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A Statistics Based Design of MAC Protocols with Distributed Collision Resolution for Ad Hoc Networks

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Abstract

Most existing collision resolution schemes are based on recent collision activities, which can not reveal the true stochastic nature of the collision activity process. In addition, they focus primarily on the system throughput without considering fairness issue. In this paper, we propose a novel collision resolution scheme that can incorporate the time-varying mean and variance of the stochastic collision process. It can also incorporate other fairness enhancement measures to achieve both good throughput and fairness performance. The scheme is adaptive in tracking non-stationary process and is also recursive which is very simple in implementation and energy efficient. Simulation results demonstrate that such scheme can improve the throughput and fairness significantly for IEEE 802.11 ad hoc networks.

1. Introduction

In Wireless ad hoc networks medium access control (MAC) protocols are a key component for many performance issues such as throughput, delay, and fairness. It is very challenging to address multiple performance issues such as throughput, fairness and QoS in the distributed contention-based wireless ad hoc networks where no centralized controller exists [1]. In this paper, we focus on the performance, including fairness performance, of the distributed contention-based, especially collision resolution-based MAC protocols. Conventionally the performance of such MAC protocols degrade significantly when it is in high network load. This is because of excessively high collision rate generated by the MAC algorithm [1]. Much research effort has been made to improve the performance of the IEEE 802.11 MAC protocols [1]-[6], to name just a few here. Cali, Conti and Gregori [2][6] showed that if a station has exact knowledge of the medium status, it is possible to tune the backoff algorithm to achieve a protocol capacity very close to the theoretical maximum. Because exact knowledge of the medium status cannot be realized in real cases, they propose a way of adapting the contention window (CW) by observing the length of both the last idle period and the last transmission attempt. They use these two parameters to estimate the collision probability. The collision probability is then used to adjust the CW size. An improved mechanism AOB scheme has been proposed in [3]. Instead of estimating the number of active stations, the AOB scheme tries to measure the network contention level through the estimation of the slot utilization and the average size of transmitted frames. The major drawback is that it is still costly to estimate all the parameters needed. For instance, it needs to monitor the channel status most of the time which is undesirable for mobile devices where battery power is very limited.

It is observed that an efficient collision resolution is necessary to increase the throughput performance [1]. Kim and Hou [4] proposed to insert a delay before a station (STA) attempts transmission of its pending frame in order to reduce the contention level. Bononi, Conti and Donatiello [5] have combined the backoff algorithm with virtual collision feedback. It adds an additional stage between the original scheduling part and the physical access, which is called DCC scheme. At this extra stage the scheduled transmission is evaluated again based on an estimated medium utilization value. The DCC scheme may defer the transmission at this stage with a probability based on the level of the medium utilization. In [1], Kwon, Fang and Latchman proposed a fast collision resolution (FCR) algorithm. It is observed that main deficiency of most distributed contention-based MAC algorithms is due to the packet collisions. The FCR algorithm intends to resolve the collisions quickly by increasing the contention window sizes of both the colliding stations and the deferring stations in the contention procedure. One disadvantage of this scheme is its complexity and it also requires to incorporate self-clocked fair queuing, a priority scheme based on differentials to improve fairness performance.

Bianchi and Tinnirello [9] provided a simple method to estimate the number of competing nodes that affect system throughput performance. However, it is unclear how to use this information to improve network performance in a dynamic environment where the number of competing nodes in the ad hoc network is changing all the time. In addition, research effort along this line concerns only throughput and fairness issue has rarely been discussed. It should be pointed out that the assumption of saturation has been made in [9] and yet non-saturation is desirable for good fairness performance [7].

In this paper, we attempt to address these issues from a new angle. We view collision activities as a non-stationary process where its mean and variance are stationary AR processes. The dynamic time-varying mean and variance can best describe the stochastic collision process and hence can be good design parameters to improve network performance. For our variance based DCC_V algorithm, the calculation of the mean and variance is recursive which virtually does not require keeping historical data except only one accumulated value. It also provides a mechanism to balance the long term statistics and short term activities through weighting. As these stochastic statistics can provide certain degree of global information, it can help resolve the fairness issue by nature. In addition to these advantages, the scheme can also incorporate other distributed contention-based schemes such as inserting a extra delay between TCP layer and MAC [7] to further enhance the performance especially the fairness performance. Extensive simulation demonstrated a significant performance improvement in terms of high throughput, low collision rate and fairness over the standard IEEE 802.11 MAC protocol as well as other enhanced IEEE 802.11 MAC protocols.

2. Stochastic Distributed Contention-Based MAC Protocols

Bononi, et [5] introduced the concept of slot utilization to estimate the contention level before going attempting the next medium access, which is called DCC algorithm. It is calculated as the ratio of the number of the backoff slots sensed as busy and the number of the total number of slots that have been backed off, which is shown in the follow equation

$$SlotUtilization = \frac{NumBusySlots}{InitBackoff}\ , \quad (1)$$

where parameter *InitBackoff* is the randomly selected length of the backoff period and the parameter *NumberBusySlots* is the number of backoff slots that were sensed as busy.

A. New Distributed Collision Resolution Algorithms

1) Simple average method

The *SlotUtilization* used in the DCC algorithm is a transient value as it samples only one backoff period, which represents a most current collision status of the system. However, as collision is a stochastic process, information derived from such a short period can not describe the stochastic process accurately. One simple solution is to add an average parameter derived from history to make a balance. A simple choice can be expressed by the following equation [10]

$$Cw = colAvg + colAvg \times (SlotUtilization + K)\ , \quad (2)$$

where the parameter *colAvg* is calculated from the collision history that is longer than one backoff period. The parameter K is a threshold where a *SlotUtilization* value below $-K$ will result in the CW size being decreased. The collision window is designed as a circular buffer. When a new collision record is added in, the old collision records are shifted towards the end of the buffer accordingly until it is pushed out of the buffer. In the remainder of this paper, this scheme is refereed as the *DCC_A* algorithm.

2) Collision resolution scheme based on variance statistics

The collision resolution scheme based on slot utilization and simple collision average over collision window can cover both long term and short term patterns of the stochastic collision process. However, as the parameter *colAvg* is calculated as the average value within the buffer, a good estimate of the true average collision activities will need a long collision window size (long buffer) which is undesirable in our environment. More importantly, mean value cannot capture the variation of the stochastic process.

In order to capture the non-stationary process, we use an AR model to track time-varying mean and variance. Hence the dynamic mean is estimated as

$$\hat{m}_{n+1} = (1-g)\hat{m}_n + gX_n, \quad (3.1)$$

where $\hat{m}_n$ is the estimated mean at the *n*th step and X_n is the measured number of collisions that has occurred within the history window at the *n*th step. (1-g) is a decaying parameter that forgets the historical data in an exponential way. Similarly the time-varying variance is estimated as

$$\hat{V}_{n+1} = (1-h)\hat{V}_n + h(X_n - \hat{m}_n)(X_n - \hat{m}_n)^T$$

where $\hat{V}_n$ is the estimated variance at the *n*th step and (1-h) is a decaying parameter. From standard statistics, we can use a more simpler standard deviation expression to replace variance expression and hence it produces

$$\hat{D}_{n+1} = (1-h)\hat{D}_n + h|X_n - \hat{m}_n| \quad (3.2)$$

Therefore, our new collision resolution scheme based on variance statistics is given as

$$CW = A + A \times (slotUtilization + K) + (L \times D) \quad (3.3)$$

where L is the weight to balance the mean, *slotUtilization* and variance in the adjustment of the contention window.

As the recursive nature of the formula, we need only to store one value to represent the collision history. Extensive simulation using NS-2 simulator has found following sub-optimal parameters

$$\begin{aligned} g &= 0.25 \\ h &= 0.5 \quad . \quad (4) \\ L &= 4 \end{aligned}$$

These parameters are rather stable with different scenarios. In the remainder of the paper, we will refer this collision resolution scheme as DCC_V algorithm.

3. Simulation Evaluation

In this section, we will conduct extensive simulation to compare the performance of the standard IEEE 802.11 MAC protocol, the *DCC* MAC algorithm, simple average *DCC_A* MAC protocol, and variance based *DCC_V* MAC protocol. We also consider the incorporation of extra delay between TCP layer and MAC layer that has been introduced in [7]. In all of the simulation conducted in this paper, we use NS-2 simulator. We provide two illustrative examples with different topology, data traffic etc.

A.. Example 1

The setup for the example 1 is described below:

Table 1
Network Parameter Settings for Example 1

Wireless channel BW	2 Mbps
Wireless node interface queue limit	50 packets
Nominal radio transmission range	250 m
Buffer management for wireless nodes	Drop-Tail priority queue
Network area	800 x 800 m
Number of nodes	44
Routing protocol	DSR
Topology	Ring – fully meshed

Table 2
Traffic Settings for Example 1

Transport protocol	UDP
Packet size	512 bytes
Packet type	CBR
Packet interval	0.001

Table 3
MAC Settings for Example 1

SIFS	10 us
Mini. contention window	31 slots
Max contention window	1023 slots
Colli. Hist. Win. size	0.02 s (1024 *20us)

The simulation result is shown in Fig.1. The *DCC* MAC protocol has slightly higher throughput than that of the standard IEEE 802.11 MAC protocol while our proposed *DCC_A* MAC protocol and *DCC_V* MAC protocol have significantly higher throughput. The proposed variance based collision resolution protocol *DCC_V* MAC protocol outperforms all other protocols significantly.

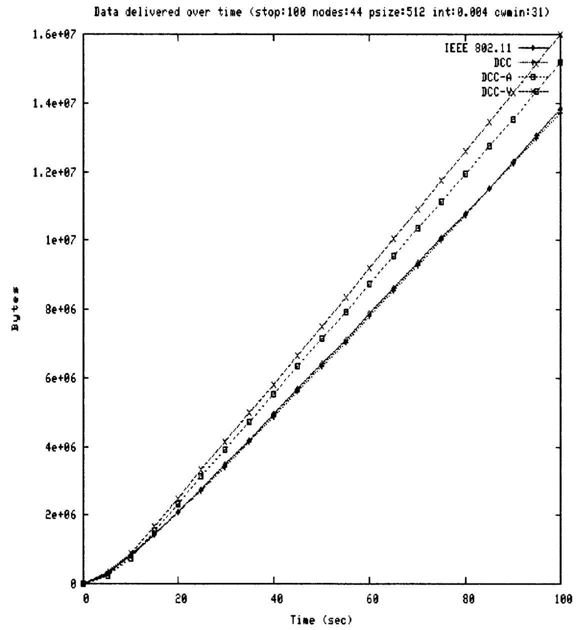

Fig. 1. Bytes transferred over time

The improvement of throughput is mainly due to the good characterization of the stochastic process that helps to reduce the collision significantly. As shown in Fig. 2, *DCC_V* MAC protocol can not only reduce the collision significantly, it has also reduced the fluctuation of this stochastic process significantly.

B. Example 2

We demonstrate our fairness algorithm by simulations using a similar scenario as discussed by [7]. We consider 5 nodes aligned 200m apart to form a string topological ad hoc network. Two TCP flows are considered with one TCP flow starting at the time 0 second and another at the 10th second. The first TCP flow (TCP 2) hops twice from node 4 to node 2 to reach the destination. The second flow (TCP 1) is a single hop flow from node 0 to node 1. Detailed simulation setup and parameters are given in Tables 4 through 6. These parameters are mostly obtained from [7] and the delay parameters have been identified to be the most suitable after extensive simulation by the authors.

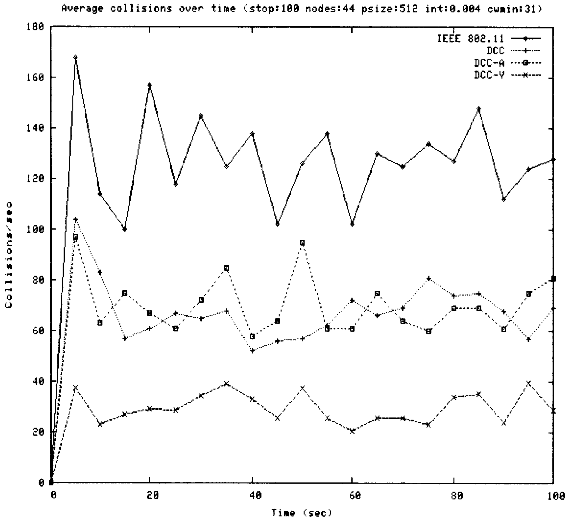

Figure 2. Collision activity over time

Fig. 4 has demonstrated the performance under the standard IEEE 802.11 MAC protocol. It is observed that the first TCP session gets completely blocked down by the second one after 12.48 seconds. This matches the same observation in [7], which demonstrates serious unfairness performance of the standard IEEE 802.11 protocol. Extensive simulation indicates that varying TCP congestion window size has no effect to improve this fairness problem. In [7], it has been proposed to insert a delay between the TCP layer and MAC layer to improve the fairness. To make a good comparison, we will incorporate such delay into various algorithms in the experiment.

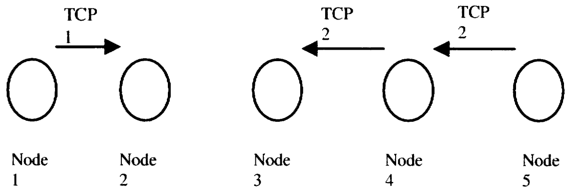

Figure 3. String topology

Table 4

Network Parameter Settings for Example 2

Wireless channel band.	2 Mbps
node interface que. Lim.	50 pack.
Radio trans. range	250 m
Buffer management for	Drop-Tail priority

wireless nodes	queue
Network area	1000 x 1000
Number of nodes	5
Routing protocol	DSR
Topology	string

Table 5
Traffic Settings for Example 2

TCP version	NewReno
Packet size(constant)	1024 bytes

Table 6
MAC Settings for Example 2

SIFS	10 us
Mini contention win.	31 slots
Max contention win.	1023 slots
Colli. Hist. Win. size	0.02 s (1024 * 20us)

Table 7
Delay Parameter Settings for Example 2

X	10000 bytes
Y	20000 bytes
Z	50000 bytes
D21	0 s
D22	0.002 s
D23	0.005 s
D24	0.01 s
Updating interval (T)	2 s

In [7] the timer for the delay between the TCP layer and MAC layer was set based on the summation of 3 variables namely, D1, D2 and D3. The parameter D1 is a value calculated by dividing the packet size by the channel bandwidth. D2 denotes the delay calculated based on the recent queue output rate. The queue output rate is calculated every T seconds and D2 takes one of the four (D21, D22, D23, D24) values based on the de-queued packets. D3 is another delay component determined by a random value between 0 and D2. D3 was used to avoid the synchronization phenomenon.

According to the result in [8], we set the max cwnd limit of 4 for the two-hop flow. The simulation results for the enhanced IEEE 802.11 MAC protocol [7] and proposed *DCC_V* MAC are shown in Figs. 5 & 6. As shown in Fig. 5, the enhancement scheme [7] can reduce the medium contention level and hence improve the fairness performance to a certain extent. However the improvement is very limited and still poor. As shown in Fig. 6, our proposed *DCC_V* MAC protocol has demonstrated an excellent fairness performance. This good performance is mainly due to the fact that *DCC_V* MAC protocol can incorporate information about the overall collision stochastic process. By Nyquist theorem, if the sampling rate is twice the highest frequency of the whole data, the sampled data set can fully recover the information of the whole set. As *DCC_V* MAC samples all the historical collision data, it can provide a very good estimate of the overall collision stochastic process.

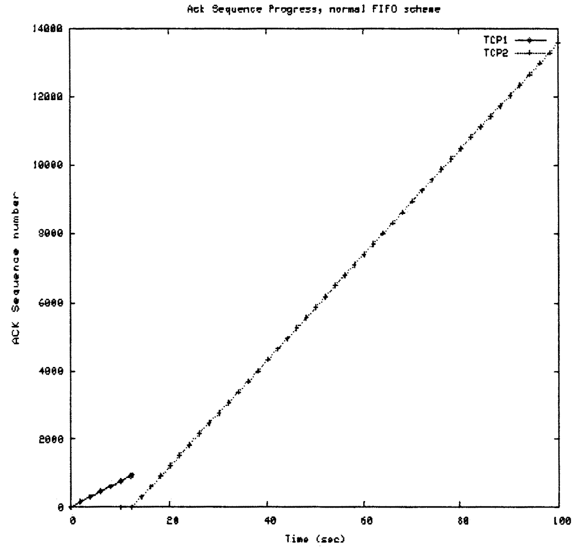

Fig. 4. Multiple TCP flows under the standard IEEE 802.11 MAC protocol

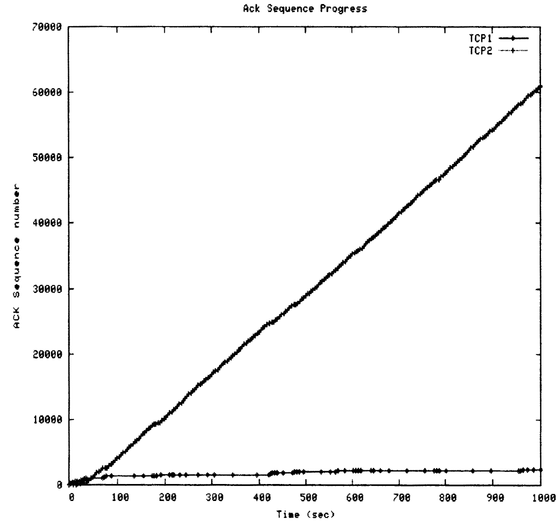

Fig. 5. Multiple TCP flows under the improved IEEE 802.11 MAC proposed in [7]

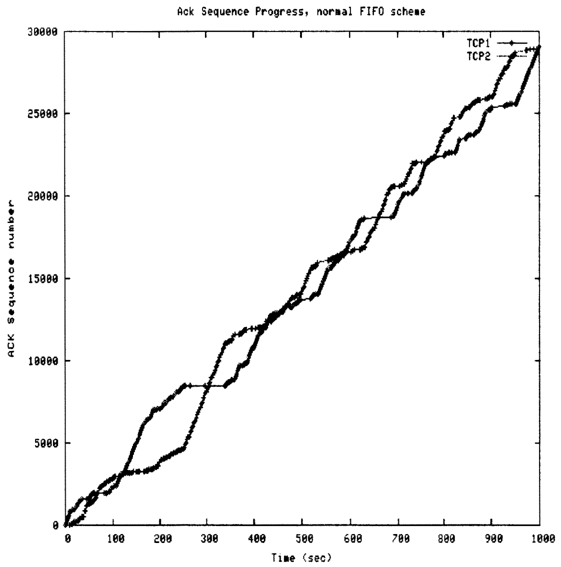

Fig. 6. Multiple TCP flows under proposed *DCC_V* MAC scheme

4. Conclusions

Most existing MAC protocols are based on the most recent collision activities, and can not describe the main features of the stochastic collision process. In this paper, we propose to adjust the contention window by dynamically incorporating the knowledge of the collision process via the standard mean and variance statistics. The calculation is recursive which does not require extra buffer to store historical data and can track non-stationary process. As every station uses a good global collision process indicator, it can naturally reduce the potential collision and get better fairness access. Incorporation of our algorithm with other fairness enhancement measures can provide further flexibility to handle throughput and fairness performance concurrently. Extensive simulation experiment has demonstrated that our new MAC protocol has excellent performance in terms of throughput, less collision, and fairness.

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