A Channel Reservation Procedure for Fading Channels in Wireless Local Area Networks

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***Abstract*—IEEE 802.11-based wireless local area networks (WLANs) are one of the most popular mediums for interconnecting portable devices. All the devices (stations) communicating over WLANs share a common wireless channel. In order to avoid potential collisions an RTS-CTS handshake procedure is used to acquire the channel. However, most of the existing channel reservation protocols in WLANs view the wireless channel capacity as time invariant for each station and thus assign radio resources accordingly. This results in poor channel utilization particularly when channel gets assigned to stations that are in deep fading. In this paper, we devise a novel handshake-based channel-aware (HCA) media access control (MAC) protocol that assigns channel according to its fading status observed by each station and thus improves channel utilization. We give theoretical analysis of the overhead due to handshake procedure and prove that the expected value of handshake overhead is bounded as the number of stations in the system increases. Our analysis and simulation results show that the proposed protocol can ameliorate the contention among multiple users as well as reduce the packet loss due to channel fading. For example, in a system consisting of 16 stations when the average probability of channel being "healthy" is 0.5, the proposed handshake procedure reduces the packet-error rate (PER) to 8%, which satisfies the minimum requirement of IEEE 802.11-based protocols. However, this is without utilizing additional power. Under the same channel conditions any standard implementation of DCF would result in a packet error of 50% and would have to significantly increase the power level to achieve PER above 8%. The improvement in channel utilization due to the proposed protocol ranges from 11% to 460% depending upon channel conditions and traffic load.**

***Index Terms*—Channel aware, energy efficient, IEEE 802.11, medium access control (MAC), wireless local area network (WLAN).**

I. INTRODUCTION

THE USE of wireless local area networks (WLANs) in home and enterprise network infrastructures is widespread for interconnecting portable and mobile devices and providing access to the Internet. The IEEE 802.11 standard for WLANs defines two modes of function, namely distributed coordination function (DCF) and point coordination function (PCF). In the DCF mode, all stations compete for the communication medium (in this case the wireless channel) in a fashion similar to the regular LANs. The media access control (MAC) layer protocol for DCF realizes the well-known carrier sense multiple access/collision avoidance (CSMA/CA) mechanism using a two-way ready-to-send/clear-to-send (RTS-CTS) handshake procedure. The PCF mode is used to provide prioritized access to the communication medium. The MAC layer protocol for PCF is based on polling, and access point (AP) centrally controls access to the medium. In both the protocols and in most of the research literature on throughput-delay analysis of wireless LANs, the wireless channel capacity is assumed to be time-invariant from the viewpoint of each individual station. On the contrary, statistical models developed to capture the temporal characteristics of wireless channels have shown that fading in wireless environment, as perceived by individual stations, makes the channel capacity vary with time.

Recently investigation of channel aware protocols has gained significant interest [18]–[23]. In [22], it is shown that the channel capacity of a CDMA cell can be maximized by assigning channel to the station with best channel status. In our earlier work we have also reported similar results for infrastructure WLANs [13]. However, in most of these protocols, it is assumed that channel information is already available. We argue that collection of channel information is a nontrivial problem. Although synchronization packets are broadcast periodically and can be used to estimate the channel status, the rate of synchronization is very slow in WLANs. For example, in 802.11-based WLANs, beacons for synchronization are broadcast every 0.1 s. In this time frame, more than 100 packets of 1024 B can be transmitted over an 11 Mb/s physical layer (802.11b). An intuitive method for collecting channel information is to let AP poll all the stations one by one. This elementary approach has a major drawback that the overhead of polling would increase linearly with the number of stations in the system. Further, if the channel is fluctuating fast, the channel information polled from the stations in the beginning may already be obsolete by the end of the pooling round, thus making it useless for the channel allocation process. In this paper, we propose an efficient channel aware protocol with a novel handshake procedure. Our basic idea is to let stations measure the channel status by themselves and compare to a threshold. A station having data to transmit bids for the channel only when its status is better than the threshold otherwise it blocks itself.

Let us consider the MAC protocol for 802.11 infrastructure networks shown in Fig. 1. The circle shows the communication area of the access point. In this network, each station can communicate with the access point, but probably hidden from each other. Since all the stations share a single radio channel, only one station can communicate with the access point and the station-to-station traffic is through the access point. Due to the

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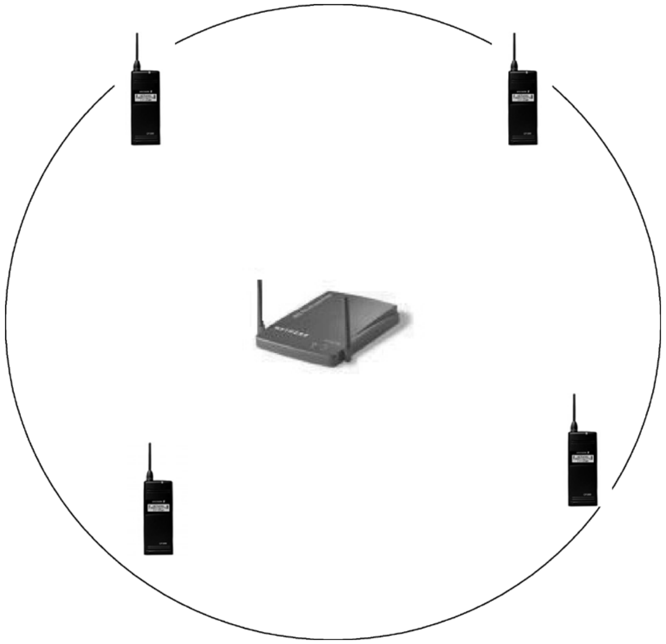

Fig. 1. 802.11 WLAN with four stations. These stations can talk to the AP but cannot hear each other.

presence of hidden stations, "carrier sense" cannot detect the packet collision, so the only way to avoid collision is to exchange RTS-CTS packets between the stations and the access point. The RTS-CTS exchange scheme for uplink works as follows: a station sends an RTS packet to the AP. When AP receives this packet, it replies to the station with a CTS packet. Then, the station starts sending the actual data packet. All the stations hearing the RTS and/or CTS packets (though may not be both) postpone their transmission to avoid collisions. If RTS from a station conflicts with an RTS from another station, the RTS-CTS handshake procedure is repeated several times using a binary exponential backoff (BEB) scheme until a collision-free RTS-CTS exchange is achieved. If the system is heavily loaded, almost all the stations send RTS packets to AP as soon as the media is free.

As described earlier, in a channel-aware protocol, channel information from each competing station is used to decide access to the channel. For example, AP can transmit a test packet and let all the stations measure their channel by the receiving power of this packet and compare it with a threshold. Only stations with healthy channel status send RTS. The threshold should be chosen carefully. If the threshold is set too high, then the probability of no stations satisfying the threshold is also very high. This may result in no station getting the channel and eventually wasting the time slot. If the threshold is set too low, too many stations may qualify to get the access thus increasing collision among the candidate stations and eventually increasing channel reservation overhead. Furthermore, the channel measurement scheme should be unbiased so that each station has a fair chance to reserve the channel.

In this paper, we design an efficient channel-aware MAC protocol based on a novel handshake procedure. For the handshake, we develop and analyze a threshold selection process considering different traffic characteristics. We formally prove the upper bound of the overhead induced by the handshake procedure. We also analyze the channel capacity utilization of the proposed protocol and compare it with the existing IEEE 802.11-based DCF implementations. Our simulation results show that the proposed protocol significantly improves the packet-error rate (PER), particularly under bad channel conditions. For example, in a system consisting of 16 stations when the average probability of channel being "healthy" is 0.5, the proposed handshake procedure reduces the PER to 8%, which satisfies the minimum requirement of IEEE 802.11-based protocols. However, this is without utilizing additional power. Under the same channel conditions any standard implementation of DCF would result in a packet error of 50% and would have to significantly increase the power level to achieve PER above 8%. The improvement in channel utilization due to the proposed protocol ranges from 11% to 460% depending upon channel conditions and traffic load.

The organization of the rest of the paper is as follows. In Section II, we present the proposed handshake procedure for different traffic load conditions and analyze its overhead. Section III describes the analytical model of the expectation value of the protocol overhead and formally analyzes the upper bound of the overhead in terms of handshake rounds. The simulation results are presented and compared in Section IV. Finally, we draw some conclusions in Section V.

II. HANDSHAKE PROCEDURE

We first introduce the channel model used in our analysis.

Channel Model: Let us now consider the channel propagation model. The total channel path loss is estimated as follows:

$$L(t) = L_s(t)L_f(t)$$

where $L(t)$ is the total channel loss and consists of two parts, the slow fading or shadowing $L_s(t)$ and fast fading $L_f(t)$. We assume that $L_s(t)$ changes slowly so that it can be estimated by averaging over several packets, i.e., $L_s(t) \approx (1/T)\sum_{i=0}^{T-1} L(t-i)$. The value of T should be chosen large enough such that $L_f(t)$ cancels out but at the same time it should be small enough such that $L_s(t)$ does not change significantly during that time. This is indeed achievable since the speed of fast fading and slow fading are relatively different.

We then use $L_f(t)$ as the measure of channel status and estimate it as follows:

$$L_f(t) = \frac{L(t)}{L_s(t)} = \frac{L(t)}{\frac{1}{N}\sum\limits_{i=0}^{N-1} L(t-i)}.$$

Now, we concentrate on the packet level fast fading $L_f(t)$. It is modeled as Rayleigh fading, as in [13]. The channel envelope is the square root of two orthogonal Gaussian variables with zero mean and same variance

$$r(t) = \sqrt{x_I(t)^2 + x_Q(t)^2}.$$

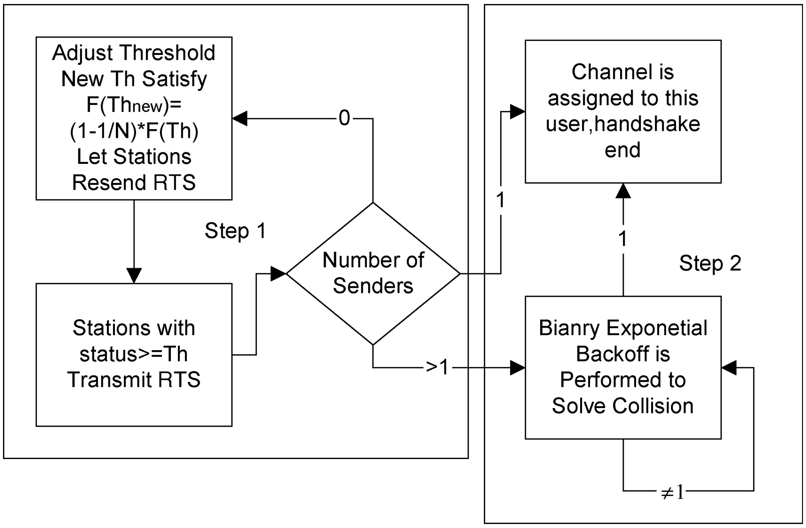

Fig. 2. Diagram of uplink handshake procedure.

By normalizing the variance to one, we have the identical and independent (i.i.d.) probability density function (pdf) for all the stations as follows:

$$f(r) = re^{-\frac{r^2}{2}}, \quad r \geq 0.$$

The channel fluctuation is characterized by the correlation of the Gaussian variables

$$\begin{aligned}\langle x_I(t)x_I(t+\tau)\rangle &= \langle x_Q(t)x_Q(t+\tau)\rangle = J_0(2\pi f_d\tau) = \rho\\ \langle x_I(t)x_Q(t+\tau)\rangle &= \langle x_Q(t)x_I(t+\tau)\rangle = 0\end{aligned}$$

where τ is the time difference between two packets, f_d is the maximum Doppler frequency shift ,and J_0 is the zero-order Bessel function of first kind. Given the channel status $r(t)$, we can predict the channel status of next packet by the following conditional probability:

$$\begin{aligned}f\left[r(t+\tau)|r(t)\right] = &\frac{r(t+\tau)}{(1-\rho^2)}\\ &\times \exp\left[-\frac{\rho^2 r^2(t) + r^2(t+\tau)}{2(1-\rho^2)}\right] I_0\left(\frac{\rho r(t) r(t+\tau)}{1-\rho^2}\right)\end{aligned}$$

where I_0 is the zero-order modified Bessel function of first kind.

Let us consider a system in which all the stations are power controlled so that they have the same average receiving signal strength. In such a system, packet decoding depends on the station's fading status. We use a simple threshold model. That is the packet error probability is formulated as

$$\mathrm{Pr}_{\mathrm{error}}(r) = \begin{cases} 0, & r > Th_{\mathrm{decode}}\\ 1, & r \leq Th_{\mathrm{decode}}.\end{cases}$$

We say a channel is healthy if $r > Th_{\mathrm{decode}}$ and define channel health rate as the percentage of time channel is healthy. Given the current channel status, we can predict the $\mathrm{Pr}_{\mathrm{error}}$ for the next packet. Since $\mathrm{Pr}_{\mathrm{error}}$ is monotone to r, reserving the wireless channel for the station with best channel status can minimize the $\mathrm{Pr}_{\mathrm{error}}$ thus maximizing the channel utilization. Note that even if the stations are not power controlled, the analysis of fading status is still valid. However, in such a case different stations may have different PERs.

A. Proposed Handshake Based Channel Aware (HCA) MAC Protocol

We propose a three-step channel reservation protocol based on a novel handshake procedure. Step 1 is called the "Qualify" step. In this step, AP sends a beacon and a threshold, all stations measure the signal level of this beacon and compare to the threshold. The stations having channel status greater than the threshold are qualified and send an RTS, other stations block themselves. If more than one station qualifies, then Step 2, called "Eliminate," is performed. At the end, only one station wins the channel and all others are blocked and postpone their transmission till the next slot. The diagrams of Step 1 and Step 2 are shown in Fig. 2. Once the winning station has started transmitting packets, Step 3, the "Rehandshake" step, is performed depending on the channel conditions. In the following, we further elaborate on these steps.

Step 1 (Qualify):

- After receiving the previous frame, a beacon (an acknowledgement (ACK) signal in the case of uplink) is sent to acknowledge the received frame as well as to set the air free. The qualifying threshold Th_q is initialized. All the stations attached to the AP measure the power signal strength of this beacon by $r = (L(t)/(1/N)\sum_{i=0}^{N-1} L(t-i))$, where $L(t)$ is the path loss of this beacon. A station whose $r \geq Th_q$ sends an RTS, otherwise keeps silent.
- If AP receives no RTS frame, it implies that all the stations are in relatively bad status. So, AP decreases the threshold Th_q and broadcast the new threshold. This process is repeated until AP receives at least one RTS frame or the threshold reaches to a predetermined minimum value.

Step 2 (Eliminate)

- If AP receives only one RTS frame, it sends a CTS frame to acknowledge the successful reception of the

RTS frame. The channel is reserved for that station and the handshake procedure ends.

- If AP detects collision, then it knows that more than one station is sending RTS. In this scenario, it sends out a CTS-like control frame to start a p-persistence slotted ALOHA procedure to resolve the contention. All qualified stations of Step 1 are allowed to send a new RTS frame with probability p. There are three cases:
  - *Case 1:* No station sends a new RTS frame in a slot. Then probability p remains unchanged in the next slot.
  - *Case 2:* Only one RTS is received. AP sends a CTS frame to acknowledge the successful reception of the RTS frame and channel is reserved. The handshake procedure ends.
  - *Case 3:* RTS frame collision happens again. Then, the new persistent probability p is set to $p/2$ and Step 2 is repeated.

Step 3 (Rehandshake)

- The station currently occupying the channel keeps track of its channel status and starts a new handshake round by relinquishing the channel either when the channel is not healthy (specified by a threshold, Th_{round}). To prevent a station from occupying the channel forever, a threshold $T_{\max}$ is set. AP starts a new handshake round after a station has occupied the channel for $T_{\max}$ seconds, regardless of the channel status. The station can learn its channel status by listening to the ACK frames from AP.

B. Computing Threshold Th_q for Fully Loaded Systems

In the case of full traffic load, we assume that stations always have packets to transmit when the air is free. Therefore, the number of stations competing for the channel is fixed. We choose Th_q to maximize the probability of successful handshake, which is minimizing the number of rounds of Step 1. This is because fewer the rounds the handshake needs, the more accurate is the channel status. Also, this reduces the handshake overhead. The condition of successful handshake requires that only one station is qualified and all others are disqualified. Suppose there are N stations in total. Given the threshold Th_q, event E_s of successful handshake can be formulated as

$$E_s(\exists i, r_i \geq Th_q, r_j < Th_q, \forall j \neq i, 1 \leq i, j \leq N).$$

Since the stations are randomly located, it is reasonable to assume that all the stations observe change in their channel status independently. Let the cumulative distribution function (cdf) of r be $F(r)$, where r is the fading envelope of current packet. Then, the threshold Th_q should be chosen to maximize the probability of event E_s

$$Th_q = \arg\max_{Th_q} \left[\Pr(E_s)\right].$$

In networking theory, it is well known ([10, Sec. 4.2.4]) that the channel capacity can be maximized if every station transmits with a probability of 1/N and the maximal channel capacity that can be reached is given as $(1-(1/N))^{N-1}$

Since the probability of a station attending the channel reservation is $\Pr(r \geq Th_q) = 1 - F(Th_q)$, so we can set

$$Th_q = F^{-1}\left(1 - \frac{1}{N}\right). \tag{1}$$

Note that here we do not require F being identical for all stations. So, AP can set different Th_q for different stations which still satisfies the condition given in (1). If r is Rayleigh distributed, then $F(r) = 1 - \exp(-r^2/2)$, so the optimal threshold is $Th_q = \sqrt{2\ln(N)}$.

In Step 1, if no RTS or CTS frame is received, the threshold needs to be recalculated. This event implies that the signal strengths of all the stations are below threshold Th_q. Let $Th_{q0} = Th_q$ denote the initial threshold setting and F_1, Th_{q1} denote the cdf and the new threshold, respectively, for the second iteration of Step 1. Then we have

$$F_1(r) = F(r|r \leq Th_{q0}) = \begin{cases} 0, & r \leq 0 \\ \frac{F(r)}{F(Th_{q0})}, & 0 \leq r \leq Th_{q0} \\ 1, & r \geq Th_{q0} \end{cases}. \tag{2}$$

By using the result of (2), the threshold of second iteration needs to satisfy the following:

$$Th_{q1} = F_1^{-1}\left(1 - \frac{1}{N}\right) Th_{q0} = F^{-1}\left[\left(1 - \frac{1}{N}\right)^2\right]. \tag{3}$$

By induction, we can easily prove that at the kth iteration of Step 1, the threshold is $Th_{q(k-1)} = F^{-1}[(1-(1/n))^k]$ and $Th_{q(k-1)} = \sqrt{-2\ln[1-(1-(1/n))^k]}$ for Rayleigh-distributed-fading channel.

This scheme can also be used for downlink channel access. The difference is that for the downlink access, interference or noise level may also fluctuate, so the fading of path loss may not represent the channel condition correctly. In that case, we can use the signal-to-interference ratio (SIR) instead. The SIR distribution function may not be Rayleigh or even may not be identical. Note that in the above derivations we do not use the identical assumption. Stations can compute their own threshold, the only condition need to be satisfied is $F(Th_{q(k-1)}) \geq (1-(1/N))^k$. Also note that we use downlink path loss to predict uplink path loss, or vice versa, this is reasonable since in WLAN uplink and downlink channels share same frequency and same propagation path.

Next, we describe the handshake procedure for partially loaded systems.

C. Computing Th_q for Partially Loaded Systems

In the case of partially loaded systems, we still assume that there are N stations in total but the overall bandwidth requirement of all the stations is less than the channel capacity. Let us assume that each station has a bandwidth requirement of B_i, $1 \leq i \leq N$, that satisfies $B = \sum_{i=1}^{N} B_i$, $B \leq 1$.

For sake of simplicity, first we assume that all the stations have identical bandwidth requirement. In this case, the total bandwidth requirement $B = N \times B_i$. To avoid recursively lowering the threshold to zero in Step 2, we wish to compute a minimum threshold $Th_{\min}$ for the handshake. If no station has attended the handshake until the threshold has reached $Th_{\min}$, Step 2 ends. This means either no station has packets to send or all the stations are having bad channel status. In such a situation, AP then waits for a time equal the transmission of a packet of average length. In principle, the percentage of waiting time should be equivalent to 1-B. After this time, the system can be treated as fully loaded system except for the waiting time.

Let $q_{\min} = \Pr(r \geq Th_{\min}) = 1 - F(Th_{\min})$. The $q_{\min}$ is the handshake probability, i.e., the probability of a station to attend the channel reservation procedure. Since all the stations have same bandwidth we assume that all the stations have same $q_{\min}$ as well. Obviously, the probability of no station attending reservation, $(1 - q_{\min})^N$, should be equal to the channel idle time $1 - B$. So we let

$$\begin{aligned}(1 - q_{\min})^N &= 1 - B,\\ q_{\min} &= 1 - \sqrt[N]{1 - B} \quad \text{and}\\ Th_{\min} &= F^{-1}(1 - q_{\min}).\end{aligned}$$

For example, suppose there are 16 stations and $B_i = 0.05$, so $B = 1 - 16 \times 0.05 = 0.2$ and $q_{\min} = 1 - \sqrt[16]{1 - 0.8} \approx 0.1$. After determining $Th_{\min}$, the protocol described in Section II-A can be applied to reserve the channel.

If stations have different bandwidth requirement then the protocol needs to guarantee that the chance for a station to win the channel is equal to its bandwidth requirement. In the case of contention, if we assume that all the stations should have equal probability of winning the channel, then the probability of a station to take part in the channel reservation q_i should satisfy the following condition:

$$B_i = q_i \sum_{k=1}^{N} \frac{1}{k} \Pr(C_{i,k-1}) \text{ for all } i$$

where $\Pr(C_{i,k-1})$ is the probability of $k-1$ stations among $N-1$ stations (except station i) attending the channel reservation bid and this is a function of all q_i.

D. Computing Rehandshake Threshold

The value for Th_{round} should be chosen such that the overall channel utilization is maximized. If the threshold Th_{round} is set too high, then the frequency of handshakes will also increase. If the threshold Th_{round} is set very low, then the PER would be very high thus wasting the channel resources. Assuming that in the initial handshake when we admit the admit a station, we can always pick up a station with channel status better than Th_{round}, then the probability of next handshake occurring, $p_{\text{handshake}}$, can be computed as

$$p_{\text{handshake}} = \Pr\left[r(t+\tau) < Th_{\text{round}} \,|\, r(t) > Th_{\text{round}}\right].$$

The average PER, on the other hand, can be computed as follows:

$$PER = \Pr\left[r(t+\tau) < Th_{\text{decode}} \,|\, r(t) > Th_{\text{round}}\right]$$

where Th_{decode} is the threshold for correct decoding, as defined in Section II.

The total channel capacity utilization can be computed as

$$\text{Utilization} = \frac{T_{\text{packet}}}{O_{\text{total}} \times p_{\text{handshake}}(Th_{\text{round}}) + T_{\text{packet}}} \times [1 - PER] \quad (4)$$

where T_{packet} is the time duration for transmitting a packet and O_{total} is the average handshake overhead as computed in Section III. Since $p_{\text{handshake}}$ is monotonously increasing and PER is monotonously decreasing function of Th_{round}, it is easy to search for the maximal value of Utilization by computing the first derivative of (4).

III. PERFORMANCE ANALYSIS OF THE PROPOSED HANDSHAKE PROCEDURE OVERHEAD

A. Protocol Overhead

In this section, we analytically compute the overhead introduced by the handshake procedure proposed in Section II. The overhead is measured in terms of number of rounds. A "round" is defined as an RTS-CTS packet exchange, which include time spent on sending an RTS frame, receiving the corresponding CTS frame, and propagation and processing delays. We compute the handshake overhead for each step separately. The overheads for Step 1 and Step 2 are denoted as O_{step1} and O_{step2}, respectively. In Step 1, the handshake procedure identifies all the qualified stations. If only one station qualifies to participate in Step 1, then Step 2 is not performed. If more than one station are qualified, Step 2 consisting of p-persistent BEB procedure is performed to eliminate multiple contesting stations. The total overhead is $O_{\text{total}} = O_{\text{step1}} + O_{\text{step2}}$.

1) Overhead of Stage One: Suppose there are N stations in the system. In Step 1, the probability of a station not qualifying for admission is $(1 - (1/N))$. Since channels are fading independently, the probability that all the stations fail to qualify is $Q_f = (1 - (1/N))^N$. This probability is same for each round. So the average number of rounds for Step 1 can be computed as follows:

$$O_{\text{step1}}(N) = \sum_{k=0}^{\infty} kQ_f^k(1 - Q_f) = \frac{Q_f}{1 - Q_f} = \frac{\left(\frac{N-1}{N}\right)^N}{1 - \left(\frac{N-1}{N}\right)^N}.$$

We show that this overhead converges as N approaches infinity.

Lemma 1: $O_{\text{step1}}(N)$ converges as N approaches to infinity.

Proof:

$$\lim_{N\to\infty} \left(1 - \frac{1}{N}\right)^N = e^{-1} \Rightarrow \lim_{N\to\infty} O_{step1} = \frac{e^{-1}}{1-e^{-1}} \approx 0.582$$

■

2) Overhead of Step 2: In Step 2, qualified stations compete for the channel by performing a p-persistent backoff procedure. The initial persistence value for p is set to 1. Step 2 can be modeled as an infinite state machine, as shown inFig. 3. The transfer rate among the states depends on n, where n is the number of stations participating is in Step 2 at any given in time. So, we first compute $Q(n)$, the probability of n stations participating in Step 2. The probability $Q(n)$ is the probability of n stations

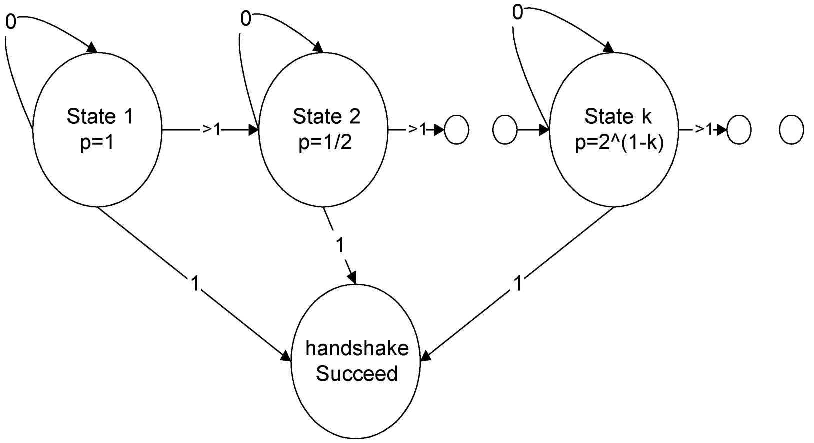

Fig. 3. State machine for Step 2. The labels on the arcs represent the number of stations participating in the channel reservation procedure.

participate handshake conditioned on at least one station participating

$$Q(n) = \frac{\binom{N}{n}\left(\frac{1}{N}\right)^n\left(1-\frac{1}{N}\right)^{N-n}}{1-\left(1-\frac{1}{N}\right)^N}, \quad 1 \le n \le N. \tag{5}$$

Then, the average overhead of Step 2 O_{step2} can be formulated as

$$O_{\text{step2}}(N) = \sum_{n=1}^{N} Q(n) \times O_n. \tag{6}$$

Where O_n is the average overhead of Step 2 for n stations.

Now, we compute the average handshake overhead O_n. By using total probability equation, the summation of

$$O_n = \sum_{k=1}^{\infty} S_k On_k \tag{7}$$

where S_k is the *probability* of handshake pass state k and On_k is the average reside time of state k.

To formulate S_k, first we define the following probabilities in state k.

1) S_{k_idle} is the probability of the channel to be idle in a round, i.e., no RTS is sent. $S_{k\_\text{idle}} = (1-p)^n = (1-2^{1-k})^n$, where p is the persistence in state k, so $p = 2^{1-k}$.
2) S_{k_resolve} is the probability of contention resolved in state k, i.e., only one station sends RTS. $S_{k\_\text{resolve}} = np(1-p)^{n-1}$.
3) S_{k_collide} is the probability of collision happening in state k and state transfers from k to $k+1$, i.e., more than one stations send RTS. $S_{k\_\text{collide}} = 1-(1-p)^n - np(1-p)^{n-1}$.

The average reside time of state k, can be formulated as

$$On_k = \sum_{l=1}^{\infty} l \times (S_{k\_\text{idle}})^{l-1}(1-S_{k\_\text{idle}}) = \frac{1}{1-S_{k\_\text{idle}}}. \tag{8}$$

The probability of handshake process pass state k is the probability of the handshake procedure not resolved in all $k-1$ states preceding state k. Since procedure must pass States 1 and 2, So $On_1 = On_2 = 1$, and the probability of the procedure not resolved in state l is

$$\frac{S_{l\_\text{collide}}}{S_{l\_\text{resolve}} + S_{l\_\text{collide}}} = 1 - \frac{n \times 2^{1-l} \times (1-2^{1-l})^{n-1}}{1-(1-2^{1-l})^N}$$
$$\text{and} \quad S_k = \prod_{l=2}^{k-1} \frac{S_{l\_\text{collide}}}{S_{l\_\text{resolve}} + S_{l\_\text{collide}}} \tag{9}$$

By substituting (8) and (9) into (7), we have

$$O_n = 1 + \frac{1}{1-2^{-n}} + \sum_{k=3}^{\infty} \frac{1}{1-(1-2^{1-k})^n} \times \prod_{l=2}^{k-1}\left(1 - \frac{n \times 2^{1-l}(1-2^{1-l})^{n-1}}{1-(1-2^{1-l})^n}\right), \quad n > 1. \tag{10}$$

By substituting (5) and (10) in (6), we can compute O_{step2}.

Next, we show that O_{step2} also converges when N, the number of stations, increases. In order to prove this, first we show O_n increases no faster than logarithm.

Lemma 2: $O_n < C\log(n)$, where C is a constant.

Proof: First, we show $1-(n \times 2^{-l}(1-2^{-l})^{n-1}/1-(1-2^{-l})^n) \le n \times 2^{-l}$.

For $n \times 2^{-l} \ge 1$, it is trivial since the left side is less than 1. For $n \times 2^{-l} < 1$

We have

$$1-(1-2^{-l})^n = \sum_{i=1}^{\infty}(-1)^{i-1}\binom{n}{i}2^{-l\times i}.$$

Let $I_i = \binom{n}{i}2^{-l\times i}$.

So $I_i/I_{i+1} = ((i+1)/(n-i+1)\times 2^{-l})) > (1/(n\times 2^{-l})) > 1$.

So $1-(1-2^{-l})^n = \sum_{i=1}^{\infty}(-1)^{i-1}\binom{n}{i}2^{-l\times i} < n \times 2^{-l}$.

Using this result, we have

$$1 - \frac{n\times 2^{-l}(1-2^{-l})^{n-1}}{1-(1-2^{-l})^n} < 1 - \frac{n \times 2^{-l}(1-2^{-l})^{n-1}}{n \times 2^{-l}}$$
$$= 1-(1-2^{-l})^{n-1} < (n-1)\times 2^{-l} < n \times 2^{-l}.$$

Then

$$\begin{aligned} O_n &= 1 + \frac{1}{1-2^{-n}} + \sum_{k=1}^{\infty} \frac{1}{1-(1-2^{-k-1})^n} \\ &\quad \times \prod_{l=1}^{k} \left(1 - \frac{n \times 2^{-l}(1-2^{-l})^{n-1}}{1-(1-2^{-l})^N}\right) \\ &< 2 + \sum_{k=1}^{\left\lceil \frac{\log n}{\log 2} \right\rceil - 1} \frac{1}{1-(1-2^{-k-1})^n} \\ &\quad + \sum_{k=\left\lceil \frac{\log m}{\log 2} \right\rceil}^{\infty} \frac{1}{1-(1-2^{-k-1})^n} \\ &\quad \times \prod_{l=1}^{k} \left(1 - \frac{n \times 2^{-l}(1-2^{-l})^{n-1}}{1-(1-2^{-l})^n}\right) \\ &< 2 + \log_2(n) \times \frac{1}{1-e^{-1}} + \sum_{k=1}^{\infty} \frac{1}{n \times 2^{-k-1}} \\ &\quad \times n^{k+1} \times 2^{-\frac{k(k+1)}{2}} \\ &< C_1 \ln(n) + \sum_{k=1}^{\infty} \frac{m^k}{2^{\frac{(k-2)(k+1)}{2}}} \\ &< C_1 \ln(n) + C_2 \sum_{k=1}^{\infty} \frac{n^k}{k!} \\ &< C \ln(n) \end{aligned}$$

where CC, C_1 and C_2 are constant. ■

Lemma 3: The overhead of Step 2 is bounded.

Proof: Since $\log(n) < n < 2^n$ for $n > 1$

By using lemma 3, we have

$$\begin{aligned} O_{\text{step2}} &< \sum_{n=1}^{N} \frac{\binom{N}{n}\left(\frac{1}{N}\right)^m \left(\frac{n-1}{n}\right)^{n-m} C\log(n)}{1-\left(\frac{n-1}{n}\right)^N} \\ &< C \sum_{m=1}^{N} \frac{\binom{N}{n}\left(\frac{1}{N}\right)^n \left(\frac{N-1}{N}\right)^{N-n} 2^N}{1-\left(\frac{N-1}{N}\right)^N} \\ &= C\frac{\left(\frac{2}{N}+\frac{N-1}{N}\right)^N - \left(\frac{N-1}{N}\right)^N}{1-\left(\frac{N-1}{N}\right)^N} \\ &= C\frac{\left(\frac{N+1}{N}\right)^N - \left(\frac{N-1}{N}\right)^N}{1-\left(\frac{N-1}{N}\right)^N}. \end{aligned}$$

So

$$\lim_{n\to\infty} O_{\text{step2}} < \lim_{n\to\infty} C\frac{\left(\frac{N+1}{N}\right)^N - \left(\frac{N-1}{N}\right)^N}{1-\left(\frac{N-1}{N}\right)^N} = C\frac{e-\frac{1}{e}}{1-\frac{1}{e}} < \infty.$$

■

Theorem: The overhead of the proposed handshake procedure $O_{\text{total}} = O_{\text{step1}} + O_{\text{step2}}$ is bounded when the number of stations approaches infinity.

Proof: By Lemmas 1 and 3. ■

B. Protocol Robustness

In this analysis, we have assumed that the control frames (i.e. RTS, CTS, and ACK) are always received error free. Although this assumption is reasonable since these frames are transmitted with protection. In the following, we outline our treatment in case of errors.

If an ACK frame is lost, then the transmitter treats this as a transmission failure and buffers the transmitted packet for future retransmission. Other errors in control frames are skipped and the stations and AP execute the procedure as if no control frames were received. For example, if an RTS from a station is lost and AP receives no valid RTS in Step 1, it just lowers the threshold. If the last CTS frame to acknowledge the successful channel reservation is lost, then the corresponding station is unable to send data. In such a case when AP detects no data transmission at the expected point in time, it generates a handshake error and sends out a beacon to restart the handshake. The performance degradation caused by such errors is examined in Section IV.

IV. NUMERICAL AND SIMULATION RESULTS

In this section, we provide the numerical and simulation results of the proposed handshake-based channel aware (HCA) protocol and study its performance. For comparison purposes, we also give the performance of IEEE 802.11 protocol and a polling-based channel aware (PCA) protocol [13] that sequentially polls through all the stations for handshake. The simulations have been carried out in MATLAB using communication toolbox. In these simulations, we simulate Rayleigh-fading channel and the behavior of handshake procedure. A first-order Markov model is used to characterize the temporal relationship of the fading envelop. The channel correlation factor ρ is set to be 0.8. For a physical layer of 2.4 GHz and the time difference $\tau = T_{\text{data}}$, this channel correlation factor corresponds to a maximal moving speed of 10 m/s or 22.4 mph. The success/failure of each transmission is decided based on the channel fading status and the given threshold.

Our simulations assume a system consisting of 16 stations that are placed along a circle and AP is placed at the center of the circle. Therefore, each station has the same mean path loss. Since in this setup the only way to learn the contention is to listen to AP due to the hidden problem, our formulation of the handshake overhead consisting of RTS-CTS rounds is valid. In our simulations we compute the overhead for each round as follows:

$$T_{\text{round}} = T_{RTS} + SIFS + T_{CTS} + SIFS$$

where $SIFS$ is the transmission-to-receiver turnaround time.

We assume an IEEE 802.11b 11 Mb/s physical layer, which is the major type in the products currently in the market. However, the relative performance of the methods studied is independent of speed of the physical layer. According to the protocol, the RTS frame has 20 bytes and CTS frame has 14 B, both are transmitted at a speed of 1 M b/s, and the SIFS is 10 μs. So the time for a single handshake round is

$$T_{\text{round}} = 160 + 10 + 112 + 10 = 292\ \mu\text{s}. \tag{11}$$

We assume fixed data frame length of 2200 B, which is close to the maximal length allowed by IEEE 802.11 protocol. The time to transmit a data packet ($T_{\text{Transmission}}$) is 1600 μs. Since the

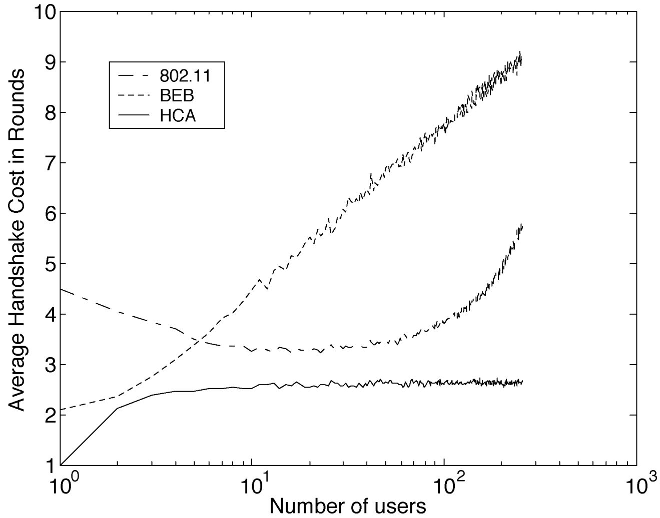

Fig. 4. Comparison of handshake overhead.

ACK frame also has 14 B, so the total time to transmit a data packet is

$$\begin{aligned} T_{\text{data}} &= T_{\text{Transmission}} + SIFS + T_{ACK} + DIFS \\ &= 1600 + 10 + 112 + 50 = 1772\ \mu\text{s} \end{aligned} \tag{12}$$

The term $DIFS$ refers to the inter frame duration that must be observed between any two successful transmissions. To begin with, we assume that control frames such as RTS and CTS are error free. The case of error in control frames is discussed later in this section.

First, we compare the handshake overhead of the proposed scheme given in Section II-A with the overhead incurred in an IEEE 802.11 DCF protocol and the pure BEB protocol [24]. The initial persistence value for is set to 0.25 for BEB. Each data point in our simulations is averaged over 10 000 accesses for each setup. From the simulation results shown in Fig. 4, we see that the number of rounds for pure BEB increases logarithmically with the number of stations in the system while that of our scheme the number of rounds converges to about 2.6. This verifies our analytical analysis in Section III and shows the protocol efficiency of proposed HCA protocol.

Next, we analyze the performance of HCA for fully loaded systems in terms of channel capacity utilization and PER. For fully loaded systems, we assume that a station always has data to transmit. We compare the performance of our scheme with both the standard IEEE 802.11-based protocols and PCA protocol. The IEEE 802.11-based protocol is simulated as follows. Each station maintains a counter and initializes it with a random number in the contention window (CW). In each round, stations decrease the counter by one. If the counter is equal to zero, an RTS is sent. If RTS contention happens, the station doubles the contention window and resets the counter. Meanwhile, if another station sends an RTS, it stops the counter and resumes it in the next round, as defined in the protocol.

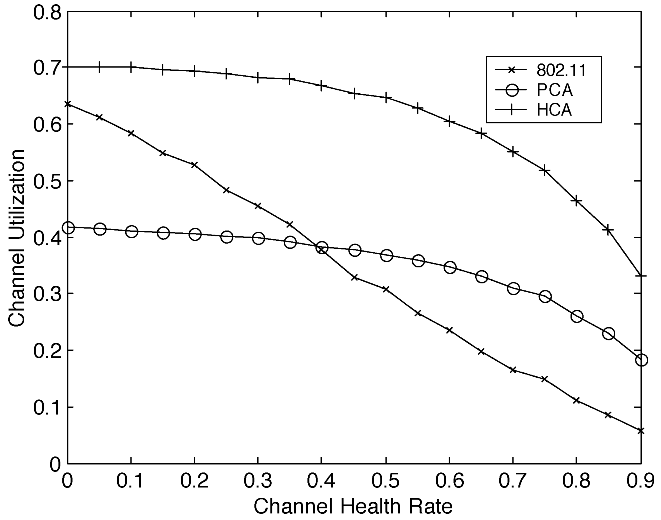

Fig. 5. Channel utilization for fully loaded system.

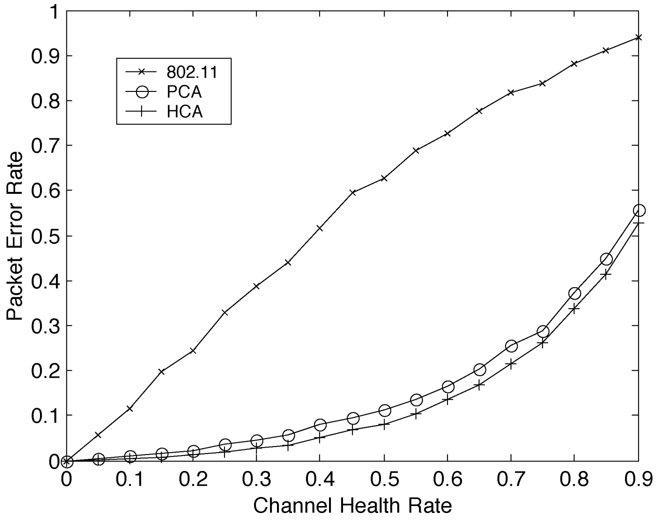

Fig. 6. Packet-error rate for fully loaded system.

The PCA protocol is simulated as follows. At the beginning of each transmission, each station send an RTS, then AP measures the receiving power from each station and picks up the station with the best channel condition. So, in this case, the handshake overhead is

$$T_{PCA} = 16 \times (T_{RTS} + SIFS) + T_{CTS} + SIFS = 8.5T_{\text{round}}$$

Fig. 5 compares the channel capacity utilization and Fig. 6 compares the PER. The channel utilization is measured as the portion of time used to transmit data packets. In the IEEE 802.11-based protocol, if a packet is lost, the packet is retransmitted until it is received successfully. In the HCA and PCA protocols if packet error happens, first another round of handshake is initiated. The PER can be computed numerically by using the conditional probability equation derived in Section II, or evaluated by simulations. From Fig. 5, we find that the HCA proposed in this paper yields much higher channel utilization compared to the IEEE 802.11-based protocol and PCA protocol for all channel health rates considered. Specifically, the improvement in channel utilization due to the proposed protocol ranges from 11% to 460% depending on the channel conditions. Even when the channel is perfect on the average, improvement in channel utilization is 11%. This is due to the fact that the

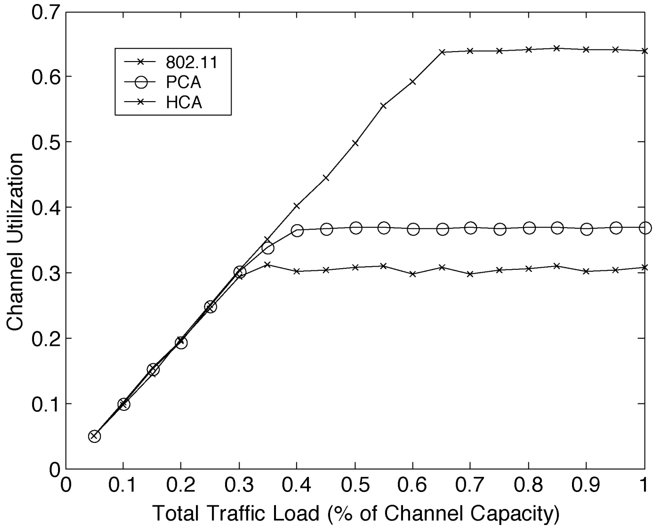

Fig. 7. Channel utilization for partially loaded system.

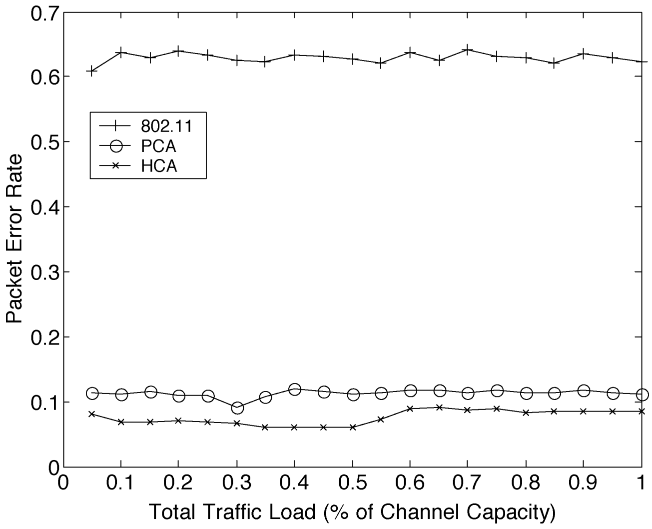

Fig. 8. PER for partially loaded system.

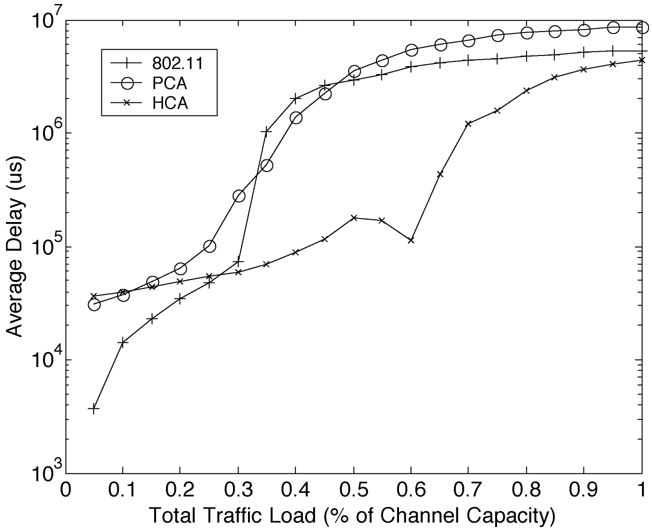

Fig. 9. Average delay for partially loaded system.

handshake overhead is reduced as not all the stations attend channel reservation.

The PER of the proposed HCA protocol is also much better than the IEEE 802.11-based protocol. Our simulations show PER improvements in the range of 43% to 92% depending on the channel conditions. Interestingly, when the channel health rate is set to 50%, the PER of the proposed scheme is 8%, still satisfying the minimum 8% PER requirement of the IEEE 802.11 physical layer. This is because in our scheme only stations with healthy channel condition participate in the transmission. Where, as in IEEE 802.11-based protocols, the PER will be proportional to the average channel condition in a fully loaded system. In IEEE 802.11, in order to achieve 8% PER, the power level is increased. This also implies that under the same average channel conditions, the system employing the proposed HAC protocol can achieve same performance as IEEE 802.11, but with less power consumption on the part of stations, which is an attractive feature for battery-life aware equipments such as laptops and PDAs. Note that the PER of the proposed protocol is also better than the PCA protocol. This is because in the PCA protocol by the time polling is complete, the channel information gathered may already be stale due to the large delay incurred in sequential polling, thus inducing incorrect channel reservation decisions.

Next, we compare the performance of the protocols assuming partial traffic loads. In our simulations, we are using Poisson process to generate traffic. The probability of k packets arriving in time T is modeled as $\Pr(k) = (\lambda T)^k e^{-\lambda T}/k!$, where λ is the packet arrival rate in a station.

Fig. 7 compares the channel utilization. We can see that all three protocols have ideal congestion control performances. i.e., when traffic load is low, the channel utilization increases linearly with respect to the traffic load and all the protocols maintain their performance when the channel is overloaded. However, the HCA protocol reaches at its saturation point when the traffic load is close to 65% of the channel capacity. This is an improvement of more than 50% compared to the saturation point of IEEE 802.11-based protocol and 40% compared to the PCA protocol.

Fig. 8 compares the PER assuming that channel is healthy 50% of the time. As expected, when channel condition is kept fixed, all the protocols have constant PER regardless of the traffic load. However, the PER of the proposed HCA protocol is lowest. This also implies that the energy wasted in retransmission is minimized by HCA.

Fig. 9 presents the delay performance of the proposed HCA. In IEEE 802.11-based protocols, the delay is primarily due to retransmissions. In the case of HCA and PCA protocols, the delay also includes the time for a station to reach to a good status. The delay is computed by comparing the time a packet arrives in the transmission buffer and the time it is received successfully by the AP. The data points are averaged over all the successfully transmitted packets. For most of the traffic loads, the average delay of the proposed HCA protocol is better than both the PCA and IEEE 802.11 protocols.

Next, we analyze the performance of our proposed HCA protocol assuming different threshold values of (Th_{round}) used to decide when to start the next round of handshake, given that the channel condition is deteriorating. We believe that setting this

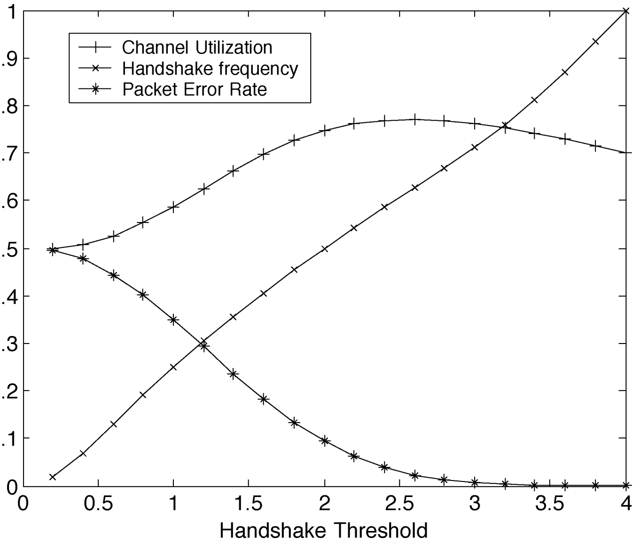

Fig. 10. Numerical results of channel utilization versus handshake threshold.

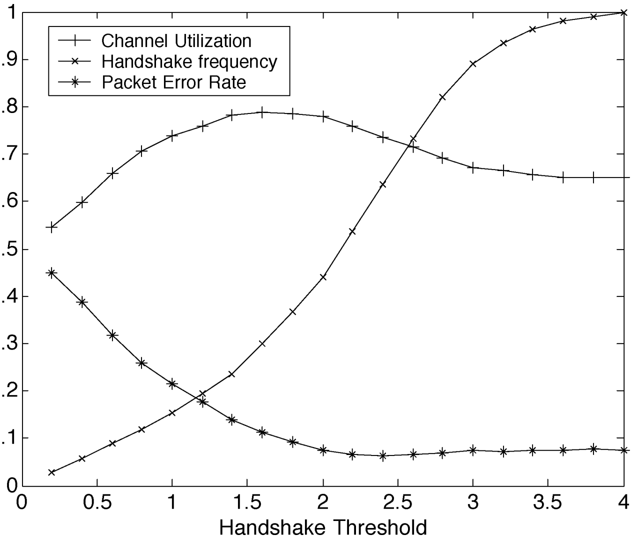

Fig. 11. Simulation results of channel utilization versus handshake threshold.

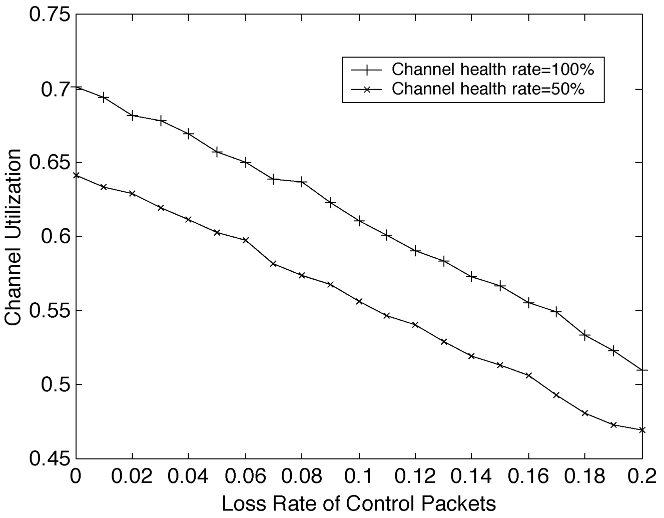

Fig. 12. Protocol robustness. Channel utilization versus PER of control frames.

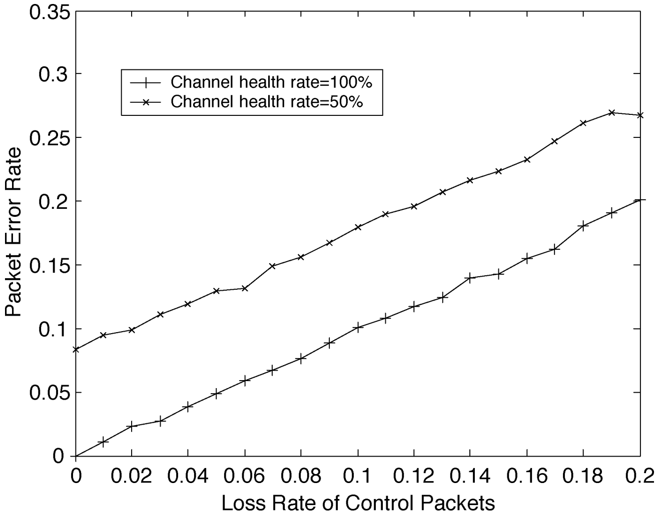

Fig. 13. Protocol robustness. PER of data frames versus PER of control frames.

threshold lower than the Th_q (the threshold used to compete for channel access) will improve channel utilization and reduce the number of handshake rounds. The performance results are shown in Fig. 11 for channel utilization, handshake frequency, and PER, assuming different values of the handshake threshold (Th_{round}). In the simulation, we fix the maximum time duration (50 packets) a station can use the channel. We show that by applying the handshake threshold, channel utilization can be improved to a maximum of 78%, which is 20% more than the case when this threshold is not applied under the same average channel condition of 50% (see Fig. 7). Our simulation results are very close to the numerical results shown in Fig. 10, which is computed based on (11)–(13).

Finally, we examine the robustness of our protocol. We allow the control frames (RTS, CTS, and ACK frames) to be lost with certain probability. We study the robustness under the following two channel conditions: perfect channel condition (with no packet error) and channel health rate of 50%. In both the cases, we assume the systems are fully loaded and handshakes are performed before each transmission. The simulation results are shown in Figs. 12, 13, and 14. Fig. 12 shows the channel utilization. When the loss rate for control packets is 20%, the channel capacity degrades down to 51% for perfect channel condition and down to 47% for channel health rate of 50%. The degradation in channel utilization is linear with respect to the loss rate. Fig. 13 shows the PER. In the case of perfect channel condition, the packet error is solely due to the loss of ACK frames. Whereas in the case of channel health $\mathrm{rate} = 50\%$, the packet errors are caused either by transmission itself or the ACK loss. Our results show that the PER is linear with respect to the control frame loss rate for both the cases. Fig. 14 shows the average number of handshake rounds, the number of handshake rounds increases since more contention and handshake failures happen when the control frame loss rate increases.

V. CONCLUSION

In this paper, we have developed an efficient channel access protocol for WLANs based on novel handshake procedures for

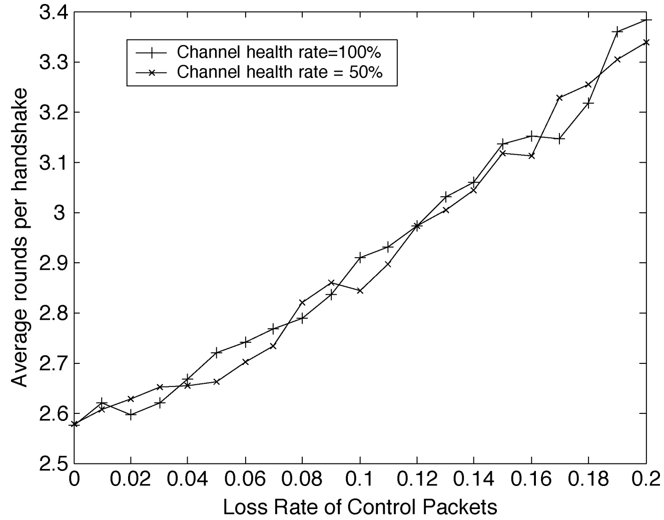

Fig. 14. Protocol robustness. Handshake overhead versus PER of control frames.

different traffic loads. We derive an analytical model for the handshake overhead and prove that the overhead is bounded regardless of the number of stations in the system. Our simulation results verify the accuracy of our analytical model. Furthermore, we show that the channel utilization (throughput) of the wireless network can be improved by applying the proposed HAC protocol. The maximum channel utilization achieved by the proposed protocol is 78% when the channel healthy rate is 50%. This is 20% improvement over the standard IEEE 802.11 protocol operating under perfect channel condition. Indirectly, this result further implies the proposed HAC protocol provides better throughput than IEEE 802.11 while using much lower battery power, a very attractive feature for power-constrained devices such as laptops and PDAs.

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