Wide-Sense Stable Hexanary-Feedback Contention Access for Wireless Networks

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***Abstract*- Most existing contention access schemes are inherently unstable resulting in exponentially deteriorating throughput under increased traffic loads. In this paper, we propose a wide-sense stable, efficient *Hexanary-Feedback Contention Access (HFCA)* scheme, capable of providing signaling traffic high performance while retaining maximal throughput for wireless access networks. HFCA performs incremental contention resolution via a two-phase process. The two-phase process is augmented with hexanary feedback control facilitated by a Pdf-based Multi-user Estimator (PMER) implemented at the physical layer. We present throughput and stability analyses in which HFCA is shown wide-sense stable, and the strict-sense stability condition is derived. Finally, analytic and simulation results delineate that, HFCA achieves high performance with respect to maximum stable and saturated throughputs, access delay, and blocking probability.**

1. Introduction

Wireless access networks are expected to support multiple services with a wide range of service rates and different Quality of Service (QoS) requirements. Expected supported services include CBR, VBR, ABR, and in-band signaling traffic for making bandwidth reservation for above traffic. It has been shown that the former three types of guaranteed (or semi-guaranteed) traffic could be efficiently governed by reservation access. The signaling traffic, on the other hand, is most suitably directed by contention access [1,2]. A key challenge pertaining to such wireless access networks has been the design of contention access satisfying access efficiency and QoS guarantees [1].

Among existing Time Division Multiple Access (TDMA)-based [3] contention access schemes, a set of methods [4] adopts the use of minislots in an effort to maintain system stability for traffic loads up to channel capacity. However, due to high cost for maintaining global minislot synchronization, we disregard the mini-slot-based approach. Among prevailing schemes, splitting-based collision-resolution schemes [5,6,7] have been consider promising. The basic idea is to speed up the resolution process by probabilistically [5] or time [6,7] splitting contenders into transmitting and non-transmitting sets based on various types of feedback that is made available to users. There are three feedback types- binary, ternary [5], and multiplicity [6]. Specifically, multiplicity feedback enables improved access efficiency, but at the expense of high implementation complexity. The goal of the paper is to design an efficient, tractable *hexanary feedback-based* contention access scheme, in which hexanary feedback can simply be facilitated in hardware.

Exploiting feedback control, existing algorithms [5,6,7] exhibit different merits with respect to stability, saturated throughput, maximum stable throughput, and implementation complexity, as summarized in Table I. Notice that our intention is not to provide a thorough survey of existing algorithms. Our aim to introduce salient performance terms and highlight the impact of different designs on these performance metrics. First of all, a Medium Access Control (MAC) scheme is *Wide-Sense Stable* (WSS) [1,5] if the network retains goodput even when the system is saturated. The positive throughput under the saturated condition is called the saturated throughput. Next, both WSS and unstable [6,7] schemes experience stable behavior when the traffic arrival rate is below a threshold. The maximum achievable throughput under the stable condition is referred to as the maximum stable throughput. Furthermore, a scheme is classified as *Strict-Sense Stable* (SSS) if not only it is WSS but each user's queue is retained stable. Finally, implementation complexity is incurred by full sensing of feedback [7], probability functions [5] computation, and hardware energy detectors [6].

In this paper, we propose a WSS *Hexanary-Feedback Contention Access (HFCA)* scheme, providing signaling traffic high performance while retaining maximal throughput. HFCA performs incremental contention resolution, via a two-phase process. The two-phase process is augmented with hexanary feedback control facilitated by a Pdf-based Multi-user Estimator (PMER) implemented at the physical layer. We further present throughput and stability analyses, in which HFCA is shown wide-sense stable, and the strict-sense stability condition is derived. Finally, analytic and simulation results delineate that, HFCA achieves high performance with respect to maximum stable and saturated throughputs, access delay, and blocking probability.

The remainder of this paper is organized as follows. In Section 2, we describe the network and system architectures. In Section 3, we introduce the design of PMER. In Section 4, we detail the two-phase HFCA scheme, followed by the throughput and stability analyses. Analytic and simulation results are also demonstrated in the section. Finally, concluding remarks are given in Section 5.

2. Network and System Architectures

The wireless network architecture is the classical cell with a Base Station (BS) serving a finite set of Mobile Terminals (MT's) via a shared radio medium. On the basis of Frequency-Division-Duplex (FDD), bandwidth is divided into uplink and

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downlink channels. The uplink channel transfers information from MT's to the BS according to our newly proposed HFCA scheme described later. Time on the uplink channel is divided into variable-size TDMA frames each of which is further subdivided into a fixed number of slots. The downlink channel typically broadcasts information and acknowledges previous transmissions made on the uplink channel. Notice that due to FDD and small propagation delay, immediate feedbacks and acknowledgements from the BS can be made available to MT's prior to the subsequent slot of the uplink channel.

The system architecture of the BS consists of two layers-physical (PHY) and MAC layers. At the PHY layer, particularly for reverse uplink traffic, the received signal is down-converted to baseband by the RF transceiver module. In the case of signaling traffic, the baseband signal is delivered into PMER for the estimation of colliding user population size before being demodulated. Otherwise, the signal is directly demodulated and decoded to recover the transmitted data. At the MAC layer, reservation access manages the access for CBR/VBR/ABR traffic, and the HFCA scheme governs that for signaling traffic. The operation of reservation access is beyond the scope of the paper. An MT wishing to establish a CBR, VBR, or ABR connection has to make a signaling request in a slot within contention bandwidth based on the HFCA scheme described in Section 4.

3. Pdf-based Multi-User Estimator (PMER)

3.1. Design Concept

We discover that under a given Signal-to-Noise-Ratio (*SNR*), for received signals contributed by different but small numbers of users, their envelope/phase probability density functions (pdf's) are distinctive. Specifically, if there are less than six users, pdf's of multi-user signals are distinguishable. Otherwise, signals are Gaussian distributed. Thus, a priori pdf library can be constructed in advance under various *SNRs* and numbers (one to five) of concurrent users.

We now describe the design of PMER assuming Additive White Gaussian Noise (AWGN) channel. During the on-line operation at the end of each slot, taking the received signal $R(t)$, the envelope detector first generates the associated envelope $y(t)$ and normalized envelope $x(t)$. The normalized envelope pdf is quantized via a histogram builder, constructing the corresponding normalized envelope histogram. The goodness-of-fit tester then conducts goodness-of-fit tests [8] for the resulted histogram against the priori envelope library previously constructed. The output of the tester is the estimated number of concurrent users, $\hat{L}$. Notice that the $\hat{L}$ value, ranging from 1 to 5, together with "idle", corresponds to six different outcomes of feedback.

3.2. Statistics of Received Multi-user Signal

In the sequel, we derive the normalized envelope pdf of the received multi-user signal under the AWGN channel. During the on-line operation at the end of each slot access, a phase-modulated signal ($R(t)$) received by the BS, which is contributed by L users, can be given as

$$R(t)=\sum_{i=1}^{L} S_i e^{j[2\pi f_0 t+\phi_i(t)]}+n(t)e^{j2\pi f_0 t}, \quad (1)$$

where S_i is the square root of the i_{th} MT's power at the receiver, f_0 is the carrier frequency, $\phi_i(t)$ is the modulated waveform from the i_{th} MT, and $n(t)$ represents the Gaussian noise with zero mean and variance $2\sigma_n^2$. For ease of illustration, we assume that power control is exerted at each MT, leading to S_i=S for all i's. Denote $y(t)$ the envelope of $R(t)$. Let $v(t)$ be the real part of $R(t)$. We obtain the characteristic function of $v(t)$ as

$$f_v(t)=\prod_{i=1}^{L} J_0(S_i t)\, e^{-(\sigma_n^2 t^2/2)}=J_0{}^L(St)e^{-(\sigma_n^2 t^2/2)}, \quad (2)$$

where $J_0(\cdot)$ is the Bessel function of the first kind of order zero. The pdf of $y(t)$ can then be derived [8] as

$$p_y(y)=\int_0^\infty yt J_0(yt) f_v(t)dt=\int_0^\infty yt J_0(yt) J_0{}^L(St)e^{-(\sigma_n^2 t^2/2)}dt,\ y>0 \quad (3)$$

To normalize the received signal power according to

$$x^2(t)=\frac{y^2(t)}{\text{mean received power}}=\frac{y^2(t)}{L\cdot S^2+2\sigma_n^2}, \quad (4)$$

the corresponding pdf of the normalized envelope $x(t)$ can be derived from Equation (3) as

$$p_x(x)=(L\cdot\Lambda+1)x\int_0^\infty te^{-t^2/4}J_0(xt\sqrt{L\cdot\Lambda+1})J_0^L(t\sqrt{\Lambda})dt, \quad (5)$$

where $\Lambda=\frac{S^2}{2\sigma_n^2}=SNR$. We clearly notice from Equation (5) that $p_x(x)$ is a function of L and *SNR*. Thus, a priori envelope pdf library can be offline constructed based on Equation (5). Partial results of the library for different numbers of users (L=1 to 5) under *SNR*=10 dB are depicted in Figure 1. Clearly, the stronger the SNR, the more distinctive the pdf's are.

3.3. Simulation Results

Based on 500 and 2000 samples collected at the end of each slot, we interrogated the mean and standard deviation of the estimated user number $\hat{L}$. Simulation was operated for a total of

Table I. Evaluation of feedback-based collision-resolution algorithms

Collision- Resolution Algorithm	Feedback Type	Stability	Maximum Stable Throughput	Saturated Throughput	Implementation Complexity
Binary Tree [7]	Ternary	Unstable	0.487	0	Medium
Georgiadis [6]	Multiplicity	Unstable	0.532	0	High
Paris [5]	Ternary	WSS	0.487	0.368	High
HFCA	Hexanary	WSS	0.605	0.522	Medium

500 slots in length. Results are plotted in Figure 2. We observe that the mean estimated $\hat{L}$ values (1 to 5) using 2000 samples completely agree with the actual L values under SNR=20 dB. As for the results based on 500 samples, estimation is profoundly precise particularly under $L \le 4$.

4. Hexanary-Feedback Contention Access

The basic idea behind the design is to overcome system instability by probabilistic reducing the contention size to less than six, followed by efficient collision resolution with the aid of hardware-based hexanary feedback. The hexanary feedback informs six possible outcomes- idle, success, and two- to five-user collisions.

4.1. Basic Operation

The HFCA operation within a frame consists of repeated executions of admission and resolution phases. The two-phase process repeats until the maximum blocking probability is satisfied (before all users are resolved). Notice that new users that become active during the current frame's contention period are inhibited from transmitting.

Immediately prior to the first phase, the mean number of MT's wishing to transmit, i.e., the initial group size (denoted as N), is revealed to the BS via a priori call distribution or simple prediction. Notice that it can be easily shown that HFCA is robust against prediction discrepancy. The priori or predicted initial group size, denoted as $\hat{N}$, is then broadcast to all MT's via the downlink channel. In the admission phase, each active MT accesses the subsequent slot based on the Controlled Slotted-Aloha (CS-Aloha) protocol parameterized by admission probability, $P_A(\hat{N}) = \kappa_{opt} / \hat{N}$, where κ_{opt} is the optimal value yielding maximized saturated throughput. Upon receiving the signal, PMER estimates the number of colliding MT's ($\hat{L}$). If a collision occurs ($2 \le \hat{L} \le 5$), the operation proceeds to the second phase. All active MT's are in turn notified with the $\hat{L}$ value, and assign the value to the reduced group size (m). If $\hat{L} \le 1$, the current two-phase cycle terminates. If the number of colliding MT's exceeds five ($\hat{L} > 5$), which happens with small probability, no user can be admitted and a feedback of $\hat{L} = 0$ is returned, resulting in one-slot waste.

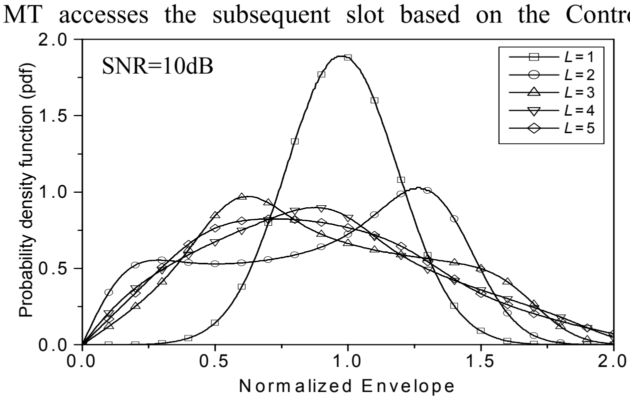


Figure 1. Normalized envelop pdf's for different L's.

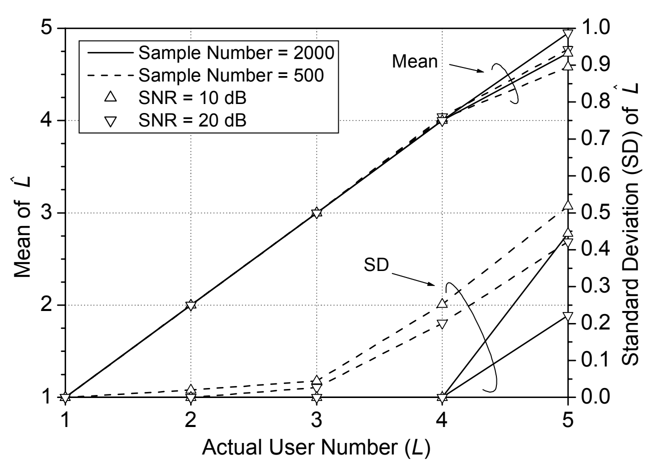


Figure 2. Mean and standard deviation of $\hat{L}$.

In the resolution phase, each admitted unresolved MT designates its transmitting probability inversely proportional to the current number of MT's in the group. Namely, each MT accesses the next contention slot based on the CS-Aloha protocol parameterized by resolution probability $P_R(G) = 1/G$, where G is the current group size. At the end of slot access, each MT takes different actions depending on the feedback ($\hat{L}$). If $\hat{L} = 1$ (success), the current group size (G) is decremented by one. If $\hat{L} = 0$ (idle), or $\hat{L} \ge 2$ (collision) but $\hat{L} \ne G-1$, resolution recursively repeats with G remained unchanged. Significantly, if $\hat{L} \ge 2$ (collision) but $\hat{L} = G-1$, by taking advantage of having a single MT in the non-transmission set, HFCA allows dedicated access within the subsequent slot to this MT. All other MT's in the transmission set result in one slot delay and reduce G by one. The phase-two operation repeats until all admitted group users are resolved, i.e., $G = 0$.

4.2. Throughput and Stability Analyses

In the analyses, system regenerative points are placed at the beginning of each contention period. Let $\tilde{N}$ and N respectively represent the random variable and variable for the total number of active MT's wishing to transmit requests at the beginning of the contention period of a frame. $\tilde{N}$ is assumed Poisson distributed with parameter α . We assume all N users are resolved at the end of the contention period. Denote by random variable $\tilde{C}_N$ the contention period length, namely the total number of slots required to resolve the user group of size N; and $C_N = E[\tilde{C}_N]$. Let variable m denote the first reduced group size, i.e., the number of active MT's admitted at the end of phase one. Denote by random variable $\tilde{D}_m$ the total number of slots required to resolve all m users in a reduced group in phase two; and $D_m = E[\tilde{D}_m]$.

(i) Computation of C_N

If there is no request ($N = 0$), or only a single request ($N = 1$), wishing to transmit in the first slot (first phase), the contention period lasts for one slot, that is $\tilde{C}_0 = \tilde{C}_1 = 1$. For $N \ge 2$, the probability that exactly m of N users make transmissions and are admitted in the first phase is

$$Q_N(m) = \binom{N}{m} (\frac{\kappa}{N})^m (1 - \frac{\kappa}{N})^{N-m} \qquad 0 \le m \le N. \tag{6}$$

Given that m of N users have made transmissions, the contention period length can be expressed recursively as

$$\begin{cases} \tilde{C}_{N|m} = 1 + \tilde{D}_m + \tilde{C}_{N-m} & N > m \geq 2,\ N \geq 2 \\ \tilde{C}_{N|m} = 1 + \tilde{D}_m & N = m \geq 2,\ N \geq 2 \\ \tilde{C}_{N|m} = 1 + \tilde{C}_{N-m} & m < 2,\ N \geq 2 \ . \end{cases} \quad (7)$$

We now compute C_N. First, we have $C_0 = C_1 = 1$. For $N \geq 2$, C_N can be derived by taking expectation from Equation (7). Taking expectation on both sides of Equation (7), and by unconditioning, one gets

$$C_N = 1 + \sum_{m=2}^{N} Q_N(m) \cdot D_m + \sum_{m=1}^{N-1} Q_N(m) \cdot C_{N-m} + Q_N(0) C_N \quad N \geq 2 \ . \quad (8)$$

Solving for C_N, we obtain

$$C_N = \frac{1 + \sum_{m=2}^{N} Q_N(m) \cdot D_m + \sum_{m=1}^{N-1} Q_N(N-m) \cdot C_m}{1 - Q_N(0)} \qquad N \geq 2 \ . \quad (9)$$

(ii) Computation of D_m

Given that i of m users ($m \geq 2$) in the reduce group made transmissions in the first slot of phase two, the phase-two period length can be formulated recursively as

$$\tilde{D}_{m|i} = \begin{cases} 1 + \tilde{D}_{m-1} & i = 1 \\ 2 + \tilde{D}_{m-1} & i = m-1 \\ 1 + \tilde{D}_m & i = 0,\ 2 \leq i < m-1, \text{ or } i = m \ . \end{cases} \quad (10)$$

For $m \geq 2$, the probability that exactly i of m users have made transmissions in the first slot of phase two is

$$R_m(i) = \binom{m}{i} \left(\frac{1}{m}\right)^i \left(1 - \frac{1}{m}\right)^{m-i} \qquad m \geq 2 \ . \quad (11)$$

To compute D_m for $2 \leq m \leq N$, we first have $D_1 = 1$. We next solve the second boundary condition for D_2 by the following recursive equation: $D_2 = 1 + R_2(1) \cdot D_1 + [1 - R_2(1)] \cdot D_2$. We get $D_2 = 3$. For $m > 2$, taking z-transform from both sides of Equation (10), unconditioning variable i, and solving for $F^*_{\tilde{D}_m}(z)$, we obtain the recursive form as

$$F^*_{\tilde{D}_m}(z) = \frac{F^*_{\tilde{D}_{m-1}}(z) \cdot [z \cdot R_m(1) + z^2 \cdot R_m(m-1)]}{1 - z \cdot [1 - R_m(1) - R_m(m-1)]} \qquad m \geq 3 \ . \quad (12)$$

Taking the first derivative of $F^*_{\tilde{D}_m}(z)$ at $z = 1$, we obtain

$$D_m = \sum_{k=3}^{m} \frac{1 + R_k(k-1)}{R_k(1) + R_k(k-1)} + D_2 + D_1 \qquad m \geq 3 \ , \quad (13)$$

where $D_1 = 1$ and $D_2 = 3$ which have been previously derived.

(iii) Throughput Computation

Since $\tilde{N}$ is Poisson distributed, with C_N (and D_m) given by Equations (9) and (13), the system throughput can be given as

$$\bar{S} = \frac{E[\tilde{N}]}{E[C_{\tilde{N}}]} = \frac{\sum_{N=0}^{\infty} N \cdot \frac{e^{-\alpha}\alpha^N}{N!}}{\sum_{N=0}^{\infty} C_N \cdot \frac{e^{-\alpha}\alpha^N}{N!}} \ . \quad (14)$$

Notice that $\bar{S}$ in Equation (14) is a function of α and κ. We now define *saturated throughput* ($\bar{S}_{sat}$), and *maximum stable throughput* ($\bar{S}_{\max}$). First, $\bar{S}_{sat}$ is defined as

$$\bar{S}_{sat} \equiv \lim_{\alpha \to \infty} \bar{S}. \quad (15)$$

The optimal value κ_{opt} applied during phase one is chosen such that $\bar{S}_{sat}$ is maximized, i.e., $\bar{S}_{sat}(\kappa_{opt}) = \max\{\bar{S}_{sat}(\kappa), \forall \kappa\}$. A system is WSS if it has a positive saturated throughput. Maximum stable throughput ($\bar{S}_{\max}$) is the maximum achievable throughput when the system is stable.

To numerically evaluate κ_{opt}, $\bar{S}_{sat}$, and $\bar{S}_{\max}$, we carried out analytic computation via Mathematica 4.0. Since Poisson converges to the Gaussian distribution with the same mean and variance α, we consider $N_{\max} = \alpha + 5\sqrt{\alpha}$ to be applied in Equation (14), resulting in sufficiently high confidence to the evaluation ($P(N > \alpha + 5\sqrt{\alpha}) < 2.86653 \times 10^{-7}$). First of all, for a given α, κ_{opt} was determined by using Mathematica function *FindMinimum*[1- $\bar{S}$ [$N_{\max}$, α , κ_{opt}], κ_{opt}]. We obtained that $\bar{S}_{sat}$ is maximized under $\kappa_{opt} = 1.52$. Applying κ_{opt} to $\bar{S}$ in Equation (15) with $\alpha \geq 400$, we got $\bar{S}_{sat} \approx 0.522$. HFCA is proved WSS. Applying the κ_{opt} value and using *FindMinimum*[1- $\bar{S}$ [$N_{\max}$, α , 1.52], α], we reveal that $\bar{S}$ is maximized at $\alpha_{\max} = 1.88$. Applying the $\alpha_{\max}$ value to $\bar{S}$ in Equation (14), we arrive at that $\bar{S}_{\max} = 0.605$ at $\alpha_{\max} = 1.88$.

(iv) Stability Analysis

First, since $\bar{S}_{sat} \approx 0.522$, HFCA is WSS. Second, notice that ratio N / C_N can be perceived as the effective service rate. Then, if there exists a lower bound of N / C_N, then there exists a *system capacity* [9] defined as the supremum of new arrival rates that ensure strict-sense stability of the system. Due to mathematical intractability for deriving the closed form of C_N from Equation (9), we derived C_N and N / C_N by means of numerical computation. We claim in the following remark that the system capacity of HFCA is $\bar{S}_{sat}$, i.e., HFCA is SSS is the new arrival rate is lower than $\bar{S}_{sat}$.

Remark: The HFCA system is SSS if the new arrival rate is lower than $\bar{S}_{sat}$.

First, numerical results show that N / C_N ($N \geq 1$) is a monotonically decreasing function. Next, by taking advantage of linearty of C_N, we obtain

$$\bar{S}_{sat} = \lim_{\alpha \to \infty} \frac{E[\tilde{N}]}{E[C_{\tilde{N}}]} = \lim_{\alpha \to \infty} \frac{\alpha}{C_{E[\tilde{N}]}} = \lim_{\alpha \to \infty} \frac{\alpha}{C_\alpha}. \quad (16)$$

Namely, N / C_N converges to $\bar{S}_{sat}$. We can conclude that N / C_N is lower bounded by $\bar{S}_{sat}$, i.e., $N / C_N \geq \bar{S}_{sat} \approx 0.522$.

Therefore, if the new arrival rate is lower than $\overline{S}_{sat}$, it is lower than the effective service rate N / C_N, the system is SSS. ■

4.3. *Experimental Results*

We draw comparisons of performance between HFCA and four existing schemes via event-based simulation. These schemes are Binary-Feedback Collision Resolution (BFCR), Paris [5], Clipped Binary (CB)-Tree, and S-Aloha. The BFCR scheme is the binary-feedback version of HFCA, namely, with PMER removed. In the simulation of Paris (a near-optimal collision resolution algorithm), we extracted different *p* values under different loads from function *p(u)* analytically computed in advance. The access delay of an MT was measured as the total number of slots required until the MT successfully transmits its signaling request. An MT's request was considered

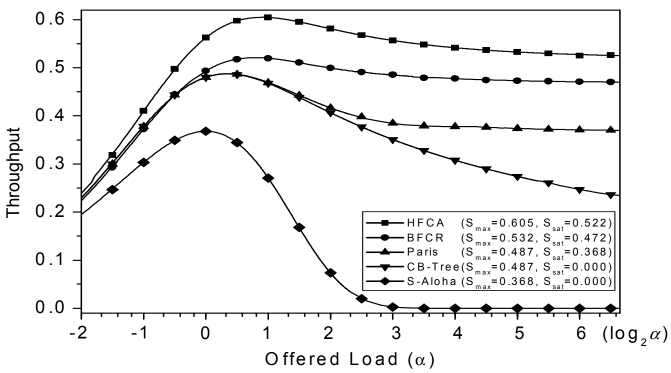
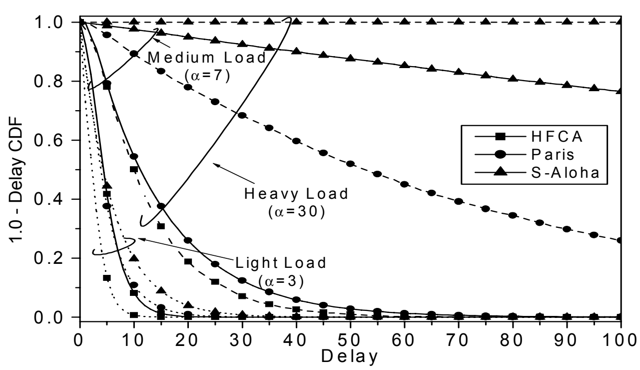
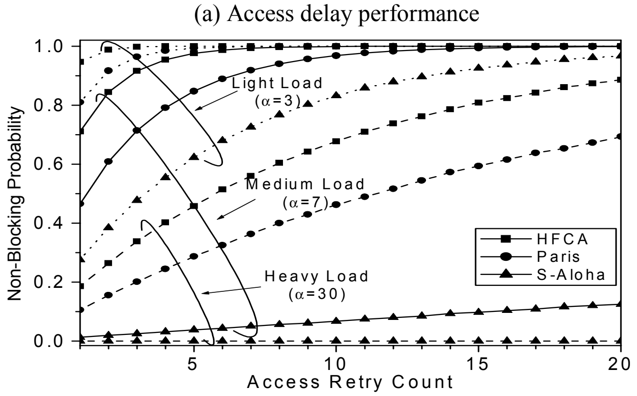


Figure 3. Comparison of system throughput.



(a) Access delay performance



(b) Non-blocking probability performance

Figure 4. Comparisons of access delay and blocking probability.

blocked if the number of slot accesses exceeds the predefined access retry count in units of slots. Simulation was terminated after reaching 95% confidence interval.

In Figure 3, we discover that HFCA, BFCR, and Paris schemes are WSS assuring converged saturated throughput. Both BFCR and HFCA outperform Paris. We clearly observe from Figure 4 that, owing to being unstable, S-Aloha results in drastic increases in access delay and blocking probability under both the medium and heavy loads. Besides, HFCA profoundly outperforms Paris on both performance metrics particular under medium and heavy loads.

5. Conclusions

In this paper, we proposed a WSS contention access system, HFCA, and its multi-user estimator, PMER, for supporting signaling traffic over wireless access networks. HFCA is capable of leveraging access efficiency by using a two-phase algorithm augmented with hexanary feedback facilitated by PMER. HFCA was shown to achieve the highest maximum stable throughput (≈ 0.605) and saturated throughput $\overline{S}_{sat}$ (≈ 0.522) reported to-date. The stability analysis showed that HFCA is SSS is the new arrival rate is lower than $\overline{S}_{sat}$.

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