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Simulation of Capture Behaviour in IEEE 802.11 Radio Modems

C. Ware
University of Wollongong

Joe F. Chicharo
University of Wollongong, chicharo@uow.edu.au

Tadeusz A. Wysocki
University of Wollongong, wysocki@uow.edu.au

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Simulation of Capture Behaviour in IEEE 802.11 Radio Modems

Christopher Ware, Joe Chicharo, Tadeusz Wysocki
Telecommunications and Information Technology Research Institute,
University of Wollongong, Wollongong, NSW, Australia, 2522
chris@titr.uow.edu.au

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 empirical data. The Message Retraining capture model is shown to provide a good estimate of actual system performance in varying signal strength conditions.**

I. INTRODUCTION

The IEEE 802.11 wireless Physical Layer (PHY) and Medium Access Control (MAC) protocol has been instrumental in the recent widespread adoption of wireless local area networking. However, recent experiment [1], [2] 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 [3], [4], [5] 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*, and compare against the empirical data presented in [1], [6].

We illustrate that the standard capture models are unable to accurately reflect the fairness properties evident in each trace. A new capture model termed *Message Retraining* is presented based on the physical operation of an IEEE 802.11 radio modem [7]. This model is derived from work investigating the impact of multiple access interference [2], [8] and parallel receiver structures [9]. We investigate the fairness properties of traces generated using this model.

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. This is an appropriate fairness goal given the MAC is a best effort protocol, containing to service differentiation or other QoS mechanism. 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, and for the support of real time traffic streams.

We consider a network model involving hidden terminals over a semi-slotted 802.11 MAC/PHY layer, as illustrated in Figure 1. All nodes employ a common spreading code with no power control. The *ns* package contains an 802.11 MAC layer model, and provides 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 II presents details of current capture models. Section III presents details of the Message Retraining Reception model. Sections IV and V present an investigation of the fairness properties of the trace data, while Section VI concludes the paper.

II. CAPTURE MODELS

The development of models describing the initial capture of a frame by a radio modem represents a significant body of literature [3], [4], [5]. 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, then determine the resulting channel throughput achieved as the product of capture probability and offered load.

Capture can be considered to occur at two levels:

- *Modem Capture* being a property of both the radio modem and modulation technique employed [11]. 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, [3] 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 [12], [13], or higher layer retransmission and backoff timers are employed [14], [15], [16].

Two significant stages are present in the successful reception of a frame by a radio modem. Initially, the frame must be successfully detected and captured by the receiver. Following this,

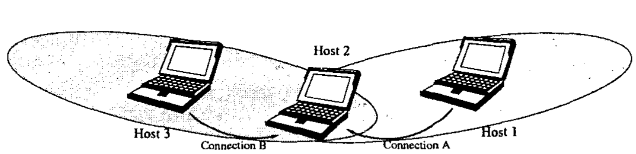

Fig. 1. Topology

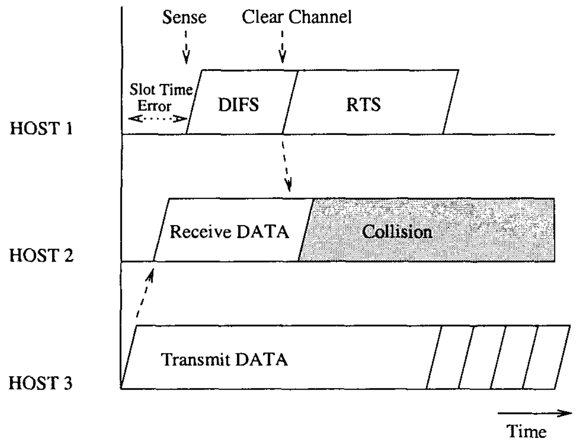

Fig. 2. Potential Slot Time Error

successful reception of the frame must be achieved in the presence of interference, from other transmissions and external noise sources. Most literature [3], [4] has considered only 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 [11], [8], [2] and depends significantly on the modulation technique and spreading codes employed.

Capture models are often used when simulating the performance of wireless networks. However, results presented in [1], [2] suggest a more complex capture behaviour is present in the case of an IEEE 802.11 radio interface, resulting in the significant unfairness evident in experimental data. Further complications arise in cases where hidden nodes are likely (e.g. a mobile ad hoc network). Specifically, there is a strong probability 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 reception.

In scenarios where carrier sense mechanisms are unreliable, it is possible for a node to have little 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 Figure 2, 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 coordinate 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.

In the example shown in Figure 2, Host 3 has commenced a data transfer prior to Host 1 (being hidden from Host 3) initiating 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 presented in the literature.

A. Delay Capture

Delay capture originally described by Davis and Gronemeyer [4], 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.

B. Power Capture

Power capture, originally described with Rayleigh fading, and constant transmitter power [5], is described by the following inequality over the interval $[0, T_c]$:

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

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.

C. Hybrid Capture

The hybrid model was originally proposed by Cheun and Kim [3]. 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

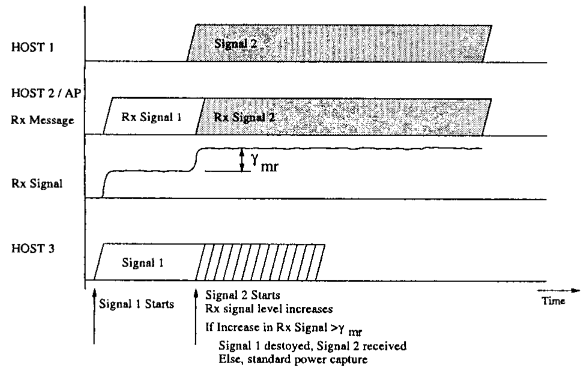

Fig. 3. Operation of the Message Retraining model

with the initially detected frame and reject other transmissions as noise.

III. Message Retraining Reception Model

Contrary to each of the models presented above, [7] 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.

Another factor which motivates a new model is the behaviour of the correlation detection circuit when a new stronger signal arrives, causing interference with an ongoing reception process. In cases where the energy of the new frame is sufficiently higher than the initial frame, then the potential exists for the correlation detector to be 'reset' by this increase in energy. This is due to the use of common spreading codes for all users in the network, as the correlation peaks appear to be identical for signals from all users. The result may be the subsequent loss of the initial frame, and successful reception of the new frame. In cases where the detection circuit does not employ multiple reception paths (discriminating between users through time separation of the arriving signals [9]) the receiver will be unable to receive the initial frame when the interfering frame has sufficient power, whereas the stronger frame would suffer little interference due to the weaker frame.

In either case, 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 or slot. We therefore propose an extended capture model, termed *Message Retraining* which incorporates this enhanced capture behaviour.

The model allows the modem to receive a new transmission (Signal 2 in Figure 3) which may arrive at a random time during the reception of a previous frame (Signal 1 in Figure 3), provided the new transmission has sufficient relative power to enable successful synchronisation and demodulation of the frame preamble. [2] illustrates 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. Results indicate the previous frame will be unintelligible if the signal power difference between the new and existing transmission is greater than a threshold of between 3 and 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 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, (1) holds.

IV. Fairness Study

To make a quantitative comparison of each capture model with the empirical 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], [6], 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. The reader is referred to [1], [6] 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.

A. *Jain's Fairness Index*

This index has been used widely in the literature to describe the fairness characteristics in both congestion control [17] 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).

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

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.

B. *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.

$$D\left(\Gamma||\tilde{\Gamma}\right) = D\left([\rho_1, \rho_2 \cdots \rho_n] \,||\, \left[\frac{1}{N}, \frac{1}{N} \cdots \frac{1}{N}\right]\right) \qquad (5)$$

$$= \left(\sum_{i=1}^{N} \rho_i \log_2 \rho_i\right) + \log_2 N \qquad (6)$$

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

V. Results

In [1], [6], 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 with a UDP "null" transport layer. The reader is referred to [1] for further detail on each experiment.

Simulation trials of the stationary and controlled signal power experiments were undertaken, and each fairness index calculated using a sliding window method along the trace. The average value of each fairness index is presented as a function of the sliding window size. Figure 5 presents controlled signal power

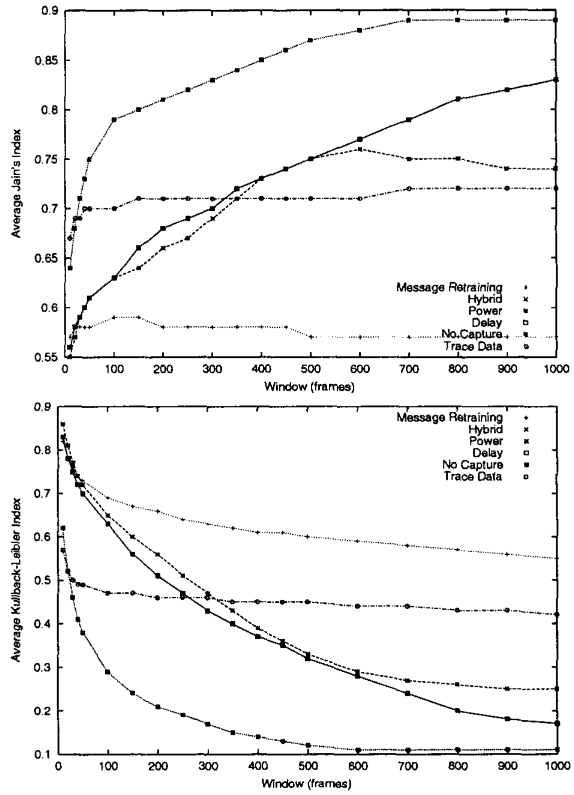

Fig. 4. Stationary signal power experiment. Fairness index as a function of sliding window size

UDP results, illustrating both fairness indices for the capture models, 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.

Commencing with the stationary signal power experiment, the Power, Delay, and Hybrid models over estimate the measured fairness as the window increases in size. At very small window sizes, all models illustrate significant unfairness. The Power, Delay, and Hybrid models quickly display increased fairness as the window increases. Figure 4 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 power experiment the Message Retraining model follows the same trend as the trace data, yet maintains a consistent offset. This may be due to a lack of variation in signal power, and the model allowing a stronger connection to capture a channel for a longer period than is evident in the trace data. The result indicates that the Message Retraining model follows the same flat trend as the empirical data across the range of window investigated, in contrast to the other models.

The controlled signal power experiment result, Figure 5, illustrates how the Message Retraining model is able to match experimental data while other capture models over estimate the

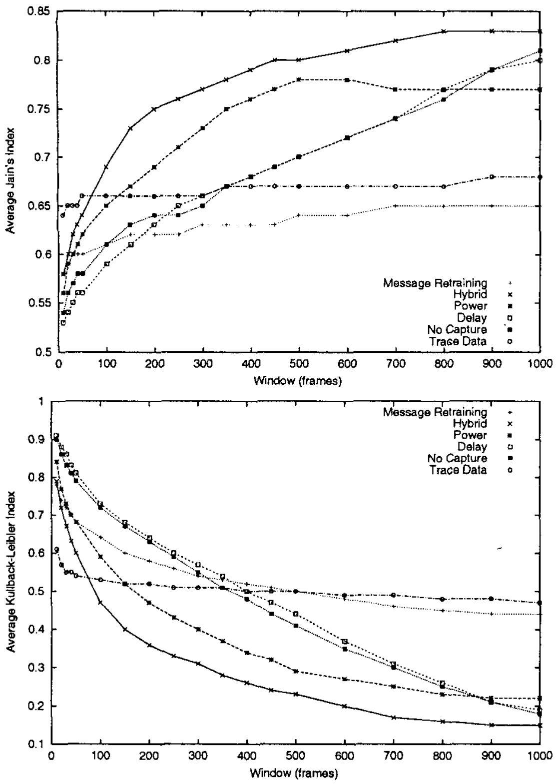

Fig. 5. Controlled signal power experiment. Fairness index as a function of sliding window size

fairness present in the trace. 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, implementation subtleties may lead to variation in the 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.

VI. Conclusions

In this paper, we have investigated the performance of several capture models in terms of the accuracy with which they are able to model the fairness properties of a real system. We have proposed and investigated the fairness properties of a new Message Retraining capture model, as a mechanism to provide a more 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 MAC/PHY 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.

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