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Statistical Estimation of the Number of Contending Stations and its Application to a Multi-round Contention Resolution Scheme

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Abstract

With the increased popularity of IEEE 802.11 WLAN, the density of the WLAN devices per access point has also increased, resulting in throughput performance degradation. One of the solutions to the problem is improving the protocol efficiency by a using multi-round contention scheme. This paper first discusses how to estimate the number of contending stations in a WLAN network by using minimum elapsed backoff counter values that can be easily monitored by each station. An approximate closed form expression is derived for the number of active contending stations using the smallest backoff counter value in the network. We then apply this result to adapt the number of contending rounds according to the network loading level to enhance the throughput performance of a multi-round contention scheme. Through simulation, we show that the accuracy of the estimation algorithm depends on the contention parameters of W and the number of backoff counter observing samples, and found a reasonable value for each parameter. We clearly show that our adaptive multi-round contention scheme outperforms the standard contention scheme that uses a fixed number of rounds.

Keywords: CSMA/CA, IEEE 802.11, multi-round contention

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1. Introduction

All wireless networks have their own random-access mechanisms that define the network access and communication procedures. Among these, the IEEE 802.11 standard employs Distributed Coordination Function (DCF) as a primary random-access scheme, which is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) with binary exponential backoff [1]. In [2], it has been shown that the performance of the CSMA/CA scheme strongly depends on the number of contending stations[1] in the network. In particular, the performance depends on the number of active contending stations that are trying to send packets into the air simultaneously. The 802.11 Access Points (APs) have information about the number of associated stations, but this information can differ to the number of active competing stations since some of the associated stations can be idle [3].

As the popularity of IEEE 802.11 WLAN has increased, the number of stations in an AP has also increased. Because of the CSMA/CA protocol's limitation, the network performance such as throughput decreases with the increase in the number of stations. To address this issue, several solutions have been proposed to reduce the number of contending stations. One approach is to divide all the stations into groups, and the random-access is performed within the group [4]. Another approach is to split a single contention period into multiple rounds either in the time domain [5-7] or the frequency domain [8].

For the multi-round contention schemes, a station that wins consecutive rounds is given access to a channel. Rather than using one large contention window, a shortened contention window is used for each round to enhance the contention resolution capability with the same overhead. An advantage of both multi-round schemes is the characteristic that its contention resolution capability improves with the increase in the number of contending stations because the number of surviving stations at the end of each round decreases exponentially. The performance of the multi-round contention schemes has been analyzed in [9].

The number of contending rounds is very important parameter in the multi-round contention scheme to achieve a good throughput performance. Geometric probability distribution is exploited with the multi-round contention scheme since a portion of contenders deferring their transmissions in each round. On the other hand, uniform distribution is exploited with the conventional contention scheme. As the size of the contention window influences the resolution capability of the uniform random counter selection scheme, the number of rounds in multi-round schemes greatly affects the performance of the contention in terms of network throughput, which is a function of collision probability (i.e. contention resolution capability) and the amount of resource (i.e. time overhead) consumed for a contention. Therefore, a new estimation scheme for the multi-round contention method is required, although similar research for the conventional contention method has been extensively conducted [10, 11].

In this paper, we derive an approximate closed form expression of the number of contending stations using the smallest backoff counter value that can be derived from each station's initial and frozen backoff counters. We then apply this result to our proposed adaptive multi-round contention that adjusts the optimal number of contention rounds according to the tracked number of contending stations. The adaptive multi-round contention scheme shows much improved throughput performance compared to the standard contention scheme. Note that in this paper, *k*-EC [5] is used as a reference multi-round contention

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[1] In this paper, we use the terms 'station' and 'node' interchangeably.

scheme. However, our proposed scheme is not limited to *k*-EC, but can be applied to any multi-round contention scheme.

This paper is organized as follows. In Section 2, a brief explanation on 802.11 DCF and *k*-EC is presented. In Section 3, we show the derivation for the estimated number of competing stations with the smallest backoff counter, and use it in conjunction with *k*-EC in Section 4. Through simulation, in Section 5, we show that the station number tracking scheme works well with reasonable contending parameters of contention window size and the number of backoff counter samples, and improves the performance of *k*-EC. Finally, concluding remarks are given in Section 6.

2. Background

In this section, we explain how IEEE 802.11 DCF works and briefly review the *k*-EC scheme.

2.1 IEEE 802.11 DCF

DCF is a contention based distributed access scheme defined in the IEEE 802.11 standard [1]. To access the shared wireless medium, each node that has a frame to transmit selects a randomly chosen backoff counter, b, in the range [0, CW], where CW is the size of the contention window. CW is expressed as $2^x - 1$, where x is a positive integer, and CW is varied as follows:

$$\begin{aligned} &CW \leftarrow \min\{2CW+1, CW_{\max}\} && \text{for collision} \\ &CW \leftarrow CW_{\min} && \text{for success} \end{aligned} \qquad (1)$$

Therefore, consecutive collisions increase the CW, which introduces much contention overhead. The backoff counter b is decremented by one at each slot if the medium is idle. If the medium becomes busy before the node finishes its backoff countdown, the node ‘freezes’ the counter and it waits until the medium becomes idle again for a DCF Inter Frame Space (DIFS) time period. When the backoff counter reaches zero, the node can access the channel and transmit a data frame or a Request-to-Send (RTS) frame. At the end of the data or RTS frame reception, the receiver node replies with an ACK or a Clear-to-Send (CTS) frame after a Short Inter Frame Space (SIFS) period. By receiving the ACK frame, the sender releases the channel, and sets the CW value to $CW_{\min}$ according to Eq. (1). The node now prepares for the next transmission. If a collision occurs, then the receiver will not generate an ACK frame. In this case, the sender doubles its CW as shown in Eq. (1), and runs the backoff procedure again. When the number of consecutive transmission failures arrives at a retransmission limit, the node drops the frame.

2.2 *k*-EC Scheme

In *k*-EC, each node can have a different contention window and a random backoff counter for each contention round. Therefore, we express contention windows and backoff counters as vectors, $\mathbf{W}$ (of which the elements are written as W_i) and $\mathbf{b}$ (of which the elements are written as b_i) respectively, where i $(\in \{1, 2, \cdots, k\})$ represents the contention round. That is, W_i and b_i are the contention window size and backoff counter of the *i*th contention round, respectively. Let W denote the total contention window. Then, we have $\sum_{i=1}^{k} W_i = W$. At the beginning of each contention stage,[2] each node picks k random backoff counters in $[0, W_i]$, where W_i is varied according to the collision event.

Note that one of the important questions in the *k*-EC scheme is how the total contention window W is divided into $\mathbf{W}$. In [5], it is assumed that the contention window size is the same for each round.

In the first contention round, each node uses its own backoff counter b_1, and contends by following the same method as in CSMA/CA. Each winning node[3] with the smallest b_1 transmits a tone signal on the channel to notify its winning and enters the second contention round. The other nodes, after detecting the signal, freeze their backoff counters and wait for the next contention stage. Following the same process, only the winning nodes are allowed to proceed to the next round. Finally, the last winner(s) in the k th round transmits data or an RTS frame. There can be several winners with very low probability at the final round. In this case, the period will result in collision similar to that in the IEEE 802.11 DCF algorithm.

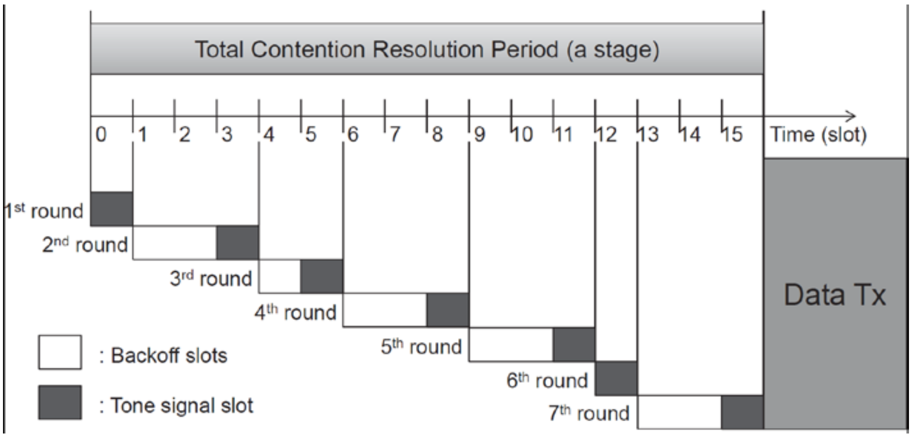

Fig. 1. Example of *k*-EC with 7 rounds (*k*=7).

Fig. 1 shows an example of the *k*-EC operation with $k = 7$. In the first round, a number of nodes selected 1 as their first element of the counter transmit tone signals. The remaining nodes that had selected a larger value defer their transmission until the next stage. Then, in the second round, the nodes with a counter value of 3 transmit tones and they proceed to the next rounds. Following this, the node(s) with 2, 3, 3, 1, 3 in their 3 to 7 rounds wins the contention stage and starts packet transmission.

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[2] In this paper, we define 'stage' as the period that has a contention phase and a data transmission phase, regardless of whether or not the transmission is successful.

[3] At the end of each round, several nodes can win together.

3. Estimation of the Number of Contending Stations

In this section, we derive the number of stations N, using the smallest backoff counter value in a network, which can be derived from the frozen and initially selected backoff counter of each station, assuming there is only a single contention round, i.e. conventional contention scheme. Then, we apply the estimation method to the multi-round contention scheme in Section 4. Because there is one contention round, its contention window size is the same as the total contention window W. For the estimation of N, we define B^* as a random variable denoting the smallest backoff counter value in the network of N stations with a single round contention mechanism. We assume that we know N first, and estimate B^*. Then, we calculate $E[B^*]$ to obtain the relation between B^* and N.

When N stations are contending with the contention window W, the probability mass function (pmf), $f_{B^*}(x) = \Pr\{B^* = x\}$, can be calculated using order statistics. To do this, the cumulative distribution function (cdf) is derived as follows.

$$\begin{aligned} F_{B^*}(x) &= \Pr\{B^* \le x\} \\ &= 1 - \Pr\{\text{All counters of } N \text{ stations} > x\} \\ &= 1 - \left(\frac{W-x}{W+1}\right)^N. \end{aligned} \tag{2}$$

We can then obtain $f_{B^*}(x)$ as follows.

$$\begin{aligned} f_{B^*}(x) &= \Pr\{B^* \le x\} - \Pr\{B^* \le x-1\} \\ &= \left(\frac{W-x+1}{W+1}\right)^N - \left(\frac{W-x}{W+1}\right)^N. \end{aligned} \tag{3}$$

Using Eq. (3), we can obtain the expected value of B^* as follows.

$$\begin{aligned} E[B^*] &= \sum_{i=0}^{W} i \cdot f_{B^*}(i) \\ &= \frac{1}{(W+1)^N} \sum_{i=0}^{W} \{ i(W-i+1)^N - i(W-i)^N \} \\ &= \sum_{i=0}^{W} \left(\frac{i}{W+1}\right)^N. \end{aligned} \tag{4}$$

Since the process of finding the inverse function of Eq. (4) is too complicated, for a large contention window, we can approximate Eq. (4) as follows using an integration form.

$$\begin{aligned} E[B^*] &= (W+1)\cdot\sum_{i=0}^{W}\left(\frac{i}{W+1}\right)^N \frac{1}{W+1} \\ &\approx (W+1)\int_0^{\frac{W}{W+1}} x^N dx \\ &= \left(\frac{W}{W+1}\right)^N \frac{W}{N+1} \\ &\approx \frac{W}{N+1} \end{aligned} \tag{5}$$

Rearranging Eq. (5) with respect to N, we can estimate N as

$$N = \frac{W}{E[B^*]} - 1. \tag{6}$$

Note that the estimation process does not require any feedback from the network. Each station can estimate the number of competing stations through its own frozen backoff counter value. With the frozen backoff counter value, the node can calculate the realized smallest backoff counter and run the estimation algorithm independently.

4. Application of the estimated *N* to *k*-EC

We apply the above result to *k*-EC by adapting *k*, i.e. the number of contention rounds, according to the estimated number of contenders. Our adaptive *k*-EC dynamically varies *k* according to the estimated number of contending stations. Our proposed scheme increases and decreases k, with the greater and fewer number of stations, respectively.

In *k*-EC, the total contention window W, is divided into multiple rounds of k. Let W_i denote the contention window in round i. Therefore, the total feasible counter value exploited in a contention stage shows a geometric property. For example, if k is 6 and W_i is 3 for $1 \le i \le 6$, the maximum random counter value that can be chosen in the entire contention period is 728, i.e. $\sum_{i=1}^{6} 2\cdot 3^{i-1} = 3^6 - 1$. Therefore, splitting the contention window W into multiple k rounds leads to an effective contention window size $\tilde{W}$ as

$$\tilde{W} = \sum_{i=1}^{k}\left(\frac{W}{k} - 1\right)\left(\frac{W}{k}\right)^{i-1} = \left(\frac{W}{k}\right)^k - 1. \tag{7}$$

Similarly, a vector of the backoff counters of a station for all k stages, $\{b_1^*, \cdots, b_k^*\}$, is equivalent to the effective backoff counter $\tilde{b}$ as

$$\tilde{b} = \sum_{i=1}^{k} b_i^* \cdot \left(\frac{W}{k}\right)^{k-i}. \tag{8}$$

With $\tilde{W}$ and $\tilde{b}$, the number of nodes in the network is estimated through Eq. (6).

Then, with the estimated number of contending stations, the optimal k can be obtained using the methods in [12, 13]. Therefore, our proposed adaptive *k*-EC is able to dynamically adopt an optimal k according to the network load resulting in throughput performance improvement. That is, the estimation and contention run concurrently by using the multi-round contention scheme. Note that our proposed scheme is not limited to the same contention window size for each round. However, since the optimal throughput performance can be obtained by choosing optimal *k* [5], we use the same contention window size for each round.

Note that the estimation error in Eq. (6) decreases with the contention window size. However, since a large contention window induces increased idle backoff time, it leads to lowered throughput performance when a small number of stations are active. In our proposed multi-round contention resolution scheme, the splitting contention period leads to an increased effective window size, so the estimation error for the number of contending stations in *k*-EC is reduced with a relatively small number of idle slots.

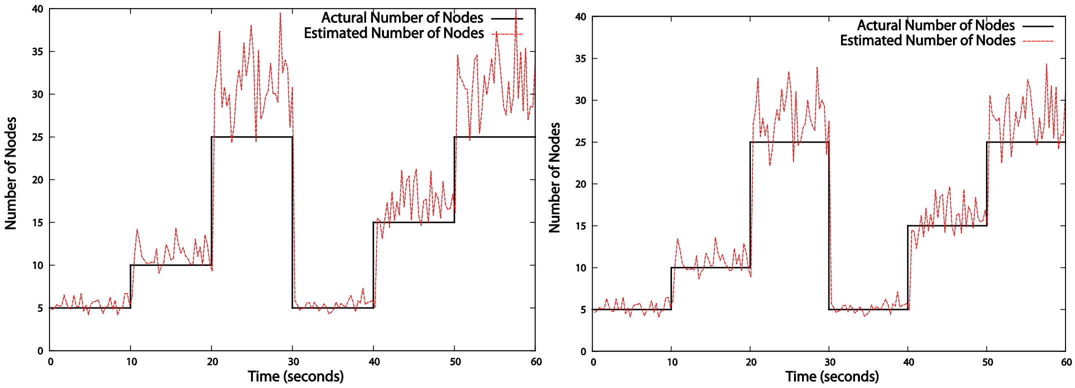
5. Simulation Results

In this section, we first check the accuracy of the estimation and find reasonable contention parameter values. Following this, we consider the performance of our adaptive *k*-EC through simulation. In simulation, we use an event-driven simulator written in C++. Note that, despite the customized simulator, the simulation results are reliable since the proposed scheme only focuses on the MAC layer.

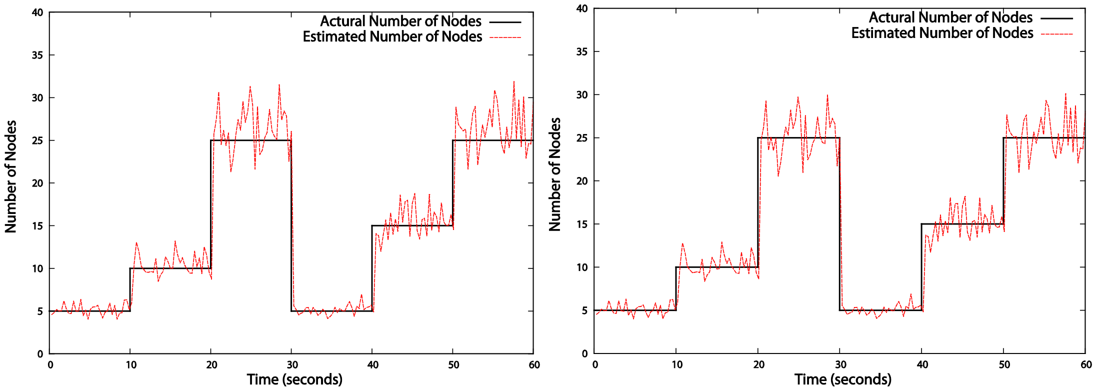
5.1 Accuracy of the Estimation

For the estimation of N, we first define contention parameters; they are contention window size W and the number of backoff counter samples in Eq. (6). We also assume that all the nodes are within a one-hop distance of each other, i.e. no hidden problem, to focus on the accuracy of estimation. Each contention period returns a frozen backoff counter sample, and the smallest backoff counter in the network can then be calculated from this.

The first contention parameter is the contention window size. Following the assumption for the estimation in Eq. (5), a large contention window is needed in order to obtain an accurate estimation result. The number of backoff counter samples, which is the second contention parameter, also significantly influences the estimation accuracy. That is, as the number of samples increases, the estimation of the number of contending nodes becomes slower. On the contrary, if the node has an insufficient number of samples, the estimation may be inaccurate. Through simulation, we attempt to find an appropriate contention window size and the number of backoff counter samples.



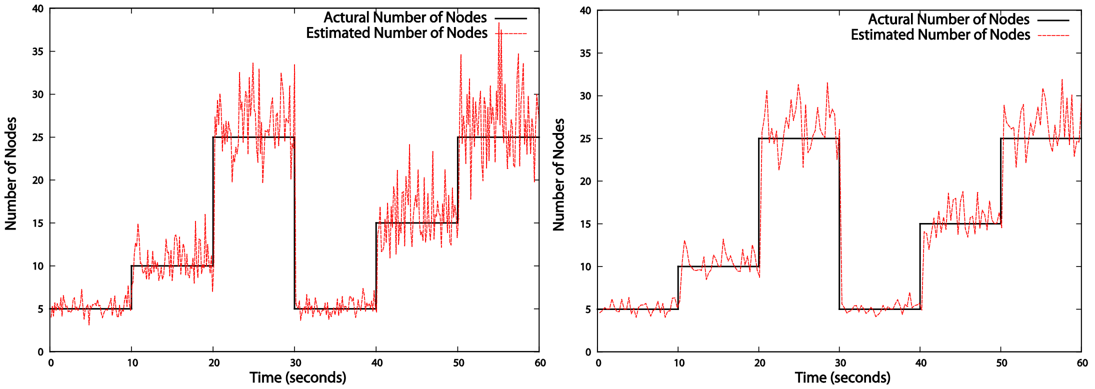
(a) $W = 64$ (b) $W = 128$



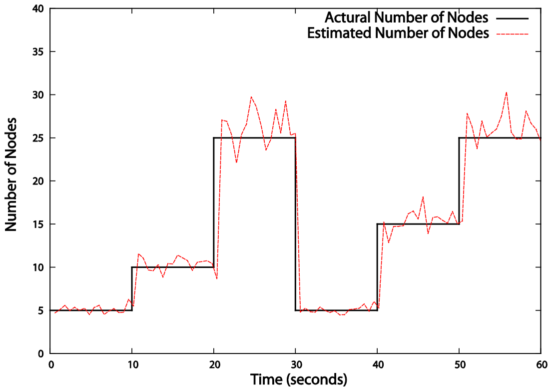
(c) $W = 256$ (d) $W = 1024$

Fig. 2. Accuracy of the estimation of 100 samples according to the contention window size W. Because of the large contention window assumption from Eq. (5), the larger contention window size results in a more accurate estimation of N.

In the simulation, we first check the effect of the contention window size, W with 100 samples. We try W of 64, 128, 256, and 1024 for the fixed number of samples. The solid and dashed lines in **Fig. 2** show the actual numbers of contending nodes and our estimation results, respectively. We vary the number of contending nodes every 10 seconds. The simulation results confirm our analysis assumption shown in Eq. (5). With a small contention window size, our approximate method gives a high error. For $W = 64$ as shown in **Fig. 2(a)**, the estimation shows unacceptable results such as about a 40% instantaneous error. However, as W increases, the accuracy of the estimation increases. We obtain an acceptable result with $W = 256$, which shows a maximum instantaneous error of 25%, as shown in **Fig. 2(c)**. The increased contention window size does not significantly improve the estimation accuracy, as shown in **Fig. 2(d)**. On the other hand, such a large contention window size induces increased idle backoff time, resulting in throughput performance degradation. The estimation error also increases with the number of nodes. When N is small, such as five, the estimation error is small, although it increases with the number of nodes.



(a) 50 samples (b) 100 samples



(c) 200 samples

Fig. 3. Accuracy of the estimation of N for $W = 256$ according to the number of samples. The increased number of samples in the frozen contention window results in a more accurate estimation and an increased amount of time with which to obtain the estimation result.

Another important parameter for obtaining the estimation of N is the number of samples for the random variable B^*. **Fig. 3** shows the effect of the number of backoff counter samples on the estimation of N. In this figure, we fix W as 256 and vary the number of samples (i.e. 50, 100, and 200 samples). In **Fig. 3(a)** (i.e. with 50 samples), the estimation runs fast, but the instantaneous error increases to 50%. In contrast, with 200 samples as shown in **Fig. 3(c)**, we observe that the error is within 20%, but the estimation speed decreases. Considering the accuracy of the estimation and estimation speed together, 100 samples as shown in **Fig. 3(b)** seems to be a reasonable choice, and is within a 25% error. Therefore, we can choose W and the number of frozen backoff counter samples as 256 and 100, respectively. One hundred samples can be obtained in about 0.1 second. Therefore, when the number of contending stations changes, our proposed estimation method follows the change with a 0.1 second delay.

Note that one sample of B^* can be obtained in $T = 0.98$ msec in IEEE 802.11n on average. That is, $E[T] = E[B^*]\sigma + T_{data} + T_{SIFS} + T_{ACK} + T_{DIFS}$, where σ, T_{data}, T_{SIFS}, T_{ACK}, and T_{DIFS} denote the durations of an idle slot, data transmission, SIFS, ACK, and CIFS, respectively [1].

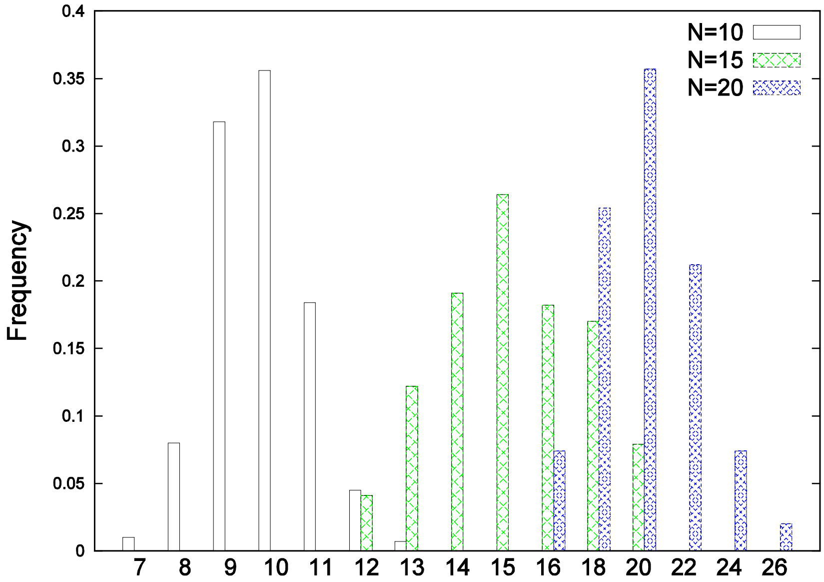


Fig. 4. Statistical results for the proposed scheme. Each case is simulated 1,000 times.

Although the estimated number of nodes converges to the actual number of nodes, its variance is also an important performance metric. The statistical behavior of the estimation results is shown in **Fig. 4**. The number of samples is set as 100 and the number of nodes is varied from 5 to 30, while only the cases of N =10, 15, and 20 are presented in **Fig. 4**. In each setting, simulations are performed 1,000 times. The results show that about 65% of the estimation results show ±10% error and that more than 95% of the results are in an error range of ±25%. We expect that similar statistical performance can be obtained in the real world experiment.

5.2 Performance of Adaptive *k*-EC

We now consider the throughput performance of our adaptive *k*-EC that adapts the number of competing rounds k optimally according to the estimated number of contending nodes. We then compare this throughput performance with that of *k*-EC that uses a fixed k. For *k*-EC, we fix k at a value from 2 to 6. For the adaptive *k*-EC, we use the relation of $\frac{W}{k}=3$, which was shown in [5] to be optimal, and 100 samples. From Eq. (7), an equivalent contention window size of *k*-EC with k rounds is $\tilde{W}$ from Eq. (7) if it is with a single contention round and the effective backoff counter value $\tilde{b}$ is used for estimating the number of nodes. Thus, with an appropriate choice of k, *k*-EC is able to estimate the number of contending nodes more accurately than the single contention round scheme.

In the estimation, we simplify the contention method by assuming that each node neither resumes the backoff counter value when reentering the contention after being defeated nor extends the contention window after collision, and it always selects a new random backoff counter vector at the beginning of each contention stage.

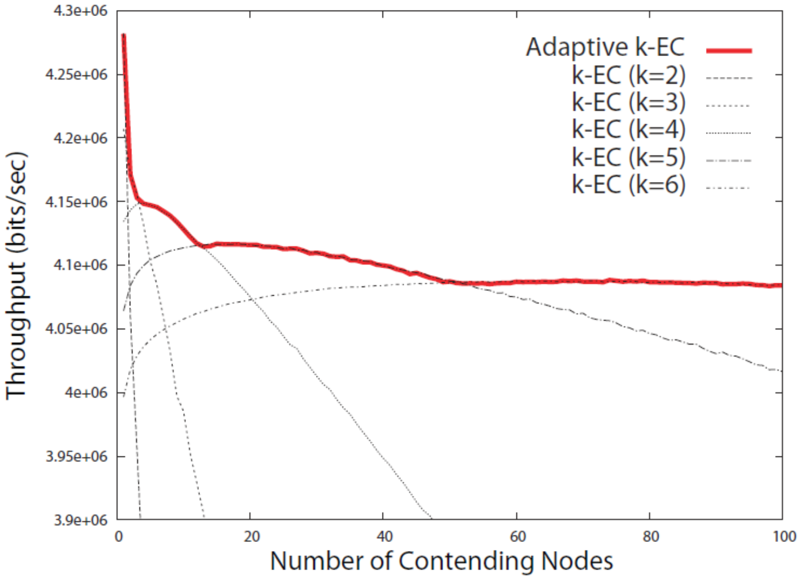


Fig. 5. Throughput comparison of our adaptive *k*-EC and the standard *k*-EC according to the contention rounds of 2 to 6. With the estimation of N, our proposed adaptive *k*-EC scheme changes the number of rounds, resulting in good performance regardless of the number of nodes.

In contrast to the general finding in [5], **Fig. 5** shows that the network throughput is somewhat sensitive to the number of contending nodes, especially when the network size is small. This leads to a better performance by our adaptive *k*-EC scheme than that of the fixed *k*-EC scheme. **Fig. 5** also shows that the adaptive *k*-EC tracks the number of contending nodes well, so that its throughput performance is similar to the hull of other lines with the fixed number of contention rounds. We run the simulation repeatedly and for a sufficiently long period so that the errors shown in **Figs. 2** and **3** are averaged. This results in a graph following the edges of curves with a fixed number of rounds.

Since we assumed that the equivalent contention window is sufficiently large in the derivation of the closed form expression, a small k has a risk of inaccurate estimation. However, as observed in **Figs. 2** and **3**, the estimation of N is more accurate in a small sized network than in a large sized network. Therefore, the risk of using a small k is reduced.

6. Conclusion

This paper discussed a method of estimating the number of contending stations in a network by using minimum elapsed backoff counter values that can be easily monitored by each station. A closed form expression which relates to the number of contenders and the minimum elapsed backoff value is derived. We then applied this result to adapt the number of contending rounds according to the network loading level to enhance the throughput performance of the multi-round contention scheme. Through simulation, we showed that the accuracy of the estimation algorithm depends on the contention parameters of W and the number of backoff counter observing samples, and found a reasonable value for each parameter. We clearly showed that our adaptive multi-round contention scheme outperforms the standard contention scheme that uses a fixed number of rounds.

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