Thorough Analysis of IEEE 802.11 EDCA in Ring Topology Scenarios with Hidden and Exposed Nodes*

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Abstract. In this paper the authors present a simulation study of five different ring networks with hidden and exposed nodes in which the IEEE 802.11 EDCA function is used as the MAC protocol. The presented analysis is crucial for understanding how the theoretically simple ring topology can be degraded by the presence of hidden and exposed nodes. Configurations with equal and mixed priorities are considered. Additionally, the usefulness of the four-way handshake mechanism is argued. Furthermore, the achieved results are compared with the results obtained for several star and line topology networks. Finally, the authors signalize the need for a better MAC protocol.

Keywords: Ad-hoc, exposed nodes, hidden nodes, QoS provisioning.

1 Introduction

Wireless communications gained, and is still gaining, a great importance in everyday life. As a consequence, wireless technologies appear almost everywhere. The IEEE 802.11 [1] standard is one of the main actors in this scenario. This technology is currently spreading, moving from laptops to smart-phones, while WiFi hotspot areas are constantly growing in number. Although wireless infrastructure networks represent the principal solution for the connectivity of IEEE 802.11 devices, such a network management model is not always feasible or available (e.g., in rural areas). In such scenarios the ability of connecting wireless devices in an infrastructure-less (ad-hoc) and opportunistic manner represents the natural solution to the communication needs of users.

Ad-hoc networks are formed using opportunistic criteria and providing discovery and routing functionalities among their members (nodes) [4]. However, their distributed nature causes a lot of problems, among which, QoS control is of significant importance. This is the result of the growing popularity of such applications as voice over IP and video streaming. These applications demand a

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minimum level of performance provisioning. Therefore, their diffusion in ad-hoc scenarios is highly conditioned to the ability of predicting and controlling QoS parameters, e.g., frame loss and communication delays.

IEEE 802.11 EDCA (Enhanced Distributed Channel Access) is a candidate solution to the problem of QoS provisioning. It is an extended IEEE 802.11 DCF (Distributed Coordination Function) which enables traffic differentiation through the configuration of several parameters of the MAC (Medium Access Control) layer algorithm. EDCA defines the concept of Access Category (AC): in order to transmit data, every node may use up to four ACs. Each AC implements a slotted CSMA/CA algorithm with its own parameter set and competes with other ACs to obtain transmission opportunities (TXOPs). The four ACs within a node represent four priority levels for data transmission. The standard names these levels as: background (P3), best effort (P2), video (P1) and voice (P0). To differentiate the behavior of the ACs, four parameters can be set: the Arbitration Inter-frame Space (AIFS[AC]), which determines the interval during which the medium must be sensed idle before an AC is allowed to transmit; the minimum and the maximum Contention Windows (CWmin[AC], CWmax[AC]), which determine the average duration of the backoff process, and, finally, the Transmission Opportunity limit ($TXOP_{limit}$[AC]), which specifies the maximum channel occupancy time in the case of a successful access (this parameter is optional).

One of the meaningful disadvantages of IEEE 802.11 ad-hoc networks is that, even though the possible PHY (Physical) Layer rates are satisfactorily high, the MAC Layer is not able to use the whole bandwidth. There are two main reasons of such performance. First of all, the current MAC proposals are suboptimal. Secondly, node starvation is unavoidable as long as hidden and exposed nodes are present in a network. This paper concentrates on the second issue. Its aim is to investigate the impact of hidden and exposed nodes on the behavior of the ring topology. The authors analyze ring topology networks with the same and mixed priorities of nodes with the four-way handshake mechanism enabled and disabled.

Hidden nodes may appear when two nodes are out of range of each other and they are unable to hear their transmissions. This may have an impact on the correct behavior of the CSMA/CA mechanism increasing the number of frames wasted in collisions. Exposed nodes may appear when a node is prevented from sending packets to other nodes due to a neighboring transmitter. The exposed terminal problem avoids exploiting parallel transmission in the network, reducing the overall network performance. Although several solutions to the hidden and exposed node problems have been proposed in the literature, most of them rely on extensions of the current communication standards [3]. Conversely, a complete characterization of standard solutions (four-way handshake combined with EDCA configuration) is still missing.

The remainder of this paper is organized as follows. Section 2 contains a description of the testbed and simulation scenarios considered during the simulation analysis. In section 3 a detailed discussion on the achieved results is given. The paper concludes with section 4 in which, additionally, a brief comparison of the ring, star and line topologies is provided.

2 Testbed

The simulation analysis was performed with the use of the TKN EDCA enhancement [2] to the ns2 simulator, improved by the authors. The adjustments affect the four-way handshake mechanism (involving Request to Send, RTS, and Clear to Send, CTS, frames) and the handling of duplicate frames because they were not correctly implemented. All important simulation parameters are given in Table 1 and Table 2.

Table 1. EDCA parameter set [1].

Priority	CWmin	CWmax	AIFSN	$TXOP_{limit}$
P0	7	15	2	0
P1	15	31	2	0
P2	31	1023	3	0
P3	31	1023	7	0

Table 2. General simulation parameters.

SIFS	10 µs	**DIFS**	50 µs
PHY data rate	11 Mb/s	**Slot Time**	20 µs
Transmission Range	250 m	**Transmission Power**	0.282 W
Frame Size	1000 B	**Traffic Type**	CBR/UDP
Carrier Sensing Range	263 m	**Distance Between Nodes**	200 m
Short Retry Limit	4	**Long Retry Limit**	7

The authors considered two scenarios. In the first scenario, they analyzed five different ring configurations (consisting of 4 to 8 ad-hoc nodes, Figure 1) in which all nodes had the same priorities. In the second scenario, they analyzed the same ring networks but with mixed priorities.

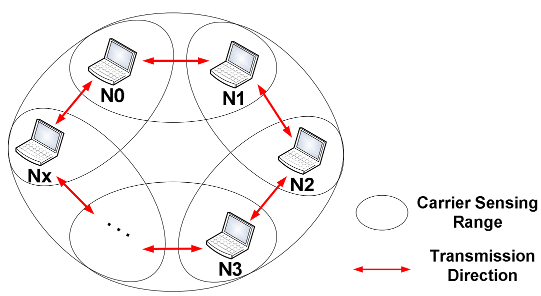


Fig. 1. Exemplary network.

The simulation study was performed with the assumption that all nodes sent traffic with a varying sending rate (from 10 Kb/s to 3 Mb/s) and DSSS (Direct Sequence Spread Spectrum) is used at the PHY layer. Additionally, in order to combat the hidden node problem, the RTS/CTS mechanism is employed. Furthermore, in all presented figures the 95% confidence intervals do not exceed ±2%.

3 Simulation Results

In this section the results obtained from the configurations with equal (subsection 3.1) and mixed (subsection 3.2) priorities will be presented. In the more interesting section 3.2, they are gathered in the form of two types of figures. Firstly, they show throughput values obtained by different nodes and, secondly, they show numbers of frames lost by these nodes. The second type needs explanation. It consists of **IFQ drops** — frames dropped in interface queues between the LLC (Logical Link Control) and the MAC layers, and **RETRY drops** — frames dropped due to the transgression of the long or short retry limit. Other kinds of frame losses which impact the throughput values are the following. **DUPLICATE drops** are the result of collisions of either DATA and ACK (Acknowledgement) frames or RTS and ACK frames which are caused mainly by the exposedness of nodes. Frames can also be lost due to a collision. These losses were not included in the figures because they are not real frame drops (i.e., they are related to frames which were unnecessarily re-sent or collided).

Scenario 1: Equal Priorities

As it was mentioned in section 2, the first phase of tests consisted of five separate ring networks in which the same priorities were assigned to all nodes. From the four priorities introduced by EDCA the authors chose only P0 and P3 because they serve traffic with the highest and the lowest requirements. As a result, their comparison shows the scope of EDCA operation. The authors assume (on the basis of their previous experience) that nodes with P1 will behave similarly to nodes with P0, and nodes with P2 will behave similarly to nodes with P3. The differences between their behavior will be only quantitative but not qualitative and, therefore, practically meaningless in regard to the discussed issue.

Table 3. Overall saturation throughput [KB/s].

Network	All nodes P0		All nodes P3	
	RTS on	**RTS off**	**RTS on**	**RTS off**
4-node ring	56	0	404	480
5-node ring	190	215	380	465
6-node ring	222	150	456	570
7-node ring	259	196	560	700
8-node ring	304	224	640	816

Table 3 contains the approximate values of the overall saturation throughput for the analyzed ring networks with the four-way handshake mechanism enabled and disabled. In all cases, nodes lose practically the same number of frames and, therefore, each has the same throughput. From the achieved results it appears that it is better to turn the RTS/CTS exchange on if the nodes send P0 traffic. In the case of P3 traffic, the performance is slightly better without RTS/CTS. This is caused by the following two facts. Firstly, in both cases turning RTS/CTS on increases the signaling overhead which causes a reduction of the available bandwidth. Secondly, the number of collisions is over six times lower for P3 than for P0 when the RTS/CTS mechanism is switched off. Because of these two factors the gain from using RTS/CTS is meaningful only if nodes send P0 traffic.

Furthermore, it can be noticed that the ring network performance is the worst for P0 traffic in the 4-node configuration. In such a network the chances for two (or more) consecutive and undistorted transmissions are very low when nodes transmit high priority traffic. In larger networks these changes increase. Surprisingly, the 4-node network gains the highest per-node throughput for P3 traffic. It is because when the number of collisions drops and the exposedness of nodes is of minor importance (i.e., nodes are not blocked by other nodes' transmissions), nodes can experience more frequent and undistorted transmissions.

Additionally, it is visible that the 6-, 7-, and 8- node networks behave similarly, i.e., they have approximately the same per-node throughput. Therefore, it may be expected that ring topology networks consisting of more nodes will behave similarly.

Unexpectedly, the behavior of the 5-node ring is a bit different. This network behaves similarly to the 6-, 7-, and 8- node rings for P3 traffic and P0 traffic with RTS/CTS enabled but, at the same time, it behaves a bit better for P0 traffic with RTS/CTS disabled. For the 5-node ring nodes experience a lot more DUPLICATE drops than for the other networks. Therefore, it appears that in such a configuration the strong exposedness of nodes leads to higher throughput.

Finally, it is noticeable that the overall bandwidth utilization is poor. Even though the connections between nodes are set to 11 Mb/s the maximum per-node utilization reaches only 120 KB/s (c.f., 4-node ring with RTS off). This is caused by the fact that each of the analyzed networks contains hidden and exposed nodes which degrade their behavior.

Scenario 2: Mixed Priorities

The second phase of tests consisted of five separate ring networks with mixed priorities. The node priorities were varied in order to check if they can influence the analyzed network performance and if they can, for example, worsen the fairness between nodes. Additionally, in order to examine the scope of EDCA, the priorities were chosen in the most opposite way, i.e., when P0 was assigned to N0 all other nodes had P3, and when P3 was assigned to N0 all other nodes had P0.

The first conclusion from the test results is that the 5-node ring behaves similarly to the 6-node ring and the 7-node ring behaves similarly to the 8-node ring. Therefore, in order to simplify the presented analysis, the authors show only the results obtained for the 4-, 6- and 8-node ring.

In all of the following figures, if there are no results presented for the scenario with RTS/CTS disabled it means that they were similar to those in which RTS/CTS was enabled. The differences between the two cases are only quantitative but not qualitative. This is done in order to simplify the presentation. Additionally, it must be stressed that all presented values of throughput and frame loss are given per-node and per collision domain. This is done in order to make the comparison between the star, line and ring topologies possible (section 4).

3.2.1. 4-node Ring, N0=P3, Others=P0

The first of the analyzed configurations was the 4-node ring in which N0 had P3 assigned and the other nodes had P0. As presented in Figure 2a, strong unfairness appears in the network. Even though N1-N3 sent traffic with the highest priority, only N2 has meaningful non-zero throughput. This behavior stays in strong relation to the number of frames lost by each node. As shown in Figure 2b, N1-N3 lose practically twice as many frames as N2 under saturation. This comparison is even worse under non-saturation. There are two explanations for this behavior. Firstly, N0 sends its traffic with the lowest possible priority and, as a consequence, it has the highest number of IFQ drops (this is typical EDCA performance). Secondly, according to the IEEE 802.11 standard, N1 and N3 should have the same frame drop ratio as N2 but, as shown in Figure 2b, they considerably differ from each other. This performance is a result of multiple collisions between RTS frames originating from N1 and N3 being hidden from each other (without RTS/CTS, the DATA frames collide). Furthermore, N1 and N3 send traffic with the highest EDCA priority, which also means that their access parameters allow for the quickest medium access, not only after each successful transmission but also after each transmission failure. N0 and N2 have opposite priorities and, therefore, they experience a noticeably lower number of collisions.

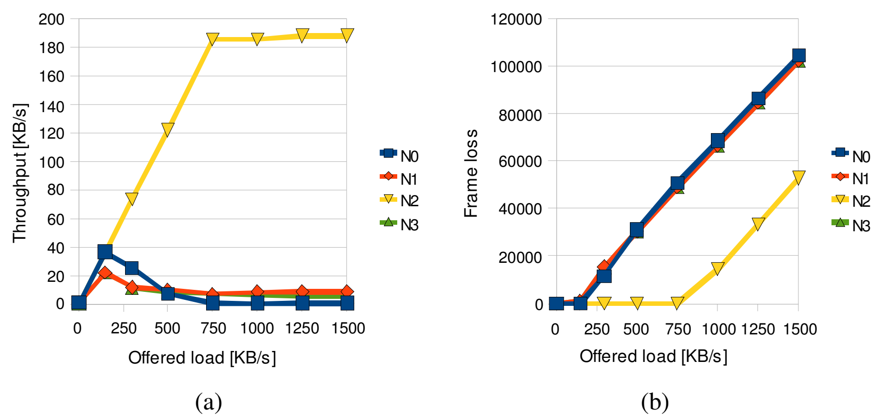
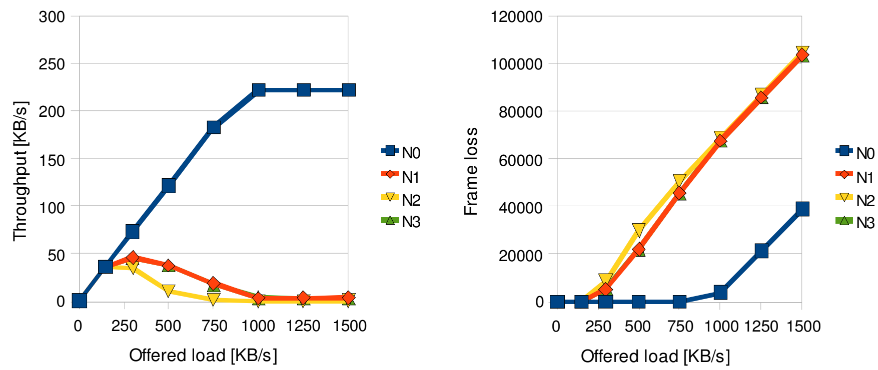


Fig. 2. 4-node ring (N0=P3, others =P0, RTS on): (a) throughput (b) frame loss.

3.2.2. 4-node Ring, N0=P0, Others=P3

As can be seen in Figure 3a, fairness among nodes considerably improves in this configuration and, in general, the order of the throughput levels is in line with EDCA guidelines. N0 sending traffic with P0 wins the competition for the channel access most frequently and loses the smallest number of frames (Figure 3). Additionally, N1-

N3 have similar throughput values (Figure 3a) and lose practically the same number of frames (Figure 3b). The slight difference between N2 and N1/N3 is caused by the fact that N2 is hidden from the high priority N0 and, therefore, it experiences more RTS collisions. Additionally, N2, after its unsuccessful transmissions, defers from medium access for a longer time (it has meaningfully larger backoff values than N0, c.f., Table 1) giving N0 the possibility of uninterrupted transmission. The fact that N1 and N3 are hidden from each other causes them to achieve smaller throughput than they would have if they were not hidden. However, due to their large CWmax values the probability of a collision is definitely smaller than in the previous configuration. As a consequence, the smaller values of throughput under saturation may be explained by the fact that N0 wins the channel most often and blocks the two nodes' transmissions.

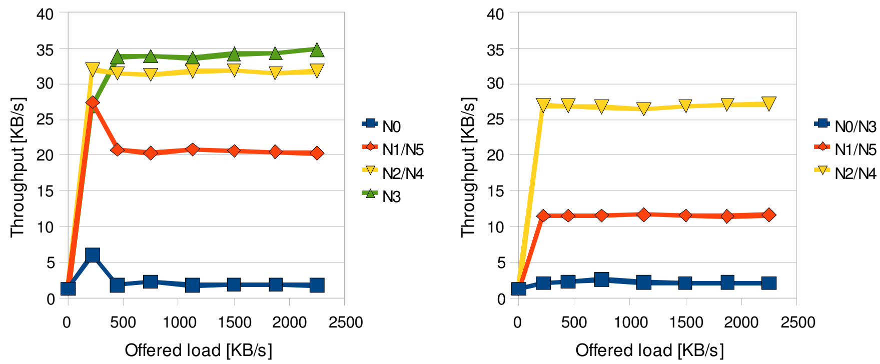


(a) (b)

Fig. 3. 4-node ring (N0=P0, others =P3, RTS on): (a) throughput (b) frame loss.

3.2.3. 6-node Ring, N0=P3, Others=P0

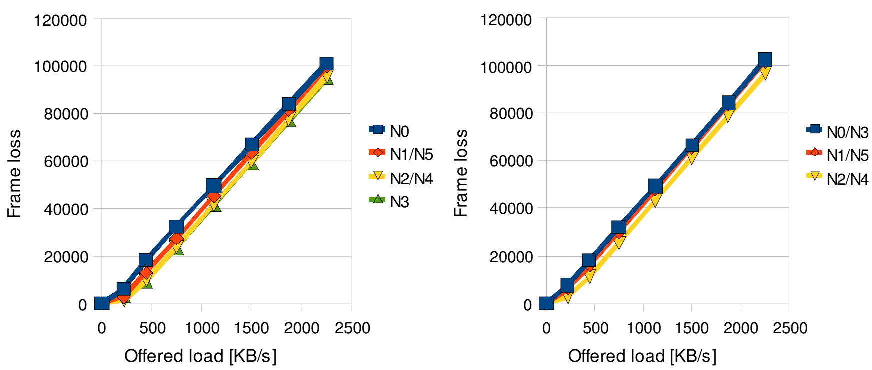
The behavior of a 6-node ring network is considerably different from that of a 4-node ring. First of all, when P3 is assigned to N0, the network performs differently when RTS/CTS is enabled (Figure 4a) and differently when it is disabled (Figure 4b). The main change between the two cases is the behavior of N3. In Figure 4a it achieves the highest throughput and in Figure 4b the lowest (together with N0). This is caused by the fact that if the RTS/CTS exchange is enabled the probability of a collision of frames originating from N3 and either N1 or N5 (i.e., nodes hidden from N3) is greatly decreased in comparison to RTS/CTS disabled. The differences in throughput obtained by the pairs of nodes N1/N5 and N2/N4 can be explained by the fact that the first pair of nodes is hidden from the high priority N3 and the second – from the low priority N0. Clearly, the throughput of N0 is an obvious consequence of its low priority.



(a) (b)

Fig. 4. 6-node ring. Throughput (N0=P3, others =P0): (a) RTS on (b) RTS off.

If we look, however, at the overall number of the lost frames (Figure 5) we hardly see any difference between the two cases. The reason for this situation is low utilization of links caused by numerous collisions of frames. They are a result of the dominance of P0 traffic in this configuration, as well as, the hiddenness of the nodes.



(a) (b)

Fig. 5. 6-node ring. Frame loss (N0=P3, others =P0): (a) RTS on (b) RTS off.

3.2.4. 6-node Ring, N0=P0, Others=P3

The behavior of the next of the analyzed configurations is again unsatisfactory. It is partially similar to the behavior of the correspondent 4-ring network because N0 obtains the highest throughput. The main difference between the two networks is that nodes placed opposite to N0 swap their positions, i.e., in the 4-node ring N2 has the smallest throughput, and in the six-node ring N3 has the highest throughput amongst the low priority nodes (c.f., Figure 3a and Figure 6a). The numbers of the lost frames given in Figure 6b can be explained by the following reasons. First of all, N1 and N5 have hardly any chance to send data because they are either blocked by N0/N2 or N0/N4, respectively. As a consequence, N1 and N5 also have a large number of IFQ drops. Secondly, low priority N2 and N4 collide with high priority N0 and, therefore, they experience a maximum number of RETRY drops. N0 does not have such a large number of RETRY drops because of its priority, which provides more possibilities for an uninterrupted transmission. Finally, N3 collides mostly with N1 and N5 but, as it was mentioned, they hardly send any traffic. Obviously, N3 has more IFQ drops than N0 due to its lower traffic class.

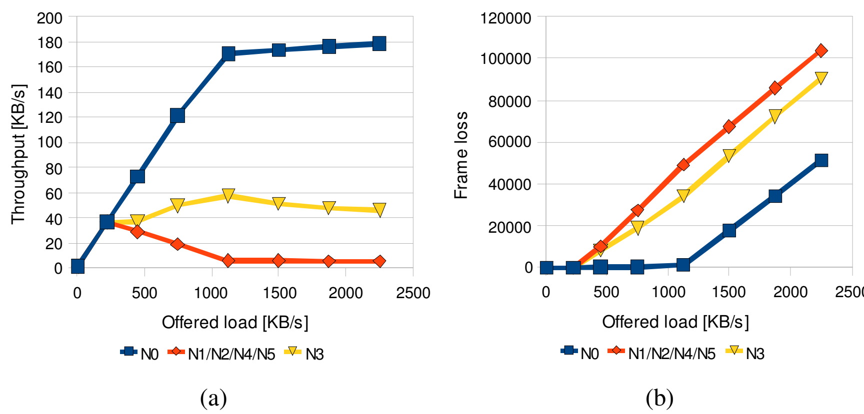
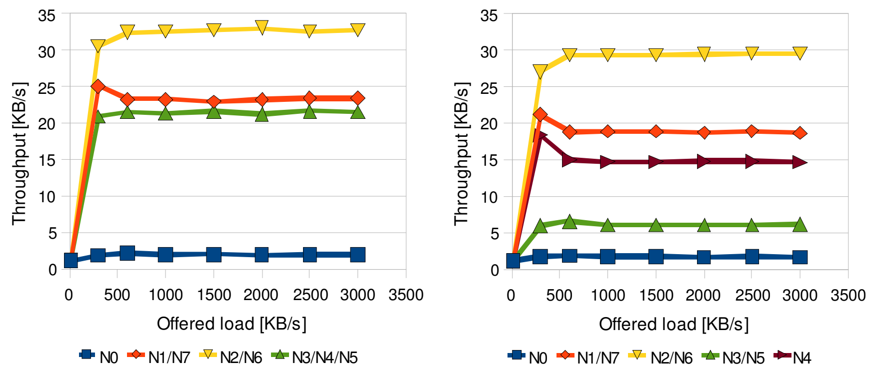


Fig. 6. 6-node ring. (N0=P0, others =P3, RTS on): (a) throughput (b) frame loss.

3.2.5. 8-node Ring, N0=P3, Others=P0

The next of the analyzed configurations was the 8-node ring network in which N0 had P3 assigned and the other nodes had P0. Similarly to subsection 3.2.3, there is a strong difference in the throughput values obtained for RTS/CTS enabled and disabled (Figure 7). The main difference is the performance of N3 and N5. Namely, with RTS/CTS disabled their throughput is four times lower. The explanation is similar as for N3 from the 6-node ring. Other similarities to the 6-node ring are the following: N2/N6 behave similarly to N2/N4 and N1/N7 behave similarly to N1/N5. The behavior of N4 needs, however, to be explained. In the case of RTS/CTS enabled it is in a similar situation as N3/N5. It competes for medium access with high priority nodes and may collide with two other high priority nodes. Additionally, the usage of the RTS and CTS frames minimizes the overall number of collisions. Therefore, the throughput of N3/N4/N5 does not differ much. When the RTS/CTS exchange is disabled, however, the placement of N4 seems much better than that of N3 and N5. N3/N5 compete with the four most privileged nodes (N1/N2/N6/N7), therefore, their throughput drops considerably. As a consequence, N4 competes with the privileged N2/N6 and the harmed N3/N5.

The authors find no sense in presenting figures with frame loss because, similarly to the correspondent 6-node network, there is practically no difference between the numbers of drops for different nodes in both presented cases. The reason for this situation is once again related to low link utilization.



(a) (b)

Fig. 7. 8-node ring. Throughput (N0=P3, others =P0): (a) RTS on (b) RTS off.

3.2.6. 8-node Ring, N0=P0, Others=P3

The final configuration was the 8-node ring in which N0 had P0 assigned and the other nodes had P3. The explanation of the throughput values obtained by N0/N1/N2/N6/N7 (Figure 8) is the same as for N0/N1/N2/N4/N5 in the correspondent 6-node ring, therefore, it will not be repeated here.

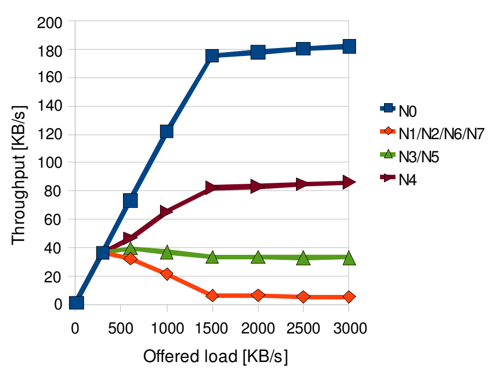


Fig. 8. 8-node ring. Throughput (N0=P0, others =P3): RTS on.

However, the difference between N4 and N3/N5 needs further explanation. Due to the exposedness and hiddenness of N2/N6, they send hardly any data. They are either blocked by N1 and N7, respectively, or defer their transmissions after colliding with the frequently transmitted, high priority N0 frames. As a result, they rarely collide with N4 and, additionally, they give more possibilities to N3/N5 to compete for the medium. On this basis, we could expect that N3/N4/N5 will obtain the same throughput, since they have the same priority. However, when N3 and N5 send DATA to N2 and N6, respectively, there is a high probability that their frames will collide with the acknowledgements of frames originating from N0. This causes a visible drop of the throughput values of N3/N5 in comparison to N4.

In order to make a comparison between the two analyzed simulation scenarios, the authors computed the approximate values of the overall saturation throughput for each configuration with mixed priorities. They are given in Table 3. As can be seen, similarly to the configurations with the same priorities, also this time it is better to turn the RTS/CTS exchange on if most nodes send P0 traffic, and turn RTS/CTS off if most nodes send P3 traffic. Additionally, it is noticeable that the overall bandwidth utilization is poor, however, in general it is better than for the configurations with the same priorities of nodes.

Table 4. Overall saturation throughput given in KB/s.

Network	**N0=P3, others=P0**		**N0=P0, others=P3**	
	RTS on	**RTS off**	**RTS on**	**RTS off**
4-node ring	404	372	458	552
5-node ring	230	212	432	500
6-node ring	278	162	496	704
7-node ring	312	246	600	800
8-node ring	354	250	712	880

4 Conclusions

This paper presents a simulation study of five ring topology networks which use EDCA as the medium access procedure. The problems caused by the hidden and exposed nodes are commented in details.

The general conclusions are as follows. Most of all, strong unfairness is noticeable for configurations with mixed priorities. Additionally, in a four-node ring with P0 traffic and RTS/CTS disabled, nodes cannot send any traffic. Furthermore, in all analyzed networks, the general throughput values are very small due to the unacceptably high number of collisions. Moreover, the four-way handshake mechanism does not significantly improve the performance of the ring topology networks. As an obvious consequence, high priority traffic cannot be properly served by current ad-hoc networks.

In the first phase of tests the four EDCA access categories were analyzed separately. In all configurations, nodes obtain practically the same, low throughput. The RTS/CTS exchange improves the overall throughput values for P0 traffic. For P3 traffic it is better to turn the mechanism off. Additionally, due to the similar performance of the 6-, 7- and 8-node networks it may be expected that larger ring networks will behave similarly.

In the second phase of tests, networks with mixed priorities were analyzed. Figure 9 shows the general prioritization patterns for these configurations. As it was mentioned, the 5-node ring behaves similarly to the 6-node ring and the 7-node ring behaves similarly to the 8-node ring. They were included in the figure only to confirm this similarity.

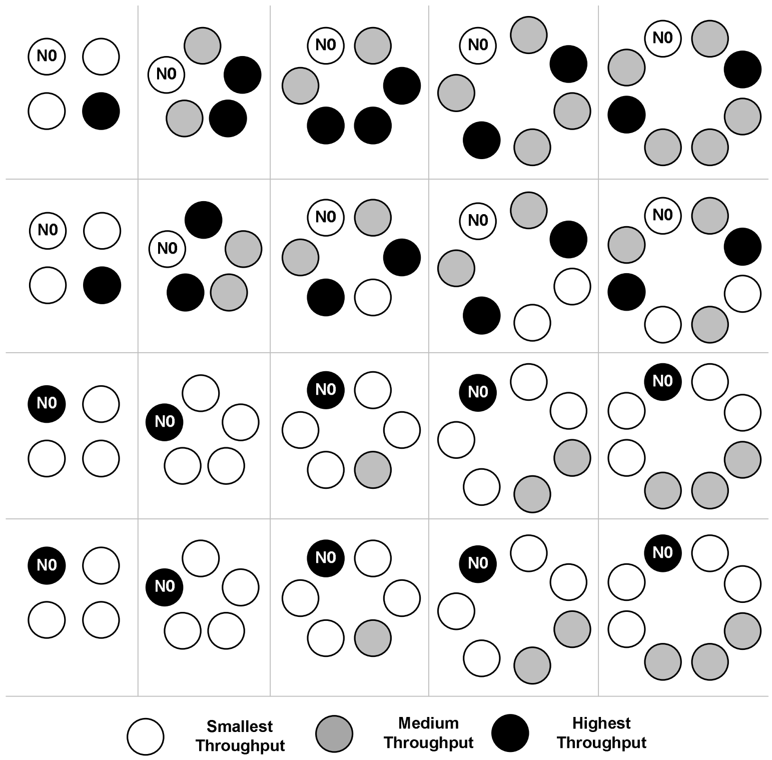


Fig. 9. General prioritization pattern. 1st row — N0=P3, RTS on; 2nd row — N0=P3, RTS off; 3rd row — N0=P0, RTS on; 4th row — N0=P0, RTS off.

As can be seen in Figure 9, practically in all configurations strong unfairness in granting medium access appears. This unfairness is visibly dependent on the number and the placement of nodes in each network. In general, it is noticeable that configurations with N0 set to P3 perform worse than those with P0. Additionally, similarly to configurations with the same priorities, it appears that is better to turn RTS/CTS on when P0 traffic is dominant in a particular network and turn it off for dominant P3 traffic. However, in all analyzed configurations, the overall bandwidth utilization is unacceptably low, regardless of the priorities or the configuration of RTS/CTS.

To the authors' surprise ring topology networks behave considerably different than line and star topologies ([5][6][7]). The main differences are the following. Only ring topology networks assure fairness in configurations with the same priorities.

However, in most cases, the overall throughput value of P0 traffic is lower for ring networks than for the other topologies. Furthermore, the star and line topologies are not able to assure fairness between nodes for both configurations, i.e., with mixed and same priorities of nodes. In the star topology, it is the middle, unhidden node which wins the channel access most often. All hidden nodes are severely harmed, especially when two or more of them have high priorities (their throughput drops to zero). For line topologies the prioritization pattern differs and is dependent on the network type. Another meaningful difference is that in the case of ring topology networks the order of the EDCA priorities is not swapped, even if the priorities are mixed. For both the line and star topologies, such behavior is very frequent. There are, however, several similarities as well. They are the following. In all topologies, significant unfairness in medium access appears for configurations with mixed priorities. Additionally, in the scenarios in which most nodes send P0 traffic, the overall throughput values are worse than these for the scenarios in which most nodes send P3 traffic. Furthermore, in the majority of the analyzed cases, turning the RTS/CTS exchange on does not eliminate the unfairness between nodes, though, it may slightly improve the performance of the harmed nodes, especially these with P0.

On the basis of the conclusions given above, the authors find it crucial to propose a novel MAC layer QoS mechanism. Therefore, their current work is focused on finding ways to detect hidden and exposed nodes, optimize the EDCA access parameters, and perform precise MAC layer measurements. These steps are needed in the process of creating a new MAC layer protocol which will, ideally, outperform the current EDCA and will be easy to implement in wireless devices.

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