Modelling Capture Behaviour in IEEE 802.11 Radio Modems

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Abstract

In this paper we investigate the performance of common capture models in terms of the fairness properties they reflect across contenting hidden connections. We propose a new capture model, Message Retraining, as a means of providing an accurate description of experimental data. Using two fairness indices we undertake a quantitative study of the accuracy with which each capture model is able to reflect experimental data. Standard capture models are shown to be unable to accurately reflect the fairness properties of the experimental data. The Message Retraining capture model is shown to provide a good estimate of actual system performance in varying signal strength conditions.

1 Introduction

The IEEE 802.11 wireless Physical Layer (PHYS) and Medium Access Control (MAC) protocols have lead to the widespread adoption of local wireless area networking over recent years. However, recent experiment [1] has indicated that in many conditions, the potential exists for significant unfairness at the MAC layer. In this paper, we investigate the ability of capture models presented in literature [2, 3, 4] to provide a realistic representation of an IEEE 802.11 radio modem. We consider the fairness properties of simulation traces, generated using the network simulator *ns*, compared against the experimental data [1].

Our results illustrate the difficulty in developing accurate models which describe the behaviour of real IEEE 802.11 modems. An intuitive definition of *fairness* is employed in this paper. Hosts should be able to achieve relatively equal transmission rates, and no host should be able to prevent others from gaining access to the channel for a sustained period. In this context, fairness is an important parameter for a wireless MAC protocol. The ability to provide fairness over the shortest possible time scale is necessary to prevent jitter in TCP acknowledgement arrivals, known to have a significant impact on TCP performance [5].

Using both TCP and UDP trace data, we illustrate that the standard capture models are unable to accurately reflect the fairness properties evident in each trace. A new capture model based on the physical operation of an IEEE 802.11 radio modem [6] is presented, termed *Message Retraining*. This model is derived from work investigating the impact of multiple access interference [7, 8] and parallel receiver structures [9]. We investigate the fairness properties of traces generated using this model.

The network model considered is one involving hidden terminals over a semi-slotted 802.11 MAC/PHYS layer, illustrated in Figure 1. All nodes employ a common spreading code with no power control. The *ns* package contains an 802.11 PHYS/MAC layer model, as well as providing excellent implementations of higher layer protocols such TCP/IP, UDP, FTP etc. The channel model employed is an Additive White Gaussian Noise (AWGN) Two-Ray Ground model. Two fairness indices are employed, Jain's fairness index, and a new index first proposed in [10], the Kullback-Leibler Index.

The remainder of this paper is organised as follows: Section 2 presents details of current capture models. Section 3 presents details of the Message Retraining Reception model. Section 4 presents an investigation of the fairness properties of the trace data, while Section 5 concludes the paper.

2 Capture Models

The development of models describing the initial capture of a frame by a radio modem represents a significant body of literature [2, 3, 4]. The common goal of each model is to determine the probability with which a given frame may be captured by the receiver, as a function of the number of active stations.

There are two significant stages in the successful reception of a frame by a radio modem. Initially, the frame must be successful detected and subsequently captured by the receiver. Following this, the frame must then be successfully received in the presence of interference, both from other transmissions and external noise sources. Most literature [2, 3] has considered the probability with which successful detection and capture of a frame at the start of a transmission slot occurs. The second aspect requires an understanding of the impact multiple access interference will have on the captured frame [7, 8, 11] and depends significantly on the modulation technique and spreading codes employed.

Capture models are often used when simulating the performance of wireless networks. Experimental data presented in [1] however, suggest a more complex capture behaviour resulting in the significant unfairness evident in the traces. Further, in cases where hidden nodes are likely (e.g. a mobile ad hoc network) there is a strong possibility of late starting transmissions colliding with other signals at the common receiver. In a scenario where all nodes are able to sense carrier, slot boundaries are easily identified and defined, thereby reducing significantly the probability

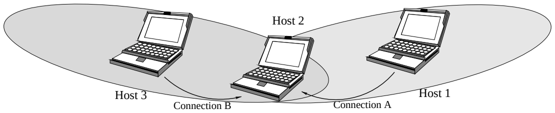

Figure 1: Topology

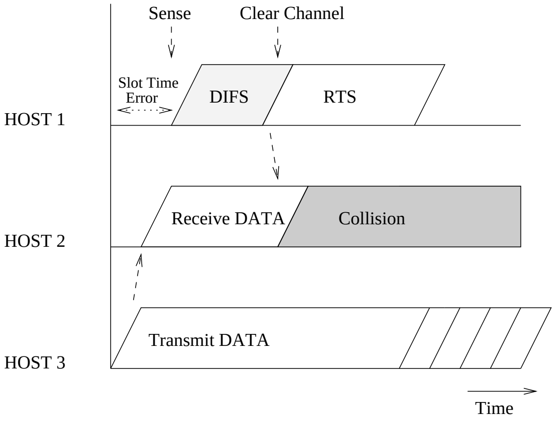

Figure 2: Slot Time Error

of a new transmission interfering with an ongoing transmission.

When carrier cannot be sensed and a node has no knowledge of an ongoing hidden transmission, an interfering transmission may arrive at a common receiver at any time during a slot. This is due to differences in the slot time boundaries observed by both hidden nodes. As illustrated in Figure 2, Host 3 has commenced a data transfer prior to Host 1 (being hidden from Host 3) commencing a channel sense. On sensing a clear channel, Host 1 defers for a DIFS period (Distributed co-ordinate function Inter-Frame Space) then transmits an RTS message. This collides with the data frame from Host 3, illustrating the potential for a late starting transmission to interfere with an ongoing transmission.

This is further complicated by the semi-slotted nature of 802.11. Rigid slot boundaries are not maintained, requiring nodes to infer slot boundaries from the beginning and end of surrounding transmissions. Data transmissions are able to occupy multiple ‘slot times’. Guard times are inserted between sensing an idle channel and transmitting (the DIFS), or returning management frames (the Short Inter-Frame Space, SIFS) to maintain the semi-slotted channel. The lack of carrier from an opposing hidden node however, allows that node to transmit at what appear random times to the common node.

In the following sections we briefly review the significant capture models considered in literature, with the Message Retraining reception model outlined in Section 3.

2.1 Delay Capture

Delay capture originally described by Davis and Gronemeyer [3], enables the capture of a frame in a given timeslot, provided no other frame arrives within a given capture time, T_c of the initial frame. Only the initial frame is able to be received. Frame arrivals are assumed uniformly distributed on the interval $[0, T_u]$. The initial frame arrives at time T_1, and may be captured by the receiver provided that $T_i > T_1 + T_c$, where T_i is the arrival time of the ith frame. This model is chiefly controlled by the parameter T_c, governing the length of time the receiver requires to detect, correlate with, and lock onto the received signal. The larger the T_c/T_u ratio, the less effective the modem is at capturing a frame.

2.2 Power Capture

Power capture, originally described with Rayleigh fading, and constant transmitter power [4], is described by the following inequality over the interval $[0, T_c]$:

$$P_{max} > \gamma \sum_{i=1}^{N} P_i \tag{1}$$

The model allows a frame to be captured provided the received power of the frame with the largest power, P_{max} is greater than the sum of the power of all other received frames, P_i, times the capture ratio, γ. The received signals are assumed to have phase terms varying quickly enough to allow the summation of the power of each received frame. This model is the most commonly employed in simulation of radio modems, allowing the first arriving frame in a slot to be received provided no other frame arrives within the capture time, T_c having a power violating (1). In the case where (1) is violated, no frame is captured.

2.3 Hybrid Capture

The hybrid model was originally proposed by Cheun and Kim [2]. The power capture effect is used to increase the capture probability of the first arriving frame in a given timeslot, even though the delay model would otherwise indicate capture has not occurred. Capture occurs when the following inequality holds:

$$\gamma \sum_{i=2}^{N} P_i \left[T_1 + T_c - T_i\right] < T_c P_1 \tag{2}$$

The total accumulated energy must be less than the energy received from the first packet, P_1 over the capture interval. This model results in a greater capture probability, reflecting the ability of a direct sequence spread spectrum receiver to correlate with the initially detected frame and reject other transmissions as noise.

3 The Message Retraining Capture Model

An enhanced capture technique is described in [6] which allows a modem to successfully receive a signal that would otherwise be considered lost by the previous models. The modem implements a *Message In Message* process, whose function is to monitor the energy received on either antenna during reception of a frame. If an increase in energy beyond a given threshold, γ_{MR} is observed, the modem attempts to synchronise with and demodulate the new energy as a potential new signal. If this is achieved a retraining process allows the modem to prepare to receive this new frame once the prior transmission has finished.

This ability implies that each of the capture models previously described will result in a pessimistic capture probability for a frame over a given duration. The message retraining ability of the modem also extends the time scale over which capture must be considered. Retraining may take place at any time during frame reception, as opposed to the delay, power and hybrid capture models which consider only a short duration at the start of a frame.

The model allows the modem to receive a transmission arriving randomly throughout the reception of another frame, provided the power of the new transmission is high enough to allow successful detection, synchronisation, and demodulation of the frame preamble. Results presented in [7], indicate that the energy associated with the new transmission will have a significant impact on the BER observed at the correlator output for the original frame. These results indicate the initial frame will be unintelligible if the signal power difference between the new and existing transmission is greater than a threshold of 3-5 dB. The Message Retraining model accounts for this by dropping the initial frame if a new frame is detected with a signal power greater than the current by the Message Retraining threshold γ_{MR}. Successful reception of a frame, F_j will occur provided that over the duration of this transmission:

$$\gamma_{MR} \sum_{i=1, i \neq j}^{N} P_i < P_j \tag{3}$$

This model results in the successful reception of the strongest frame transmitted throughout its own duration. i.e. F_j will be successfully received provided no other frame arrives over the duration of F_j with a power greater than $P_j + \gamma_{MR}$ (measured in dBm).

As the purpose of this paper is the evaluation of capture models via simulation, a more detailed analytic study of this model in terms of probability of successful reception of a frame is considered in future studies. The probability of successful capture of a given frame is given by the probability that no frame arrives (during the transmission time of the captured frame) with a received power greater than the captured frame.

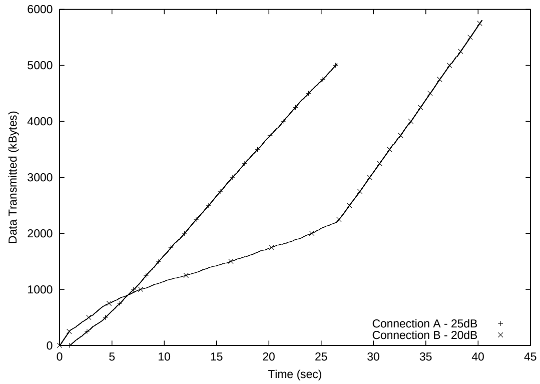

Figure 3: Stationary Signal Power UDP Trace Data

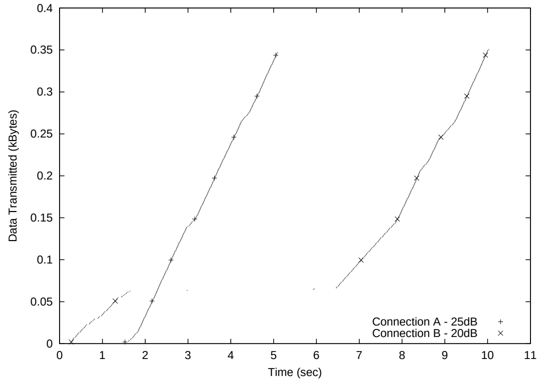

Figure 4: Stationary Signal Power TDP Trace Data

4 Fairness Study

To make a quantitative comparison of each capture model with the experimental data, a fairness metric is required. In this context we require that each node is able to access the channel without sustained delay, and that no node is able to monopolise the radio channel at the expense of other nodes. This should be independent of the physical network topology.

In [1], experiments controlling the signal power on contending hidden connections (Figure 1) illustrate that signal power is a significant factor in determining the distribution of channel access. We consider two of the experiments in this analysis. The first involved a constant signal power on each connection throughout the data transfer. Connection A has a Signal to Noise Ratio (SNR) of 25dB, with Connection B at 20dB. The second, a controlled signal power experiment, commences with the same signal power for each connection, then at 5 seconds, the signal power on Connection A is reduced by 8dBm, bringing the SNR down to 17dB. These trials are performed using both TCP and UDP. Examples of the experimental data from the stationary signal power trials are shown in Figure 3 and 4. In each case, is is evident that the weaker host is prevented from obtaining a fair share of the available channel capacity. The reader is referred to [1] for further detail on each experiment.

Following [10], we employ two fairness indices : Jain's Fairness Index, and a new index proposed in [10], the Kullback-Leibler Fairness Index. In each case, a sliding window method is used to calculate the fairness over a specified horizon. The window slides along the packet sequence indicating which node has successfully gained access to the channel, calculating an instantaneous value for each index. The average value is then calculated across the entire trace. We present curves illustrating the fairness as a function of window size.

In the TCP trial, the trace records successfully acknowledged data. Therefore these results give an indication of the fairness associated with the data transfer at the transport layer, including effects from the MAC and PHYS layers. We calculate fairness in this manner, as TCP is the most common transport protocol in use today, and any wireless PHYS/MAC protocol must be expected to support competing TCP streams without imposing additional fairness characteristics.

4.1 Jain's Fairness Index

This index has been used widely in the literature to describe the fairness characteristics in both congestion control [12] and wireless MAC protocols [10]. An ideal fair distribution of channel access would result in a value of 1 for this index, though values above 0.95 are typically considered to indicate excellent fairness properties. The index is defined in (4).

$$F_j = \frac{\left(\sum_{i=1}^{N} \rho_i\right)^2}{N \sum_{i=1}^{N} {\rho_i}^2} \tag{4}$$

where ρ_i is the fractional share achieved by the ith connection, and N is the number of active connections. A value of 0.7 would imply that 30% of nodes were suffering significant unfairness.

4.2 Kullback-Leibler Fairness Index

The Kullback-Leibler Fairness Index was first proposed in [10]. The technique considers the distribution of channel access for each node as a probability distribution, $\tilde{\Gamma}$. The Kullback-Leibler distance $D\left(\Gamma||\tilde{\Gamma}\right)$, an entropy measure of the ‘distance’ between two probability distributions, is calculated between the desired distribution Γ, and the measured distribution, $\tilde{\Gamma}$. This measure provides an indication of the fairness in the system. A value of 0 corresponds to a perfectly fair system, with values below 0.05 typically indicating a system with excellent fairness properties.

$$\begin{aligned} D\left(\Gamma||\tilde{\Gamma}\right) &= D\left([\rho_1, \rho_2 \ldots \rho_n] \,||\, \left[\frac{1}{N}, \frac{1}{N} \cdots \frac{1}{N}\right]\right) && (5) \\ &= \left(\sum_{i=1}^{N} \rho_i \log_2 \rho_i\right) + \log_2 N && (6) \end{aligned}$$

again, N is the number of nodes, and ρ_i the fractional share achieved by the ith node.

4.3 Results

Simulation trials of the stationary and controlled signal power experiments were undertaken, and both fairness indices calculated as a function of the sliding window size. Figures 5, 6, 7, and 8 present both indices for each capture model, the experimental data, and a simulation trial employing no capture. The window size in each case does not extend beyond 1000 frames, as this represents half the number of frames transferred on each connection. As expected, the fairness improves as the horizon is increased.

The stationary signal power trials, Figures 5 and 6, illustrate how the Delay, Power, and Hybrid models significantly overestimate the fairness performance achieved in each trial. The experimental data exhibits significantly worse unfairness than each of these models indicate. In Figure 5 with TCP, the Message Retraining alternates between under and over estimation of the fairness evident in the trace. This can be attributed to a large timeout in the experiment data [1] which did not occur in the Message Retraining trace. The experimental data reaches a ‘fairness peak’ at a window of 500 frames which may be related to the timeout event in the trace data. Figure 6 with UDP also illustrates the significant difference between the capture models and experiment. The Message Retraining model provides a pessimistic indication fairness according to both indices. In the stationary signal strength experiment the Message Retraining model follows

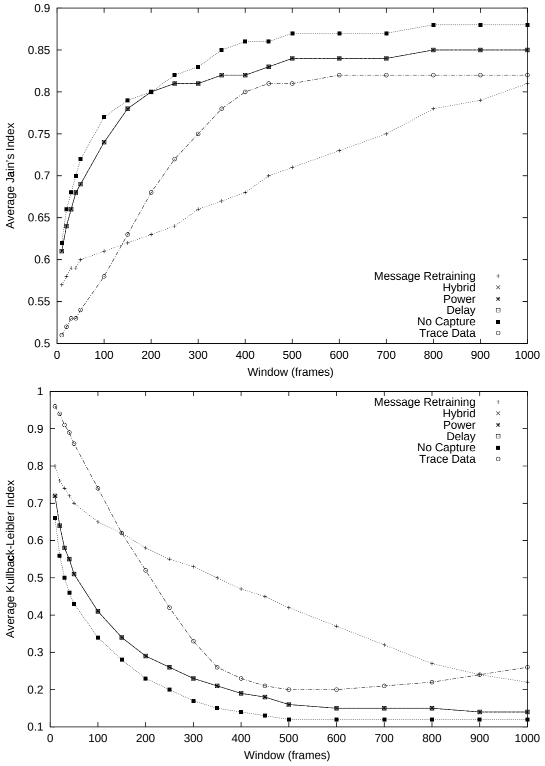

Figure 5: Stationary TCP

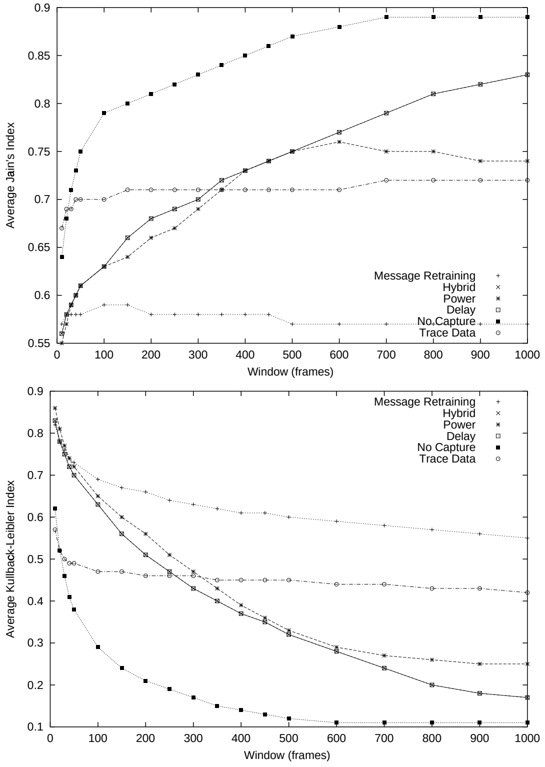

Figure 6: Stationary UDP

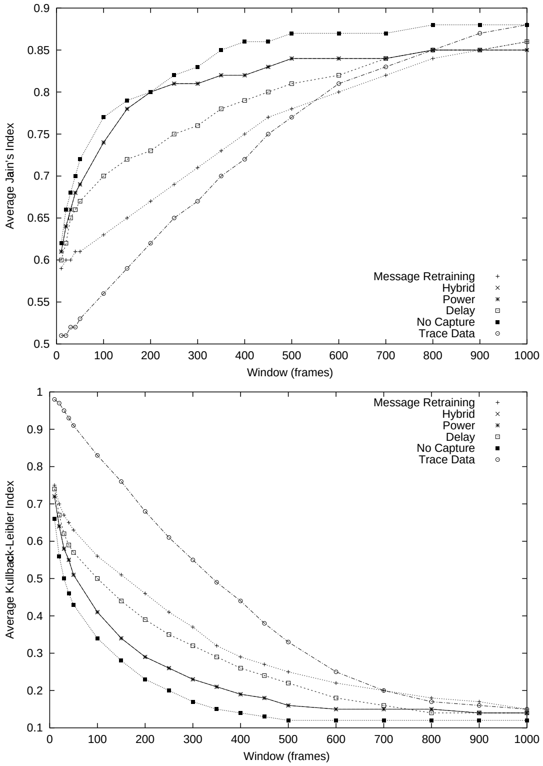

Figure 7: Controlled TCP

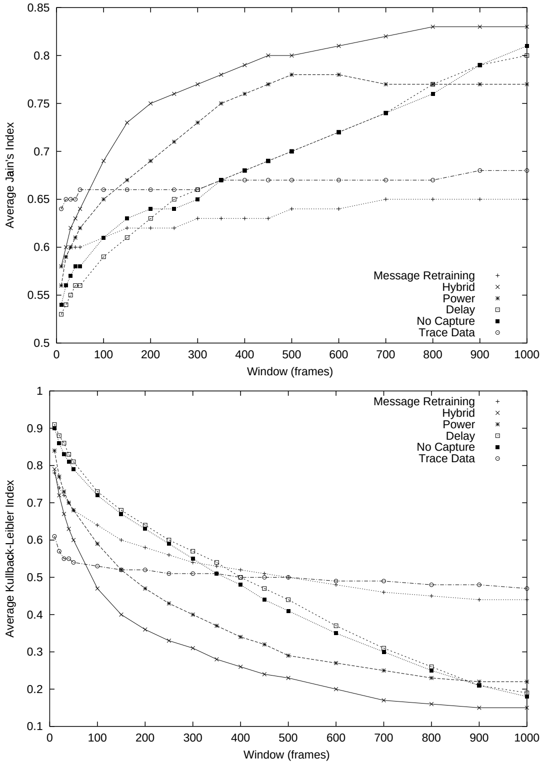

Figure 8: Controlled UDP

the same trend as the trace data, yet maintains a consistent offset. This may be due to a lack of variation in signal strength, and the model allowing a stronger connection to capture a channel for a longer period than is evident in the trace data.

In the controlled signal power experiments, Figures 7 and 8, the Message retraining model is able to follow experimental data, where the other models over estimate the fairness values. With TCP, the fairness was over-estimated (i.e. experimental data exhibited worse fairness properties), while with UDP it was under-estimated. When compared with the Delay, Power, and Hybrid models, Message Retraining is able to match the fairness time scale present in the experimental data quite closely.

Differences between the simulation models and protocol implementations must be considered when interpreting these results. While *ns* is an excellent simulation platform, there are still differences and implementation issues which may lead to varying results. In particular, subtle differences between protocol timers and those in *ns* will result in deviation between simulation and experimentally obtained data. Further, channel variations not accounted for in simulation will also have an impact on the experimental data.

These quantitative results provide a positive indication that the Message Retraining capture model is able to reflect, with reasonable accuracy, the fairness properties that may be obtained by a real system when varying signal strength conditions and hidden terminals exist. Further investigation of the Message Retraining model is required however, to account fully for the overestimation in the stationary signal power UDP experiment.

5 Conclusions

In this paper we have investigated the performance of several capture models in terms of the fairness they indicate a system may provide. We have proposed and investigated the fairness properties of a new capture model, Message Retraining, as a means of providing an accurate description of experimental data. Using two fairness indices we undertake a quantitative study of the accuracy with which each capture model is able to reflect experimental data. The Message Retraining capture model is shown to provide a good estimate of actual system performance in varying signal strength conditions.

Understanding the fairness horizon associated with a PHYS/MAC protocol is important in achieving good performance for real time multimedia traffic flows, and smoothing the flow of TCP acknowledgements. The Message Retraining model can be employed in situations where varying signal strength is expected to impact on system performance. This has specific relevance where nodes in a given topology are unable to sense carrier from near neighbours.

The Message Retraining model may also have application in the development of quality of service mechanisms for the IEEE 802.11 wireless MAC protocols. Achieving a MAC layer free from unfairness arising at the physical layer is paramount if reliable quality of service is to be offered by the MAC protocol. Mechanisms to achieve this require development. Further development and analysis of the Message Retraining capture model is necessary in order to match experimental data more closely, though the current results presented here are very encouraging.

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