A CHANNEL PREDICTOR FOR WIRELESS PACKET NETWORKS

Javier Gomez and Andrew T. Campbell

Department of Electrical Engineering and
Center for Telecommunications Research
Columbia University, New York, NY 10027, USA
{javierg,campbell}@comet.columbia.edu

ABSTRACT

For wireless channels, interference mitigation techniques are typically applied at the bit/packet transmission level. In this short paper, we present a simple channel predictor that responds to impairments that are present at the packet transmission time scale. A channel predictor determines whether to transmit a packet or not depending on the state of the wireless channel. Channel state information provided by the predictor can be used as the foundation to perform compensation for flows experiencing bad link quality.

1. INTRODUCTION

The most prominent characteristics associate with wireless networks is the premium placed on bandwidth and power efficiency as well as the use of unreliable time varying transmission links. Existing protocols for wireline networks are very limited in their ability to deal with these issues; they are generally designed to provide fixed services with little ability to adapt to highly time-varying conditions associate with wireless networks. Channel prediction allows the system to defer transmission to mobile devices experiencing time varying conditions (e.g., fading).

Much of the literature that discusses compensation mechanisms for flows due to fading conditions assumes either perfect prediction of the channel state or some apriori knowledge of the channel behavior is required. In [1] for example, fade periods are considered to last between 50 to 100 msec. Given this assumption, the scheduler defers transmission to a mobile device for a period of 50-100 msec when a fade occurs. A drawback of this approach is that if fade periods are actually shorter than 50-100 msec, the predictor will not observe good state periods in which packets could have been transmitted on the channel. In [3], the base station assumes it has instantaneous knowledge of channel conditions. In [12] two strategies are discussed to determine the state of the wireless channel. The first strategy uses link layer acknowledgments to determine if a packet has been received correctly or not. The second strategy assumes the mobile device continuously monitors packets across the air-interface, even in the case of packets addressed to other mobile devices. A problem with the second strategy is that the mobile device has to decode each packet (including headers) which has an impact on battery-powered devices. A packet exchange protocol that uses Request-To-Send (RTS) and Clear-To-Send (CTS) as a channel predictor is proposed in [4]; however, no evaluation of the scheme is discussed. In this paper, we evaluate the use of RTS-CTS as a channel predictor and show the limits of such an approach.

In this paper, we present the design and analysis of the predictor over a wireless IP network supporting IEEE 802.11 last hop wireless LANs. The paper is organized as follows. Section 2 we describe the operation of the predictor followed by an analytical model in Section 3. Section 4 presents some final remarks.

2. THE PREDICTOR

Channel prediction allows a transmitter to probe the state of the wireless channel before transmitting a packet. If the predictor detects that the channel-state is ‘bad’ then the packet remains queued in the scheduler for later transmission and the flow-state is ‘credited’ appropriately. If the channel-state is detected to be in a ‘good’ state then a packet is transmitted [4]. Previous work on channel prediction either assumes that the state of the channel or the duration of bad link periods are known in advance [4] [3] [12]. In practice, however, the state of wireless links cannot be entirely predicted.

To estimate the state of the channel, we have implemented a simple handshake probing protocol based on the well-known RTS/CTS mechanism. Our channel predictor operates as follows. Before the start of packet transmission a mobile device sends a short probing RTS packet to the designated receiver. The receiving device responds by sending a CTS packet as an acknowledgment to the RTS. If the CTS packet is received intact the state of the channel is assumed to be good. On the other hand if the CTS is not received after a given timeout then the channel state is considered to be bad. We assume that the RTS or CTS could have been corrupted, lost or incorrectly received because of degrading channel conditions which may manifest as increased bit errors and loss of signal.

In IEEE 802.11, RTS-CTS is used in DCF mode to compensate for the hidden terminal problem, which can lead to a very high numbers of collisions on the channel for heavy traffic load. However, even if RTS-CTS fails because of channel errors, the transmitting mobile device always assumes the problem is the result of hidden terminals and will back-off before trying again. During PCF operation, the access point is able to acquire the channel before any of the neighboring mobile devices in the coverage area. Therefore, there is no need to use RTS-CTS to prevent collisions in this instance. Rather any packet received in error in the PCF mode is unambiguously the result of channel conditions. In our framework the predictor operates in the PCF mode to verify the state of the channel. In IEEE 802.11/PCF mode the access point always initiate transmission for both downlink (transmitting the packet) or uplink (polling a mobile). Therefore, RTS-CTS can be used in both downlink/uplink transmission. We use RTS-CTS for downlink and Request-To-Receive (RTR) and Clear-To-Receive (CTR) for uplink as a means to differentiate between up/down link operations.

3. ANALYSIS

Our main motivation in this section is to use an analytical framework to investigate the bounds and utility of this approach. A Markov model is used to model the good and bad states of a wireless channel [15]. We assume that transmission of packets during good periods assures error free delivery. In contrast, during bad periods we assume that a transmitted packet will be received in error. This simple assumption simplifies the analysis and is realistic for IEEE 801.11 where no Forward Error Correction (FEC) protection is applied to transmitted packets and only CRC is used [11]. The transition between states occurs at discrete time instances according to the transition rates. Rather than using a single set of transition rates for a particular channel model, we analyzed the performance of the channel predictor for a wide range of rates.

Table 1 shows all the possible outcomes of RTS, CTS, DATA and ACK event combinations for one packet transmission. Note that uplink analysis is similar but uses RTR-CTR. Any packet transmitted can be received error-free (0) or in error (1). If both RTS and CTS packets are received correctly, the state of the channel is predicted as error-free, otherwise the channel is predicted in error. Depending on the reception of the DATA and the ACK packets the transmission is evaluated in the same way as the predictor.

Figure 1 shows a typical two state Markov model. More formally, let $1/\lambda$ and $1/\gamma$ be the average time the channel is in good and bad states, respectively. The transition matrix of the Markov process is as follow [15]:

RTS	0	0	1	0	0	0	0	1	1
CTS	0	1	*	0	0	1	1	*	*
prediction	0	1	1	0	0	1	1	1	1
DATA	0	0	0	1	0	1	0	1	0
ACK	0	0	0	*	1	*	1	*	1
transmission	0	0	0	1	1	1	1	1	1

Table 1: *Prediction Table (legend: 0:error-free, 1:error, *:timeout)*

$$P = \begin{pmatrix} P(0|0) & P(1|0) \\ P(0|1) & P(1|1) \end{pmatrix} = \begin{pmatrix} 1-\lambda & \lambda \\ \gamma & 1-\gamma \end{pmatrix} \quad (1)$$

With the steady state probability of the channel being in bad/good state given by:

$$\pi_1 = \lambda/(\lambda+\gamma) \quad ; \quad \pi_0 = 1-\pi_1 \quad (2)$$

Initially at time T_0 the process is in one of the states X_{T_0} and at some time T_1, the process jumps to the other state X_{T_1} and so on. If the process has just moved to a state $X_{T_n} = i$ at time T_n, the time interval from T_n until the instant the process moves to the other state, denoted by w_n, is an exponentially distributed random variable with parameter a then:

$$P = \{T_{n+1} - T_n > t | X_{T_n} = i\} = P\{w_n > t\} = e^{-at} \quad (3)$$

Now let T_{pred}, T_{tran} and $T_{pred+tran}$ be the time it takes to transmit the predictor packets (RTS and CTS) the data packets (DATA and ACK) and the whole sequence (RTS, CTS, DATA and ACK), respectively. Before the transmission of CTS, DATA and ACK packets in IEEE 802.11 the transmitter waits for a Short-Inter-Frame-Space ($SIFS$) [11], respectively.

The probability that the channel predictor is correct P_{pred}, is equal to the probability that RTS, CTS, DATA and ACK packets are received error-free plus the probability that predictor (RTS and CTS) and transmitted packets (DATA and ACK) are received in error, see Table 1. Figure 1 illustrates the four cases (1-4) in which prediction and transmission outcomes are equal. Because the four cases are disjoint, the probability that channel prediction is correct equals the sum of the probabilities for each case. If P^i_{pred} represents case i in Figure 1, then $(P_{pred}) = \sum_{i=1}^{4} P^i_{pred}$. We simplify the model by taking into consideration that at most, only one channel state transition can occur during the transmission of RTS and CTS packets. Channel state transitions much smaller than RTS and CTS packets are out of the operational range of channel prediction, where other techniques

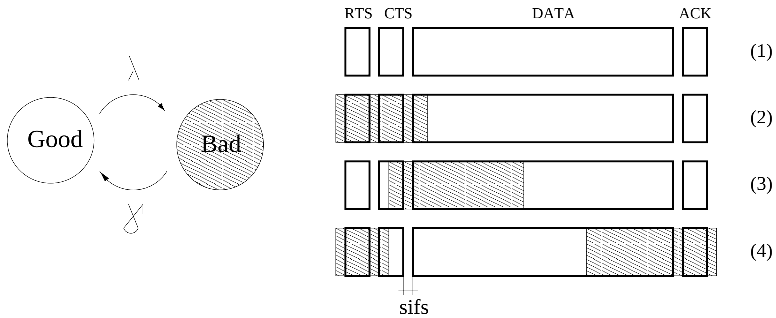

Figure 1: *Channel Model and Predictor Scenarios*

(e.g., forward error correction, interleaving), are more appropriate.

Figure 1 scenario (1) illustrates the case where the channel is in a good state at the beginning of an RTS and remains in good state until the corresponding ACK is received. We neglected the case when the channel changes from good to bad and from bad to good states during a $SIFS$ interval, then using Equation 3:

$$P^{(1)}_{pred} = P\{T_1 - T_0 > T_{pred+tran}; X_{T_0} = good\} \qquad (4)$$

$$\begin{aligned} P^{(1)}_{pred} &= P\{T_1 - T_0 > T_{pred+tran} | X_{T_0}\} P\{X_{T_0} = good\} \\ &= \pi_0 e^{-\lambda t_{pred+tran}} \end{aligned} \qquad (5)$$

Predictor packets (RTS-CTS or RTR-CTR) and data packets (DATA-ACK) can be received in error in different ways as illustrated in Figure 1 scenarios (2), (3) and (4). Figure 1 scenario (2) illustrates the case where the channel is in bad state at the beginning of RTS and remains in bad state at least until the beginning of the DATA packet. Using a similar derivation to equation 4 but now with the channel in bad state at time zero, then:

$$P^{(2)}_{pred} = P\{T_1 - T_0 > T_{pred}; X_{T_0} = bad\} \qquad (6)$$

$$\begin{aligned} P^{(2)}_{pred} &= P\{T_1 - T_0 > T_{pred} | X_{T_0} = bad\} P\{X_{T_0} = bad\} \\ &= \pi_1 e^{-\gamma T_{pred}} \end{aligned} \qquad (7)$$

In Figure 1 scenario (3) the channel is in good state at the beginning of the RTS (T_0), at time T_x the channel changes to a bad state before the CTS is completely transmitted and it remains in a bad state until the beginning of the transmission of DATA packet. If w_0 and w_1 are the intervals the channel is in good and bad states, respectively, then:

$$P^{(3)}_{pred} = \int_{T_0}^{T_{pred}} P\{w_1 > T_{pred} - T_x; w_0 = T_x - T_0\} dt_x \qquad (8)$$

$$\begin{aligned} P^{(3)}_{pred} &= \int_{T_0}^{T_{pred}} P\{w1 > T_{pred} - T_x | w_0 = T_x - T_0\} * \\ &* \quad P\{w_0 = T_x - T_0\} dT_x \end{aligned} \qquad (9)$$

$$P^{(3)}_{pre} = \int_{T_0}^{T_{pred}} (1 - e^{-\lambda T_x})(e^{-\gamma(T_{pred} - T_x)}) dT_x \qquad (10)$$

The final scenario shown in Figure 1 scenario (4) illustrates the case where the channel is in a bad state at the beginning of transmission of an RTS and at time t_x changes to a good state before the CTS is completely transmitted. Furthermore, the channel returns back to a bad state before the corresponding ACK is received. Following a similar formulation to scenario (3) in Figure 1 assuming the channel is in a bad state at time T_0:

$$P^{(4)}_{pred} = \int_{T_0}^{T_{pred}} P\{w_1 < T_{pre+tran} - T_x; w_0 = T_x - T_0\} dt_x \qquad (11)$$

$$\begin{aligned} P^{(4)}_{pred} &= \int_{T_0}^{T_{pred}} P\{w1 < T_{pred+tran} - T_x | w_0 = T_x - T_0) * \\ &* \quad P(w_0 = T_x - T_0\} dT_x \end{aligned} \qquad (12)$$

$$P^{(4)}_{pre} = \int_{T_0}^{T_{pred}} (1 - e^{-\gamma T_x})(1 - e^{-\gamma(T_{pred+tran} - T_x)}) dT_x \qquad (13)$$

The RTS-CTS probe introduces a small overhead in the protocol in PCF mode. For mobile devices experiencing continuous fading conditions, the predictor will provide enhanced throughput. In contrast, mobile devices continuously experiencing a good link will receive little benefit from the use of the predictor channel probe. The downside of this scheme is the overhead of sending the probe pair for each data packet transmission. An enhancement to this approach is to have a simple mechanism that turns the predictor off when the channel has been in a good state for some time and then turn it on only when a packet is observed to be erroneous.

Since the predictor can avoid unwarranted multiple retransmissions to a receiver in a bad channel state, the channels throughput can be enhanced. Channel prediction, however, does not provide any compensation techniques for receivers that have deferred transmission in the past due to bad channel state conditions [1]. Although receivers in a good state can benefit from the deferred transmission of receivers in a bad state, they are not typically re-compensated after the state of the deferred receiver becomes good. Therefore a mechanism to 'credit/compensate' flows is necessary.

4. CONCLUSION

In this paper we have discussed an approach to channel prediction. The implementation discussed in this paper is based on the IEEE 802.11, however, the ideas and results presented are also more broadly applicable to emerging wireless protocol that need to respond to service fluctuations in a controlled manner. Analytical results have been presented. They indicate that channel prediction accuracy diminishes quickly as the packet transmission time increases and as the channel state transitions approximate the packet transmission time. Channel prediction needs to be integrated with other channel-mitigation mechanism to provide a good estimator of the state of the wireless channel.

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