A Control Theoretic Framework for Performance Optimization of IEEE 802.11 Networks

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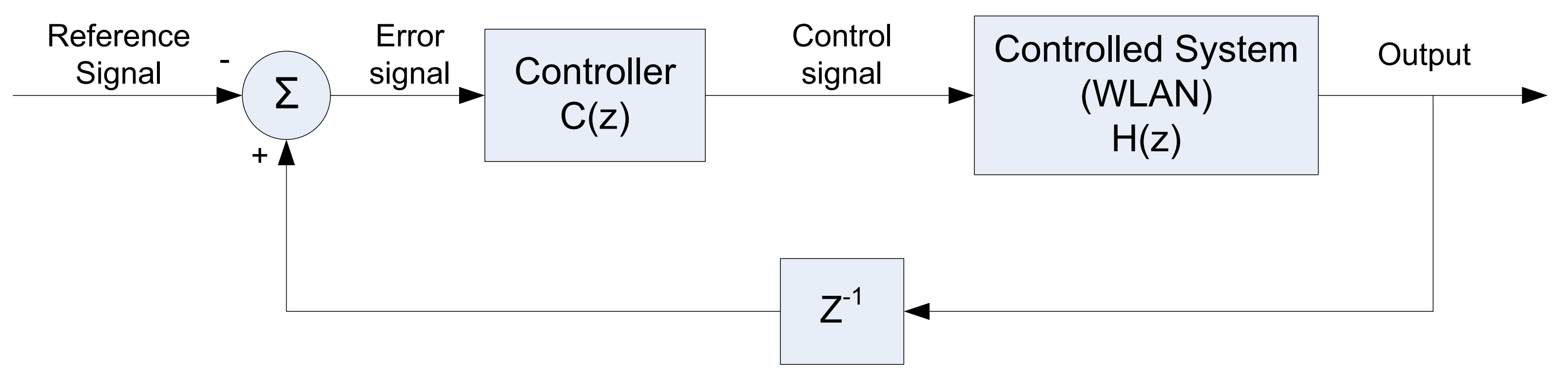
Problem Statement

- 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.
- These parameters are statically preconfigured, regardless of the conditions of the WLAN (e.g. channel idle time, collision rate or number of 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.

A Control Theoretic Framework

- In contrast to the 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 recently applied to communication networks [3], since
  - It provides the analytical tools for the design of closed-loop systems,
  - Guarantees stable operation without lessening the ability to react to changes.
- We propose to model a WLAN as a closed loop - the controlled system is the wireless network and the controller is a module which adjusts the parameters of the WLAN based on its observed state.

Control Theoretic Model of the WLAN



System Design

- 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.
- 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.

Optimization Example

- Scenario: *Throughput optimization* of the WLAN by adapting the contention window (*CW*).
- The probability τ that a saturated station attempts a transmission at a randomly chosen slot time [4]:

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

- $W = CW_{min}$, 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,

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

- The optimal transmission probability τ_{opt} that maximizes the throughput for a WLAN with n saturated stations is derived as follows

$$\tau_{opt} \approx \frac{1}{n}\sqrt{\frac{2T_e}{T_c}} \qquad (3)$$

- 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

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

- *Under optimal operation, the collision probability is a constant independent of the number of stations.*
- We design a control system to drive the collision probability to the optimal value by adjusting the *CW*.
- Controller's input: the difference between the estimated collision probability and its optimal value.
- The controller system:
  - Well known scheme from control theory - Proportional-Integrator (PI) controller
  - Implemented at the Access Point
  - Collision probability estimated over a beacon interval by examining the retry bit of the frames

$$\hat{p} = \frac{R}{R+S} \qquad (5)$$

  - The AP computes the new *CW* configuration and
  - Distributes it to all the contending stations through beacon frames (every 100 ms).
- The transfer function of the WLAN that takes as input the *CW* and gives as output p [5]:

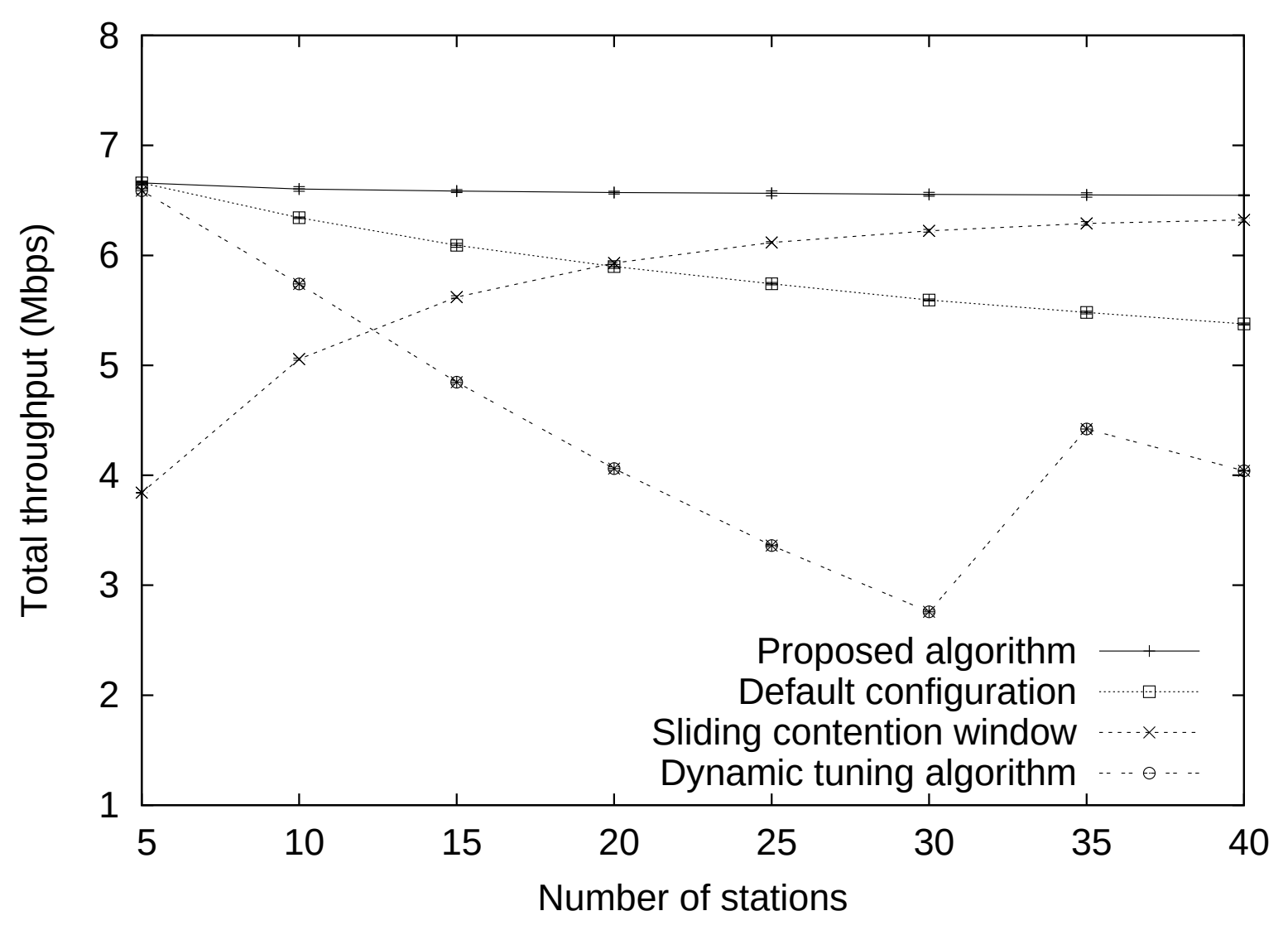
$$H(z) = -p_{opt}\tau_{opt}\frac{1 + p_{opt}\sum_{i=0}^{m-1}(2p_{opt})^i}{2} \qquad (6)$$

- The PI controller has the following transfer function

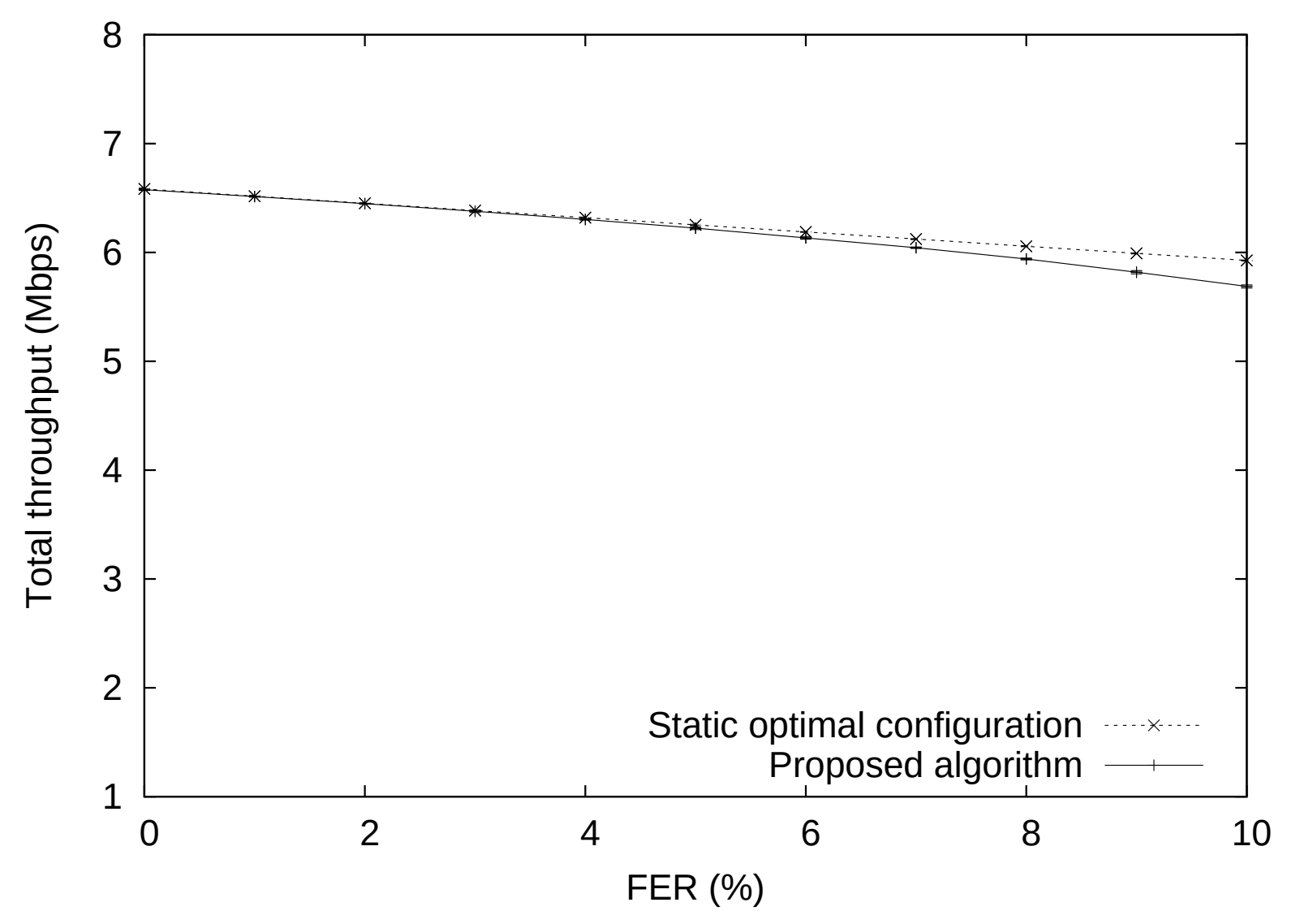
$$C(z) = K_p + \frac{K_i}{z-1} \qquad (7)$$

- Ziegler-Nichols method [6] used to determine the K_p and K_i parameters that achieve a proper tradeoff between stability and speed of reaction to changes.
- Large $\{K_p, K_i\}$ setting increases the speed of reaction to changes but the system may turn unstable.
- Small $\{K_p, K_i\}$ setting ensures stability, but will harm the ability to react to the changes.

Performance Evaluation

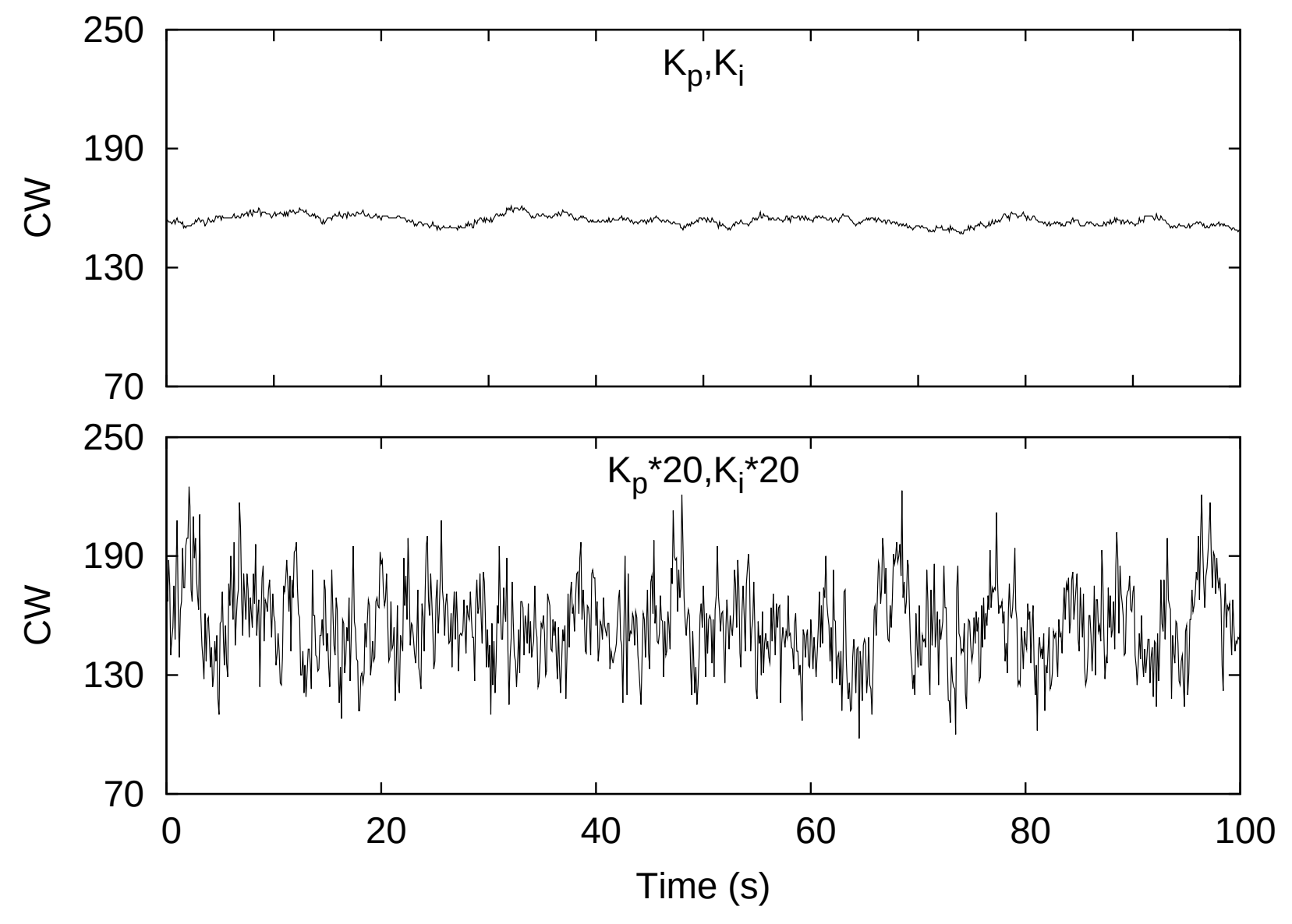


Comparison against other mechanisms

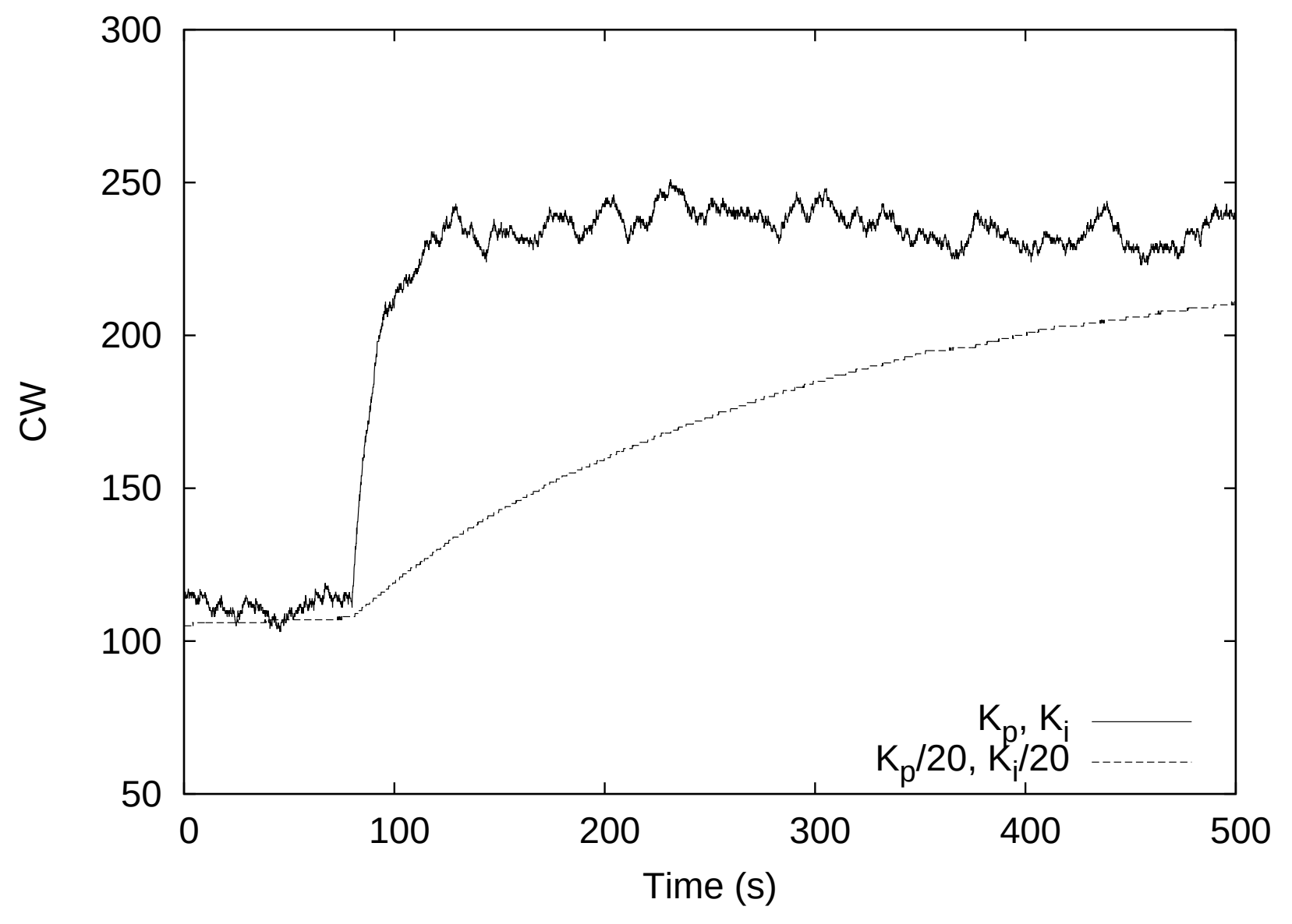


Non-ideal channel effects

Controller Validation



Stability validation



Speed of reaction to changes

Future Work

- Use control theory to design an algorithm for the configuration of the MAC parameters to provide delay guarantees to support real-time applications. Key challenge: the modeling of the 802.11e EDCA delay under non-saturation conditions. Possible approach: the model developed in [7].
- Alternative to centralized solutions: stations adaptively configure themselves in a distributed manner. Previous distributed approaches were proposed, e.g. [8], but they are based on heuristics. In contrast, we intend to develop an adaptive approach based on distributed control theory.

References

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