ANALYZING THE PERFORMANCE OF WIRELESS LOCAL AREA NETWORKS WITH AN IMPROVED COLLISION AVOIDANCE MECHANISM

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Abstract - This paper presents and analyzes a collision avoidance mechanism that increases the throughput and decreases the delay in wireless local area networks. The analysis considers the IEEE 802.11 standard parameters employed in the Distributed Coordination Function used in the Ad Hoc mode operation. The mechanism is based on the Deferral Counter (DC) algorithm proposed in the HomePlug standard. The purpose of the Deferral Counter is to increase the contention window faster than the regular IEEE 802.11 backoff function to avoid collisions. Different from IEEE 802.11, the mechanism increments the contention window of the deferring stations to minimize collisions. We implement this mechanism in the ns-2 simulator in order to compare it with IEEE 802.11. We propose three different functions to use in the Deferral Counter mechanism and evaluate their performance considering network throughput, packet delay, and the percentage of overlapping transmissions. The results show that the proposed mechanism performs better when there are more than four active stations no matter the packet size. Furthermore, we also show that the DC function, which achieves the best network throughput depends on the packet size and the number of active nodes.

Keywords: Medium Access Control (MAC), IEEE 802.11 networks, collision avoidance.

1. INTRODUCTION

The wireless communication is increasingly popular due to its high flexibility and low installation cost. Nevertheless, the wireless medium imposes singular impairments to device designers. These impairments include low bandwidth, high bit error rate, and significant variations of the physical medium characteristics. In order to cope with these singularities, the design of efficient Medium Access Control (MAC) protocols for wireless networks is of utmost importance.

The high attenuation compelled by the medium to transmitted signals makes it difficult for the emitter to detect collisions. As a consequence, the well known Carrier Sense Multiple Access with Collision Detection (CSMA/CD) [IEEE, 2002] mechanism, used in the Ethernet MAC protocol, is unsuitable to wireless networks. Therefore, the conventional solution for wireless networks is to avoid, as much as possible, the occurrence of collisions. Infrastructured wireless networks have a central entity, typically an Access Point, which supports pooling access schemes that wipe out collisions. Ad hoc networks protocols, on the other hand, can not count on such mediators. Hence, ad hoc protocols are distributed and, typically, contention-based.

IEEE 802.11 is the most popular wireless local area network (WLAN) technology. The fundamental medium access method of IEEE 802.11 is the Distributed Coordination Function [IEEE, 1999], also known as CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). The CSMA/CA protocol uses two distinct methods to minimize collisions: sensing the medium for a fixed amount of time prior to the transmission and a random backoff mechanism. The backoff mechanism sets a timer with a random number uniformly distributed between zero and a contention window size ($[0, CW]$) times a slot time. When the backoff timer goes off the station transmits its frame. Whenever a transmission fails, the current contention window size is increased by $2 \times CW_{current} + 1$. This increase happens up to a maximum threshold (CW_{max}). The contention window of deferring stations, or stations not directly involved in the collision, does not change. Although the random backoff decreases the collision probability, it can also degrade the network efficiency by adding idle slots. Clearly, there is a tradeoff between the gain with the collision reduction and the wasted time with idle slots.

There are different techniques aiming to increase the medium access efficiency of WLANs. A first approach deals with the problem of how and when to increase the contention window. An important issue addressing this problem is the increasing of the contention window of the deferring stations. Other possibilities relate to how the contention window must be decreased after a successful transmission and how to reduce the impact of idle slots.

In this paper, we analyze a mechanism to increase the contention window of the deferring stations based on the number of transmissions sensed by the station during its backoff. The number of transmissions required for the augmentation of the contention window is dictated by a counter, denominated Deferral Counter (DC). The value of this counter depends on

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the backoff stage, which is related to the number of times the backoff function was called. Our work proposes and analyzes three possibilities for the evolution of DC as a function of the backoff stage: a constant DC, a linear DC, and an exponential DC. The effects of the different approaches are evaluated based on the throughput and on the probability of collisions.

Our work is organized as follows. In Section 2 we review the related work. Section 3 gives a brief overview of the IEEE 802.11 MAC protocol. Section 4 introduces our proposed scheme and details the deferral counter (DC) mechanism. We also show three possible functions for the deferral counter. Section 5 shows the algorithm applied and a simple implementation. Section 5 presents the efficiency of the mechanism through our simulation results. Finally, we conclude the paper in Section 6.

2. RELATED WORK

Several works derive analytical expressions for the network capacity of IEEE 802.11 networks [Li et al., 2001, Villela and Duarte, 2004, Tay and Chua, 2001]. These works are based on the average value of a variable, instead of a stochastic analysis. None of these works addressed the problem of fast increase of the contention window. Tay and Chua also develop a mathematical model, which allows evaluating the best CW_{min} and CW_{max}, but not the backoff function.

[Kuo and Kuo, 2003] propose a simple backoff scheme to DCF and an analytical model based on Markov chains to analyze the throughput and delay performance of the new scheme. The analysis shows that the proposed algorithm can improve the network throughput and reduce the access delay. Although the proposed scheme performs better than IEEE 802.11, they do not analyze the results for different backoff functions and their effects on different scenarios.

[L.Bononi et al., 1998] propose a distributed contention-control mechanism to avoid collision and improve network capacity, by decreasing the mean access delay. The key idea is to distribute transmission attempts over a variable-size time window the most uniform as possible. The medium access algorithm is based on an estimation of the contention level, which is obtained by the slot utilization. Each station counts the number of busy slots during its own backoff interval. This value is divided by the backoff interval itself to obtain the slot utilization. This result is used to calculate a medium access probability that also depends on the number of unsuccessful attempts. They show that the proposed mechanism can improve network efficiency and introduces no overhead in low load cases. Nevertheless, the contention window is not optimized and the algorithm may introduce a lot of idle slots.

[Kwon et al., 2003] propose a mechanism that improves network throughput and fairness. In order to enhance the throughput, the proposed scheme is based on two strategies: fast collision resolution and reduction of idle slots. The fast collision resolution is achieved by changing the backoff window size for the deferring stations whenever they sense a busy slot. In addition, they use a larger CW_{max}, when compared to the one of 802.11, to reduce the collision probability. Idle slots are minimized by setting a much smaller CW_{min} and decreasing the backoff timers exponentially when a prefixed number of consecutive idle slots are detected. The paper also presents an extension to this mechanism to provide medium access fairness.

Our paper focuses on the problem of fast increase of the contention window. We investigate the functions, which can be used to increase the contention window for the deferring stations. The simulations take into account the number of active stations and the packet size. The effects of the different approaches are evaluated based on the throughput and on the probability of collision occurrence.

3. THE IEEE 802.11 MAC PROTOCOL

The IEEE 802.11 standard defines the Medium Access Control (MAC) and Physical Layer (PHY) specifications. In Distributed Coordination Function (DCF) mode, whenever a station wants to transmit a data frame, it must wait the medium to remain idle for DIFS (Distributed InterFrame Space), which lasts for 50μs. After DIFS, the station transmits its data frame as illustrated in Figure 1. Due to medium attenuation, which makes collision detection unfeasible, the transmitter waits an acknowledgment (ACK) from the receiver. The receiver transmits an ACK if it correctly receives a data frame. The ACK frame is transmitted after the end of the data frame reception plus a time interval SIFS (Short Interframe Space), which lasts for 10μs. As SIFS is shorter than DIFS, the ACK transmission is guaranteed before any other data transmission. To avoid collisions, after the first data frame, every transmitted data frames waits for DIFS or EIFS (Extended Interframe Space) plus a random time (backoff).

DIFS is used if the last transmission detected on the medium was received correctly, and EIFS, otherwise. The stations defer its attempt to transmit for EIFS, which is larger than DIFS, whenever they could not determine the situation of the current transmission progress. The reception of an erroneous frame means that the stations are not aware of what frame was received. Thus, they must wait a time interval large enough so that eventual ongoing transmissions end. The EIFS interval follows the reception of the erroneous frame supposing it was a data frame. The EIFS avoids collisions between data and ACK frames. It lasts for SIFS plus a period corresponding to an ACK frame transmission plus DIFS.

The backoff mechanism is activated after DIFS or EIFS. The backoff function chooses a random number uniformly distributed between zero and the contention window size $[0, CW]$. This number is used as a backoff counter and its value times a slot time (20μs) sets a backoff timer. A slot of 20μs guarantees the frame detection of an ongoing transmission by all the stations of the network.

The stations decrement by one their backoff counter if the medium remains idle for a slot time. They keep decrementing the counter until the backoff timer goes off and the transmission occurs. Nevertheless, if the medium is occupied while a station is waiting for backoff, the station must pause its backoff counter and wait the next transmission attempt to resume it. The backoff function is called if the transmitter does not receive an ACK frame from the receiver.

The backoff function handles the increase of the contention window size. This size depends on the number of times the backoff function is called during the transmission of a specific frame. The backoff function is called (Backoff Function Calls - BFC) every time the corresponding ACK frame is not received and, as a consequence, a collision is supposed to have occurred. Therefore, the contention window increase avoids collisions by decreasing their occurrence probability. In the first attempt to access the medium, the station chooses a value for its backoff counter between zero and the minimum contention-window size $[0, CW_{min}]$ ($CW_{min} = 31$). The increase in the contention-window size follows the expression $2 \times CW_{current} + 1$, where $CW_{current}$ is the current CW size used in the transmission. This increase continues up to a maximum threshold ($CW_{max} = 1023$). If the backoff function is called when CW is already equal to its maximum value (CW_{max}), the CW size is not changed. CW returns to its initial value whenever a successful transmission occurs. The values of the contention window (CW) are shown in Table 1.

Table 1. Contention window (CW).

BFC	0	1	2	3	4	5
CW	31	63	127	255	511	1023

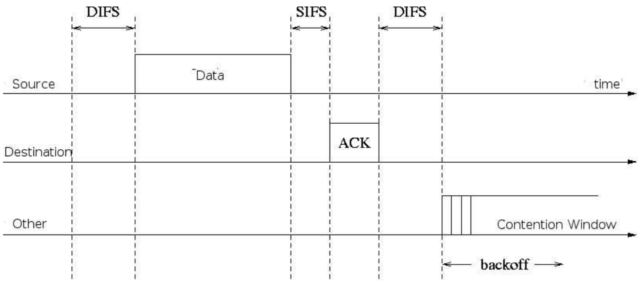


Figure 1. Distributed Coordination Function (DCF) basic operation.

The DCF implements a virtual allocation vector called NAV (Network Allocation Vector). When a station is listening to the medium, it is aware of the duration of the current transmission through the information available on the ongoing frames. Hence, the stations know for how long the medium will be busy and, as a consequence, for how long they will not be able to transmit. This scheme avoids collisions.

The RTS/CTS (Request-To-Send/Clear-To-Send) mechanism is used to carry the transmission duration, besides avoiding the hidden terminal problem. The RTS and CTS frames are used to update the NAVs from the stations that are contending for the medium. When the RTS/CTS mechanism is employed, the transmitter sends the RTS frame after DIFS. After receiving a RTS frame, the receiver transmits the CTS after SIFS. When the transmitter receives the CTS, the RTS/CTS exchange is complete. Then, it transmits a data frame after SIFS as shown in Figure 2. After the data transmission, the transmitter waits for an ACK as in the basic scheme. Every station must be able to hear the RTS or CTS frames since they are inside the transmission range of the RTS/CTS transmitter. Therefore, the RTS/CTS frames must be transmitted at the basic rate, usually 1Mbps.

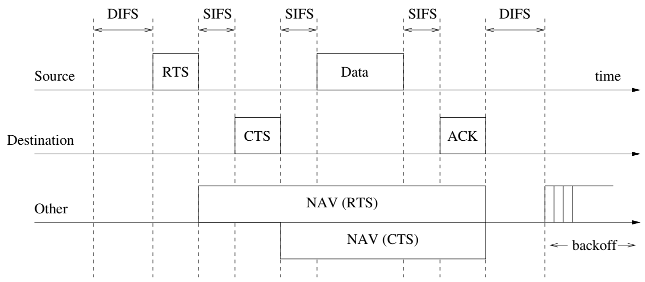


Figure 2. Distributed Coordination Function (DCF) operation with RTS/CTS.

4. USING THE DEFERRAL COUNTER WITH IEEE 802.11

The maximum performance of CSMA/CA is achieved when one frame is transmitted after the other without collisions and idle slots. In other words, to increase the performance, collisions must be avoided and the backoff time must be minimized. Our proposal is an improvement of the backoff mechanism, which allows better throughput and lower delay, using a mechanism that decreases the collision rate. This mechanism, the Deferral Counter (DC), was introduced by the HomePlug standard ([Lee et al., 2003]) used in PowerLine Communications.

HomePlug defines the MAC protocol used in high-speed data transmissions in home networks through the electrical wiring. The deferral counter was conceived to work with the backoff mechanism to avoid collisions. The DC is decremented whenever a station observes the medium captured by another station. When the DC reaches zero, the node assumes that there is a considerable number of stations trying to transmit, which increases the collision probability. Thus, a station must call the backoff function when it senses that the medium was captured again and must increment its deferral counter, as seen in Figure 3.

The Table 2 gives the values of the contention window and the corresponding values of the deferral counter used in HomePlug. HomePlug uses different channel access priorities (CAP), ranging from CA3 to CA0, where CA3 is the highest priority. These classes are assigned to provide quality of service.

Table 2. Contention window (CW) and deferral counter (DC) values defined in the HomePlug standard.

	CAP: CA3,CA2		CAP: CA1,CA0	
BFC	CW	DC	CW	DC
0	7	0	7	0
1	15	1	15	1
2	15	3	31	3
≥ 2	31	15	63	15

The Table 3 shows an example of the evolution of CW and DC. At instant 0, suppose that a node attempts, for the first

```
transmit ()
   Wait to transmit frame;
   if medium is idle for DIFS then
      start_backoff;
    if backoff is started and the medium gets busy then
      // Verify DC;
      if DC == 0 then
         stop_backoff;
         increment_DC;
         increment_CW;
         return;
      else
         decrement_DC;
         pause_backoff;
         return;
    else if backoff_timer == 0 and medium == idle then
      transmit the frame and wait for the acknowledgment;
     if the acknowledgment doesn't arrive   // Collision occurred
        increment_DC;
        increment_CW;
        return;
     else
        return;
```

Figure 3. The algorithm of the improved collision avoidance mechanism.

time, to access the medium. Nevertheless, some other node with the same priority has captured the medium first. As a consequence, the node that was unable to transmit calls the backoff function and also increases its DC to the next value, equal to 1. At instant 2, the node transmits, but a collision occurs compelling it to increase its contention window and its DC. At instants 3 and 4, the node can access the medium and transmit its frames, setting its CW size and DC at the minimum values. Starting at instant 5, the node is unable to transmit because the medium is always busy due to other transmissions. The DC value is down to zero. If another transmission occurs, the node calls the backoff function again and once more increases its DC to the next value.

Table 3. Example of backoff and deferral counter (DC) evolution.

Instant	Backoff	DC
0	7	0
1	15	1
2	31	3
3	7	0
4	7	0
5	15	1
6	15	0
7	31	3
8	31	2
9	31	1

Our work adopts the Deferral Counter mechanism to be used with IEEE 802.11. We propose three possibilities for the deferral counter values and compare them with the case without DC. The first proposal keeps the value of the DC constant; the second increases the DC values using a linear function of the form $4 \times n + 3$; and the third increases the DC values using an exponential function of the form $2^{(n+2)} - 1$. The minimum value of the deferral counter was set to three, because the IEEE 802.11 has a CW_{min} value higher than HomePlug. Thus, the collision probability would be lower and the deferral counter may be less efficient if its initial value is zero. That would represent a high overhead specially when a small number of nodes are trying to transmit. Moreover, when CW reaches its maximum value (CW_{max}), the DC value stops increasing. Table 4 shows the evolution of the DC value as CW increases for the three proposed functions.

Table 4. Backoff and DC evolution of the proposed schemes.

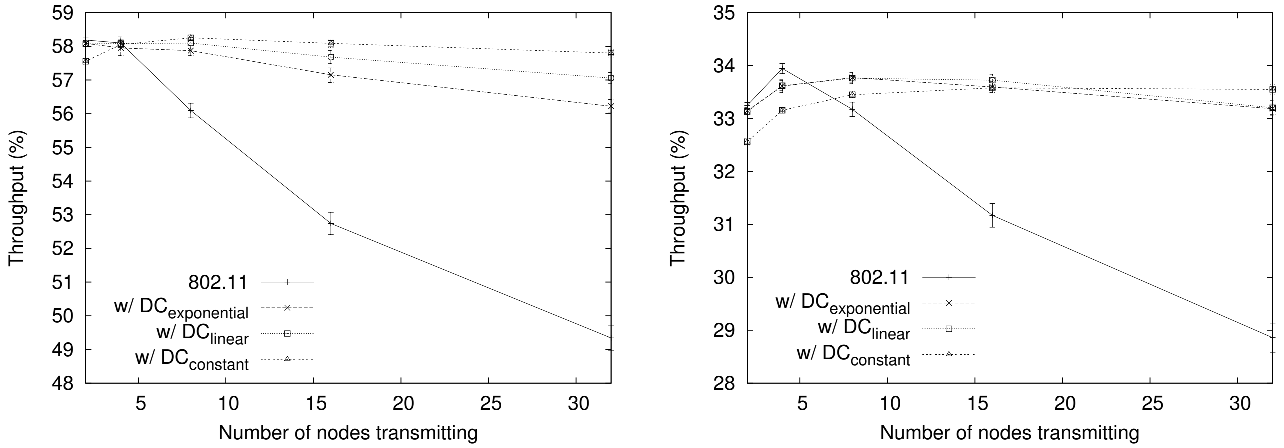
	Deferral counter (DC)		
CW	Constant	Linear	Exponential
31	3	3	3
63	3	7	7
127	3	11	15
255	3	15	31
511	3	19	63
1023	3	23	127

5. RESULTS

To implement the DC mechanism, we modify the IEEE 802.11 module available in the Network Simulator 2 (ns-2) [Fall and Varadhan, 2002]. We adapted the backoff mechanism in order to achieve the behavior shown in Figure 3. Whenever a station wants to transmit a frame, it must wait for DIFS and for a backoff time afterwards. When waiting for backoff, if the station senses the medium busy, it must verify its DC. If its DC is zero, the station must stop its backoff, increment DC and CW, and wait for the medium to get idle again. If the DC is different from zero, the station must decrement it and proceed as the usual backoff mechanism employed in IEEE 802.11, i.e., pause the backoff timer and wait for the medium to get idle again resuming it. A transmission occurs whenever the backoff timer reaches zero. After transmitting a data frame, the station waits for an acknowledgment. If the transmitter does not receive an acknowledgment, it must increment its DC and CW because a collision must have happened.

Our simulation scenario consists of a single hop network with 32 nodes randomly placed in a 150 m x 150 m area. Thus, every station can directly communicate with each other. Active stations, namely, the ones that are transmitting, are modeled by a CBR source. We assume that a packet is always available for transmission. We ran a set of simulations varying the number of active stations. The main goal is to assess the behavior of the network capacity according to the backoff function and the number of active stations. The results consider 95% confidence intervals which are represented in the figures by vertical error bars.

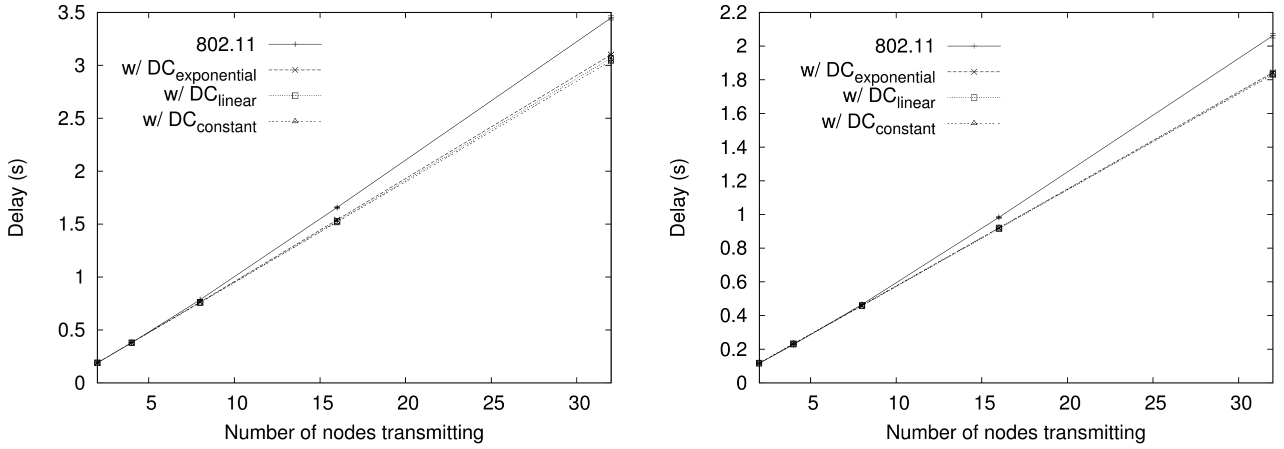
Figure 4(a) shows the network throughput for packets of 1500 bytes. Note that all three DC functions perform better than without DC, except for less than 5 active stations. In such case, the throughput behaves almost the same when using the regular backoff function (without DC), the linear DC function, and the exponential DC function. The purpose of DC is to augment the network capacity by reducing the number of collisions. When the total number of active nodes are less than 5, there is a low collision probability. There-



(a) Throughput for 1500 bytes packets.

(b) Throughput for 512 bytes packets.

Figure 4. Comparison of the throughput with and without the analyzed mechanism.



(a) Delay for 1500 bytes packets.

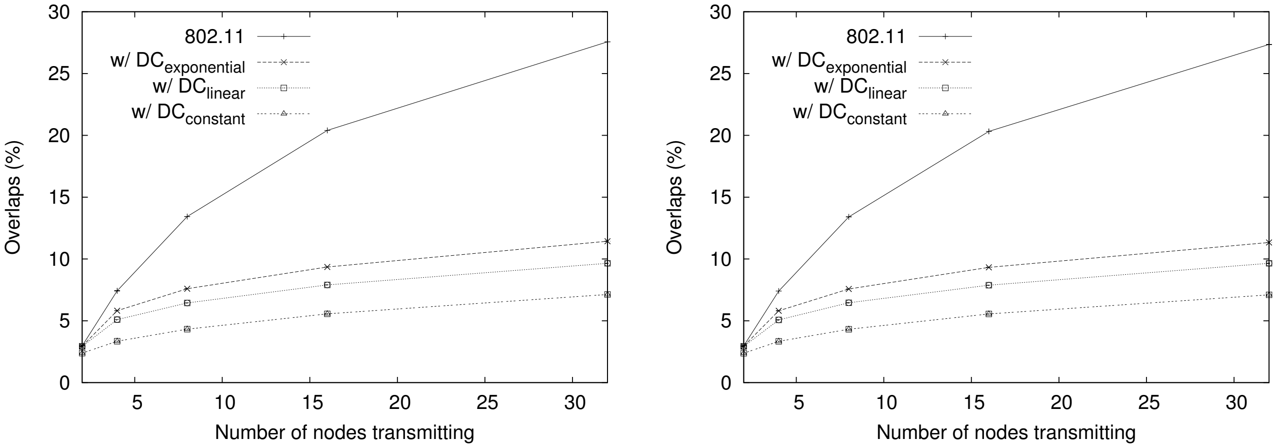
(b) Delay for 512 bytes packets.

Figure 5. Comparison of the delay with and without the analyzed mechanism.

fore, while the collision probability is negligible, the network throughput is increased with the number of active stations, because we are decreasing the amount of idle slots related to backoff. Actually, the average backoff time is divided by the number of stations. This behavior is presented in Figure 4(b), where the curve related to the regular backoff function shows a small elevation and then, after 4 stations, it goes down. In this particular case, when the collision probability is negligible, the regular backoff function performs better than the other ones because, in fact, there is no need to avoid collisions. As the number of active nodes increases, the efficiency of the regular backoff drops fast while the ones that use DC perform much better.

Figure 4(b) shows that the linear and exponential backoff functions perform better than the constant function with up to 16 active stations, which means that we do not need to increase the contention window as fast as the constant function does for a small number of stations. Worth to mention that the effect of a collision on the network throughput depends on the size of the packet. The larger is the packet the worse is the effect. This is the reason why in Figure 4(a) there is no improvement in the network capacity when there is less than 5 stations. Although a small number of collisions occur, the decreasing in the average backoff time is not enough to overcome the cost of the collisions.

Figures 5(a) and 5(b) present the impact of the number of active stations on packet delay. It is clear, in both figures, that the deferral counter mechanism can decrease the end-to-end delay. However, the curves did not reflect the network improvement achieved by the DC mechanism, as seen in Figures 4(a) and 4(b). End-to-end delay includes not only the backoff delay, but also the queuing delay. When the network operates in saturation the queuing delay might accumulate several backoff delays and reach a considerable value. This problem can make the backoff delay almost negligible for a small number of active nodes.



(a) Overlapping for 1500 bytes packets.

(b) Overlapping for 512 bytes packets.

Figure 6. Comparison of the overlapping with and without the analyzed mechanism.

Figures 6(a) and 6(b) illustrate the percentage of overlapping transmissions. We can observe that the size of the packet does not affect the percentage of overlapping transmissions. The collision probability is independent from the packet size, thus for smaller packets there will be more overlapping transmissions. However, in the same amount of time, the proportions between the number of successful sent packets and overlapping transmissions for small and large packets are the same. Figure 6(b) shows that the percentage of overlapping transmissions for the regular backoff functions is higher than the others. An expected result is that the curve disposition is ordered by the ability to enlarge the contention window. The faster it does the lower is the percentage of overlapping transmissions. The interesting observation is that just quickly increasing the contention window is not enough to find the backoff function that offers the higher network throughput. Figure 4(b) shows that for less then 15 nodes, the $DC_{constant}$ approach provides worse throughput than DC_{linear} and $DC_{exponential}$.

Figures 7(a) and 7(b) show the percentage of the number of overlapping transmissions. The results concern the scenario with 32 active stations and is limited in two and three overlapping transmissions. These results emphasize the fact that the collision probability does not depend on the packet size, since Figures 7(a) and 7(b) are almost the same. It also shows that the DC mechanism decreases collision, indeed.

This is observed, because when the DC mechanism is not used, there is a lower percentage of collisions between two nodes and a higher percentage of collisions between three nodes. When the DC is not employed the overlapping transmissions have a higher probability and events like transmission overlaps involving three or more nodes are more frequent. Overlapping between a high number of stations are not desirable because it increases the number of retransmissions.

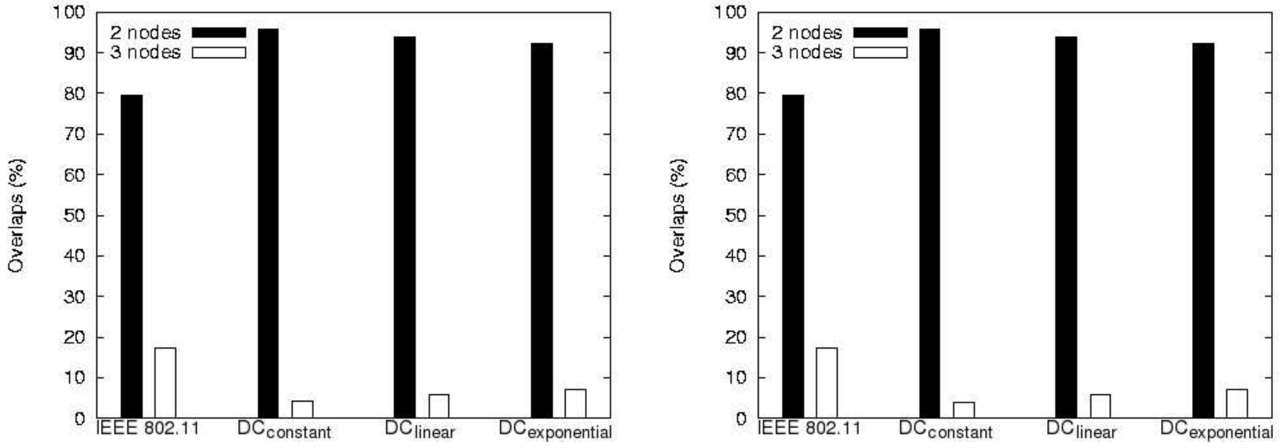
We then evaluate the performance of a DC function, which provides faster growth for the contention window. This function is a constant function with $k = 0$. Figure 8(a) shows that the $DC_{constant=0}$ just performs better for a network with more than 16 active stations, for a packet size of 1500 bytes. Additionally, for smaller packets $DC_{constant=0}$ performance gets even worse, as shown in Figure 8(b). This result shows again that increasing fast does not mean a better performance. The best result depends on the packet size and the number of active stations.

6. CONCLUSIONS

This paper presented and analyzed the performance of a collision avoidance mechanism to enhance the throughput and decrease the delay in 802.11 networks. The mechanism is based on the deferral counter (DC) algorithm proposed in the HomePlug Standard. The purpose of the deferral counter is to increase the contention window faster than the regular backoff function from 802.11 to prevent collisions. Differently from IEEE 802.11, the analyzed mechanism increments the contention window of the deferring stations to minimize collisions.

We implemented this mechanism in the ns-2 simulator in order to compare it with IEEE 802.11. We proposed the utilization of three different functions in the deferral counter mechanism and evaluated their performances taking into account network throughput, packet delay, and percentage of collisions. The results showed that the proposed mechanism performs better when there is more than four active stations no matter what the packet size is. More importantly, we showed that the DC function, which optimizes better the network capacity, depends on the packet size and the number of active nodes. This is mainly due to the tradeoff between the collision probability reduction achieved by the mechanism and the increased number of idle slots. Therefore, there is no single DC function that performs better than the others for all situations.

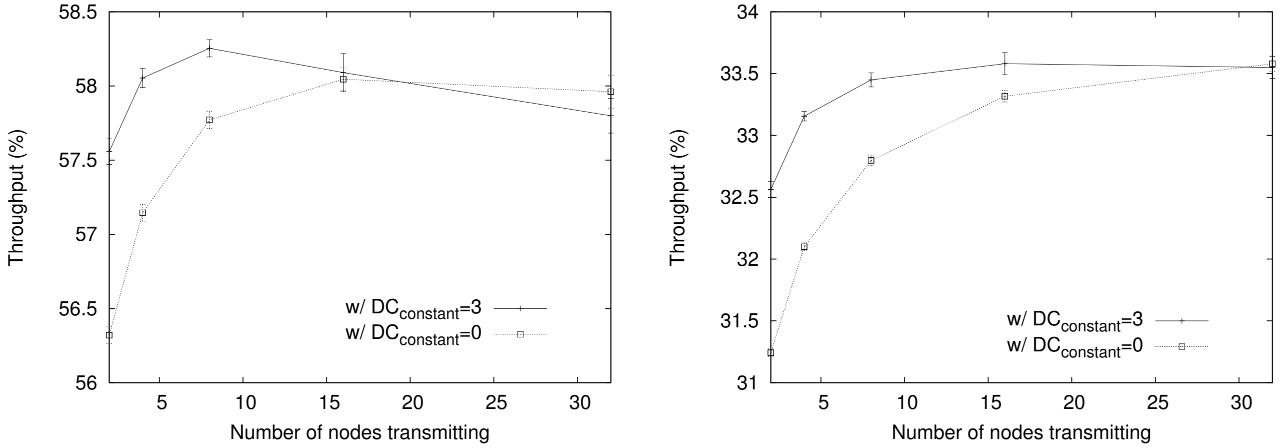
Our future work includes the proposal of a dynamic DC



(a) Distribution for 1500 bytes packets.

(b) Distribution for 512 bytes packets.

Figure 7. Overlapping distribution with and without the analyzed mechanism.



(a) Throughput with $DC_{constant} = 0$ and 3 for 1500 bytes packets.

(b) Throughput with $DC_{constant} = 0$ and 3 for 512 bytes packets.

Figure 8. Throughput for different $DC_{constant}$ values.

function, which adapts to the packet size and the number of active stations to optimize the network throughput. A decreasing backoff function to minimize the idle slots and improve the network capacity can also be studied.

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