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A modified IEEE 802.11 MAC for optimizing broadcasting in wireless audio networks

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# 1 A Modified IEEE 802.11 MAC for Optimizing Broadcasting 2 in Wireless Audio Networks

3 Christos Chousidis<sup>1</sup> · Ioana Pisca<sup>2</sup> · Zhengwen Huang<sup>2</sup>

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## 6 Abstract

7 The use of network infrastructures to replace conventional professional audio sys-  
8 tems is a rapidly increasing field which is expected to play an important role within  
9 the professional audio industry. Currently, the market is dominated by numerous **AQ1**  
10 proprietary protocols which do not allow interoperability and do not promote the  
11 evolution of this sector. Recent standardization actions are intending to resolve this  
12 issue excluding, however, the use of wireless networks. Existing wireless network-  
13 ing technologies are considered unsuitable for supporting real-time audio networks,  
14 not because of lack of bandwidth but due to their inefficient congestion control  
15 mechanisms in broadcasting. In this paper, we propose an amendment of the IEEE  
16 802.11 MAC that improves the performance of the standard for real-time audio data  
17 delivery. The proposed amendment is offering a solution for the balancing of data  
18 flow density in wireless ad-hoc networks for a multi-broadcasting environment. It is  
19 based on two innovative ideas. First, it provides a protection mechanism for broad-  
20 casting and second, it replaces the classic congestion control mechanism, based in  
21 random backoff, with an alternative traffic adaptive algorithm, designed to mini-  
22 mize collisions. The proposed MAC is able to operate as an alternative mode allow-  
23 ing regular Wi-Fi networks to coexist and interoperate efficiently with audio net-  
24 works, with the last ones being able to be deployed over existing wireless network  
25 infrastructures.

26 **Keywords** Audio networks · Congestion control algorithm · CTS-to-Self · Exclusive  
27 backoff number allocation algorithm · H-EBNA · MAC modification · Wireless  
28 audio networks · Broadcasting

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# 1 Introduction

Today the rapid growth of networking technology, along with the dominance of digital audio, makes essential the implementation of audio networks in the majority of the professional audio applications. The term “audio networking” is introduced to describe the usage of a network infrastructure for the delivery of digital audio data, between audio sources and audio processing devices, within sound installations such as recording and broadcasting studios and live music stage systems. Often, audio networks are wrongly considered as networks for generic audio delivery. In reality, the term “Audio Networks” is used to describe dedicated networking infrastructures that are offering an alternative interconnection for audio systems in live-music scenarios. The concept of such an implementation is described in Fig. 1. This figure shows a live-music system that consists of several sound source, a mixing console, several audio processing units such as equalizers, audio compressors and reverb-ation processors, a set of stage monitor speakers and a main public address (PA) system.

These devices are interconnected over a local area network and can be considered as nodes that exchanges audio data.

In the past two decades the idea of using data networks for the delivery of audio information has been introduced and a plethora of standards and systems has been proposed with the majority of them based on the Ethernet protocol. [1]. As it is usual with new technologies that have a commercial interest, the

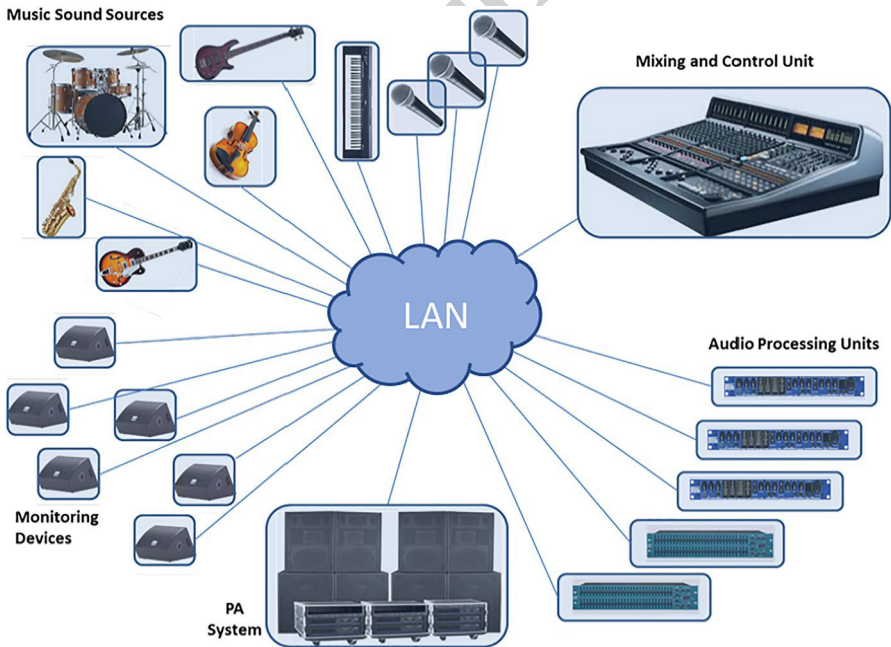


Fig. 1 The live-stage audio networking concept

50 lack of common practices and standards has led to the development of numerous  
51 proprietary systems lacking the ability to interact between each other. During  
52 the last years a standardization effort has been made in order to alleviate this  
53 problem [2]. An overview of the professional audio industry today, shows that  
54 audio networks are not widespread. This is significantly disproportionate to the  
55 general expansion of networking system in other technological fields and shows  
56 that significant progress can be made in this sector.

57 One of the key steps that is expected to help the evolution and spread of audio  
58 networks is their migration to the wireless domain. However, this requires wire-  
59 less networks that will be able to distribute data with a very low packet loss rate  
60 and delay. Moreover, they should be able to operate in a multi-broadcasting envi-  
61 ronment as each member in the network requires data from all other members.

62 The reliable multiple broadcasting of time sensitive data over wireless net-  
63 works has not been thoroughly investigated. Research in this field focuses mainly  
64 on the cross-layer optimization of single broadcasting streams [3, 4]. Authors  
65 in [5] propose a resource allocation solution that improves Quality of Service  
66 (QoS) for multimedia wireless transmission and it can be a practical solution for  
67 real-time wireless networks. However, this requires a wireless network with rela-  
68 tively high bandwidth. In [6], authors address the problem of delivering a single  
69 low-latency multimedia stream in a mobile ad-hoc environment by introducing  
70 a cross-layer congestion control strategy. The majority of the above described  
71 solutions, however, are video oriented. Authors in [7] present an optimization  
72 framework for transmitting high quality audio sequences over wireless links.  
73 Their effort however focuses on data encoding and it is a solution for low error  
74 audio delivery over hostile wireless environment.

75 In this paper we develop a custom solution specifically designed to cover the  
76 needs in throughput and latency in an audio multi-broadcasting environment.  
77 The proposed solution is based on two novel ideas. The first is the development  
78 of a protection mechanism in broadcasting, similar to the one that is used in  
79 IEEE 802.11 for unicast transmission. The second is the development of a traffic  
80 adaptive congestion control algorithm that takes into account the special charac-  
81 teristics of an audio network and is able to eliminate collisions for a finite num-  
82 ber of stations (STAs) in an ad-hoc network.

83 The rest of this paper is organized as follows. In section two, the problems  
84 that prevent the implementation of audio networks using existing wireless net-  
85 working technologies are analyzed. In section three, a novel collision protection  
86 mechanism for broadcasting in wireless networks is proposed. This method is  
87 tested for multi-broadcasting audio traffic and the results are presented and dis-  
88 cussed. In section four, the exclusive backoff number allocation (EBNA) concept  
89 is explained and simulated, and its advantages and disadvantages are thoroughly  
90 analyzed. In section five, a hybrid-EBNA method for optimal performance is  
91 proposed and the comparative results are analyzed and discussed. Finally, in sec-  
92 tion six the overall conclusions of this work are presented.

## 93 2 Defining the problem in Wireless Audio Networks

94 A white paper released by the technical committee on network audio systems  
95 (TC-NAC) of the Audio Engineering Society (AES) in 2009 [8] states that the  
96 audio networking sector will benefit from the adoption of wireless networking  
97 technologies, but it considers existing wireless protocols incapable of supporting  
98 this implementation.

99 However, it is evident that the successful development of wireless audio net-  
100 works must be based on existing commercial standards that will be able to pro-  
101 vide an efficient and inexpensive solution when it comes to hardware. The most  
102 appropriate candidate that fulfils the above requirement is the IEEE 802.11 stand-  
103 ard. IEEE 802.11 is a reliable standard that offers the necessary bandwidth for the  
104 delivery of a sufficient number of uncompressed audio channels for professional  
105 applications.

106 Audio networks are implemented in an area of few square meters and therefore  
107 there is always a good radio signal level and all nodes are in line-of-sight. Tak-  
108 ing this into account, the most efficient way to implement audio networks with  
109 multiple audio channels over IEEE 802.11 WLANs is to use an ad-hoc configu-  
110 ration and broadcasting as a delivery method. This is because all other methods  
111 require retransmission which is inappropriate for time sensitive data. However,  
112 the Medium Access Control (MAC) algorithm [9] that handles broadcasting over  
113 802.11 networks is not designed for the distribution of high-rate, time-sensitive  
114 media data. Broadcasting in IEEE 802.11 ad-hoc networks was initially designed  
115 for network control purposes. The reliable broadcasting of media data in IEEE  
116 802.11 networks is an interesting research area, nevertheless, the majority of the  
117 research related to this subject focuses in reliability issues rather than providing  
118 quality of service [10, 11, 12].

### 119 2.1 Drawbacks of Broadcasting in IEEE 802.11 networks

120 Broadcasting is the appropriate method of distributing media data as it can deliver  
121 data to multiple users with the minimum occupation of the wireless medium.  
122 However, due to the lack of a specific recipient, acknowledgment (ACK) tech-  
123 niques cannot be implemented and thus, broadcasting is unable to provide any  
124 kind of packet delivery guarantee. [13].

125 The medium access control in IEEE 802.11 networks is achieved by using the  
126 Carrier Sense Multiple Access, with Collision Avoidance mechanism (CSMA/  
127 CA). However, collisions cannot be totally avoided. In addition, due to the lack of  
128 a delivery report in the case of broadcasting, collided packets cannot be identified  
129 and recovered [14, 15].

130 The IEEE 802.11 MAC implements a probabilistic method of reducing colli-  
131 sions by assigning random waiting time intervals to all STAs that have a packet  
132 for transmission. The values of these waiting time intervals are drawn from a  
133 finite set of integers called Contention Window (CW). When a STA detects the

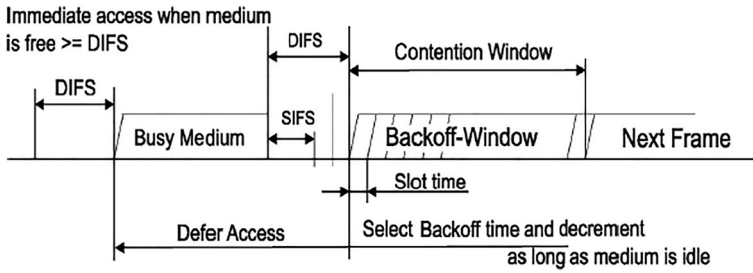


Fig. 2 IEEE 802.11 basic access method, (IEEE 802.11 Working Group, 2007)

134 wireless medium to be idle for a time frame equal to a DCF Inter-Frame Space  
 135 (DIFS) and it has a packet for transmission, the MAC algorithm assigns to it an  
 136 additional backoff time (Fig. 2) that is defined by Eq. 1.

137 
$$Backoff_{Time} = INT[CW \times Random(0, 1)] \times aSlotTim \quad (1)$$

138 Random (0, 1) is a pseudo-random number between 0 and 1, drawn using a uniform  
 139 distribution, and  $aSlotTime$  is a value defined by the protocol.

140 In a unicast transmission, when an ACK message is not received after the trans-  
 141 mission of a data packet, the CW increases exponentially, and a retransmission  
 142 attempt is performed. This process is repeated until the packet is successfully deliv-  
 143 ered or the CW reaches its maximum size. The CW is described by the  $CW_{min}$  and  
 144  $CW_{max}$  values and its size is defined from the relation  $CW_{values} = 2^x - 1$ . The initial  
 145 value of 'x' is an integer which is defined by the protocol and it can be increased up  
 146 to 10. That means that the maximum size of CW can be  $CW_{10} = 1023$ .

147 In the case of broadcasting, the size of CW remains constantly minimum as long  
 148 as the ACK technique cannot be implemented.

149 In addition to the above standard technique for the network's arbitration, the  
 150 optional technique of network allocation vector (NAV) can be also used. NAV is  
 151 a technique that distributes information related to the time that the medium will  
 152 be occupied by the STA that recently got access to it. This again, is implemented  
 153 only in unicast transmission and it is achieved by the exchange of Request-to-Send,  
 154 Clear-to-Send control messages (RTS/CTS). This is actually a dialogue between the  
 155 sender and the receiver that secures a reception readiness from the recipient's side.  
 156 Although this is a message exchange between two specific STAs, RTS and CTS are  
 157 broadcasting messages and the information they contain regarding the network's  
 158 allocation is distributed across the entire network. STAs that receive these messages  
 159 are deferring transmission for the designated time period, reducing this way the risk  
 160 of dropped and collided packets. When the transmission of a RTS is not possible,  
 161 an alternative CTS message sent from a STA with destination its own address, can  
 162 be used to distribute NAV information. This type of "blind" CTS message is called  
 163 CTS-to-Self. This method is used for collision protection from the IEEE 802.11  
 164 standard only for mixed-mode environments where extended rate physical (ERP-  
 165 802.11 g) and/or high throughput (HT-802.11n) STAs coexist with legacy 802.11  
 166 technologies [16].

167 The fact that in broadcasting ACK cannot be implemented results in the size of  
 168 CW being always its minimum value. When the number of broadcasting STAs in the  
 169 network increases, the probability of two or more STAs to select simultaneously the  
 170 same backoff number is also increased [17]. In an audio multiple-broadcasting environ-  
 171 ment the likelihood of experiencing this problem is even higher. This is because the  
 172 heavy payload created by audio data it forces STAs to intensively attempt access to the  
 173 wireless medium. In such a case a significant number of packets is lost as collisions in  
 174 broadcasting cannot be identified and collide packets cannot be recovered.

## 175 2.2 Collision probability in a multi-broadcasting environment

176 In broadcasting over 802.11 networks the CW remains always in its minimum size  
 177 ( $CW_{min}$ ). All STAs participating in a wireless audio network are constantly produc-  
 178 ing audio data as they meant to serve musicians within a group that play simultane-  
 179 ously. Therefore, all STAs within an audio network attempt constantly to access the  
 180 wireless medium [19]. When a STA finds the medium idle for a DIFS, its MAC  
 181 algorithm, following a uniform distribution, selects a random integer backoff time  
 182 within a sample space of  $[0-CW_{min}]$  and assigns this number to the backoff counter.  
 183 The backoff counter is decremented for every time slot that the medium is sensed  
 184 idle. If during this countdown the medium becomes busy, the countdown stops and  
 185 resumes whenever the medium becomes idle again. However, if two or more STAs  
 186 perform the backoff process concurrently and they select equal backoff numbers,  
 187 they will all reach zero and broadcast simultaneously causing, therefore, a collision  
 188 [19]. For the above scenario, the probability  $p_1$  of a STA to transmit in an arbitrary  
 189 slot will be:

$$190 \quad p_1 = \frac{1}{CW_{min}} \quad (2)$$

191 Therefore, the probability of a STA not to transmit in an arbitrary slot  $p_2$  is:

$$192 \quad p_2 = 1 - \frac{1}{CW_{min}} \quad (3)$$

193 If a network consists of  $n$  number of STAs and at an arbitrary slot the STA  $i$  is trans-  
 194 mitting, then the number of non-transmitting STAs in the network will be  $j=n-1$ .  
 195 In broadcasting over an ad-hoc network all attempt of accessing the medium are  
 196 independent events [20]. Taking also into account Eq. (3) and the product law of  
 197 independent events, the probability  $p_{2(j)}$  of no other STAs transmitting in this spe-  
 198 cific slot will be:

$$199 \quad p_{2(j)} = p_{2(1)} \times p_{2(2)} \times \dots \times p_{2(i-1)} \times p_{2(i+1)} \times \dots \times p_{2(n)} \quad (4)$$

$$200 \quad p_{2(j)} = \left(1 - \frac{1}{CW_{min}}\right)^{n-1}$$

201 Therefore, a collision will take place when one or more STAs will attempt to trans-  
 mit a packet during this slot and it can be expressed as follows:

202

$$p_{(collision)} = 1 - p_{2(j)} = 1 - \left(1 - \frac{1}{CW_{min}}\right)^{n-1} \quad (5)$$

203 From (5) it is shown that broadcasting in a saturated IEEE 802.11 ad-hoc network is  
204 affected only by the number of STAs in the network and the size of CW.

205 Plotting (5) in Fig. 3, we can see that the probability of collision in a multi-broad-  
206 casting environment reaches dramatically high values when the number of broadcast-  
207 ing STAs increases [21]. This is in reality the reason that IEEE 802.11 technologies  
208 cannot be used to implement wireless audio networks, despite the available bandwidth.

### 209 2.3 The modified IEEE 802.11 MAC algorithm

210 The aim of the amendment of the IEEE 802.11 MAC algorithm, proposed in this  
211 paper is to resolve the collision problem and thus to allow the implementation of  
212 this technology in wireless audio networks. This amendment consists of two core  
213 innovative ideas. The first one is to develop a protection mechanism for broadcasting  
214 and the second, to design an alternative congestion control mechanism that elimi-  
215 nates collisions. The above modifications are designed to work together and also to  
216 ensure the interoperability between the classic and modified MAC algorithm when  
217 they coexist in the same WLAN.

### 218 3 A collision protection mechanism for reliable broadcasting

219 The collision protection mechanism proposed in this work is based on the amended  
220 use of CTS-to-Self message. This is achieved by two key modifications.

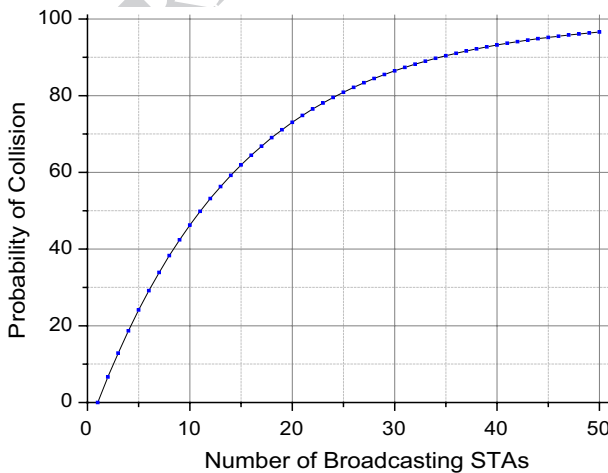


Fig. 3 Probability of collision in broadcasting, (CW = 15)

221 In the first modification, the congestion control algorithm was programmed to add  
 222 a CTS-to-Self transmission prior to each data packet transmission [22]. Therefore,  
 223 in this amended MAC, when a STA successfully completes the random backoff pro-  
 224 cess and gains access to the medium, it sends a CTS message with NAV information  
 225 to its own address. This informs the rest of the STAs for the time the network will  
 226 be occupied, in order to avoid unnecessary attempts to access it. In addition, when two  
 227 or more STAs complete their backoff process simultaneously, according to the case  
 228 described in section II-B, the inevitable collision will take place between the CTS-  
 229 to-Self messages rather than the data packets. This causes a significantly shorter jam  
 230 in the network (Fig. 4) and therefore increases throughput. In the case that no col-  
 231 lision occurs, the same STA regains immediately access to the network by waiting  
 232 only for a SIFS and successfully broadcasts the packet, following the procedures  
 233 described in the original IEEE 802.11 protocol.

234 In the second modification the content of the CTS-to-Self is also reprogrammed.  
 235 As it was mentioned earlier in this paper, this control message is originally used  
 236 for protection when legacy 802.11 technologies are identified in a network and it is  
 237 broadcasted using the lowest possible rates. In our case, the function that generates  
 238 this message is reprogrammed in order to always adjust with the current data packet  
 239 transmission rate, avoiding this way to slow down the entire wireless network.

### 240 3.1 CTS-to-Self modification (simulation and results)

241 This study is performed using OPNET Modeler 17.1. The simulation is based on  
 242 the IEEE 802.11g standard. The configuration of the network is ad-hoc and the bit  
 243 rate is set at 54 Mbps. The population of the network is dynamic, starting from 5  
 244 STA and gradually increasing to 60 STAs. The data in each STA are created using  
 245 a packet generator that produces a data rate of 256 Kbps. The final broadcasting

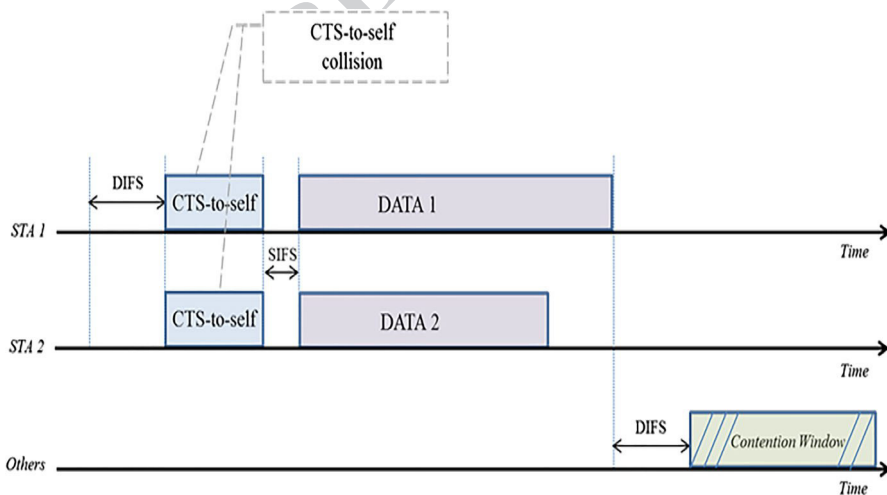


Fig. 4 CTS-to-Self collision

246 rate is measured to be 320 Kbps. This increase is caused by the MAC overhead.  
247 The network is considered saturated and the generation of data load remains constant  
248 in all scenarios. However, for each increase of the population three different  
249 scenarios are tested using variations of packet size. This is because, for a given  
250 data load, the packet size is directly affecting the number of attempts accessing  
251 the medium and therefore the number of additional CTS-to-Self messages that are  
252 broadcasted. The packet sizes used for this study are 2048, 1024 and 512 bytes.  
253 All simulations are performed with both the modified and the classic 802.11  
254 MAC, for comparison reasons. The collected statistics are:

- 255 • Throughput
- 256 • Number of Collisions per STA
- 257 • Overall End-to-End Delay

258 The results are analytically presented and discussed in [22]. Here we only  
259 present results for the 2048 bytes packet size, where we experience the higher  
260 throughput improvement. As it is shown in Fig. 5, a constant improvement of  
261 throughput is observed in all cases, when the modified 802.11MAC is used.

262 However, when the number of broadcasting STAs increases beyond 40, the  
263 modified MAC is able to handle this traffic, contrary to the classic 802.11 MAC  
264 which experiences significant data losses.

265 In Fig. 6 it is shown that the modified MAC causes an increase of the End-  
266 to-End delay which nevertheless remains in acceptable levels. This is expected,  
267 and it is caused by the additional traffic that enters in the network from the use of  
268 CTS-to-Self messages.

269 Figure 7 shows the average number of collisions per STA, as the number  
270 of STAs increases. We can see here that, although the number of collisions

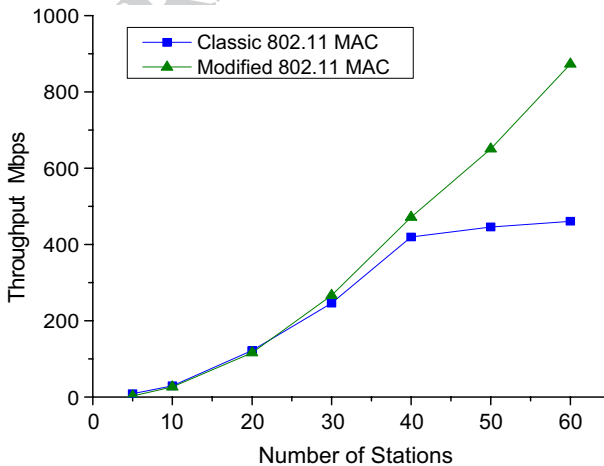


Fig. 5 Throughput performance for 2048 bytes, packet size

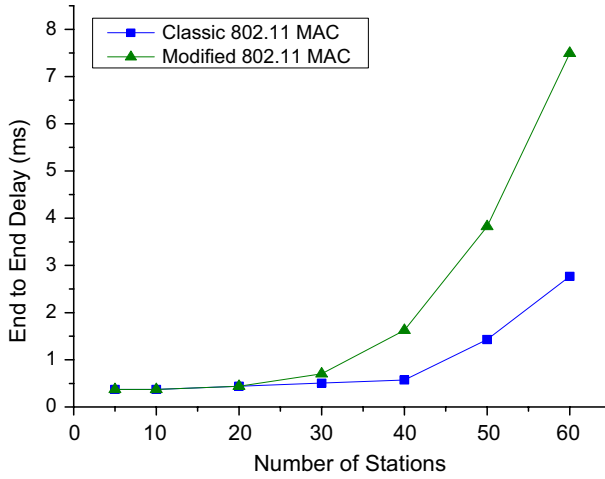


Fig. 6 End-to-end delay for 2048 bytes packet size

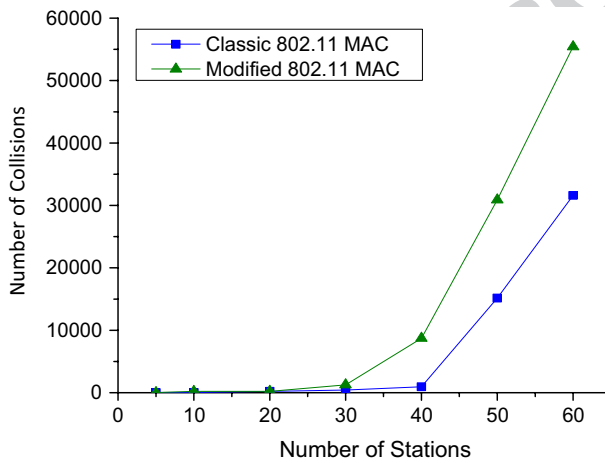


Fig. 7 Average number of collisions per STA for 2048 bytes packet size

271 increases, as the number of broadcasting STAs increases throughput performance  
272 also increases.

273 This is because most collision occurs between CTS-to-Self messages rather  
274 than data packets and, as it was mentioned earlier, this reduces the negative effect  
275 of collisions.

276 **4 The EBNA concept**

277 Using the collision protection mechanism proposed in section three we have a sig-  
 278 nificant decrement of collision rate. However, some collisions will always happen.  
 279 This is due to the nature of the congestion control mechanism of IEEE 802.11 stand-  
 280 ard, and most specifically to the random backoff process. In order to deal with this  
 281 issue, an alternative congestion control mechanism is proposed in this section. The  
 282 design of this mechanism is based on the fact that audio networks have by nature  
 283 some specific characteristics. These are mainly the finite and controllable population  
 284 of the STAs and also of the spatial limitations of the network.

285 The proposed mechanism replaces the random way that the backoff numbers are  
 286 assigned in broadcasting packets in the classic 802.11 MAC by assigning exclusive  
 287 pairs of numbers to different STAs in the network. The operating principle of this  
 288 Exclusive Backoff Number Allocation (EBNA) algorithm is described as follows:

289 Assume an ad-hoc network where each STA upon joining the network obtains a  
 290 STA ID (STID). Let us also assume that each STA knows the overall number of STAs  
 291 (*No\_of\_STAs*) in this network at any given time. In this case we define the size of the  
 292 CW as:



$$CW = 2 \times (No\_of\_STAs) \tag{6}$$

294 We also divide this CW in two groups according to the following rule:

$$group1 \leq \frac{No\_of\_STAs}{2} \tag{7}$$

$$group2 > \frac{No\_of\_STAs}{2} \tag{8}$$

297 When a STA has a packet to transmit and attempts to access the medium, the EBNA  
 298 algorithm assigns to a variable called GRP, a random value between 1 and 2 using  
 299 a uniform distribution. The purpose of this process is for the algorithm to randomly  
 300 select for the next steps one of the two groups defined in (7) and (8). When GRP=1,  
 301 the *group1* is selected and when GRP=2, the *group2* is selected. In the first case,  
 302 the algorithm assigns to the STA a backoff number equal to its STID. In the sec-  
 303 ond case the algorithm assigns to the STA a backoff number which is symmetrically

CW = 20  
 Number of STAs = 10  
 STID = 2   
 STID = 6 

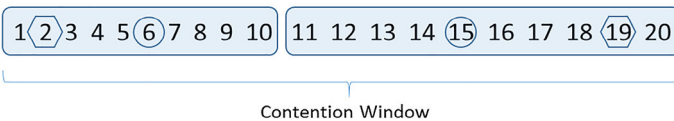
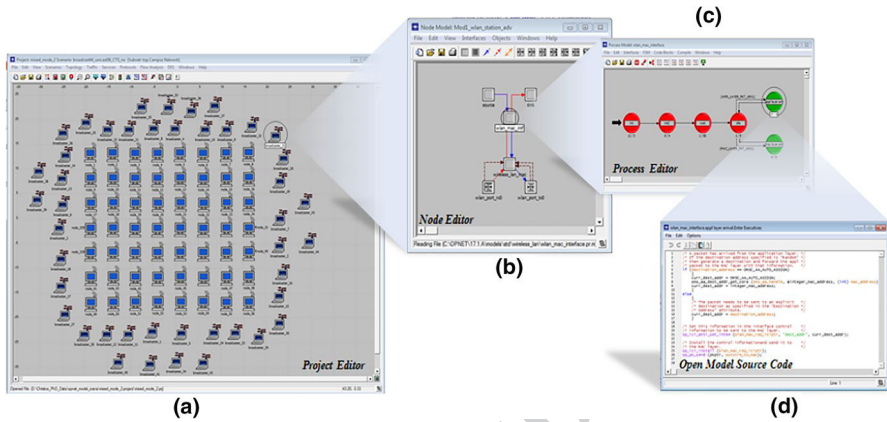


Fig. 8 The EBNA implementation, (an example for STID=2 and STID=6)

**Table 1** Traffic generation parameters

Attributes	Values
Start time	Normal distribution (1, 0.01)
On-state	0.25 s
Off-state	0.25 s
Interarrival time	Constant distribution (24.3 ms)
Packet size	2200 bytes



**Fig. 9** OPNET Modeler hierarchical architecture: A 56 audio STAs scenario, (a) project editor, (b) node editor, (c) process editor, (d) code editor)

304 opposite to its STID number within the CW, as it is shown in Fig. 8. As we can see,  
 305 in all cases a STA with a specific STID that tries to access the medium, will obtain  
 306 a backoff value which will randomly retrogress between a unique pair of numbers,  
 307 exclusively allocated to this STA. The allocation of backoff slots for each STA is  
 308 described in the algorithm below:

309 
$$\text{for } GRP = 1 \quad Backoff_{slots} = STID \tag{9}$$

310 
$$\text{for } GRP = 2 \quad Backoff_{slots} = [(No\_of\_STA) \times 2] - STID + 1 \tag{10}$$

311 Taking into account that this allocation is based on a uniform distribution and also  
 312 that the possible values of backoff slots are complimentary within the CW, this pro-  
 313 cess secures fairness in the network. The complimentary values of backoff slots  
 314 results on an equal average waiting time to all STAs, in the long run. For each STA,  
 315 the average number of backoff slots will be equal to CW/2, as it is shown in the  
 316 example in Fig. 8.

317 **4.1 EBNA (simulation and results)**

318 The simulation characteristics of the proposed EBNA algorithm are similar to  
 319 those described in section III-A. The ad-hoc network spans in a surface of  
 320  $30 \times 40$  m with the wireless STAs randomly located within it. The population of  
 321 the network is again dynamic, starting from 10 STAs and gradually increasing  
 322 to 70 STAs. The traffic generation parameters are defined in a generic “music  
 323 audio data traffic model” proposed in [23] and summarized in Table 1. This is a  
 324 stochastic model that emulates the audio data production from a music instrument  
 325 or singer based on normal distribution around the tempo of 120 bpm [24, 25].  
 326 OPNET Modeler 17.1 network simulation platform it is also used for this study.  
 327 Figure 9 provides a graphical representation of OPNET’s hierarchical architec-  
 328 ture for a 56 audio STAs scenario, with additional data STAs in the network. The  
 329 statistics collected during the simulation are Throughput and Overall End-to-End  
 330 Delay.

331 Before proceeding with the analysis of the results it is useful to clarify  
 332 throughput measurement in broadcasting. For this purpose, a wireless network  
 333 with  $n$  STAs where each of them produces a data load of  $A_i$  (bit/s) is assumed.  
 334 If we consider all transmissions to be successful over a period  $\Delta t$ , each STA will  
 335 finally receive during this period a total load  $T_{\Delta t}$  which is described by (11).

$$T_{\Delta t} = A_1 + A_2 + \dots + A_{i-1} + A_{i+1} + \dots + A_n = (n - 1) \times A_i \quad (11)$$

337 Equation (11) shows that a much higher overall throughput than the produced data  
 338 should be expected as every STA in the network receives all the data produced from  
 339 all other STAs except its own transmitted data. Having  $n$  STAs in the network, the  
 340 maximum theoretical throughput in the entire network  $\Sigma(T_{\Delta t})$  will be given by:

$$\Sigma(T_{\Delta t}) = \sum_{i=1}^n (n - 1)A_i = (n - 1) \sum_{i=1}^n A_i \quad (12)$$

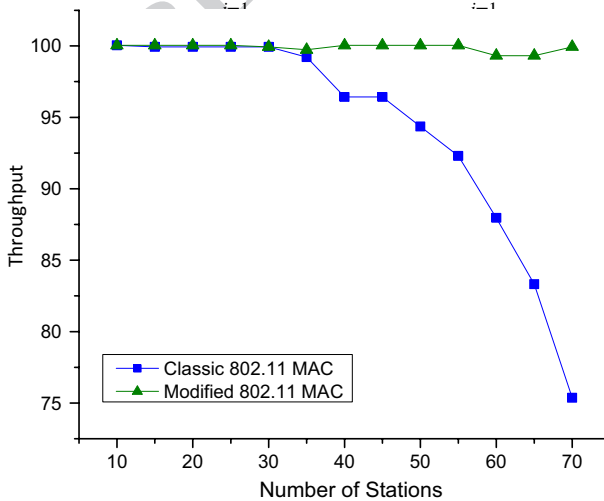


Fig. 10 Throughput performance, (Classic 802.11 vs. EBNA modified MAC)

Author Proof

342 If the data load  $A$ , that is produced from all STAs is equal, then Eq. (12) can be sim-  
 343 plified as follows:

$$344 \quad \Sigma(T_{\Delta t}) = n \times [(n - 1) \times A] \quad (13)$$

345 Equation (13) shows again that the actual throughput of the entire network, in case  
 346 of broadcasting, is higher than the overall broadcasted data load at any given time.

347 The graph in Fig. 10 shows a comparison between the classic and modified  
 348 IEEE 802.11 MAC as it is resulting from these simulations. It is clearly shown  
 349 that the EBNA modified congestion control mechanism is able to handle a vast  
 350 number of broadcasting STAs comparing to the classic 802.11 which causes a sig-  
 351 nificant number of collisions when the number of STAs in the network increases.

352 Figure 11 shows the overall end-to-end delay for both the EBNA modified and  
 353 the classic 802.11 MAC. It is shown here that by using the EBNA algorithm we  
 354 significantly increase the overall end-to-end delay in the network. This is due to two  
 355 main causes. First, it is because of the additional traffic added in the network by  
 356 using the CTS-to-Self protection mechanism, discussed in the previous section. Sec-  
 357 ond, it is because of the linear increase of CW window that results when the EBNA  
 358 algorithm is used.

359 When EBNA is applied, each increase on the network's population causes in turn  
 360 a linear increase of the CW as it shown from (6). A larger CW allows higher waiting  
 361 time values to be used and therefore increases delay.

362 This delay can be considered appropriate for media streaming but is marginally  
 363 acceptable for networks that require real time audio delivery. As it is resulting from  
 364 [26] and from the general audio engineering practices, an approximately 10 ms aver-  
 365 age delay would be required, for a 60 STAs scenario, in order for a wireless audio  
 366 network to be considered functional. Therefore, an improvement regarding delay

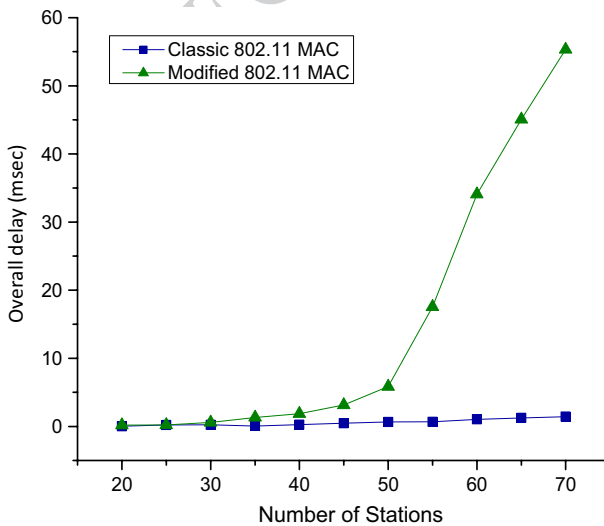


Fig. 11 Overall end-to-end delay for classic and EBNA modified 802.11 MAC

367 performance is needed in order for the EBNA concept to be used in wireless audio  
368 networking.

## 369 **5 Hybrid EBNA algorithm**

370 The implementation of EBNA in the previous section leads to a number of sig-  
371 nificant conclusions. Initially, it is shown that collisions can be eliminated by  
372 using this method. However, this technique results in an increase of the overall  
373 delay due to the linear increase of CW, which is proportional to the number of  
374 STAs in the network. On the other hand, the performance of classic 802.11 when  
375 it comes to throughput and overall delay is satisfactory especially when only  
376 few STAs are broadcasting. [27]. When a small number of STAs is broadcasting  
377 in a wireless network, the probability of collision is low (Fig. 2). Taking into  
378 account that the CW is also small, classic 802.11 achieves equivalent throughput  
379 values with the EBNA, but with a significantly lower delay.

380 The EBNA algorithm was designed for fully saturated wireless networks,  
381 where all STAs have data to broadcast at all times. For that reason, the algorithm  
382 reserves always an exclusive pair of backoff values for each STA. That means  
383 that for each new STA joining the network, the size of CW increases by two val-  
384 ues. This results in a relatively large CW, especially when the number of STAs  
385 increases. However, musical data production has a stochastic nature. That means  
386 that during a session there are several time intervals where STAs have no data to  
387 broadcast. Hence, as the size of CW remain constant, unnecessary long waiting  
388 times are added by the congestion control algorithm. The possibility of monitor-  
389 ing the network and applying the EBNA concept using a dynamic CW, only for  
390 active STAs, will result in a lower overall delay.

391 Taking into account the above characteristics, a Hybrid-EBNA (H-EBNA)  
392 algorithm is proposed in this section. This algorithm monitors the activity of  
393 all STAs in the network, calculates the probability of collisions and regulates  
394 congestion by automatically switching between the classical IEEE 802.11 and  
395 the EBNA MAC. In addition, when EBNA is selected, identifies the number  
396 of active STAs in the network and implements a dynamic CW in order to keep  
397 average backoff time in the lower possible levels. The operating principle of the  
398 H-EBNA algorithm within each STA is described below:

- 399 • The algorithm constantly monitors the network's activity.
- 400 • When the STA has a packet to broadcast, the algorithm identifies the number  
401 of active STAs in the network.
- 402 • If the probability of collision using the classic IEEE 802.11 is low, the algo-  
403 rithm selects this method to access the medium and broadcast its data.
- 404 • If the probability of collision using the classic IEEE 802.11 is high, the  
405 algorithm switches to the H-EBNA MAC. Then it accesses the medium and  
406 broadcasts its data.
- 407 • When H-EBNA is selected, the enhanced CTS-to-Self-protection mechanism  
408 is also applied by default.

409 The H-EBNA algorithm complies with the general concept of the distributed  
 410 coordination which characterizes the IEEE 802.11 standard. Therefore, the algo-  
 411 rithm is implemented independently in each individual STA in the network. That  
 412 gives flexibility in the setup and maintenance of the network which is a funda-  
 413 mental requirement in audio networking.

### 414 5.1 Generation and maintenance of the List-of-STAs

415 When the H-EBNA modified MAC is implemented, the first action of the algorithm  
 416 is to generate a record that contains all STAs in the network. STAs associating with  
 417 the wireless network obtain automatically a STID. When a CTS-to-Self is transmit-  
 418 ted prior to each data transmission, The STID of the broadcasting STA is included in  
 419 the body of this message. With this mechanism all STAs after their first access to the  
 420 medium register their STIDs with all peer STAs in the network.

421 Every STA that starts operating within the network generates a static list called  
 422 “General List of STAs”. Each record on this list contains in ascending order a STID  
 423 and the timestamp of the most recently broadcasted CTS-to-Self message, coming  
 424 from the STA with this particular ID. During the session, when a CTS-to-Self mes-  
 425 sage with a specific STID is received, the algorithm updates the timestamp for this  
 426 specific ID in the “General List of STAs”. This technique also resolves the issue of  
 427 synchronization between STAs in the network. Individual STAs can use their own  
 428 timers as no clock distributions is required. As it will be discussed later in this paper,  
 429 for the implementation of H-EBNA, time differences rather than absolute time val-  
 430 ues are required.

### 431 5.2 Defining the active STAs in the network

432 The next step for the implementation of H-EBNA is to identify the active STAs in  
 433 the network. This procedure is executed independently in each STA prior to each  
 434 transmission. When a STA has a packet to transmit, the algorithm uses the set of  
 435 information stored in the “General List of STAs” to generate the sub-set of active  
 436 STAs in the network. This sub-set has the form of a dynamic table and it is called  
 437 “List of Active STAs”. In order to create this second list, the algorithm subtracts  
 438 from the current time ( $T_C$ ) the time ( $T_A$ ) that the last CTS-to-Self has arrived for  
 439 each specific STID. Then it compares the result ( $T_D$ ) with a predefined threshold  
 440 value  $T_{threshold}$ . The decision whether an arbitrary STA  $k$  will be considered as active  
 441 or inactive is taken as follows:

$$442 \quad TD_k = [T_C] - [T_A]_k \quad (14)$$

$$443 \quad \text{For : } \begin{cases} TD_k \geq T_{threshold} & STA = \text{Active} \\ TD_k < T_{threshold} & STA = \text{Inactive} \end{cases}$$

Author Proof

444 If the IEEE 802.11 g with a transmission rate of 54 Mbps is used, each bit requires a  
 445 period of  $1.8 \times 10^{-8}$  s in order to be transmitted. Therefore, a data byte will require  
 446 a transmission time of  $1.481 \times 10^{-7}$  s. The H-EBNA is implemented using constant  
 447 maximum packet size and therefore each packet with a size of 2234 byte will need a  
 448 Packer-Transfer-Time (PTT)  $PTT=3.31 \times 10^{-4}$  s. The regular size of a CTS-to-Self  
 449 message is 14 bytes and it is also transmitted with the 54 Mbps bit rate. Therefore,  
 450 the CTS-to-Self Transmission Time (CTSTT) will be  $CTSTT=2.0735 \times 10^{-6}$  s. We  
 451 denote as “round time” the minimum time period required for all STAs in a network  
 452 to transmit a packet. The maximum expected population in a wireless audio network  
 453 is 60 STAs. Therefore, the round time in a 60 STAs scenario ( $Round_{60}$ ), will be:

$$Round_{60} = 60 \times (PTT + CTSTT + DIFS + SIFS) \quad (15)$$

455 From (15) and for  $SIFS = 10 \times 10^{-6}$  s and  $DIFS = 50 \times 10^{-6}$  s, the one round time-  
 456 frame is calculated to be 0.01,998 s. In the implementation of H-EBNA we adjust  
 457 the value of  $T_{threshold}$  in order for each STA to be given a “three rounds opportunity”  
 458 to transmit a packet using the maximum round time value ( $Round_{60}$ ). This gives con-  
 459 sequently a  $T_{threshold-60} = 0.05995$  s. Using the above described scheme, we actually  
 460 give to all STAs in the network a probability of at least 300% to gain access to the  
 461 medium and complete a packet broadcast. STAs that fail to achieve this target are  
 462 considered inactive and their ID is removed from the “List of Active STAs”. Fig-  
 463 ure 12 shows an example of the “General List of STAs” and its product “List of  
 464 Active STAs” as described above.

### 465 5.3 Switching between classic and EBNA 802.11 MAC

466 After the generation of the “List of Active STAs”, which is updated every time a  
 467 packet has to be transmitted, the algorithm has to decide whether to use the classic  
 468 IEEE 802.11 or the H-EBNA modified MAC for accessing the medium. It is impor-  
 469 tant to note here that, although there is not a central control, we are expecting all  
 470 STAs to have a coordinated transition between H-EBNA and classic 802.11. This is

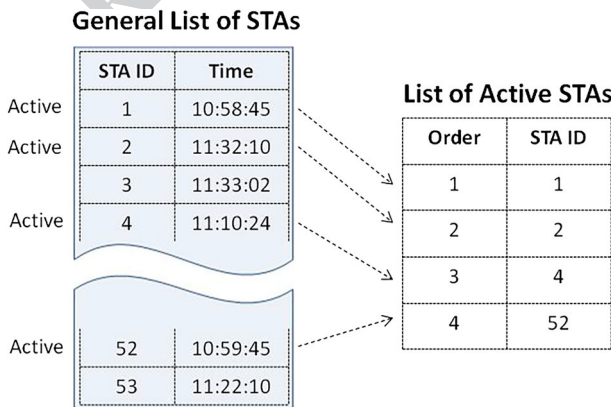


Fig. 12 The general list of all STAs and the list of active STAs (Example)

471 because all STAs are monitoring the network simultaneously and they collect identical  
 472 information when it comes to the data traffic.

473 The transition between H-EBNA and classic 802.11 is based on a critical number  
 474 of active STAs ( $N_T$ ) which consequently results a critical probability of collision  
 475 ( $p_T$ ). This probability of collision is defined indirectly by the user who is required to  
 476 declare a maximum acceptable packet loss rate. If  $P$  is the percent of the maximum  
 477 acceptable packet loss rate, the maximum acceptable probability of collision will be  
 478  $p_T = P/100$ . Using (5) we can obtain an expression for the critical number of active  
 479 STAs as follows:

$$p_T = 1 - \left(1 - \frac{1}{CW}\right)^{N_T - 1} \quad (16)$$

$$\therefore N_T = \frac{\log(1 - p_T)}{\log\left(1 - \frac{1}{CW}\right)} - 1 \quad (17)$$

482 The algorithm allows the user to set manually the parameters  $P$  and  $CW$  when the  
 483 network is formed, however these values will remain constant during the operation  
 484 of the network. The process of switching between MACs is regulated by the follow-  
 485 ing rule:

$$\begin{aligned} N > N_T & \text{ EBNA MAC} \\ N \leq N_T & \text{ Classic 802.11 MAC} \end{aligned} \quad (18)$$

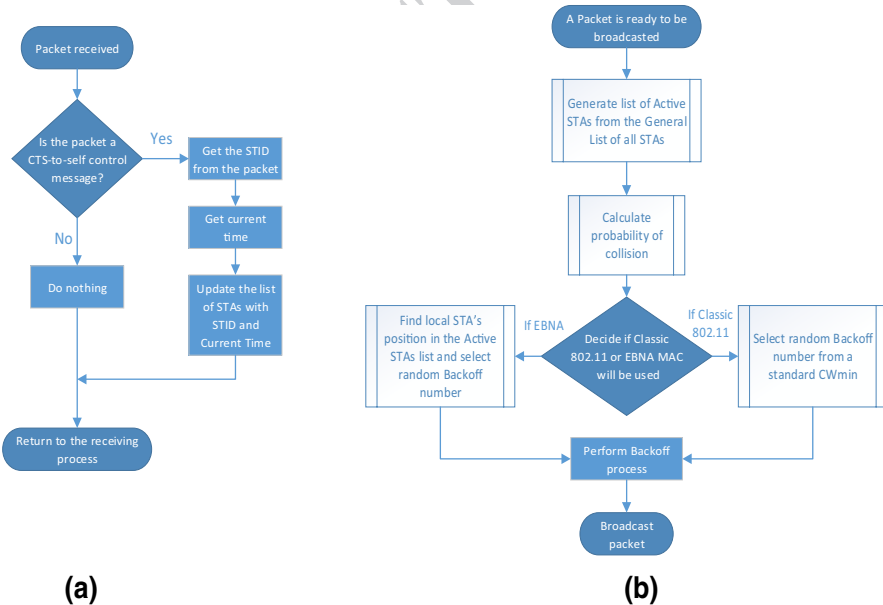


Fig. 13 Operation of H-EBNA algorithm at the receiver (a) and the transmitter (b)

487 According to (18), whenever the population of active STAs in the network becomes  
488 greater than the critical number  $N_T$ , the algorithm switches to the H-EBNA mech-  
489 anism. When the population of active STAs drops, it switches back to the clas-  
490 sic IEEE 802.11. Using this technique, the algorithm manages to maintain a high  
491 throughput while keeping the overall delay in lower levels.

492 The flowchart in Fig. 13a shows the network monitoring process at the receiver.  
493 The flowchart in Fig. 13.b shows the action taken by the algorithm at the transmit-  
494 ter. Here, when a packet is to be transmitted, the algorithm calculates the probability  
495 of collision taking also into account the users setting and decides whether to use  
496 EBNA or classic 802.11.

#### 497 5.4 H-EBNA (simulation and results)

498 The simulation characteristics, the topology, the traffic generation parameters  
499 and the collected results are the same as those in the EBNA simulation shown in  
500 Sect. 4.1.

501 Figure 14 shows the overall throughput, measured during the simulation for a  
502 60 STAs network. This graph contains the results from the three congestion meth-  
503 ods discussed in this paper. This 60 STAs scenario is a complete stress test of the  
504 H-EBNA algorithm when it comes to throughput performance because wireless  
505 audio network with this population is considered as the desirable commercial target.

506 This graph shows that both H-EBNA and basic EBNA are performing equally  
507 well when it comes to throughput. They also both give better throughput results  
508 than classic IEEE 802.11 which fail to eliminate collisions in multi-broadcasting  
509 environment.

510 However, the most significant difference is illustrated in Fig. 15 where the average  
511 delay is presented. It is shown here that the implementation of H-EBNA achieves

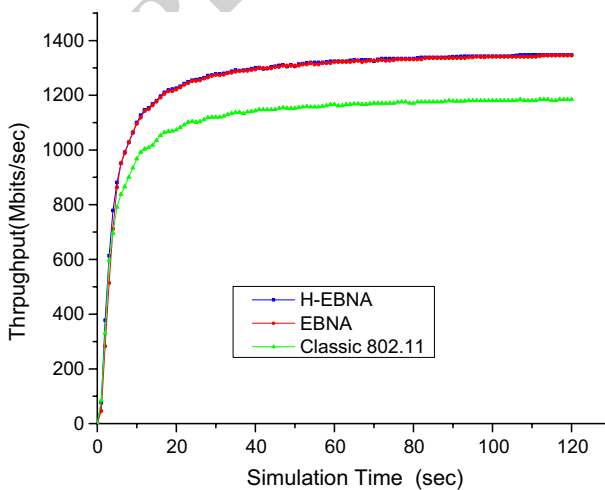


Fig. 14 Throughput performance, WLAN of 60 STAs

Author Proof

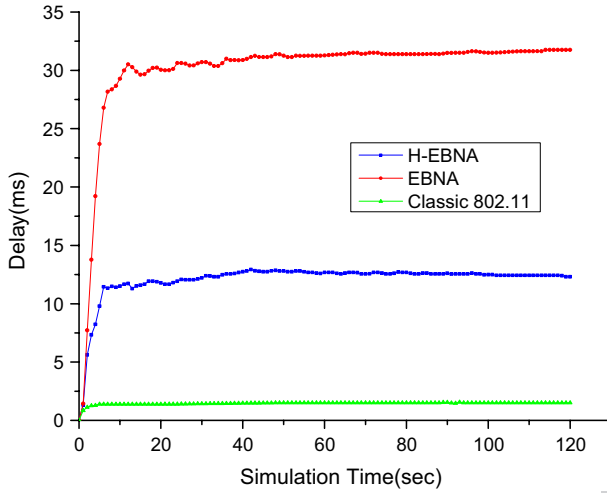


Fig. 15 Average end-to-end delay, WLAN of 60 STAs

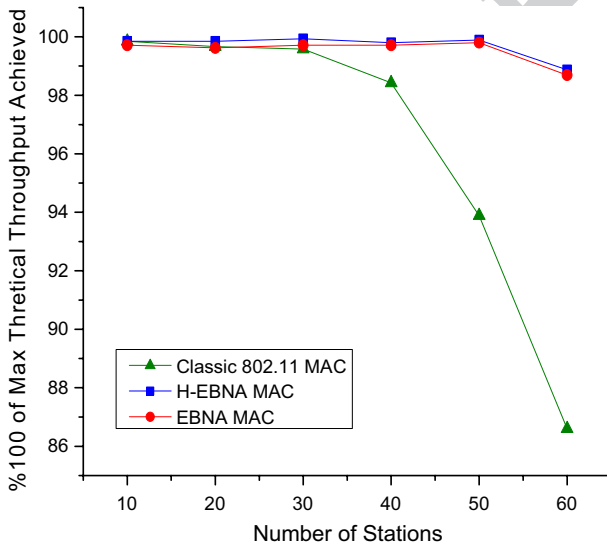


Fig. 16 Throughput performance, (Classic 802.11, H-EBNA and EBNA modified MAC)

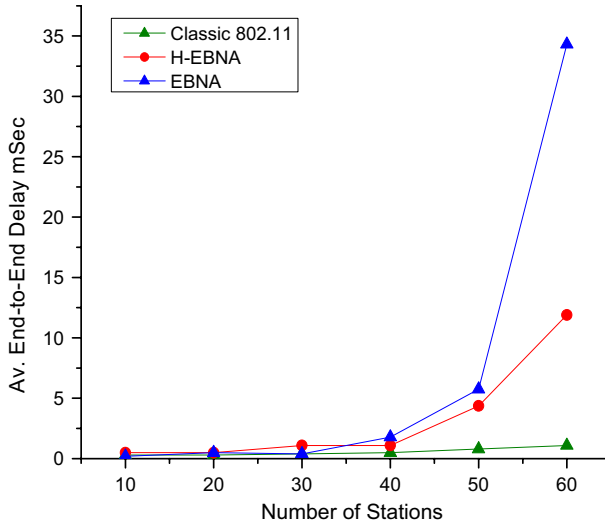


Fig. 17 End-to-end delay, (Classic 802.11, H-EBNA and EBNA modified MAC)

512 significantly lower average delay (approximately 12 ms), which is also within the  
513 commonly accepted limits for real time audio networking applications.

514 Figures 16 and 17 show the Throughput and Delay performance respectively, col-  
515 lected from all the simulation scenarios. Here it is also shown that basic EBNA and  
516 H-EBNA are equally successful when it comes to throughput, however, H-EBNA  
517 significantly outweighs when it comes to delay. It is important to mention here that  
518 the packet loss observed in scenarios of 55 STAs and above it is caused due to the  
519 buffer overflow within the STAs and not because of the collisions.

## 520 6 Conclusions

521 In this paper we propose a complete set of modifications for the IEEE 802.11 stand-  
522 ard in order to be able to support the implementation of wireless audio networks.

523 Audio networks represent a dynamically evolving sector within the audio engi-  
524 neering industry and their expansion in the wireless networking domain has signifi-  
525 cant potential. The amendment proposed in this work aims to overcome the funda-  
526 mental problems that prevent the use of the existing wireless technologies toward  
527 this direction. We focus our effort on the IEEE 802.11 standard, which is wide-  
528 spread, efficient, inexpensive and well adopted by the market.

529 The proposed set of amendments consists of two main categories of modifica-  
530 tions. The first one provides a collision protection mechanism for broadcasting by  
531 extending the use of the CTS-to-Self message. The second one resolves the con-  
532 gestion control issue by introducing an EBNA method that minimizes the probabili-  
533 ty of collision in broadcasting for a finite, known number of STAs in a wireless

534 ad-hoc network. Moreover, an extended version of this method called hybrid-EBNA  
535 is proposed.

536 Using this method, STAs in the network are able to monitor the data traffic and  
537 switch between classic 802.11 and EBNA, achieving this way high throughput and  
538 low delay.

539 The above amendments were tested in a simulation environment. The results  
540 showed that this modified IEEE 802.11 MAC mechanism achieves the necessary  
541 performance when it comes to throughput and delay, and therefore it can be used  
542 as the networking platform for the commercial development of wireless audio  
543 networks.

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