Paper

Simulating capture behaviour in 802.11 radio modems

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Abstract — Simulation plays an important role in the performance evaluation of MAC protocols. Building simulation models which are able to accurately model physical behaviour is fundamental to the outcome of such techniques. Through both qualitative and quantitative comparison of experimental trace data against simulation results obtained using delay, power, and hybrid capture models, this paper investigates the performance of various packet capture models in the simulation analysis of the 802.11 PHY and MAC layer protocols. We illustrate these models are unable to accurately describe the fairness properties of the experimental data. A new model is proposed, Message Retraining, to describe the operation of an 802.11 receiver. We illustrate that the Message Retraining reception model is able to model the fairness characteristics obtained with an IEEE 802.11 radio modem more accurately than the previous capture models.

Keywords — wireless local area networks, ad hoc networks, capture models, medium access control protocol, fairness.

1. Introduction

The IEEE 802.11 wireless physical layer (PHY) and medium access control (MAC) protocols have resulted in the widespread adoption of local wireless area networking in 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 – 4] to provide a realistic representation of an IEEE 802.11 radio modem by undertaking both a qualitative and quantitative comparison with experimental data. Our results, combined with work investigating the impact of multiple access interference [5, 6] and parallel receiver structures [7], motivates the development of a new reception model. Thereafter, we will refer to this model as the Message Retraining capture model or simply Message Retraining.

The Message Retraining model allows the modem to retrain onto a newly detected signal [8] with a higher signal power, as a means of explaining the experimental data presented in [1]. Using simulation techniques, we illustrate that this model provides a very accurate description of the physical behaviour, and can be used to investigate the impact this has on higher layer protocols. Using two fairness metrics, we compare the performance of each of the capture models against measured experimental data. The major contribution of this paper is the qualification of the important role modem receiver behaviour plays in the operation of the higher layer protocols in varying signal conditions, and the inclusion of fairness as significant factor in the application of a given packet capture model.

We use an intuitive definition of **fairness** 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. The network model considered in this paper is one involving hidden terminals over a semi-slotted 802.11 MAC/PHY layer. All nodes employ a common spreading code with no power control.

Capture can be considered to occur at two levels:

- **Modem capture** is a property of the radio modem and the modulation techniques employed [9]. Modem capture results in a given transmission being “captured” by the receiver while rejecting interfering frames as noise. Several models based on either power, time of arrival, or both, [2] have been proposed to evaluate the probability of a frame being captured by a receiver as a function of the number of interfering frames.
- **Channel capture** is induced by protocol timing, and results in a channel being monopolised by a single node, or subset of nodes in a given geographic region. Channel capture has been identified as a significant problem for multihop packet networks in many scenarios where disconnected topologies exist [10, 11], or higher layer retransmission and backoff timers are employed [12 – 14].

The original IEEE 802.11 standard [15] defines a medium access control protocol, and three distinct physical layers: an infra-red physical layer (IR), and two spread spectrum layers, one based on frequency hopping spread spectrum (FHSS), and another using direct sequence spread spectrum (DSSS). The 802.11 standard was updated [16] with the addition of the high rate (HR) physical layer extensions. This allowed the DSSS physical layer to operate at 5.5 Mbit/s and 11 Mbit/s in addition to the original 1 and 2 Mbit/s. Further extensions in the 5 GHz band employing orthogonal frequency division multiplexing have also recently been developed [17]. At the MAC layer, the distributed co-ordinate function (DCF) implements CSMA/CA, with an optional request-to-send/clear-to-send (RTS/CTS) handshake prior to transmission of DATA frames. Immediate positive acknowledgement is employed. This scheme is able to operate in a peer-to-peer ad hoc mode, being a fully distributed MAC protocol.

The remainder of this paper is organised as follows: Section 2 reviews the experimental results motivating this work [1], Section 3 presents details of current capture models, as well as our Message Retraining reception model. Section 4 outlines our simulation results. Section 5 presents an investigation of the fairness properties of the simulation and experimental trace data, while Section 6 concludes the paper.

2. Review of experimental results

Recently published experimental results investigating the performance of the IEEE 802.11 MAC protocol in a hidden terminal topology [1], have illustrated that signal strength is a significant factor in determining which node is able to access the radio channel. The experiments uncovered a reliable and repeatable channel capture effect, in which a host with a higher received signal power (measured at the common node) was able to capture the channel.

Each trial involved two simultaneous 500 kbyte file transfers from both hidden senders into the common node. The linear topology with each end node being mutually out of range is illustrated in Fig. 1. A software package called **tcpdump** [18], is used at the central node to trace the progress of each file transfer. An 802.11 compliant wireless network interface is used in the ad hoc mode, employing an RTS/CTS handshake governed by the **aRTSThreshold** management information base (MIB) parameter. This parameter indicates the frame size, above which, an RTS/CTS exchange is initiated.

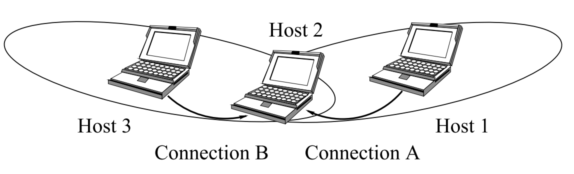

Fig. 1. Experimental topology – host 1 and 3 hidden terminals.

Several parameter combinations and signal to noise ratio (SNR) scenarios were investigated:

- **Trial 1.** No RTS/CTS equal power hidden terminal, SNR = 25 dB.
- **Trial 2.** 500 byte RTS/CTS equal power hidden terminal, SNR = 25 dB.
- **Trial 3.** 500 byte RTS/CTS near(25 dB) – far (20 dB) hidden terminal.
- **Trial 4.** 500 byte RTS/CTS controlled SNR.

The significant result from these experiments is a strong signal power dependence in the channel capture behaviour observed in each trial. In trial 1 without the RTS/CTS handshake and with equal signal power on the contending connections, random channel capture was exhibited. This result is expected, [12] as the combination of MAC and TCP backoff timers is known to result in a channel capture state for one of the contending nodes when hidden terminals are present. In trial 2, employing the RTS/CTS handshake, there was effective sharing of the channel when the signal power was equal on the contending connections. In trial 3, illustrated in Fig. 2 with a signal power differential of 5 dBm, the stronger connection was able to capture the channel, locking out the weaker contending host until the file transfer was complete. This is a reliable and repeatable observation. This result indicates that an unequal signal power scenario prevents the RTS/CTS handshake from providing fair access to the channel.

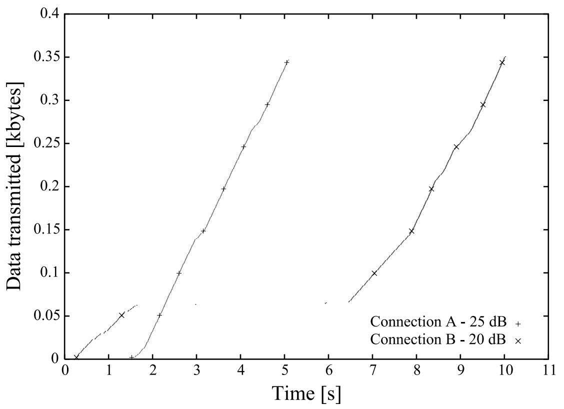

Fig. 2. Stationary SNR, RTS/CTS enabled.

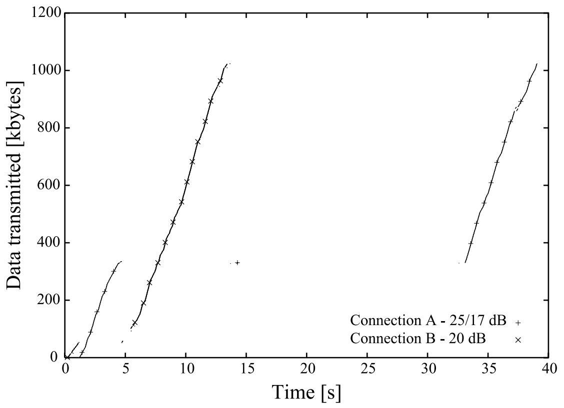

Fig. 3. Controlled SNR, RTS/CTS enabled.

To examine the signal strength dependence experimentally, a further trial was undertaken in which the signal power on one connection was controlled throughout the experiment. In this case, illustrated in Fig. 3, the SNR on connection A was controlled during the transfer. Connections A and B commence the test with a SNR of 25 dB and 20 dB respectively. Five seconds into the trial the signal power of connection A is reduced by 8 dBm through to the end of the experiment. The trace in Fig. 3, clearly illustrates behaviour where the new stronger host, connection B, manages to "re-capture" the channel once the signal power of connection A is reduced.

Once connection B has finished, connection A is able to regain access to the channel. In each case, the connection which manages to capture the channel suffers relatively few TCP timeouts, and retransmissions are simply handled by the MAC and TCP retransmission mechanisms. Conversely, the contending connection will undergo continual timeout and exponential backoff at both the MAC and TCP levels. This results in significant unfairness under heavy load conditions. In the following sections we investigate the ability of capture models presented in the literature in describing this behaviour.

3. Capture models

The development of models describing the initial capture of a frame by a radio modem represents a significant body of literature [2 – 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, and the resulting channel throughput achieved.

There are two significant stages in the successful reception of a frame by a radio modem. Initially, the frame must be successfully detected and subsequently captured by the receiver. Following this, successful reception of the frame must be achieved in the presence of interference, 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 [5, 6, 9] and depends significantly on the modulation technique and spreading codes employed.

Capture models are often used when simulating the performance of wireless networks. The results presented in Section 2 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 of a new transmission interfering with an ongoing transmission.

In scenarios where carrier sense mechanisms are unreliable, it is possible for a node to have no knowledge of an ongoing hidden transmission. This introduces the potential for an interfering transmission to arrive at a common receiver at any time during a slot. As illustrated in Fig. 4, this can be due to differences in the slot time boundaries observed by both hidden nodes. This is further complicated by the slot timing mechanisms within 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 distributed co-ordinate function inter-frame space, DIFS), or returning management frames (the short inter-frame space, SIFS) to maintain the semi-slotted channel. However, the lack of carrier from an opposing hidden node increases the possibility that the node will transmit at what appear random times to the common node.

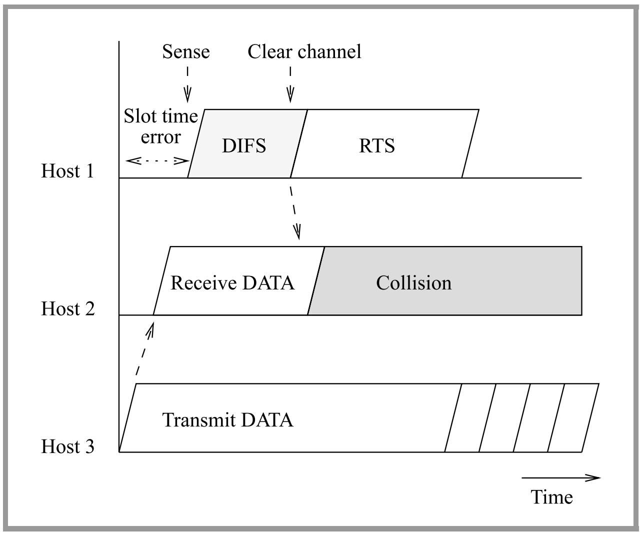

Fig. 4. Potential slot time error.

In Fig. 4, host 3 has commenced a data transfer prior to host 1 (being hidden from host 3) commencing a carrier sense operation. On sensing a clear channel, host 1 defers for a DIFS 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.

In the following sections we briefly review the significant capture models considered in literature, with the Message Retraining reception model outlined in Section 3.4.

3.1. 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 period of time required by a receiver 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.

3.2. Power capture

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

$$P_{max} > \gamma \sum_{i=1}^{N} P_i \,, \qquad (1)$$

where P_{max} is the power of the strongest of N signals arriving, each with power P_i, within the capture time T_c. The model allows a frame to be captured provided 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 incoherent addition of the received power of each frame. This model is the most commonly employed in the 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.

3.3. 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:

$$\gamma \sum_{i=2}^{N} P_i \left[T_1 + T_c - T_i \right] < T_c P_1 \,. \qquad (2)$$

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.

3.4. Message Retraining reception model

Contrary to each of the models presented above, [8] describes an enhanced capture technique 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 a short duration at the start of a frame. We therefore propose an extended capture model, termed Message Retraining which incorporates the enhanced capture ability.

The model allows the modem to receive a new transmission (signal 2 in Fig. 5) which may arrive at a random time during the reception of a previous frame (signal 1 in Fig. 5), provided the new transmission has sufficient relative power to enable successful synchronisation and demodulation of the frame preamble. As indicated in [5], energy associated with the new transmission will have a significant impact on the BER observed at the correlator output for the original frame. Results presented in [5] indicate the previous 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:

$$\gamma_{MR} \sum_{i=1, i \neq j}^{N} P_i < P_j \,. \qquad (3)$$

This model allows for the successful reception of the strongest arriving frame received throughput 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). Furthermore, the initial frame may be successfully received provided the standard power capture equation, Eq. (1) holds.

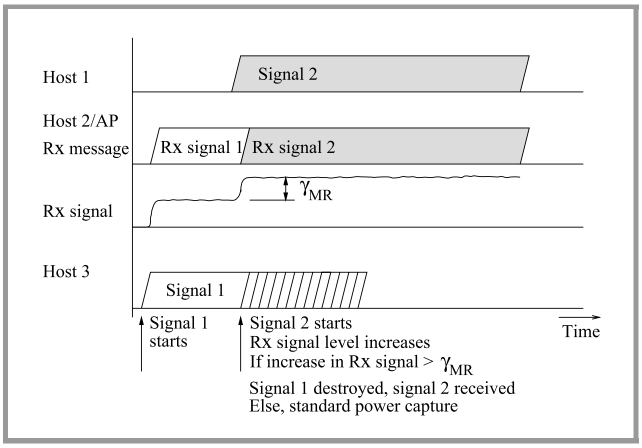

Fig. 5. Illustration of the operation of the Message Retraining model.

As the purpose of this paper is the evaluation of capture models for simulation, a more detailed analytic study of this model in terms of probability of successful reception of a frame is considered in future studies.

4. Simulation results

4.1. Simulation description

Each of the capture models described previously has been implemented using the *ns* simulation package. This package contains an 802.11 PHY/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. Capture decisions are made within each modem based on the received signal strength, capture threshold, and other relevant parameters for each model. Each node receives a copy of the transmitted packet and based on the received power, determines whether the transmission was observable or not. If the frame is received with sufficient power, a capture decision in accordance with each model is made prior to passing the frame up to the MAC protocol.

Table 1
Modem simulation parameters

Parameter	Value
γ	5 dB
P_t (nominal)	15 dBm
R_b	2 Mbit/s
Sensitivity	−95 dBm
f	2.412 GHz
T_c	120 μs

Parameters for the modem are listed in Table 1. The capture threshold is selected based on measurements presented in [1] and design parameters of the Message Retraining process in an 802.11 modem [8]. P_t represents the nominal transmitter power of the radio modem, R_b the channel bit rate (determined by the combination of spreading sequence and modulation technique employed), f the operating frequency, and T_c the capture interval which corresponds to the duration of the preamble and sync bits in the 802.11 PHY header. As the 802.11 standard requires that the PHY preamble and header are transmitted at 1 Mbit/s with an 11 chip Barker code using DBPSK modulation, or possibly 2 Mbit/s with the 11 chip Barker code using DQPSK modulation (where short the PLCP preamble/header option is available), we use a value of R_B at 2 Mbit/s.

Simulation trials of the controlled SNR experimental trial outlined in Section 2 were performed using each of the capture models. Each trial involves two hidden connections, as illustrated in Fig. 1 transferring data to a common node, using TCP. Connection B starts at 4 seconds, with connection A starting at 5 seconds. A total of 2048 packets of 512 bytes are transmitted over each connection. Initially, connection A is stronger than connection B by at least the capture ratio. At 10 seconds, this situation is then reversed for the remainder of the transfer.

In this section we present simulation traces of the controlled SNR experiment described in Section 2. The traces in Figs. 6 – 10 provide a qualitative means of comparing each of the capture models with recorded data. In Section 5 we undertake a quantitative comparison of each model with recorded data using fairness metrics over the length of the trace.

4.2. No capture

In the case where no modem capture is implemented, any colliding transmission at the common receiver will result in both frames being destroyed. Backoff and retransmission then results in reasonably effective sharing of the radio channel. In Fig. 6, alternating periods where either connection is able to dominate the radio resource are due to protocol timing interactions between MAC and TCP retransmission timers [12].

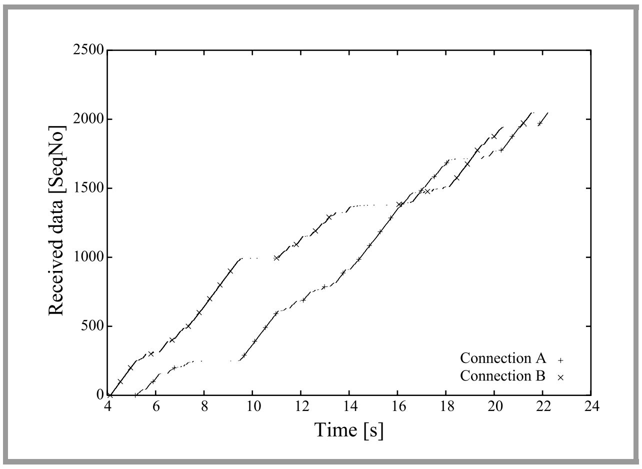

Fig. 6. No capture model – controlled SNR.

4.3. Delay capture

The delay capture model makes no account of signal strength characteristics. Figure 7 exhibits random periods during which one of the connections is able to capture the majority of the channel resource. This is again due to the interaction between MAC backoff timers and the TCP timers at the transport layer. Connection B also gains a slightly higher transfer rate than connection A, showing no evidence of the changed signal power at 10 seconds. This is due to connection B starting before connection A, and therefore having a larger TCP window at the time connection A commences. Connection B is able to expand it's TCP window without contention for the channel, whereas connection A must contend from the establishment of the TCP connection. The connection start times were staggered in this manner to match the experimental data in Section 2.

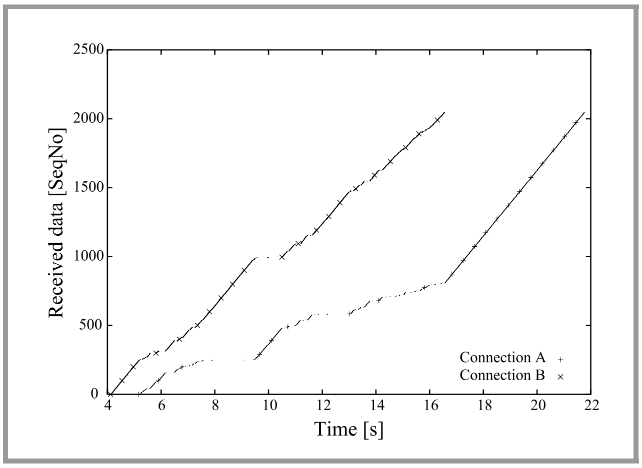

Fig. 7. Delay model – controlled SNR.

4.4. Power capture

The power capture model trace in Fig. 8 displays similar behaviour to the delay capture model. Neither connection is able to dominate. There is no evidence of the sustained channel capture exhibited in Fig. 3, nor any evidence of the transmission power change at 10 seconds.

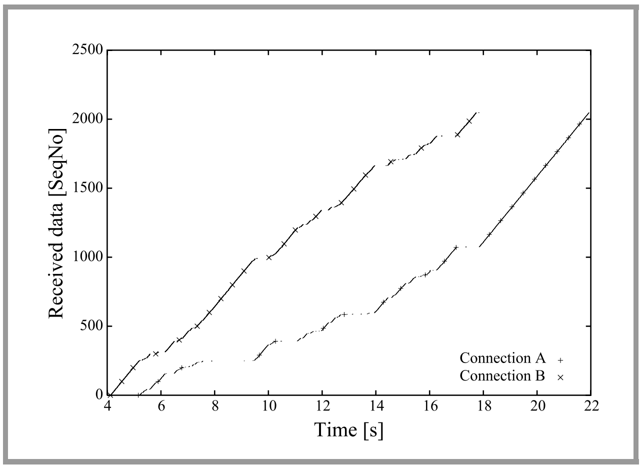

Fig. 8. Power model – controlled SNR.

4.5. Hybrid capture

Connection B again gains the advantage of a larger TCP window at the time connection A commences. As with the power model, there is no evidence of behaviour approaching that observed in the experimental trial.

In each of Figs. 6 – 9, the change in signal strength at 10 seconds has little impact on the channel access achieved by each connection. This represents a significant shortcoming for the delay, power and hybrid capture models, failing to reflect the impact varying signal strength characteristics have on connection quality.

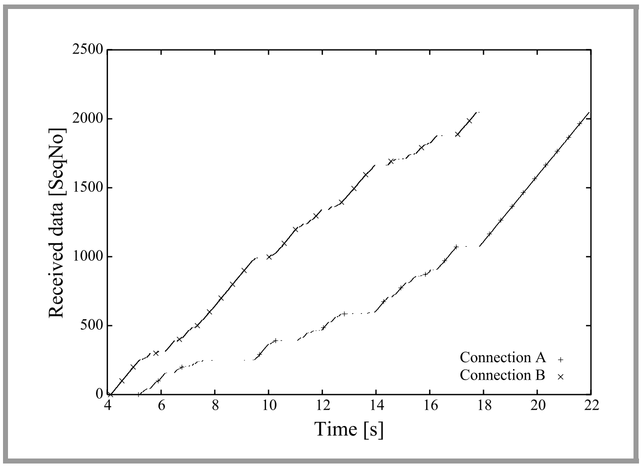

Fig. 9. Hybrid model – controlled SNR.

4.6. Message Retraining

The trace for the Message Retraining model in Fig. 10 appears to match the measured data of Fig. 3 quite closely. Once connection A commences as the stronger connection, connection B is prevented from gaining reliable channel access. 10 seconds into the trace, connection B, the new stronger connection, is able to capture the channel from connection A, which is in turn prevented from gaining fair access until connection B finishes.

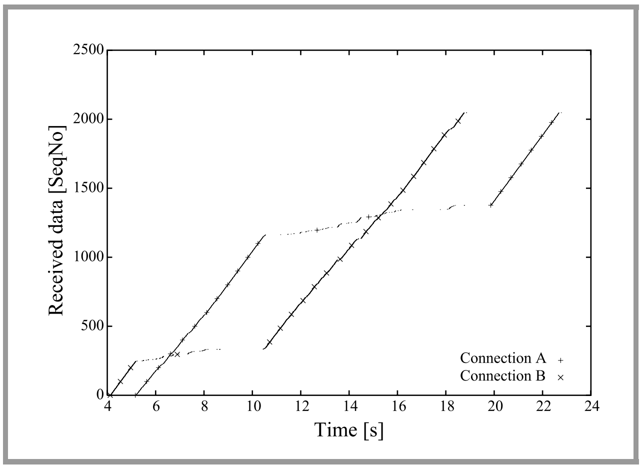

Fig. 10. Message Retraining model – controlled SNR.

In the following section, we employ two fairness indices to quantify the relative performance of each model against experimental data.

5. Comparison metrics

To make a quantitative comparison of the results obtained with each capture model, a fairness metric is required. Fairness in wireless networks can be a difficult quantity to define. 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.

Following [19], we employ two fairness indices: Jain's fairness index, and a new index proposed in [19], the Kullback-Leibler fairness index. In each case, a sliding window method is used to calculate the fairness over a horizon of 200 frames. 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. The selection of this window size is motivated by the length of the traces. A window of 200 frames corresponds to 10% of the frames transferred over each connection.

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

5.1. Jain's fairness index

This index has been used widely in the literature to capture fairness characteristics in both congestion control [20] and wireless MAC protocols [19]. A perfectly 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 good fairness properties. The index F_j is defined in Eq. (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.

5.2. Kullback-Leibler fairness index

The Kullback-Leibler fairness index was first proposed in [19]. 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, $\tilde{\Gamma}$:

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

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

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 good fairness properties.

Table 2
Fairness index comparison

Capture model	Experiment			
	stationary SNR		controlled SNR	
	Jain	K-L	Jain	K-L
None	0.80	0.23	0.80	0.23
Delay	0.80	0.29	0.73	0.39
Power	0.80	0.29	0.80	0.29
Hybrid	0.80	0.29	0.80	0.29
M-R	0.63	0.58	0.67	0.46
Trace data	0.68	0.52	0.62	0.68

Simulation of both the stationary and controlled signal power trials of Section 2 were performed and both fairness indices calculated. These results are then compared with the fairness indices from the measured traces. Table 2 illustrates the average fairness index for each capture model.

5.3. Discussion

The stationary signal power experiment illustrates that the delay, power and hybrid capture models provide an overestimate of the fairness observed experimentally. The Message Retraining model though slightly underestimating the fairness measured with both indices, provides an excellent indication of the fairness properties present in the experimental data.

The controlled signal power scenario represents a more challenging task for the capture models than the stationary signal power scenario. Varying signal conditions throughout the experiment are reflected in the measured trace, and should also be observed in a simulated trace. As illustrated in Section 4, this was not the case, and we would therefore expect the delay, power and hybrid models to significantly overestimate the fairness achieved by each connection. The results in Table 2 confirm this, with the delay, power and hybrid models all significantly overestimating the fairness present in the experimental data.

The Message Retraining model matches the experimental data according to Jain's index quite closely, though the Kullback-Leibler index is still shows significantly higher unfairness. This can be attributed to the long period in the experimental data (Fig. 3) between 15 and 32 seconds where no data is transferred. This is due to a significant TCP timeout on connection A. While the Message Retraining model resulted in a significant reduction in throughput during this time (Fig. 10), connection A was still able to maintain sufficient throughput to prevent a long TCP timeout. This result also indicates the sensitivity of the Kullback-Leibler index.

6. Conclusions

Simulation plays an important role in performance evaluation of wireless MAC protocols. In this paper we have investigated the performance of a number of common modem capture models presented in literature, in terms of their ability to accurately reflect fairness properties of experimentally derived trace data. We have proposed a new capture model, which we show is able to model the dynamic fairness properties of the IEEE 802.11 PHY/MAC with varying signal conditions more accurately than the delay, power, or hybrid capture model.

Quantitative comparison between experimental trace data and simulation traces for each capture model using both Jain's fairness index and the Kullback-Leibler fairness index, illustrates than the delay, power, and hybrid capture models provide an overly optimistic estimate of the fairness afforded to the contending hidden connections. The Message Retraining model is shown to match the experimental data well.

Our results indicate that in cases where fairness is an important component of network performance, a more detailed capture model is required to reflect the impact of varying signal strength characteristics, and describe modem behaviour in a more complete manner.

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