A Control Theoretic Framework for Performance Optimization of IEEE 802.11 Networks

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1) Problem Statement: The MAC layer of the 802.11 standard, based on the CSMA/CA mechanism, specifies a set of parameters to control the way stations access the wireless medium. However, these parameters are statically preconfigured, regardless of the conditions of the WLAN (e.g. channel idle time, collision rate or number of contending stations), thus yielding sub-optimal performance for most scenarios. To overcome this limitation, previous work proposes to adapt the values of the MAC parameters based on an estimation of the WLAN conditions. These proposals are either distributed, requiring every node in the network to implement a mechanism that adjusts the backoff behavior (e.g. the 802.11+ proposal [1]), or centralized, based on a single node that periodically distributes the set of MAC parameters to be used by all stations (e.g. the dynamic tuning algorithm of [2]). However, these works (typically based on heuristics) lack proper analytical support, thus they cannot guarantee optimal performance.

2) A Control Theoretic Framework: In contrast to these previous works, we propose to model the behavior of a WLAN from a control theoretic perspective to achieve optimal performance in terms of e.g. throughput or delay. Control theory has been commonly used in industrial applications[1] to provide the analytical tools for the design of closed-loop systems, in order to guarantee stable operation without lessening the ability to react to changes. We therefore propose to model a WLAN as a closed loop, where the controlled system is the wireless network and the controller is a module which adjusts the parameters of the WLAN based on the observed state of the network, as depicted in Figure 1.

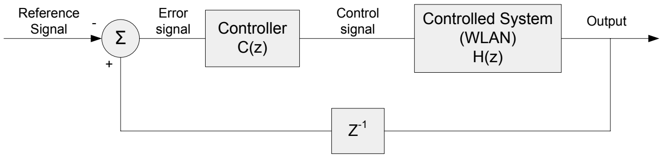

Fig. 1. Control theoretic model of the WLAN.

To design such control systems we proceed as follows:

1) Given a target parameter to optimize (e.g. throughput, average delay), we analytically derive the transfer function of the WLAN that, taking as input a MAC configuration and/or a performance metric, gives as output the target variable. This function will be generally non-linear, therefore we will linearize it when the system is analyzed around its stable point of operation.
2) We then design and model the feedback system that, given the target variable, modifies the WLAN behavior to maximize the performance. This will be realized through control theoretic analysis in order to achieve a proper tradeoff between stability and speed of reaction to changes.

3) Optimization Example: One scenario where this control theoretic framework can be efficiently applied is the throughput optimization of the WLAN by adapting the contention window (CW) of the stations. For this purpose, we first derive the analytical model as follows. Assuming all stations have always a packet to transmit, Bianchi has derived the probability τ that a saturated station attempts a transmission at a randomly chosen slot time as a function of the contention window [4]:

$$\tau = \frac{2}{1 + W + pW \sum_{i=0}^{m-1} (2p)^i} \tag{1}$$

where $W = CW_{min}$, m is the maximum backoff stage ($CW_{max} = 2^m CW_{min}$) and p is the probability that a transmission collides. In a WLAN with n stations,

$$p = 1 - (1 - \tau)^{n-1} \tag{2}$$

By expressing the throughput in the WLAN as a function of τ, Bianchi approximated the optimal transmission probability τ_{opt} that maximizes this metric for a WLAN with n saturated stations as follows

$$\tau_{opt} \approx \frac{1}{n}\sqrt{\frac{2T_e}{T_c}} \tag{3}$$

where T_c and T_e are the durations of a collision and an empty slot, respectively. The corresponding optimal collision probability can be approximated by

$$p_{opt} = 1 - \left(1 - \frac{1}{n}\sqrt{\frac{2T_e}{T_c}}\right)^{n-1} \approx 1 - e^{-\sqrt{\frac{2T_e}{T_c}}} \tag{4}$$

This result shows that, under optimal operation with saturated stations, the collision probability in the WLAN is a

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[1] Recently it has also been applied to communication networks [3].

constant independent of the number of stations. Based on this observation, we design a control system to drive the collision probability to this optimal value by adjusting the CW parameter. The control signal is the CW, the output of the system is the measured collision probability, and the input to the controller is the difference between the estimated collision probability $\hat{p}$ and its optimal value p_{opt} as given by Eq. (4).

For the controller we use a well known scheme from control theory, namely the Proportional-Integrator (PI) controller, which will be implemented at the AP. The estimation of the collision probability over a beacon interval (100 ms) is performed as follows. Let S be the number of frames received by the AP during this period with the retry bit unset, and R be the number of frames received with the retry bit set. Then, if we assume that no frames are discarded due to reaching the retry limit, the collision probability p can be estimated as

$$\hat{p} = \frac{R}{R+S} \tag{5}$$

since the above is precisely the probability that the first transmission attempt of a frame collides. With the above, the AP will compute the new CW configuration and distribute it to all the contending stations through beacon frames.

Next we model the WLAN as a system that takes as input the contention window and gives as output the collision probability. In [5] we have shown that this transfer function can be expressed as

$$H(z) = -p_{opt}\tau_{opt}\frac{1 + p_{opt}\sum_{i=0}^{m-1}(2p_{opt})^i}{2} \tag{6}$$

The remaining challenge is the design of the PI controller, which has the following transfer function

$$C(z) = K_p + \frac{K_i}{z-1} \tag{7}$$

In order to determine the K_p and K_i parameters that achieve a proper tradeoff between stability and speed of reaction to changes, we use the Ziegler-Nichols rules [6], which have been designed for this purpose. Note that properly dimensioning the parameters of the controller is essential: using a large $\{K_p, K_i\}$ setting will increase the speed of reaction to changes but the system may turn unstable. This is depicted in Figure 2a where the evolution of the CW offset is plotted for K_p and K_i values 20 times larger than the optimal ones. On the other hand, a smaller $\{K_p, K_i\}$ setting will ensure a stable system, but this will harm the system's ability to react to the changes in the WLAN. This effect is shown in Figure 2b where we compare the evolution of the control signal for our configuration and one using K_p and K_i values 20 times smaller, under a scenario in which the number of active stations is increased from 15 to 30.

4) Future Work: We are currently studying how to use control theory to design an algorithm for the configuration of the MAC parameters to provide delay guarantees, which is required to support real-time applications. To our knowledge this problem has not been addressed in the literature and previous adaptive approaches focus mainly on throughput optimization. One key challenge that needs to be addressed in order to design such a solution is the modeling of the 802.11e EDCA delay under non-saturation conditions. To this aim, we intend to use the model developed by the authors in [7]. This model will help finding the reference signal for an optimally configured WLAN, which will be used afterwards to obtain the error signal that will be fed into the controller.

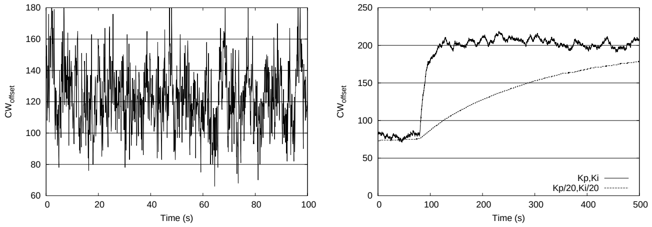

Fig. 2. a. Unstable configuration; b. Speed of reaction to changes

The approach proposed above is a centralized one, which has the advantage of allowing an easy integration with the 802.11e standard. However, it has the drawback of introducing signaling overhead, which limits the frequency with which parameters can be updated. Another future work activity that we intend to conduct is an alternative to this proposal, that avoids the highlighted drawback. Namely, the stations will adaptively configure themselves in a distributed manner. Indeed, a number of works in the literature have proposed such distributed approaches, e.g. [8]. A limitation of all these previous proposals is that they are based on heuristics and not sustained on a well established mathematical basis. In contrast to these, in our future work we intend to develop an adaptive approach based on distributed control theory [9], which ensures global stability as well as convergence to optimal values.

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