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Research Article

On Adaptive Contention Resolution Schemes for IEEE 802.16 BWA Systems

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According to the latest version of the IEEE 802.16 standard, the mandatory contention resolution method is the truncated binary exponential backoff, with the initial window size and the maximum window size controlled by the base station. However, the problem of choosing the right set of backoff parameters for the current network level remains unsolved and left as an open issue since this strategy might incur a high collision probability and the channel utilization could be degraded in congested scenario. In this paper, we propose two pragmatic adaptive algorithms, namely semi-dynamic and quasi-dynamic contention resolution schemes, that allow the base station to adjust its backoff window size based on current channel status. By controlling the size of backoff window according to varying network conditions, both schemes are able to achieve higher performance in comparison with the legacy IEEE 802.16 standard.

1. Introduction

High-speed transmission, fast deployment, and cost saving have made *Broadband Wireless Access* (BWA) systems a rapidly emerging field of activity in computer networking, attracting significant interests in the communities of academia and industry. In the mean time, the IEEE standard for BWA systems, IEEE 802.16 [1–3], has gained global acceptance and popularity in wireless computer networking markets and is also anticipated to take place of broadband access solutions like *digital subscriber line* (DSL) and cable.

The IEEE 802.16 standard specifies two modes for sharing the wireless medium: *point-to-multipoint* (PMP) and *mesh* (optional) modes. In the PMP mode, the nodes are organized into a cellular-like structure, where a *base station* (BS) serves a set of *subscriber stations* (SSs) within the same antenna sector in a broadcast manner, as shown in Figure 1.

The communication path between SSs and BS has two directions: uplink channel (from SSs to BS) and downlink channel (from BS to SSs). The downlink channel is a broadcast channel, while the bandwidth of uplink channel is shared by the SSs. The subframe in uplink channel includes three periods: Initial Maintenance period, Request Connection Opportunities period, and Scheduled Data grants period. The BS announces these periods and associates burst classes in the preceding downlink subframe's *uplink map* (UL-MAP).

Initial ranging and bandwidth request are two primary parts of the Call Admission Control (CAC) procedure. The BS periodically reserves bandwidth in the uplink channel for SSs to register or send their bandwidth request. When a SS needs registration or bandwidth, it has to go through the contention resolution procedure to send its requests.

The IEEE 802.16 contention resolution mechanism is controlled by two sets of parameters: the number of the contention slots and the backoff initial/maximum window values. These parameters are set at the BS and transmitted to SSs in the UL-MAP. When an SS has information to send and wants to enter the contention resolution process, it sets its internal backoff window size equal to the request size of initial backoff window defined in the *uplink channel descriptor* (UCD) message. The SS randomly selects a number within its initial backoff window. This random value indicates the number of contention transmission opportunities that the

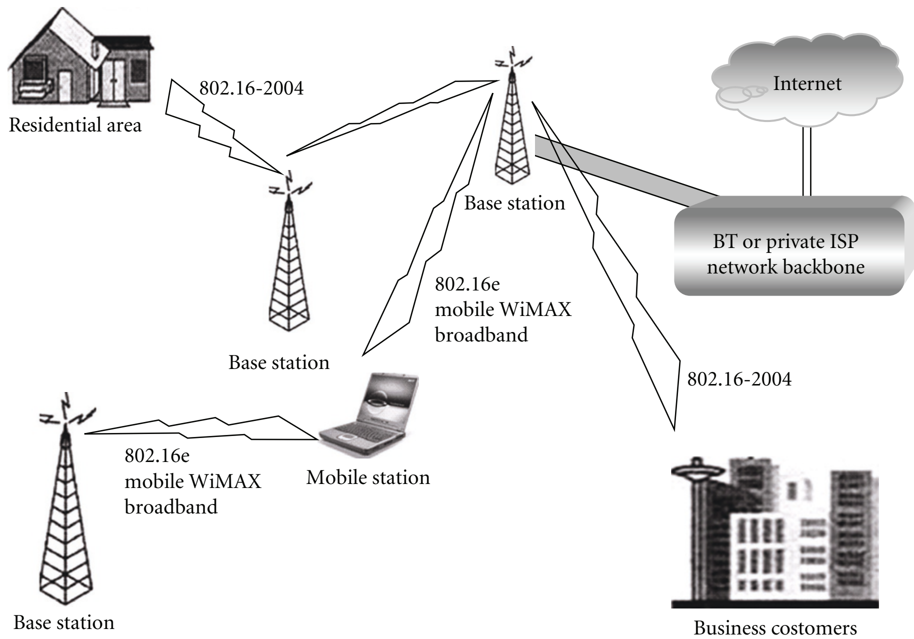

Figure 1: Broadband wireless access system.

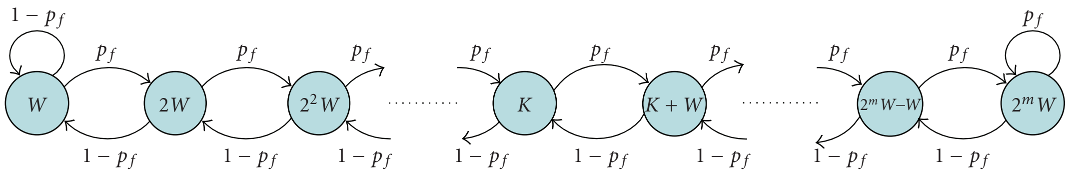

Figure 2: State transition diagram of semi-dynamic contention resolution scheme.

SS defers before transmitting. However, collisions might still occur if two or more SSs select the same backoff value. When this happens, the SS increases its backoff window by a factor of two, as long as it is less than the maximum backoff window. The SS randomly selects a number within its new backoff window and repeats the deferring process described above. This retry process continues until the maximum number of retries has been reached.

According to the IEEE 802.16 standard, the backoff parameters of its collision resolution mechanism are far from optimal setting since it selects a small initial value of backoff window by a naive assumption of a low level of congestion in the system. Hence, the problem of choosing the right set of backoff parameters for the current network level remains unsolved and left as an open issue since this strategy might incur a high collision probability and the channel utilization could be degraded in congested scenario.

Although in literatures there have been excellent discussions on the issues on contention resolution mechanism and its performance analysis [4, 5]. However, these studies do not propose any mechanisms to force the SSs to adopt an adaptive backoff window size that maximizes the channel capacity for current channel status. In [6], Yao et al. analyzed the impact of contention slots allocation on system throughput and thus proposed an algorithm to optimize the utilization of uplink bandwidth by dynamically adjust the number of contention slots. In [7], Sayenko et al. presented analytical calculations to determine optimal values for the backoff initial/maximum values and an optimal number of the request transmission opportunities. In [8], Lin et al. proposed an efficient performance improvement method by using dynamic window adjustment for initial ranging. However, none of the above studies is satisfactory since they did not tell us how to run-time estimate the channel status. The algorithm proposed in [9] automatically adjusts the initial contention window to a near optimal point according to the traffic activity, thus avoiding bandwidth wastage due to improper contention window setting. However, this scheme was designed for WLANs, and we did not know whether the proposed algorithm can be applied to IEEE 802.16 standard.

Based on above observations, we propose that a proper choice of the size of backoff window in accordance with current channel status, which has a great influence on overall network performance. Hence, in this paper, two pragmatic adaptive algorithms, namely semi-dynamic and quasi-dynamic contention resolution scheme, that allow the base station to adjust its backoff window size dynamically are proposed. Both schemes can be implemented in the present IEEE 802.16 standard with only relatively minor modifications and use very simple feedback signals. In

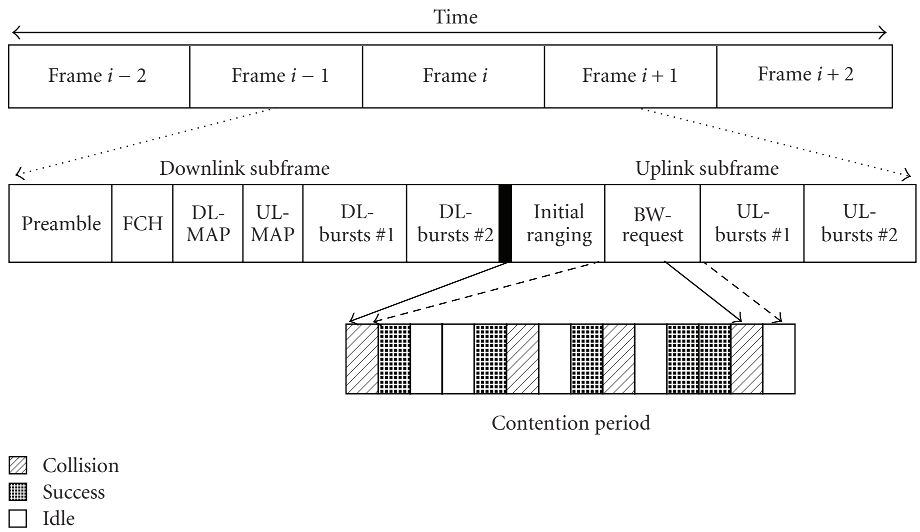

Figure 3: The channel status of IEEE 802.16 contention resolution mechanism.

addition to the analytical analysis, we have also carried out comprehensive simulations implemented by network simulator NS2 [10] to evaluate the performance of the proposed schemes. The results show that both schemes are able to achieve higher performance in comparison with the legacy IEEE 802.16 standard.

The remainder of this paper is organized as follows. Sections 2 and 3 introduce the proposed semi-dynamic and quasi-dynamic contention resolution schemes, respectively. Simulation and experimental results are given in Section 4, followed by Section 5 which concludes this paper.

2. Semi-Dynamic Contention Resolution Scheme

As an effort to improve on the previous schemes, we introduce our proposed schemes in detail in this and next section. Before we start to discuss the issues of interest, important notations and variables are defined in Table 1, and they will be used throughout this paper.

In an IEEE 802.16 BWA system, a low transmission collision rate implies that the number of competing SSs is low, and the contention window should be set small. On the other hand, consecutive transmission collisions indicate that there are numerous competing SSs in the system. In such cases, the size of backoff window should be set considerably large to avoid collisions in the future transmission.

In the proposed semi-dynamic contention resolution scheme, an active SS uses the analytical model described in [11] to estimate the number of competitive SSs, and then a threshold of backoff window size is set to determine the number of competitive SSs. For more details, the reader is referred to our previous work [11].

In the beginning, corresponding to the period of connection start-up, the backoff window is exponentially increased so as to quickly adjust itself to the current channel status. After the backoff window size reaches the threshold, the size of backoff window linearly grows until a packet transmitted successfully. Algorithm 1 describes the proposed scheme.

Table 1: Notations and variables used in analytical analysis.

Notations and variables	Meaning and explanation
K	Number of estimated active connections
p_f	Probability of a contention failure
p	Transmission probability
ρ	Utilization factor of contention period
p_{opt}	Optimal value of parameter p
W	Initial backoff window size
$W_{\max}$	Maximum backoff window size
m	Maximum number of backoff stages
$\overline{W}$	Average contention window size
$\overline{W_{\text{opt}}}$	Optimal contention window size

Figure 2 shows the state transition diagram of backoff window variation in the proposed semi-dynamic contention resolution scheme. In sum, when the current backoff window size is smaller than the threshold, K, we increase/decrease the size of backoff window exponentially in response to a light network load. On the other hand, we increase/decrease the size of contention window linearly in response to a heavy network load when the contention window size is larger than the threshold.

3. Quasi-Dynamic Contention Resolution Scheme

In order to exploit the information about the actual channel status, we define the probability of contention failure, p_f, to be the probability that a request slot transmitted by the SS of interest fails (collisions), and the utilization factor of contention period, ρ, to be the average utilization rate

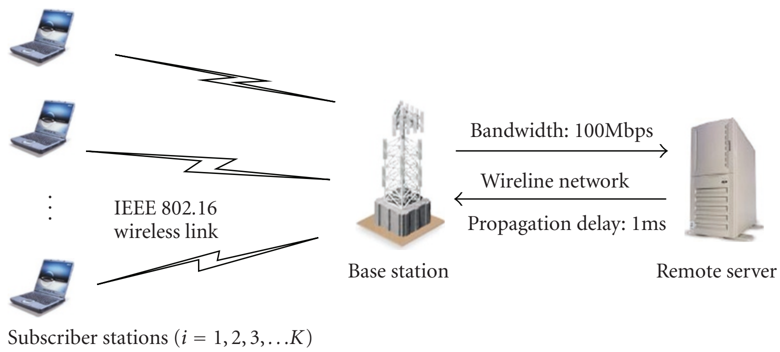

Figure 4: Simulation topology.

Function Semi-Dynamic Backoff
repeat
if Response received from BS **then**
  if backoff window size ≤ threshold **then**
    if backoff window size == W **then**
      backoff window size = W
    else
      backoff window size = backoff window size ÷ 2
  else
    backoff window size = backoff window size $-W$
else
  if backoff window size < threshold **then**
    backoff window size = backoff window size × 2
  else
    if backoff window size == $W_{\max}$ **then**
      backoff window size = $W_{\max}$
    else
      backoff window size = backoff window size + W
until no more packet to transmit
end.

Algorithm 1

of contention periods. Recall that the channel status of contention period (initial ranging or bandwidth request) can be generally divided as two states: busy and idle states as shown in Figure 3. It is noted that busy state includes collision and successful contention. Since the absence of an immediate response in the following UL-MAP will be regarded as a failed contention, p_f can be obtained by counting the total number of responses observed in the following UL-MAP, divided by the total number of observed contention attempts on which the measurement is taken in the contention period.

As for the utilization factor of contention period, ρ, it can be obtained by counting the total number of contention attempts observed in the contention period, divided by the total number of observed contention opportunities on which the measurement is taken in the contention period.

Assume that there are K connections working in asymptotic conditions in the system, meaning that the transmission queue of each connection is assumed to be always nonempty.

Instead of the legacy binary exponential backoff algorithm used in the 802.16 standard, the backoff interval of the proposed analytical model is sampled from a geometric distribution with the parameter p and defers the transmission with probability$1-p$, and then repeats the procedure at the next empty slot. Based on geometric densities, the probability that there are x failures of Bernoulli trials before the first success is

$$P(X = x) = (1-p)^{x-1} p, \quad 1 \le x \le \infty. \tag{1}$$

Hence, the average contention window size is determined by the expected value of random variable X, and thus we have

$$\frac{\overline{W}+1}{2} = \frac{1}{p}. \tag{2}$$

Now let us try to estimate the average backoff window size at a saturation condition. Since the backoff time is uniformly distributed over $\{0, W\}$ for the first attempt, the average backoff window size is

$$\overline{W} = \frac{\left(1-p_f\right) W + p_f\left(1-p_f\right) 2W + \cdots + p_f^m \left(1-p_f\right) 2^m W}{1-p_f^{m+1}}. \tag{3}$$

Substituting $\overline{W}$expressed in (2) into (3), we obtain:

$$\begin{aligned} p &= \frac{2}{\overline{W}+1} \\ &= \frac{2\left(1-2p_f\right)\left(1-p_f^{m+1}\right)}{W\left(1-p_f\right)\left(1-(2p_f)^{m+1}\right) + \left(1-2p_f\right)\left(1-p_f^{m+1}\right)}. \end{aligned} \tag{4}$$

Since the probability of a contention failure is defined as the probability that a transmitted request encounters a collision, this yields

$$p_f = 1 - (1-p)^{K-1}. \tag{5}$$

From (5), we obtain

$$K = 1 + \frac{\log\left(1-p_f\right)}{\log(1-p)}. \tag{6}$$

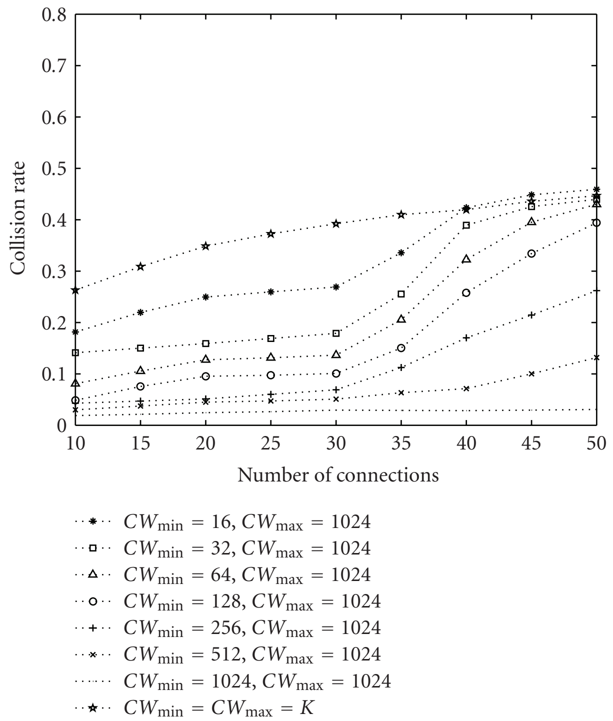

Figure 5: Collision rate as a function of start contention window size and traffic load.

Substituting p as expressed in (4) into (6), we obtain

$$K = 1 + \log\left(1 - p_f\right) / \left(\log\left[1 - 2\left(1 - 2p_f\right)\left(1 - p_f^{m+1}\right) / \left(W\left(1 - p_f\right)\left(1 - \left(2p_f\right)^{m+1}\right). + \left(1 - 2p_f\right)\left(1 - p_f^{m+1}\right)\right)\right]\right) \quad (7)$$

Since $K \times p = 0$ indicated that a slot in the contention period remains empty, we have

$$K \times p_{\text{opt}} = \sum_{i=1}^{K} i \cdot P\{K = i\} \geq \sum_{i=1}^{K} P\{K = i\} = 1 - p\{K = 0\} = \rho. \quad (8)$$

Substituting $\overline{W}$ and Kas expressed in (2) and (7), respectively, we can obtain the approximated optimal contention window size ($\overline{W}_{\text{opt}}$) which is defined as follows

$$\left(2\left(1 + \log\left(1 - p_f\right) / \left(\log\left[1 - 2\left(1 - 2p_f\right)\left(1 - p_f^{m+1}\right) / \left(W\left(1 - p_f\right)\left(1 - \left(2p_f\right)^{m+1}\right) + \left(1 - 2p_f\right)\left(1 - p_f^{m+1}\right)\right)\right]\right)\right) - \rho\right) / \rho. \quad (9)$$

Table 2: Default attribute values used in the simulation.

Parameter	Value
MAC layer	
Channel capacity	32 Mbps(QPSK)
Number of subchannels	30
Symbol rate	16 Megabaud
Slot size	1 byte
Frame duration	4 ms
Physical slots per frame	4000
Downlink/uplink ratio	3 : 2
Ranging opps. Per frame	12 OFDMA symbols
Number of ranging retry	16
Bandwidth request opp. per frame	12 OFDMA symbols
Number of bandwidth request retry	6
Backoff start value	4
Backoff end value	10
Initial ranging CID	0
Basic CIDs	1–1000
Primary CIDs	1001–2000
Threshold	512
System time	
OFDMA symbol time	100.84 μs
OFDMA frame length	5 ms
Ranging interval interval	1210.08 μs
Bandwidth request interval	1210.08 μs
TTG	200 μs
RTG	200 μs
T1-T26	As defined in IEEE 802.16 standard
Physical layer	
Spectrum	5.0 GHz
Bandwidth	5 MHz
Simulation topology	1100 m × 1100 m
Offered traffic load	0.12 Mbps
QPSK 1/2	4.99 Mbps
QPSK 3/4	7.48 Mbps
16-QAM 1/2	9.97 Mbps
16-QAM 3/4	14.96 Mbps
64-QAM 2/3	19.95 Mbps
64-QAM 3/4	22.44 Mbps
QPSK 1/2	−79 dBm
QPSK 3/4	−76 dBm
16-QAM 1/2	−72 dBm
16-QAM 3/4	−69 dBm
64-QAM 2/3	−65 dBm
64-QAM 3/4	−63 dBm

Table 3: Fairness index versus number of connections.

Number of connections	$CW_{min} = CW_{max} = K$	Legacy IEEE 802.16	Semi-dynamic scheme	Quasi-dynamic scheme
10	0.975299	0.979776	0.996461	0.998155
15	0.954031	0.960398	0.993762	0.994366
20	0.933515	0.948921	0.990311	0.992507
25	0.927668	0.945344	0.988443	0.995792
30	0.910177	0.930308	0.973221	0.996529
35	0.889325	0.914136	0.958744	0.988715
40	0.861827	0.892372	0.932492	0.980814
45	0.815158	0.858453	0.887228	0.964915
50	0.738294	0.785694	0.831944	0.948761

4. Simulations and Performance Evaluation

4.1. Simulation Environment. Our simulation model is built using the network simulator NS2. The transmitting power used for each SS is assumed to be high enough to cover transmission range. Figure 4 shows an overview of the simulated system topology. To focus on the contention resolution issue and to reduce the complexity of the simulation, what follows are the basic assumptions in our simulation environment. First, no stations operate in the "power-saving" mode. Second, transmission errors are generated according to the Gaussian channel assumption. The evaluation is made with respect to the collision rate, average access delay, achievable throughput, and fairness index under different offered traffic load.

The default values used in the simulation are listed in Table 2. The values for the simulation parameters are chosen carefully in order to closely reflect the realistic scenarios as well as to make the simulation feasible and reasonable. All the simulations are conducted on FreeBSD 6.0 on a Xeon 3.4 GHz Server with 2 GB memory. The version of NS2 is ns-2.29, and each simulation run lasts for 20 simulation seconds.

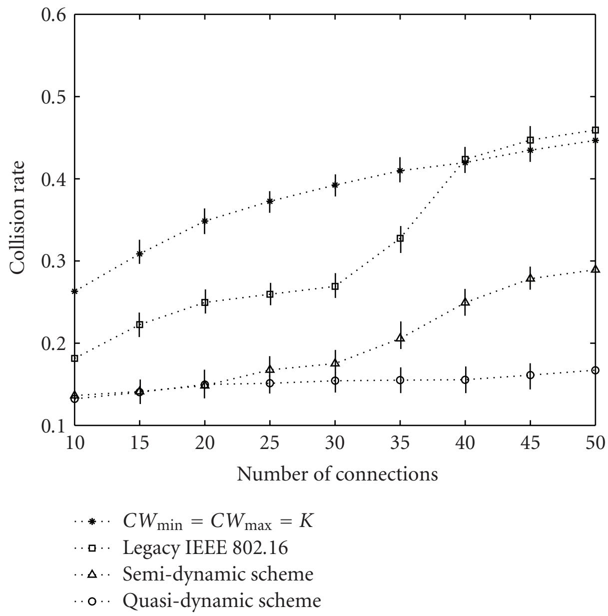

Figure 6: Collision rate versus number of connections.

4.2. Simulation Results. Simulation results are shown below in the form of plots. The variation of collision rate as a function of traffic load is then plotted as shown in Figure 5. It is an intuition that the maximum throughput is obtained by setting the transmission probability of each station equal to $1/K$, that is, $W = W_{max} = K$. However, based on our simulation results, the collision rate could be larger than 0.4 as the number of the connections reaches 30 if the backoff window size is fixed to the number of requested connections in the network. Under such circumstances, the performance of the network will be severely degraded as significant transmission loss occurs due to collisions caused by simultaneous transmission of requests. Besides, as shown in Figure 5, different size of W for different traffic load is plotted. It can be seen that, as long as the requested connections increase beyond 30, the collision rate raises sharply and reaches close to 0.4. Similar plots are obtained by setting W size to 32, 64, and 128. Observations that can be drawn from these results are as follows: (1) the initial backoff window size should be at least equal to the number of competing connections (SSs) in the network, and (2) the size of initial backoff window should better generally be maintained large to reduce the collision rate.

Figure 6 compares the collision rate from the proposed scheme with the legacy IEEE 802.16 protocol and the aforementioned scheme (the size of W and W_{max} is fixed to the number of connections in the network). We can see that although there is not much difference in the values of the performance measures when traffic load is light, however, the proposed schemes both provide significantly better performance at heavy load. Besides, as we expected, the quasi-dynamic scheme can get the best performance since it can dynamically adjust its backoff window based on run-time measurements of current channel status.

Figure 7 depicts the average access delay as the number of connections increases. As illustrated in Figure 7, we can see that there is not much difference in the values of the performance measures when traffic load is low. However, the proposed schemes provides a better performance than the legacy IEEE 802.16 protocol as the number of connections increased, especially when the number of connections

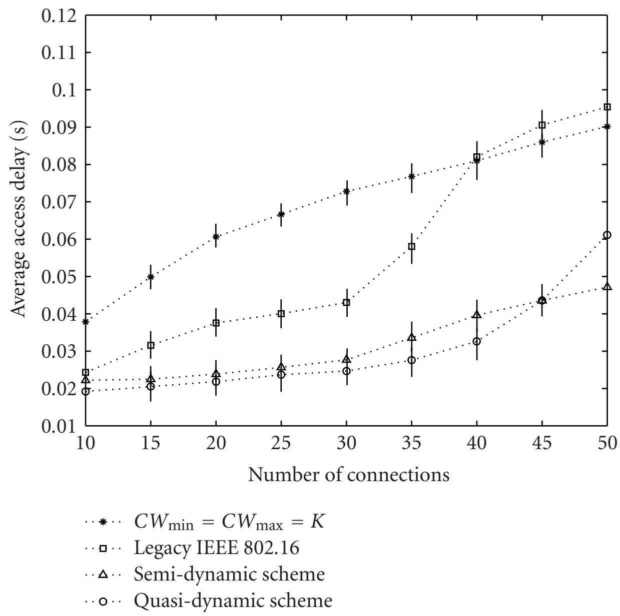

Figure 7: Average access delay versus number of connections.

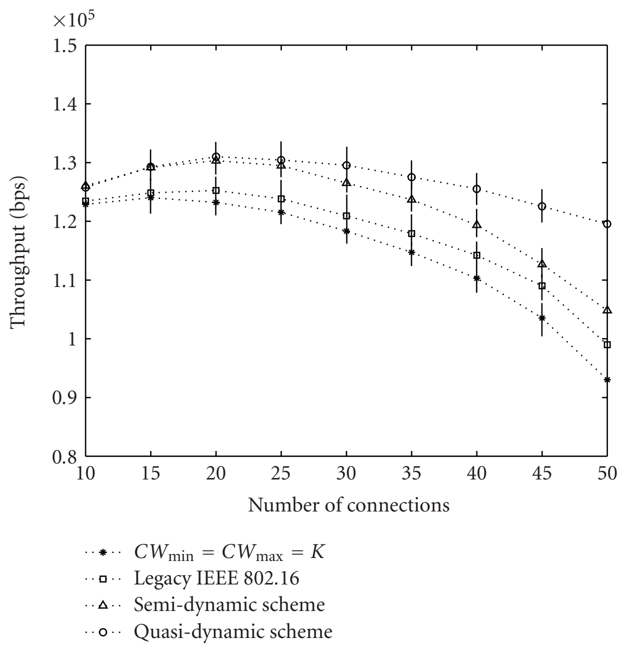

Figure 8: Achievable throughput versus number of connections.

reaches approximately to 40. It should be noted that the quasi-dynamic scheme will get longer access delay than semi-dynamic scheme in congested scenario since it tends to select a large backoff window size to alleviate the probability of collisions.

Figure 8 depicts the achievable throughput as the number of connections increases. As shown in the figures, the throughput improvement can be as much as about 20% in congested environments. It reveals that both of our proposed schemes could reduce the collision probability without sacrificing the overall system performance.

Finally, we investigate and analyze the performance discrimination of the proposed schemes. We use the fairness index defined by Jain et al. [12] to evaluate how fair it is. The fairness index is defined as

$$\text{Fairness index} = \frac{\left(\sum_{i=1}^{n} T_i\right)^2}{n \times \sum_{i=1}^{n} T_i^2} \tag{10}$$

where n is the number of connections, and T_i is the throughput of connection i. From Cauchy-Schwartz inequality, we obtain Fairness Index ≤ 1, and the equality holds if and only if all T_i are equal.

As shown in the Table 3, as the number of connections for each scheme increases, the difference of throughput also increases. Hence, performance discrimination appears as the number of stations increases.

5. Conclusions

Different from the legacy exponential binary backoff algorithm used in the IEEE 802.16 standard, in this paper, we propose two pragmatic adaptive algorithms, namely, semi-dynamic and quasi-dynamic contention resolution scheme, that allow the base station to adjust its backoff window size based on current channel status. Through extensive simulations, we have demonstrated quantitatively the effectiveness of both proposed schemes. Furthermore, the given results show that the quasi-dynamic scheme can achieve better performance than the semi-dynamic scheme in most cases. However, in order to acquire sufficient knowledge of the current channel status, the quasi-dynamic scheme tends to be more computationally complex compared to the semi-dynamic scheme.

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