On Carrier-Sense Integration in Learning Automata-based MAC Protocols for Ad-hoc Wireless LANs

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Abstract

A Carrier-Sense-Assisted Learning Automata-based MAC Protocol for Wireless LANs, capable of operating efficiently under bursty traffic and unreliable channel feedback, is introduced. According to the proposed protocol, the mobile station that is granted permission to transmit is selected by means of Learning Automata. At each station, the Learning Automaton takes into account the network feedback information in order to update the choice probability of each mobile station. The proposed protocol utilizes carrier sensing in order to reduce the collisions that are caused by different decisions at the various mobile stations due to the unreliable channel feedback.

1 Introduction

There are fundamental differences between wireless and wired LANs that pose difficulties in the design of Medium Access Control (MAC) protocols for wireless LANs (WLANs) [1]. The wireless medium is characterized by bit error rates (BER) having an order of magnitude even up to ten orders of magnitude of a LAN cable's BER. Furthermore, in WLANs errors occur in bursts, whereas in traditional wired systems errors appear randomly. Finally, a fully connected topology between the nodes of a WLAN cannot be assumed. As a result, WLANs are characterized by unreliable links between nodes resulting in bursts of errors and dynamically changing network topologies.

Modern WLAN MAC protocols should be able to efficiently handle the bursty traffic that is expected to be generated by WLAN applications (such as client/server and file transfer applications between WLAN nodes). This paper proposes Carrier-Sense-Assisted Adaptive Learning MAC Protocol (CS-SAP) MAC Protocol for Wireless LANs. The proposed protocol builds on that of AHLAP proposed in [2], which utilizes Learning Automata [7, 8] in order to grant to stations permission to transmit. According to AHLAP the Learning Automata take into account the network feedback information in order to update the choice probability of each mobile station. It is proved [3] that the learning algorithm asymptotically tends to assign to each station a portion of the bandwidth proportional to the station's needs.

However in a wireless environment links can be highly unreliable resulting to non-common feedback for the mobile stations. Thus stations can make different decisions on which one will transmit and packet collisions will occur. To this end, CS-SAP utilizes carrier sensing in order to reduce the probability of packet collisions and increase protocol performance.

2 The CS-SAP Protocol

According to CS-SAP, each mobile station is equipped with a Learning Automaton which contains the normalized choice probability Π_i for each mobile station u_i in the network. The protocol operates as follows: After the network feedback is received for the transmission at slot t, at each station u_i the basic choice probabilities for slot t, $P_i(t)$, are normalized in the following way:

$$\Pi_i(t) = \frac{P_i(t)}{\sum_{k=1}^{N} P_k(t)}. \quad (1)$$

$\sum_{i=1}^{N} \Pi_i(t) = 1$, where N is the number of mobile stations. Initially, the choice probabilities $P_i(0)$ are the same for all network stations, thus $\Pi_i(0) = 1/N$.

We assume a slotted channel and packets of equal lengths. We define a time slot to have the time duration necessary for a data packet transmission to successfully take place. Thus, this time interval also includes control overhead. At the beginning of each time slot, the carrier-sense mechanism is applied. This will be described later on. We now focus on the way probability updating takes place in CS-SAP.

At each time slot t, the normalized probabilities $\Pi_i(t)$ are used to grant permission to transmit to a mobile station. After each slot has elapsed, the basic choice probability $P_i(t)$ of the selected station u_i is updated according to the network feedback information. If station u_i transmitted a packet during slot t, then its basic choice probability is increased. Otherwise, if station u_i was idle, its basic

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choice probability is decreased. The following probability updating scheme is used:

$$P_i(t+1) = P_i(t) + L(1 - P_i(t)),$$
$$\text{if } u(t) = u_i \text{ and } SLOT(t) = SUCCESS$$

$$\tag{2}$$

$$P_i(t+1) = P_i(t) - L(P_i(t) - a),$$
$$\text{if } u(t) = u_i \text{ and } SLOT(t) = IDLE$$

$L, a \in (0,1)$ and $P_i(t) \in (a, 1)$. L governs the speed of the Automaton convergence and the selection procedure for a value of L reflects the classic speed versus accuracy problem. The lower the value of L the more accurate the estimation made by the Automaton, a fact however that comes at expense over convergence speed. The role of parameter a is to enhance the adaptivity of the protocol. This is because when the choice probability of a station approaches zero, then this station is not selected for a long period of time. During this period, it is probable that the station transits from idle to busy state. However, since the mobile station does not grant permission to transmit, the Automaton is not capable of "sensing" such transitions. Thus, the use of a non-zero value for parameter a prevents the choice probabilities of the stations from taking values in the neighborhood of zero and increases the adaptivity of the protocol.

The above probability updating scheme suits well to bursty traffic conditions. This is due to the fact that when the selected mobile station had a packet to transmit, its choice probability is increased. On the other hand, if the selected station does not have buffered packets, its choice probability is reduced. This kind of behaviour suits well bursty conditions in which a packet transmission attempt (transmission absence) by the selected station implies back-to-back transmission attempts (transmission absences) by the same station in the near future.

CS-SAP updates the choice probabilities of mobile stations according to the network feedback information. It is proved [3] that the choice probability of each mobile station converges to the probability that this station is ready to transmit. Thus for any two mobile stations u_i and u_j, with d_i and d_j being their probabilities of being ready to transmit respectively, CS-SAP asymptotically tends to satisfy the relation:

$$\frac{\Pi_i}{\Pi_j} = \frac{P_i}{P_j} = \frac{d_i}{d_j} \tag{3}$$

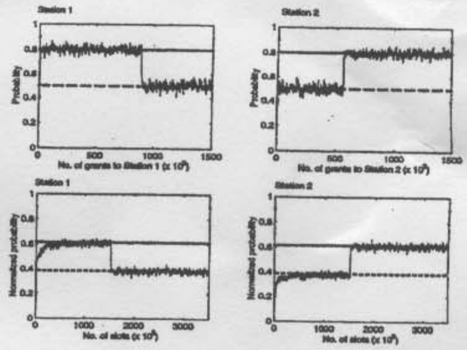

Figure 1: Convergence of basic and normalized choice probabilities for stations 1, 2.

In order to obtain a better understanding of the claim of the above Equation, we performed a simulation study for an CS-SAP WLAN of 10 mobile stations, from which only stations 1 and 2 are active, with $d_1 = 0.8$ and $d_2 = 0.5$. In order to simulate a changing environment, after some time, d_1 and d_2 change values to $d_1 = 0.5$ and $d_2 = 0.8$. The result of this experiment, which can be seen in Figure 1, shows that the Automaton estimates of the basic choice probabilities P_1 and P_2, both before and after the environmental change, converge to d_1 and d_2 respectively. The same stands for the normalize choice probabilities Π_1 and Π_2 which converge to $d_1/(d_1 + d_2)$ and $d_2/(d_1 + d_2)$ respectively in all cases. Thus, the claim of Equation (3) indeed stands.

Based on the above discussion, it is clear that in a noiseless environment, CS-SAP is collision-free. This is due to the fact that all stations use the same protocol and due to the broadcast nature of the wireless medium the network feedback is common for all stations. Therefore, at each slot, all stations choose the same station to be granted permission to transmit and the protocol is collision-free despite its distributed nature. However, in the presence of a noisy environment, it is possible that the network feedback is not common for all stations. Thus, the choice probabilities values may be different at several network nodes and thus collisions may occur. In order to avoid excessive collisions, CS-SAP piggybacks the K largest probabilities in the station's data packet and the rest of the probabilities, which obviously correspond to those stations that are not favoured to transmit at this time, take the value of a. This is done in an effort to reduce the differences between the probability distribution vectors of the various stations. The selection for the value of K depends on the number of stations N. If the network comprises a large number of stations, then a selection for K with $K < N$ will limit the overhead caused by the protocol.

[2] showed that the dissemination of the probability distribution vector provides satisfactory performance for the protocol compared to TDMA and IEEE 802.11 DCF. However under relatively highly unreliable wireless links a considerable number of collisions will still take place in [2], despite the piggybacking mechanism. CS-SAP provides additional performance improvement by integrating a carrier sense mechanism in order to reduce the number of collisions.

Carrier sensing in CS-SAP works as follows: At the beginning of each slot a small time window (contention window) is dedicated to contention for channel access by stations that have granted themselves permission to transmit. Recall that this is possible to be done since the automata at some stations will typically receive different network feedback for the same slot and the piggybacking mechanism does not ensure probability vector consistency at the mobile stations. The size of the contention window can be easily adjusted to consist of a number of l minislots, with $l \propto N$. Each contending station selects a random minislot $r, r \in [0..l-1]$ and transmits a burst signal until the end of the contention stage if it hasnt heard a burst at minislots between 0 and $r-1$. Contending stations that hear the burst back off for this time slot and thus the station that selected the lower minislot gains access to the channel.

Of course a collision can still occur in CS-SAP if a) more than one contending stations choose the lower minislot or b) the station that chooses the lower minislot is "hidden" (out of range) of one or more other contending stations. However, as will be seen in the next section, the integration of the carrier sensing scheme in networks with relatively highly unreliable links yields performance improvement over AHLAP and additional performance improvement over IEEE 802.11 DCF.

3 Performance evaluation

Using simulation, we compared CS-SAP against AHLAP and the IEEE 802.11 DCF. The simulator models N mobile clients and the wireless links as separate entities. Each mobile station uses a buffer to store the arriving packets. The buffer length is assumed to be equal to Q packets. Any packets arriving to find the buffer full, are dropped. Each simulation run is carried out until R packets successfully reach their destination.

The bursty traffic was modeled in the following way [?, 9, 10]: We define "time slot" as the time duration required for a data packet to be transmitted over the wireless link. Each source node can be in one of two states, S_0 and S_1. When a source node is in state S_0 then it has no packet arrivals. When a source node is in state S_1 then, at each time slot, it has a packet arrival with probability Z. Given a station is in state S_0 at time slot t, the probability that this station will transit to state S_1 at the next time slot is P_{01}. The transition probability from state S_1 to state S_0 is P_{10}. It can be shown that, when the load offered to the network is R packets/slot and the mean burst length is B slots, then the transition probabilities are: $P_{01} = \frac{R}{B(NZ-R)}$ and $P_{10} = \frac{1}{B}$.

The simulation assumes that the channel slots can be in one of the following three states: successful transmission, collision or idle. The simulator takes into account the following possibilities:

1. A "successful" slot is perceived by a station as "idle", due to the fact that this station is out of range of the transmitting one.
2. A "successful" slot is perceived by a station as a "collision" one, due to bit errors imposed by the wireless channel.
3. A "collision" slot is perceived by a station as "successful", due to the power capturing phenomenon.
4. A "collision" slot is perceived by a station as "idle", due to the fact that this station is out of range of the transmitting one.

In our simulation model, the condition of the wireless link between any two stations was modeled using a finite state machine with two states. The model, comprises the following two states:

- Stage G, denotes that the wireless link is in a relatively "clean" condition and is characterized by a small BER, which is given by the parameter G_BER.
- Stage B, denotes that the wireless link is in a condition characterized by a high BER, which is given by the parameter B_BER.

We assume that the background noise is the same for all stations and thus the principle of reciprocity stands for the condition of any wireless link. Therefore, for any two stations A and B, the BER of the link from A to B and the BER of the link from B to A are the same. The time periods spent by a link in states G and B are exponentially distributed, but with different average values, given by the parameters TG and TB. The status of a link probabilistically changes between the two states. When a link has spent its time in state G, the link transits to stage B. When a link has spent its time in state B, the link transits to stage G.

We simulated the protocols for the following two different network configurations:

1. Network N_1: N=10, Q=10, B=10, Z=1.0. TG/TB=1.

2. Network N_2: N=10, Q=10, B=10, Z=1.0, TB/TG=3.

In the simulations, the following parameter values remain constant: $R = 4000000$, G_BER=10^{-10}, B_BER=10^{-4}, TG= 3 sec, $K = 2$, R_LIM=6, $P_c = P_{iG} = 0.1$, $P_{iB} = 0.5$. R_LIM sets the maximum number of retransmission attempts per packet. P_c is the probability that when two or more data packets collide, one of them is successfully decoded at the destination station due to the power capture phenomenon. P_{iG} is the probability that a transmission from station S1 does not get through to station S2 when the link from S1 to S2 is in the G state. Similarly, P_{iB} is the probability that a transmission from station S1 does not get through to station S2 when the link from S1 to S2 is in the B state. In both cases, S2 perceives the slot as idle. The DATA packet size is set to 2000 bits and the sizes of all control packets for the protocols are set to 100 bits. The wireless medium bit rate was set to 1 Mbps and the propagation delay between any two stations was set to 0.0005 msec corresponding to inter-station distances of 150 meters. The time duration of a minislot equals 0.001 msec. Finally, we did not take into account the hidden terminal problem for IEEE 802.11 DCF due to the fact that the proposed protocol is not affected by it. Thus, stations in 802.11 are not allowed to collide with ongoing CTS-DATA-ACK packet exchanges. Despite the fact that hidden terminals are not accounted for in IEEE 802.11 DCF, the proposed protocol still performs significantly better than IEEE 802.11 DCF.

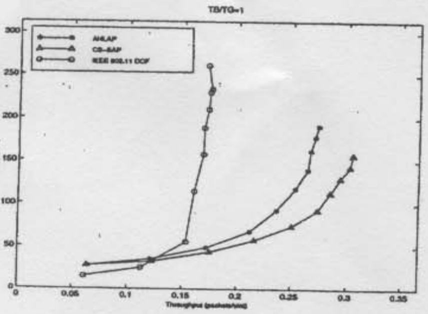

Figure 2: The Delay versus Throughput characteristics of CS-SAP, AHLAP and IEEE 802.11 DCF when applied to network N_1.

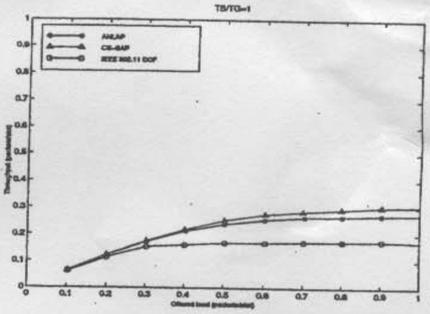

Figure 3: The Throughput versus Offered load characteristics of CS-SAP, AHLAP and IEEE 802.11 DCF when applied to network N_1.

The delay versus throughput characteristics of the compared protocols when applied to networks N_1 and N_2 are shown in Figures 2 and 4 respectively, while the throughput versus offered load characteristics when applied to networks N_1 and N_2 are shown in Figures 3 and 5 respectively. The main conclusions that can be drawn from the Figures are the following:

- CS-SAP provides additional performance improvement over AHLAP. This happens especially in high loads, where the increased aggregate network offered load and the unreliable feedback cause an increase in collisions.
- The reasons for AHLAP performance superiority over IEEE 802.11 DCF have also been adressed in [2]. However, in an increased unreliable environment such as the one in our simulations, IEEE 802.11 is negatively dominated by the RTS-CTS-DATA-ACK four-way handshake. In order for a succesfull data packet reception, all of these packets must be received correctly. An increased P_i (which is obviously the average of P_{iG} and P_{iB} averaged over the durations of the G and B states) affects this four-way handshake more than the two-way one of CS-SAP and AHLAP.

4 Conclusion

Modern WLAN MAC protocols should be able to efficiently handle the bursty traffic that is expected to be generated by WLAN applications. This paper proposes CS-SAP, an ad-hoc Learning-Automata-based wireless MAC protocol utilizing carrier sense. The protocol is able to achieve significantly higher throughput and lower delay values compared to the AHLAP protocol and IEEE 802.11 DCF under bursty traffic conditions in wireless environments with unreliable channel feedback.

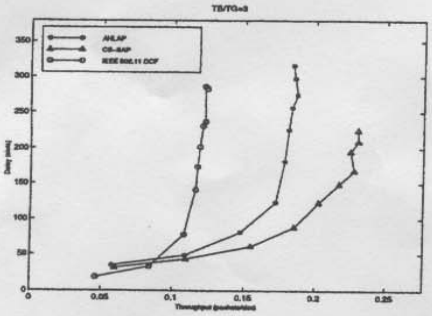

Figure 4: The Delay versus Throughput characteristics of CS-SAP, AHLAP and IEEE 802.11 DCF when applied to network N_2.

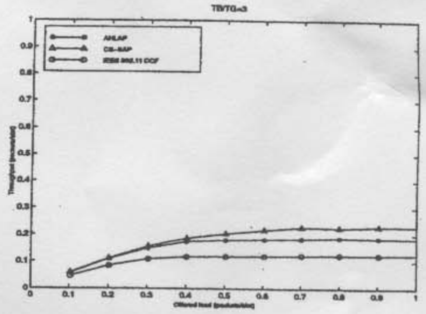

Figure 5: The Throughput versus Offered load characteristics of CS-SAP, AHLAP and IEEE 802.11 DCF when applied to network N_2.

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