BusySiMOn - a New Protocol for IEEE 802.11 EDCA-Based Ad-Hoc Networks with Hidden Nodes
Katarzyna Kosek-Szott, Student Member, IEEE, Marek Natkaniec, Member, IEEE, Andrzej R. Pach, Member, IEEE

Abstract—This article presents a new MAC layer protocol for IEEE 802.11 EDCA-based ad-hoc networks with hidden nodes. The key idea of the proposed solution is based on an intelligent two-step reservation procedure which is combined with the advantages of EDCA service differentiation. The new protocol achieves significant performance improvement for high priority traffic (e.g., Voice) in terms of fairness, throughput and average frame delay. It is also compatible with the IEEE 802.11 standard. The obtained results emphasize the advantages of the new protocol over the currently used four-way handshake mechanism.

Index Terms—EDCA, Hidden Nodes, MAC Protocol, QoS

I. INTRODUCTION

The IEEE 802.11 standard is currently one of the most popular wireless access technologies. It allows for quick and simple configuration of local broadband networks and greatly facilitates Internet access. With the growth of the popularity of IEEE 802.11, the number of available services also increased and the need for Quality of Service (QoS) provisioning became apparent. As a remedy to this problem, the Enhanced Distributed Channel Access (EDCA) function of the IEEE 802.11 standard was proposed [1].

Unfortunately, the IEEE 802.11 standard has a serious disadvantage. Due to the half-duplex nature of the wireless devices hidden nodes may appear within a wireless system. As a result, in a network with hidden nodes not only the overall throughput value may greatly decrease but also EDCA service differentiation and fairness among the nodes may be strongly deteriorated [5].

A number of MAC layer protocols trying to address the problem of hidden nodes have been proposed in the literature. Exemplary solutions are presented in Table I. As can be noticed, the majority of protocols rely on RTS/CTS-based or similar frame exchanges during the channel reservation process. All presented solutions can be divided into five major protocol types: contention-based, multi-channel, busy tone-based, energy-efficient and directional antenna-based. The most important advantages and disadvantages of each protocol type are presented in Table II. Among all available solutions, only the legacy four-way handshake mechanism has become broadly used and implemented in wireless devices. Currently it is the only mechanism recommended by the IEEE 802.11 standard to minimize the negative effects caused by hidden nodes. Unfortunately, as it was shown in [5], its effectiveness is insufficient to provide appropriate service differentiation in EDCA-based ad-hoc networks.

In this article we propose Busy Signal-based Mechanism turned On (BusySiMOn) — a new MAC layer protocol which combines smart reservation of the wireless channel with the advantages of EDCA service differentiation. The proposed approach remarkably improves QoS provisioning in IEEE 802.11 ad-hoc networks with hidden nodes in terms of throughput, average frame delay and fairness among the nodes. It also assures compatibility with the IEEE 802.11 standard.

The outline of this article is the following. Firstly, we describe EDCA and BusySiMOn. Then, we provide the simulation scenario which evaluates the performance of the proposed protocol and shows its advantages over the four-way handshake mechanism. Finally, we devote a section to our conclusions.

II. IEEE 802.11 EDCA

In networks with heterogeneous traffic the QoS requirements of each service should be carefully taken into account. In particular, in the case of simultaneous transmissions of voice and data traffic the delay constraints of the voice service should be primarily met. To achieve this goal voice traffic should have certain priority over data traffic. Within wireless ad-hoc networks it is the EDCA function of the IEEE 802.11 standard which was designed to satisfy this requirement.

The EDCA function defines several QoS enhancements to the legacy IEEE 802.11 DCF which are based on the idea of Access Categories (ACs). Four ACs (priorities) are defined: Voice, Video, Best Effort, and Background. To provide traffic differentiation each AC has a different set of the following medium access parameters: the contention window minimum ($CW_{min}$) and maximum ($CW_{max}$) size, the arbitration interframe space number ($AIFSN$), and the transmission opportunity limit ($TXOP_{lim}$). The functions of the access parameters are as follows. $CW_{min}[AC]$ and $CW_{max}[AC]$ determine the number of Backoff slots:

$$Backoff[AC] = \begin{cases} 0, & \text{if } CW_{min}[AC] = 0 \\ \text{random}\left(2^k(CW_{min}[AC] + 1) - 1, CW_{max}[AC]\right) & \text{otherwise} \end{cases}$$

where $k$ is the number of collisions occurred to the currently transmitted frame. $AIFSN[AC]$ determines the minimum time interval before a frame transmission may begin:

$$AIFS[AC] = AIFSN[AC] \times T_e + SIFS$$

K. Kosek-Szott, M. Natkaniec and A. R. Pach are with the Department of Telecommunications, AGH University of Science and Technology, Krakow, Poland. E-mail: {kosek, natkaniec, pach}@kt.agh.edu.pl
where $T_e$ is the duration of a single slot time. $TXOFLimit[AC]$ allows for the consecutive transmissions of several frames after gaining channel access, known as contention free bursting. This parameter is optional.

In the literature there are a number of articles which describe the advantages of EDCA traffic differentiation. Most of the studies, however, consider systems without hidden nodes. In [4] it has been proven for the first time that EDCA tends to cease to function in environments with hidden nodes. In particular, it has been shown that:

- Unhidden nodes are generally favored over hidden nodes in the channel access, regardless of their access category.

This may lead to situations in which low priority traffic (e.g., Background) transmitted by an unknown node receives better service than high priority traffic (e.g., Voice) generated by a hidden node.

- The four-way handshake mechanism may sometimes improve the throughput values achieved by the hidden nodes, however, it does not completely eliminate the unfairness in granting medium access.

- The higher the priority of traffic transmitted by hidden nodes the more collisions occur, even if the four-way handshake is used.

All these observations were also confirmed in [5]. Therefore, it became obvious that a new MAC protocol is required to meet the severe demands of high priority traffic (Voice and
III. BusySiMON

The key idea of the proposed MAC protocol is to minimize the probability of collisions of the signaling data within wireless systems with hidden nodes. To achieve this goal we propose a new channel reservation procedure consisting of the following two steps which are depicted in Figure 1:

1) Preliminary reservation of the wireless channel using two busy tone signals (Busy 1 and Busy 2). Both signals are very short — Busy 1 has the length of one slot time period (STP) and Busy 2 has the length of three STPs. Therefore, the preliminary channel reservation can be done very quickly. The lengths of the busy tone signals are distinguished in order to avoid the problem of mistaking Busy 1 for Busy 2 and vice versa.

2) Distributing information about the transmission duration as well as the source and destination node addresses with the use of the legacy RTS and CTS frames.

The proposed intelligent reservation of the wireless channel allows to minimize the probability of collisions of signaling data which happen when the four-way handshake mechanism is used.

The length of Busy 2 is set to three STPs in order to minimize the risk of mistaking consecutive transmissions of Busy 1 tones for Busy 2. An exemplary scenario in which three Busy 1 tones transmitted by hidden nodes are mistaken for Busy 2 is presented in Figure 2. For this scenario we can assume saturation conditions and that the Backoff is chosen from the range [0, 7]. Then, with the use of simple probability analysis, we can calculate the probability of misleading the unhidden node. It is equal to 0.38 and 0.05 for a Busy 2 length of two and three STPs, respectively. This relation is preserved in scenarios with a different number of hidden nodes and in the case of other Backoff ranges. Therefore, it is better to set the length of Busy 2 to three STPs. The gain of using longer Busy 2 tones is negligible.

The problem of traffic prioritisation is resolved in BusySiMON by the combination of the proposed reservation mechanism with the unchanged EDCA access parameters (c.f., Figure 1).

IV. Effectiveness of Channel Reservation

In the case of the legacy RTS/CTS-based channel reservation three types of collisions may happen — collisions of RTS with either another RTS, CTS or DATA. They are common even for the simplest line topology depicted in Figure 3. In the first scenario two RTS frames sent by the hidden nodes collide with each other. After the collision is detected they have to be re-transmitted after a random Backoff time. The number of possible retransmissions is limited to the Short Retry Limit defined by the IEEE 802.11 standard. It is worth noting that due to the low sending rate of RTS frames (1 Mb/s for HR/DSSS) hidden nodes do not have to simultaneously start their RTS transmissions to cause a collision. In the second scenario, node N1 positively reserves the wireless channel with the use of the RTS/CTS exchange. At the same time, however, the RTS frame sent by N3 collides with the CTS frame sent by N2. Obviously, after a random Backoff time, N3 will try to resend its RTS frame. If the Backoff value will be small enough, the resent RTS frame will collide with the DATA frame currently being transmitted by N1. As a result, N1 will have to resend its DATA frame.

Fig. 2. Overlapping of busy tones

For a given Backoff stage, with the use of simple probability analysis, we can compute the lower bound of the probability
of a successful channel reservation by either of the two hidden nodes \( p_{s_H}^{H,RTS} \) in the first scenario:

\[
p_{s_H}^{H,RTS} = \max \left[ 0; \frac{(\max[CW] - T_{RTS})(\max[CW] - T_{RTS} + 1)}{2(\max[CW] + 1)^2} \right]
\]

where \( \max[CW] \) is the maximum possible size of the current contention window and \( T_{RTS} \) is the time required to send the RTS frame (together with its PLCP header and preamble). Both values are given in STPs.

If BusySiMOn was used to reserve the wireless channel the probability \( p_{s_H}^{H,Busy1} \) would be the following:

\[
p_{s_H}^{H,Busy1} = \max \left[ 0; \frac{(\max[CW] - T_{Busy1})(\max[CW] - T_{Busy1} + 1)}{2(\max[CW] + 1)^2} \right]
\]

where \( T_{Busy1} \) is the number of STPs required to send the Busy 1 signal, which is equal to one.

The evaluation has been done in terms of throughput, collision domain for different values of per flow offered load.

### Table III

<table>
<thead>
<tr>
<th>PHY</th>
<th>PLCP Header and Preamble [µs]</th>
<th>Slot time [µs]</th>
<th>Lowest TX rate [Mbps]</th>
<th>( \max[CW] ) [STP]</th>
<th>( T_{RTS} ) [STP]</th>
<th>( H,RTS )</th>
<th>( p_s^{H,RTS} )</th>
<th>( T_{Busy1} ) [STP]</th>
<th>( H,Busy1 )</th>
<th>( p_s^{H,Busy1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSSS</td>
<td>192</td>
<td>20</td>
<td>1</td>
<td>15 31 1023</td>
<td>17.60</td>
<td>0.00</td>
<td>1.00</td>
<td>0.00</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>OFDM</td>
<td>20 or 40 or 80</td>
<td>9 or 13 or 21</td>
<td>6</td>
<td>7 15 31 1023</td>
<td>5.19 or 5.13 or 5.08</td>
<td>0.04</td>
<td>0.34</td>
<td>1.00</td>
<td>0.41</td>
<td></td>
</tr>
</tbody>
</table>

### V. Compatibility with EDCA

BusySiMOn is compatible with EDCA because it does not change the values of the channel access parameters defined by the IEEE 802.11 standard. Furthermore, because the RTS/CTS/DATA/ACK exchange is part of the proposed protocol, each node implementing BusySiMOn is able to respond to legacy IEEE 802.11 nodes. Additionally, if a BusySiMOn node wants to communicate with a legacy node it must have at least one other BusySiMOn neighbor. In Figure 4 Nodes A and B implement BusySiMOn and Node C is a legacy node. After Node B broadcasts Busy 1 to all nodes within its range, Node A sends Busy 2 in response. This allows Node B to communicate with Node C using the traditional RTS/CTS/DATA/ACK exchange.

### VI. Simulation Study

Simulation results were gathered from the ns-2 simulator patched with a considerably improved version of the TKN EDCA extension [2]. The wireless channel introduced no errors. Table IV contains the major parameters selected for the simulations. As can be noticed, HR/DSSS (commonly known as IEEE 802.11b) was chosen as the PHY layer, although BusySiMOn can be applied to any other 802.11 PHY. The general conclusions presented in this section remain the same regardless of the chosen PHY. The EDCA parameters were set as defined by the IEEE 802.11 standard [1]. \( TXOP_{Limit} \) was set to zero to avoid contention free bursting.

The performance of the new protocol has been evaluated in an exemplary wireless ad-hoc network presented in Figure 5, in which N0 is the only unhidden node. Nodes N1, N2 and N3 are hidden from N4, N5 and N6 and vice versa.

The evaluation has been done in terms of throughput, average frame delay and fairness obtained within a single collision domain for different values of per flow offered load.
A collision domain is defined as a single carrier sensing range. In Figure 5 there are four flows in each of the two collision domains. The per flow offered load is the total number of bits generated by a single node for a single flow per time unit (second). Throughput is defined as the ratio of the number of correctly received bits per time unit. In the results presented in this section both the average per node throughput and the overall (per collision) throughput are considered. The average frame delay is the average time of a successful transmission, measured from the frame generation at the source node until its successful reception at the destination node. This is computed separately for each simulated AC. The fairness is defined as the Jain’s fairness index which is given by the following equation

\[
Fairness = \left( \frac{\sum x_i}{n \sum x_i^2} \right)^2
\]

where \(x_i\) is the average throughput of the \(i\)-th flow and \(n\) is the number of flows with the same AC.

From the list of available MAC protocols for networks with hidden nodes (Table I) we have chosen only the four-way handshake in our comparison. This is because, as it was already mentioned, the RTS/CTS exchange is the only solution implemented in wireless drivers which is recommended by IEEE 802.11 to be used in environments with hidden nodes.

Two different scenarios were considered. In the first scenario, the efficiency of three different medium access methods (EDCA without RTS/CTS, EDCA with RTS/CTS and BusySIMOn) was compared under saturation. Each hidden node generated a load of 2.5 Mb/s. The unhidden node generated a load of 5 Mb/s (2.5 Mb/s in each collision domain). In the second scenario, the maximum values of possible network load were found under which the wireless network was not yet saturated. This was done separately for BusySIMOn and EDCA with RTS/CTS. Then, the two protocols were compared with regard to the overall throughput and the average frame delay obtained for the found values of the network load. Additionally, in order to determine whether the ad-hoc nodes transmitting traffic with the same AC receive a fair share of the wireless channel resources, the Jain’s fairness index was computed for both scenarios.

A. Saturated Network Conditions

The results obtained for the first scenario are presented in the upper half of Table V. The table contains the comparison of the efficiency of three different MAC protocols in four different configurations.

In the first two configurations, all nodes transmitted flows with the same AC — Voice and Background, respectively. For Voice traffic the highest overall throughput and the best fairness is achieved for BusySIMOn. For Background traffic the overall throughput achieved with the use of the new protocol is slightly worse in comparison with EDCA. On the other hand, the fairness of the new protocol is almost two times better.

In the next two configurations the traffic flows of the hidden nodes were assigned ACs opposite to that of the unhidden node. When the hidden nodes transmitted Background traffic, the performance of BusySIMOn was four times better than the performance of the four-way handshake mechanism and over 12,000 times better than the performance of pure EDCA. When the hidden nodes transmitted V oice traffic, the performance of the new protocol was practically the same as the performance of EDCA with RTS/CTS.

In summary, BusySIMOn assures fairness among all ad-hoc nodes under saturation. Therefore, it eliminates the problem of prioritizing unhidden nodes over hidden nodes described in [5].

B. Unsaturated Network Conditions

So far, it has been shown that BusySIMOn outperforms the four-way handshake with respect to the fairness among the nodes and improves the throughput of the hidden nodes. However, for delay-sensitive traffic it is the average frame delay which is the most important constraint. The Voice service can tolerate a maximum frame delay of 150 ms, Video — 300 ms. For both services, frames with greater delay are dropped.

The lower half of Table V contains the comparison of the new protocol with the four-way handshake with respect to the delay constraint in four different configurations. The total offered load generated in the first and the third configuration was the maximum load under which the network was not yet saturated for BusySIMOn. The second and the fourth configuration considers the maximum load which did not cause saturation for EDCA with RTS/CTS. In each configuration
the new mechanism behaves better not only in terms of the average frame delay but also in terms of the offered load, fairness and the overall throughput. This means that with the use of BusySiMON the delay-sensitive traffic is provided with much better level of QoS than with the use of the four-way handshake mechanism.

VII. CONCLUSIONS

The article presents a new method of channel reservation for IEEE 802.11 EDCA-based ad-hoc networks with hidden nodes. The simulation results have demonstrated that the currently used four-way handshake mechanism is inefficient, especially for high priority flows transmitted by hidden nodes.

The key advantage of the new protocol is the minimized risk of collisions of signaling data during the preliminary wireless channel reservation, which results in increased channel efficiency, reduced average frame delay and improved fairness among the nodes. Additionally, the combination of the preliminary reservation procedure with the RTS/CTS exchange and the unchanged values of the EDCA access parameters assures compatibility with mechanisms implemented in current wireless devices.

It is worth mentioning that BusySiMON can be applied to more varied network configurations (involving all EDCA ACs). In each case its performance for the high priority traffic will outperform the performance of the four-way handshake mechanism.

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REFERENCES


