Understanding the Impact of Mobility to the Performance of the IEEE 802.11 DCF

Jun Liu
Computer Science Department, University of North Dakota
Grand Forks, ND 58202-9015
jliu@cs.und.edu

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Abstract

IEEE 802.11 series standards have been widely used to specify the MAC mechanism in wireless networks. The 802.11 DCF has not taken into account of the mobility of wireless stations, instead, it is defined based on the assumption that the mobility is not present or is very low. Mobility of wireless stations downgrades the saturation performance of the IEEE 802.11 DCF. This paper made its efforts to anatomize into the relations between the mobility movement and the damaged coordination incurred.

Reducing the average backoff duration is a viable approach to improve the average saturation throughput. We suggested an additive increase and multiplicative decrease (AIMD) algorithm to determine the backoff time. Such an AIMD backoff algorithm helps to take mild reactions to non-persistent collisions induced by mobility of wireless stations. Results obtained from simulations under the new AIMD backoff algorithm show that the average saturation throughput is improved in the presence of mobility of stations. The improvement mainly attributes to the shortened average backoff duration under the AIMD backoff algorithm.

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1 Introduction

In wireless networks, ad hoc routing protocols focus on specifying methods of route discovery without explicitly taking into account of the interactions with the underlying medium access control (MAC) protocols. The performance of an ad hoc routing protocol is, however, jointly dependent on the performance of the routing method in use, the performance of the MAC mechanism, and the stability of the underlying wireless channel [6]. The MAC protocols largely affect the performance of ad hoc routing protocols because the MAC protocols adjudicate the successful transmission of packets which are sent by the routing protocols. Failure of sending/receiving packets to/from the underlying wireless channel compromises the operations of routing protocols or algorithms. Therefore, in-depth studies of the MAC protocols help to improve the overall performance of routing protocols.

IEEE 802.11 series standards have been widely used as the MAC layer protocol in wireless networks, which specify the arbitration of channel access under contentions among multiple wireless transmission devices. In particular, the IEEE 802.11a/b/g standards are used to specify the MAC mechanism in wireless local area networks (WLANs) [12, 4, 17]. The difference among these three WLAN standards is mainly on carrier frequencies and on transmission speed [17]. A crucial component in these standards is the Distributed Coordination Function (DCF) which is implemented in each wireless transmission devices (a.k.a. stations). A DCF is a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism [15, 2]. Under a CSMA protocol, only one station is allowed to transmit at a time, and a station can transmit only when the channel is idle. Unlike detecting collisions in a wireline channel where senders and receivers have equal abilities in detecting channel contentions, in a wireless channel, only the receivers can detect the channel contentions due to two reasons: 1) a wireless device shuts off its reception amid of a transmission because most wireless stations only adopt a half duplex radio; 2) the propagation decays of wireless signals are high such that a pair of sender and receiver perceive different strengths of the same contending signal. Therefore, resolution of simultaneous channel contentions in wireless channels is more difficult than in wireline channels.

Mobility of wireless stations downgrades the performance of the 802.11 DCF-based MAC protocols. The original IEEE 802.11 series standards have not taken into account of the mobility of stations. That is, the DCF in the IEEE 802.11 series standards is defined based on the assumption that mobility is not present or only a very slow mobility is present. Mobility of wireless stations compromises the effectiveness of the DCF, and, in a sequel, the performance of 802.11 DCF-based MAC protocols is affected. Therefore, it is necessary to derive methods for improving the performance of the MAC layer in the presence of medium to high mobility. In this paper, we first demonstrate the downgrade on the performance of the 802.11 DCF caused by the mobility of stations, and we exhibit the potential causes to the performance downgrade using observations obtained in simulations of wireless networks. Next, we further demonstrate the main cause to the performance downgrade by modeling the performance of the 802.11 DCF. From both the observations (obtained in simulations) and the modeling, we found that the longer average backoff duration, in the presence of mobility, is the key factor leading to the performance downgrade of the 802.11 DCF. The longer average backoff duration is caused by the damaged coordination among stations, and the mobility of stations directly causes an existing coordination to be invalidated. Lastly, based on the analysis and modeling, we suggest an additive increase and multiplicative decrease (AIMD) backoff algorithm to be used to determine the contention window size. The original bounded exponential backoff (BEB) algorithm in the 802.11 DCF is appropriate for resolving persistent contentions, and it over-reacts to non-persistent contentions caused by mobility of stations. Simulation results show that improvement on the performance of the original 802.11 DCF can be achieved by adopting an AIMD backoff algorithm.

In the rest of this paper, the related work is presented in Section 2. The mobility impact to the performance of the 802.11 DCF is demonstrated in Section 3. The new AIMD backoff algorithm, as well as the demonstration on the improvement to the performance of the original 802.11 DCF, is demonstrated in Section 4. Our work is summarized in Section 5.

2 Related Work

The MAC protocol is crucial to the performance of the upper-layer protocols. Karn [15] proposed the MACA protocol for media access control in packet radio. MACA is a CSMA media access control scheme, and the virtual carrier sense method using RTS-CTS handshake was introduced in MACA. Bharghavan *et al.* [2] proposed the MACAW protocol which further revised MACA in order to improve the efficiency of the MACA protocol. The performance of the DCF specified in the IEEE 802.11 series standards has been analyzed in a number of papers. These analyses can be categorized into single-hop based ones and multi-hop based ones.

The single-hop based analyses focus on analyzing either the average saturation transmission throughput for each station [8, 3] or the single-hop transmission delay between two stations which can hear each other directly [5]. Coupechoux *et al.* [8] modeled the medium utilization of a slotted time division multiple access (TDMA) protocol. which is based on the discrete-time Markov chain. Bianchi [3] has studied the modeling of the saturation transmission throughput of the CSMA/CA mechanism. This analysis is based on several assumptions: 1) ideal channel conditions; 2) finite but a large number of contending stations; 3) each station is ready to transmit data frames whenever it is allowed to access the medium (the channel); and 4) each transmission attempt collides with other frames with constant probabilities which are only dependent of the size of a current contention window in-use, and the collision probabilities under different backoff periods, selected the same contention window, are independent. Based on the analytical model developed in [3], Carvalho *et al.* [5] modeled the single hop delay in a saturated 802.11 WLAN. Two delays have been studied. The first delay is called a service time which is the time delay for making one transmit attempt, and it is total time duration from the moment a sender station starts to transmit a data frame to the moment this data frame is fully transmitted. The second delay is the jitter needed for a successful transmit of a data frame, and it is different from the first delay in that way that a jitter consists of the time needed for making multiple transmit attempts until a data frame is transmitted collision-free to its destination.

The multi-hop based analyses focus on modeling the throughput of multi-hop communications in WLANs. The multi-hop throughput is the end-to-end throughput, whereas the single-hop throughput is just the hop-by-hop throughput. The performance of the multi-hop communication has close relations with the single-hop performance in the following ways. An uneven performance of single-hop communication will likely lead to an uneven performance of multi-hop communication, and an even performance of single-hop communication may not lead to an uneven performance of multi-hop communication. Chhaya *et al.* [7] also studied the performance modeling of asynchronous data transfer methods under the IEEE 802.11 MAC protocol. They observed that each station views non-identical throughput and delay characteristics due to uneven probabilities of capture and collisions, which, in turn, are caused by distances between stations and traffic patterns. Carvalho *et al.* [6] studied the modeling the throughput of multi-hop communications by taking into account of the effect of physical-layer parameters on the success of transmissions, the MAC protocol on the likelihood that stations can access the channel, and the connectivity among stations.

The impact of mobility to the performance of 802.11 DCF has also been previously studied in empirical measurements on the performance of a wireless media streaming service [1]. In this service, a server delivers stream media to client wireless stations in the existence of mobility. Two observations have been found: 1) mobility of client stations can significantly degrade the performance of a media stream delivery service; 2) mobility of a single client station can affect not only its own performance, but also the performance of other client stations which are standstill. In our study, we also have observed the apparent impact of mobility on the performance of 802.11 DCF in simulations.

Among the possible factors causing the performance downgrade, the increase in backoff time is the significant factor. The binary backoff (EB) algorithm is commonly used in CSMA protocols. The main advantage of adopting the EB algorithm is to achieve a stability on throughput, *i.e.*, EB guarantees a certain amount of throughput no matter how many contending stations are present in a network [22]. However, this stability is an asymptotic behavior, when ther are infinite backoff stages and the number of contending stations are very large. The backoff algorithm used in the 802.11 DCF is a bounded binary backoff (BEB) algorithm [15] with finite number of backoff stages. Therefore, the appropriateness of adopting a BEB algorithm in 802.11 DCF has been discussed and is inconclusive. In the meantime, improving the performance of 802.11 DCF through modifications to the original BEB algorithm has been studied in a number of works. Tay *et al.* [23] studied a new backoff scheme which adopts a nonuniform probability distribution used to randomly select contention slots. This probability distribution is the unique probability distribution that minimizes collisions between contending stations. Pang *et al.* [18] proposed a self-adaptive contention window adjustment algorithm which is called a multiplicative increase multiplicative/linear decrease (MIMLD) algorithm. The main idea of the MIMLD algorithm is to add a linear decrement operation used to automatically adjust the initial contention window size to the "optimal" window size contingent to the actual collision status in a wireless channel.

The performance of the MAC layer protocols directly affects the performance of upper level protocols. Modifications to the 802.11 DCF, besides the modifications to the BEB algorithm, have also been proposed to make the MAC layer to cope with the special requirements of upper level protocols/applications. Vaidya *et al.* [24] proposed a fair scheduling algorithm based on the 802.11 DCF such that bandwidth of the medium can be allocated in proportion to weights of data flows sharing the medium. Ji *et al.* [13] proposed a Medium

Access Diversity (MAD) scheme to adapt to different requirements on transmission rate by aggressively exploiting multiuser diversity. In this scheme, data frames are selectively transmitted to their destinations based on the instantaneous channel condition information probed from ongoing transmission, in order to largely eliminate the unfairness of winning the access to the medium among multiple stations. Holland *et al.* [11] proposed a receiver-based auto-rate MAC protocol. In this protocol, the sender stations are made to adapt to the rates of receiver stations in order to achieve a higher overall throughput compared to the throughput achieved under a sender-based auto-rate MAC protocol. Gambiroza *et al.* [10] proposed a distributed layer 2 fairness algorithm which targets to achieve the fairness of medium access among multiple stations in order to improve overall end-to-end throughput. Kanodia *et al.* [14] devised a distributed priority scheduling technique based on the 802.11 DCF for supporting multi-hop QoS communications with delay and throughput constraints. In this technique, a priority tag of the head-of-line frames pending to be sent is piggybacked in RTS/DATA frames. Consequently, under the priority scheduling technique, downstream stations increase a frame's relative priority to compensate for the excessive delays incurred upstream.

Cross-layer designs become a promising approach in order to achieve the fairness of medium access and to, consequently, enhance the overall end-to-end throughput in multi-hop communications under various constraints. Sadeghi *et al.* [21] proposed the Opportunistic Auto Rate (OAR) protocol to better exploit durations of high-quality channels conditions. The key mechanism of the OAR protocol is to opportunistically send multiple back-to-back data packets whenever the channel quality is good. Under the OAR protocol, significant throughput gains can be achieved compared to other auto-rate adaptation mechanisms. Coupechoux *et al.* [9] discussed several promising cross-layer design techniques for drastically increasing the capacity of the MAC layer for multi-hop networks. These techniques include synchronization, multi-user diversity, and multi-packet reception, etc. Nahm *et al.* [16] studied the TCP behavior over 802.11 multi-hop ad hoc networks by jointly taking into account of TCP, on-demand ad hoc routing protocol, and the IEEE 802.11 MAC protocol in ad hoc networks. It has been shown in their studies that TCP over-reacts to the dynamics in routing and to the contentions in the MAC layer.

3 Impact of Mobility on The Performance of 802.11 DCF

The impact to the performance of 802.11 DCF in the existence of mobile wireless stations is demonstrated using observations obtained in simulations of wireless LANs (WLANs). The behavior of the 802.11 DCF is monitored on both the sender side and the receiver side. The events recorded on the receiver side are mainly the abnormal collision events observed by a receiver station. An abnormal collision means that this collision event is not supposed to occur under the 802.11 DCF, *e.g.*, a collision between two DATA frames should be impossible under a RTS-CTS-DATA-ACK four-way handshaking when mobility is not present. The events recorded on the sender side are those which characterizes the efforts of making successful transmissions of DATA frames, and they are recorded on a per DATA frame basis. The events recorded on the sender side include, the average number retransmissions made on RTS frames and on DATA frames, the average amount of backoff time spent.

3.1 Simulation Scenarios

A wireless network consisting mobile wireless stations is simulated using the wireless and mobility extension [19] to the NS-2 simulator [20]. Each mobile station is equipped with only one IEEE 802.11 wireless interface. The 802.11 DCF is run under the optional mode, *i.e.*, a RTS-CTS-DATA-ACK four-way handshaking is used for transmissions of DATA frames. Mobile stations move within a $3000 \times 3000 \,\mathrm{sq.\,meters}$ square. A instant hopping movement pattern is used for demonstrating the impact of mobility to the performance of 802.11 DCF.

An example instant hopping movement pattern is shown in Figure 1. Two small regions are mutually remotely located in the $3000 \times 3000 \,\mathrm{sq.\,meters}$ area, such that communications between stations which are located in different regions are made impossible. In each region, there are 7 fixed stations and 1 mobile station, and each stations can perform single-hop communications with any other stations in the same region. The fixed stations do not change their positions after being set up at the beginning of a simulation. The mobile stations can change their positions by making instant jumps. In each region, all stations, including the hopping stations, are randomly positioned at the beginning of a simulation. The two mobile stations in different regions periodically make instant hops to each other's positions at the same time. Higher mobility patterns are realized when the time intervals between two consecutive hoppings are made shorter. A number of different hopping movement patterns have been used in our simulations by selecting different time intervals between two consecutive hoppings.

In each region, one fixed station is dedicated to communicate with the current mobile station in the same region as itself, and other fixed stations do not communicate with the current mobile station. In order to generate a high volume of traffic in the network, every station participates in one and only one communication with another station in the same region. When a mobile station hops into a different region, it begins to communicate with the dedicated fixed station in the new region. A saturated data transmission between a pair of source and sink stations is realized by adopting a constant bit-rate (`cbr`) transmissions with the source station having unlimited data frames to send. An ad hoc on-demand routing protocol is used to deliver data frames to their sink stations. All simulations last 100 seconds.

Two network scenarios are used in the following demonstration. One network scenario is called the mobility-free scenario in which all stations stay in their fixed positions throughout a simulation. The second network scenario is called the scenario with mobility, which follows almost all configurations used in the mobility-free scenario, except that two mobile stations hop to each other's position every 10 seconds. Each mobile station is unaware of the changes in position, but it is required to communicate with the dedicated fixed station in the new region when it hops into this new region. Having the two scenarios to follow the same layout of stations and the same communication arrangement makes it possible to compare the performance measured in the two scenarios.

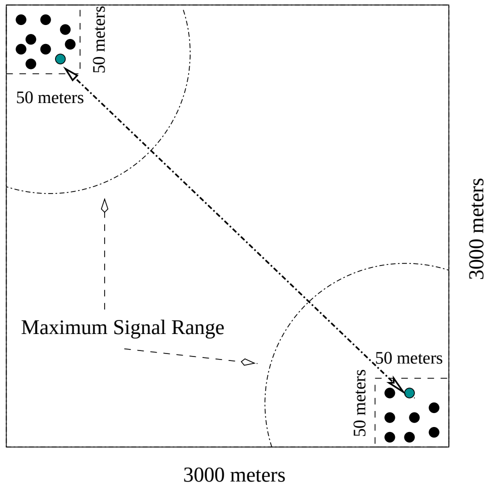

Figure 1: Hopping movement pattern with 2 regions. In each region, there are 7 fixed stations and 1 hopping station. The two hopping stations periodically make instant hops to each other's positions at the same time.

3.2 Observations On the Sender Side

The observations on the sender side is demonstrated through a comparison between the measurements obtained under mobility and the measurements under no mobility. The network scenario used in the demonstration is that there are 7 fixed station and 1 mobile station in each of the 2 regions. When the mobility is present, the 2 mobile stations hop to each other's position every 10 seconds. In each figure shown below (Fig. 2 and Fig. 3), the history of the average values of a metric is used with the bin size being 1 second in deriving the average values.

3.2.1 Time Duration of Backoffs and Deferring

The comparison of average backoff time is shown in Fig. 2 (1) and (2), which show the history of the average values of the duration of one backoff, and the history of the average percentage of time spent in backoff in each 1-second interval, respectively. When the mobility is not present, the average time duration of one backoff stays pretty close to the long-term average value which is about 47 ms (ref. Fig. 2 (1a)). Each sender also spends 77% of the time, on average, in doing backoff, thus, the amount of time spent in backoff is significant (ref. Fig. 2 (2a)). When the mobility is present, the hopping mobility affects both the average duration of one backoff and the average percentage of time spent in backoff (ref. Fig. 2 (1b) and (2b)). The average duration of one backoff is increased almost at the same time when a hopping movement occurs, and the average duration maintain at the higher values for a while before the values of average duration are restored to previous level. A similar behavior can be observed on the the average percentage of time spent in backoff. This phenomenon can be interpreted as that a current coordination among stations in a region can be disturbed when a mobile station suddenly enters this region and continues to transmit frames without having the coordination knowledge in this region. In this case, extra collisions will be introduced into the region, and some stations are forced to do

backoff in order to establish a new coordination in the region.
The comparison of average deferring time is shown in Fig. 2 (3) and (4), which show the history of the average values of the duration of one deferring, and the history of the average percentage of time spent in deferring in each 1-second interval, respectively. There is no noticeable pattern can be observed from the history of average duration of one deferring when the mobility is present, although there is a difference between the values of overall average duration of one deferring under mobility and under no mobility (ref. Fig. 2 (3a) and (3b)). When mobility is present, the count-down of an in-use defer timer is unlikely to be paused due to a busy state in the channel, because sender station have to spend more time in backoffs. The percentage of time spent in deferring also oscillate with the 10-second hopping pattern as the backoff time does (ref. Fig. 2 (4b)). The average percentage of time duration stays low, less than 0.15%, in both cases (ref. Fig. 2 (4a) and (4b)).

3.2.2 The Average Throughput of DATA Frames

When mobility is present, the long-term average throughput is almost a half of value of the corresponding metric in the mobility-free scenario (ref. Fig. 3). Furthermore, the run-time average throughput is downgraded to a lower level following each hopping movement.

3.3 Summary

The throughput of DATA frames is obviously downgraded by mobility of stations. This downgrade mainly attributes to two observable facts. One fact is that each station takes longer time in doing backoffs. The other fact is that each station also needs to perform more RTS-CTS handshakings for winning the access to the channel. Both facts are the direct outcomes of the damaged coordination due to mobility. When a mobile station newly enters into a region, it still follows the original coordination information obtained in the old region. Correspondingly, if this station tries to access the channel using the old coordination information, then it could destroy the existing coordination in the new region. When the coordination is destroyed in a region, many stations in the region are forced to backoff for some time in order to re-establish the coordination. A period of time is needed for a new coordination to be re-established in a region, thus, both the average backoff time and the average number of RTS-CTS handshakings are kept at their higher levels before a new coordination is established. In order to further demonstrate the impact of mobility to the average throughput, modeling of the throughput becomes necessary.

4 Reducing the Backoff Duration Using An AIMD Backoff Algorithm

The average backoff duration plays an important role in the estimation of the average saturation throughput under the 802.11 DCF. A bound exponential backoff (BEB) algorithm is adopted in the original 802.11 DCF. Under this BEB algorithm, the current contention window size is doubled each time when a collision has been detected; the contention window size is reset to the minimum contention window size when the current DATA frame is successfully transmitted. After the contention window size has been doubled for a number of times, *i.e.*, a certain threshold has been reached, the current DATA frame is given up transmission, and the contention window size is also reset the minimum contention window size. The BEB algorithm was designated to resolve persistent contentions, and it over-reacts to non-persistent contentions by spending more time in backoffs than necessary.

Collisions caused by the mobility of stations are usually non-persistent, instead, they are more opportunistic-oriented. The BEB algorithm might be over-sensitive to tentative collisions caused by mobility. We suggest to determine the contention window size using an additive increase and multiplicative (AIMD) backoff algorithm. Under this AIMD algorithm, an initial contention window size is set to be the minimum contention window size, denoted as CW_{min}. The number of contention stages is still denoted as m, and the contention window size in stage k is denoted as $CW(k)\,(0 \leq k \leq m-1)$. The backoff time in stage k is specified as a number of time slots $n_k\,(0 < n_k < CW(k))$. When a collision has been detected in stage k, the current contention window size is updated as: $CW(k+1) \leftarrow CW(k) + CW_{min}$. When the current DATA frame has been successfully transmitted in stage k, the initial contention window size for the transmission of the next DATA frame is set as: $CW(0) \leftarrow CW(k)/2$.

Additive increase of the contention window size upon collisions can be viewed as taking mild reactions to collisions. The contention window size under the AIMD algorithm is increased in a much slower manner than under the BEB algorithm. Multiplicative decrease of the contention window size upon the successful transmission of a DATA frame cab viewed as cumulating previous contention information in order to make later transmissions to quickly approach the appropriate contention level in the channel. When the contention level is high in a channel, the contention window size under the AIMD algorithm is still able to reach high values, but reaching high values takes longer time.

The same set of simulations has been run, and the observations made on the sender side are exhibited in Fig. 4 and Fig. 5 for demonstration of the improvement to the performance of the 802.11 DCF adopting an AIMD backoff algorithm. The meanings of the metrics shown in this section are exactly the same as those explained in Section 3.

In summary, when an AIMD backoff algorithm is adopted, the average saturation throughput of the 802.11 DCF can be improved roughly by a factor of 50% (ref. Fig. 3 and Fig. 5). This improvement mainly attributes to the reduction of backoff duration (ref. Fig. 2 and Fig. 4).

5 Conclusions and Future Work

Mobility of wireless stations downgrades the saturation performance of the IEEE 802.11 DCF. The fundamental assumption made in the 802.11 DCF that each station has full knowledge of the coordination status in the wireless channel is no more valid in the presence of mobility of wireless stations. This paper made its efforts to anatomize into the relations between the mobility movement and the damaged coordination incurred. When newly appearing in a region where a coordination has been established, a mobile station could damage the existing coordination by introducing unexpected collisions which should not occur under the 802.11 DCF, due to its lack of coordination knowledge in the new region. Upon the existing coordination being damaged, many sender stations are forced to do backoffs in order to establish a new coordination. It takes some amount of time before a new coordination can be established, thus, the sender stations have to experience a period of longer backoff duration and of performing more RTS-CTS handshakings. In turn, the number of DATA frames that can be transmitted during this period is lowered, and a corresponding low average saturation throughput is resulted during this period. The impact of mobility to the average saturation throughput can also be revealed through modeling the average throughput. The longer the average backoff duration is, the lower value the average throughput is.

Reducing the average backoff duration is a viable approach to improve the average saturation throughput. The BEB algorithm used in the 802.11 DCF is too conservative to collisions. The unexpected collisions induced by mobility of stations typically exhibit a transient nature, *i.e.*, non-persistent. We suggested an additive increase and multiplicative decrease (AIMD) algorithm to determine the backoff time. In this AIMD backoff algorithm, the current contention window size is linearly increased upon the occurrence of contentions such that the contention window size does not over-react to occasional collisions. A contention window size multiplicatively decreases upon a successful DATA-ACK handshaking, such that the new contention window size still contains contention information without being completely purged. Results obtained from simulations under the new AIMD backoff algorithm show that the average saturation throughput is improved in the presence of mobility of stations. The improvement mainly attributes to the shortened average backoff duration under the AIMD backoff algorithm.

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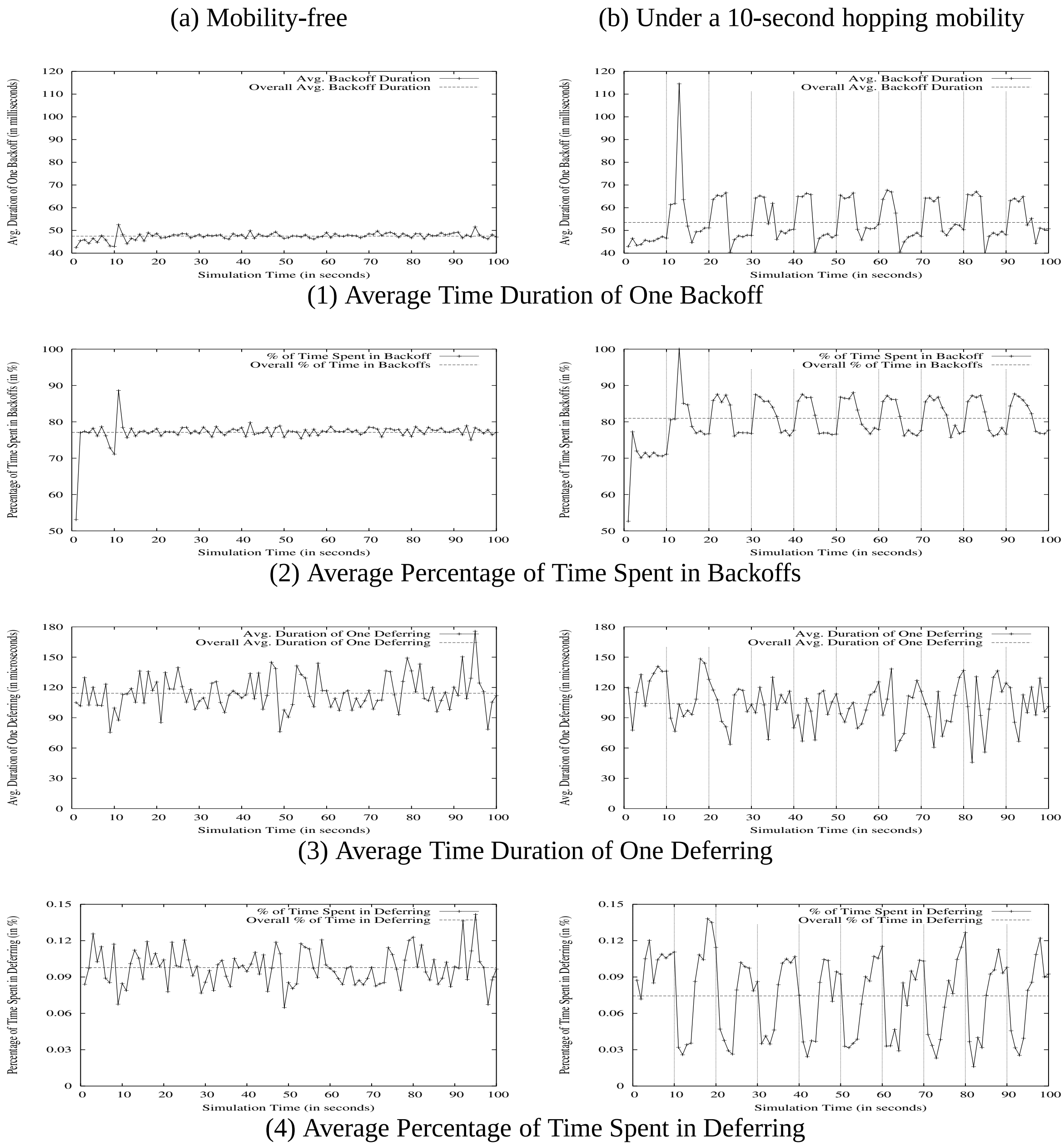
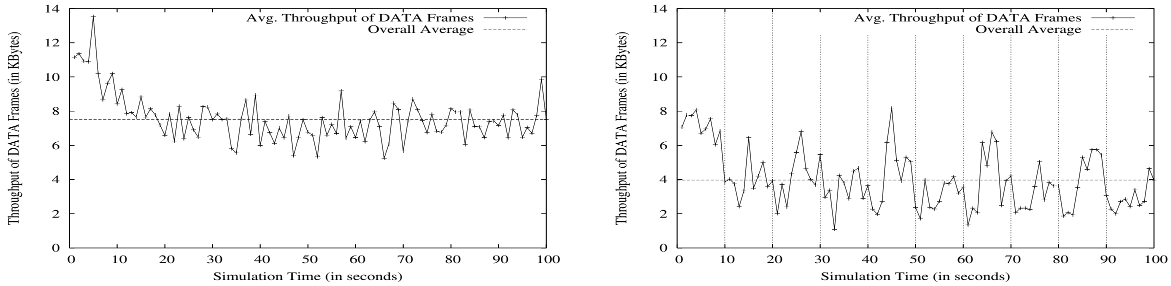


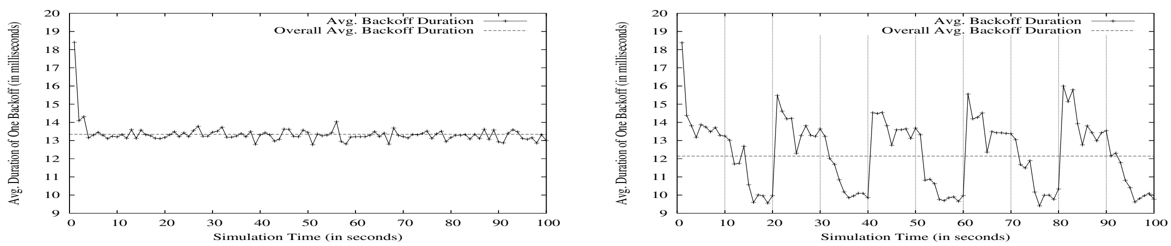
Figure 2: The backoff and deferring time observed at the sender stations. Each curve demonstrates the history of the average values of a corresponding metric under an 1-second bin size.



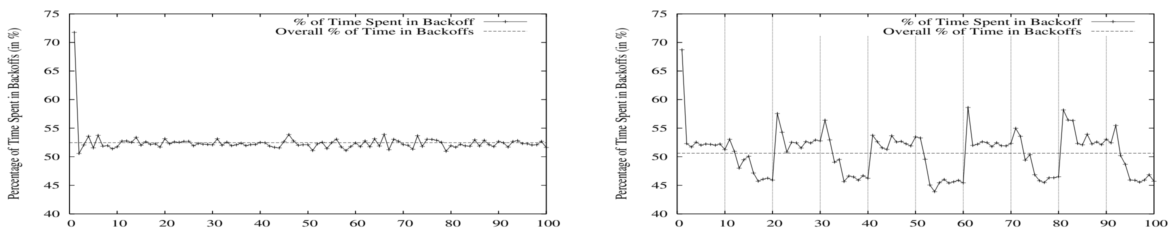
(1) Mobility-free (2) Under a 10-second hopping mobility

Figure 3: The per-station average throughput observed at the MAC layer at sender stations. The throughput shown here is measured as a ratio of the number of collision-free DATA frames received at the MAC layer to the duration of a time interval under concern.

(a) Under no mobility (b) Under a 10-second hopping mobility

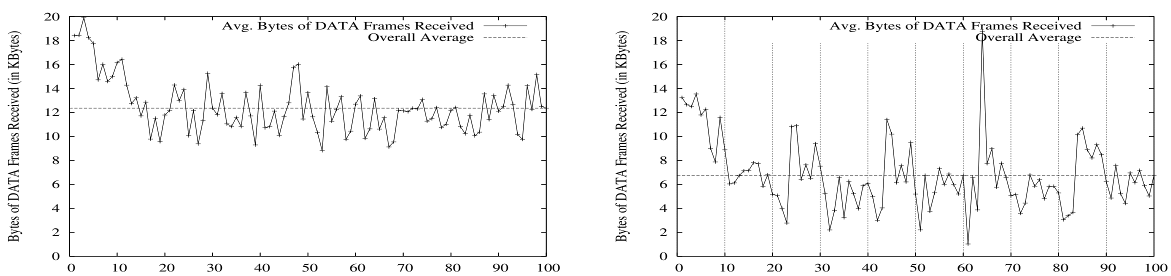


(1) Time Duration of One Backoff



(2) Percentage of Time Spent in Backoffs

Figure 4: The average backoff duration when the AIMD backoff algorithm is in use.



(1) Under no mobility (2) Under a 10-second hopping mobility

Figure 5: The per-station average throughput observed at the MAC layer at sender stations. The throughput shown here is measured as a ratio of the number of collision-free DATA frames received at the MAC layer to the duration of a time interval under concern.