397	30.54dB
Proposed	42	93	36.16dB

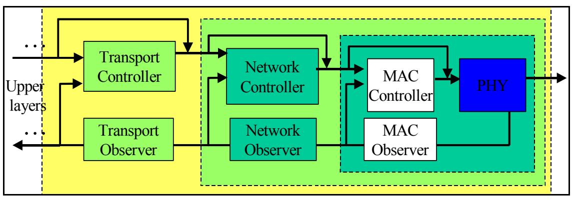

Fig. 1: Hierarchical cross-layer interface model.

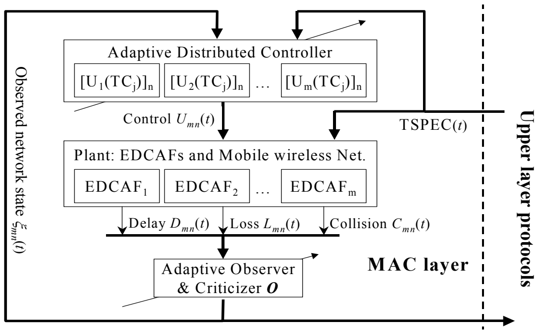

Fig. 2: The architecture of the 802.11e control system.

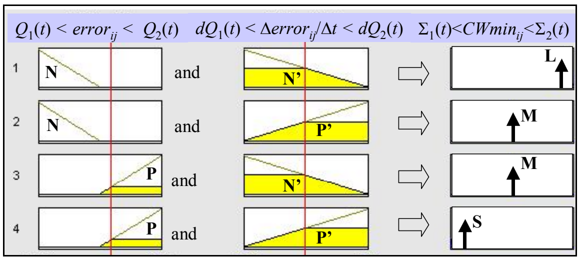

Fig. 3: The membership functions and fuzzy rules of the fuzzy controller.

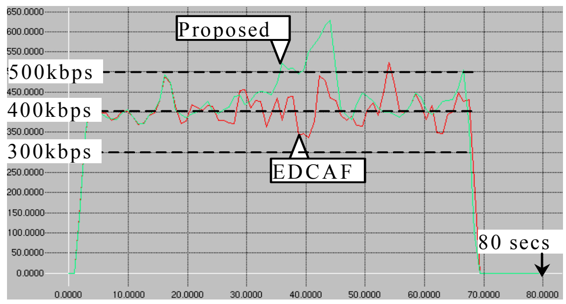

Fig. 4: Throughput comparison.

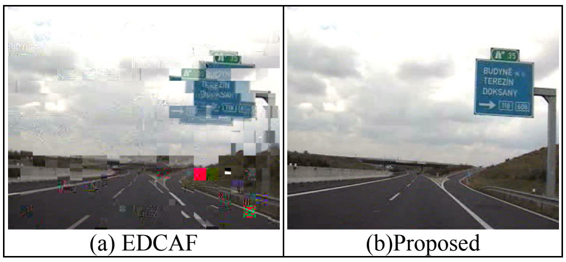

Fig. 5. Video captured from the NS2 simulator.

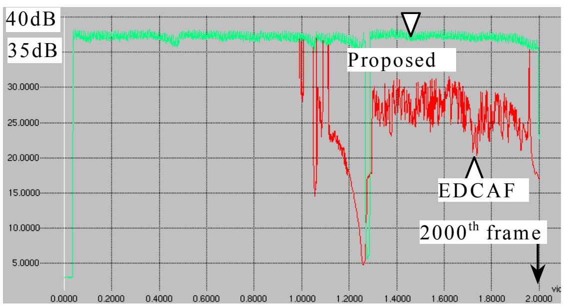

Fig. 6: Comparison of the PSNR performance.