Implementation and Performance Analysis of Cooperative Medium Access Control protocol for CSMA/CA based Technologies

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Abstract— **In this paper we investigate three different MAC protocols based on CSMA/CA in terms of throughput and channel access delay. The investigation is based on analytical models and real implementations on a testbed developed for this purpose. While the first MAC approach is alike IEEE802.11, the other two approaches are based on packet aggregation per node and on cooperative approaches. It can be shown that the two novel MAC schemes are increasing the throughput compared to the standard CSMA/CA approach, but only the cooperative approach is resulting in lower channel access delays.**

I. INTRODUCTION

State of the art wireless communication standards like IEEE 802.11 Wireless LAN and Bluetooth provide continuously higher data rates. Current research aims at achieving even higher transmission rates at the physical layer by means of new technologies such as MIMO. However wireless communication protocols consumes a portion of the channel capacity to avoid interference from and to other nodes. This is done by Medium Access Control (MAC) protocols at the link layer (also known as the MAC layer).

In the case of IEEE 802.11 the MAC protocol features inter frame spaces, backoff windows, acknowledgement and reservation of the medium using Request To Send (RTS)/Clear To Send (CTS) packets. This introduces a significant amount of overhead and in the case of high load in the network, the contention for the medium will result in increased packet collision and thus decreased throughput. To achieve general information about IEEE 802.11 technology, the interested reader is referred to [2].

If more efficient wireless MAC schemes was developed, i.e. minimization of contention or less overhead in general, the actual data rate of a wireless link could be increased without increasing the physical data rate. In this paper the aim is to develop add-ons to IEEE 802.11 instead of a whole new design of the MAC (as it was done years ago in the HiperLAN and HiperLAN2 approaches).

One way to optimize a MAC protocol in a wireless network is to let the nodes transmit multiple packets when the RTS/CTS handshake is successful. This way less time is spent on the channel for contention among the nodes.[1]

An even better way would be to let the nodes cooperate e.g. by forming cooperative clusters. The nodes may then aggregate their packets and save multiple fights for the channel [6, p. 513-529]. Currently the idea of cooperative MAC strategies are discussed at the VHT working group [8].

A cooperative MAC protocol does only make sense in a scenario with many nodes in range of each other and high load in the network. Otherwise the commonly used individual RTS/CTS scheme performs sufficiently well.

This paper will investigate current work in the field of MAC protocols and analyze different approaches to increase throughput in wireless network at the link layer in the context of IEEE 802.11. The aim will be to implement a Cooperative MAC protocol and evaluate the performance of this in a real life scenario compared to the individual RTS/CTS strategy. The protocols will be implemented on the OpenSensor [5] platform developed by Aalborg University. A description can be found in Section IV-A.

However current work in the field of wireless MAC protocols must be investigated with regard to different performance metrics, in order to show how the individual MAC protocols performs and how they can be improved.

In the following sections different state of the art MAC schemes will be described and investigated with regards to saturated throughput and channel access delay, namely CSMA/CA, Packet Aggregation and the cooperative approach One4All. For all three approaches an analytical description is presented based on state of the art literature. Additionally the One4All protocol is modified and renamed to the Cooperative MAC protocol in order to make implementation possible on the available platform. Finally all three protocols are implemented and their performance is evaluated.

II. PROTOCOL OVERVIEW

In a wireless network where only one or few channels are available, the nodes must communicate through this shared medium in a fair fashion. This can be done by using CSMA protocols where nodes listens to a desired frequency before transmitting anything. If a carrier is detected on the frequency, the node will postpone the transmission. If the medium is idle the node is allowed to begin transmitting. In most cases carrier sensing can avoid collisions of data packets, but it can still happen that two nodes sensing the medium idle decides to transmit at once. In order to minimize these types of collisions a back–off period can be applied to avoid multiple transmissions immediately after a busy medium.

A. CSMA/CA and RTS/CTS

Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is used in IEEE 802.11 among others, but even though carrier sensing is applied and nodes wait a random time before transmitting, a collisions can still occur at the receiver if two transmitters are placed on either side of the receiver, out of range of each other. This is known as the hidden terminal problem. To solve the problem, virtual carrier sensing is introduced. In this scheme, short RTS and CTS packets are exchanged between sender and receiver to reserve the medium and let the neighboring nodes know that a transmission is in progress. A node is allowed to transmit when it receives a CTS from the destination node. All neighboring nodes are advised by the CTS of the following transmission and the data packet can be sent without collisions. The receiving node will reply with an Acknowledgement (ACK) to verify a correct transmission.

B. Packet Aggregation

In wireless LAN IEEE 802.11 a portion of the bandwidth is used to transmit overhead traffic both on the physical and MAC layer which is not good for the overall throughput of the wireless system. One solution to lower the amount of overhead in the wireless system is to use Packet Aggregation. This means that instead of transmitting just one packet when the channel is idle, more packets are concatenated into one larger packet. Now only the overhead for one packet is needed in order to transmit the packet which will be split at the receiver. An example of a transmission of three packets with and without Packet Aggregation can be seen in Fig. 1.

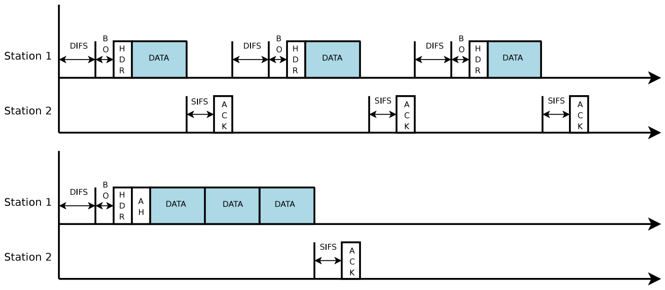

Fig. 1. Packets transmitted without (top) and with Packet Aggregation (bottom).

Packets can be aggregated in several ways e.g. by removing physical and MAC header from each packet and aggregate the packets to one large packet, or by transmitting several packets in a row. The model for Packet Aggregation will be based on transmitting several packets in a row due to a limited packet size for the wireless interface used in the implementation.

The same packets can, if Packet Aggregation is used, be transmitted in less time if it is assumed that all packets are ready in the transmission buffer before aggregation. This is also shown in Fig. 1.

This Packet Aggregation scheme performs best in a scenario where there is little interference on the wireless medium. The reason for this is that the time spent to transmit the aggregated packet is larger than the non-aggregated which makes the transmission more vulnerable to collisions. If collisions occur the whole aggregated packet must be retransmitted and the benefit of Packet Aggregation may be lost. This problem can be solved by introducing block ACK, which contains an ACK flag for each aggregated packet. In this way it can be determined which packets were received and which were lost.

C. One4All

The One4All [6, p. 513-529] strategy propose a cooperative media access strategy, where wireless devices cooperate in a cluster to access a common central Access Point (AP), see Fig. 2. Motivation for this proposed strategy is to reduce the contention period for accessing the AP. By removing contention within a cluster, data collision which otherwise may occur caused from contentions can be fully avoided, and thereby the average data throughput and energy consumption of those cooperative devices will be improved.

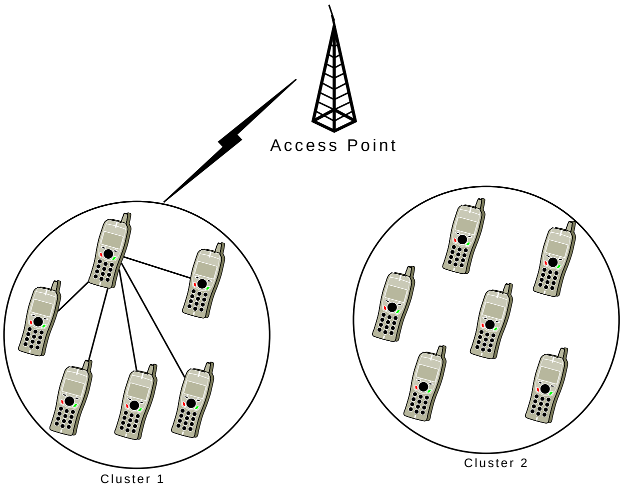

Fig. 2. Two cooperative clusters contending to get the channel access to the central Access Point.

Devices using the One4All strategy are assumed to have two air interfaces:

- Long-range: For accessing the channel to the AP.
- Short-range: Is used to form a cooperative cluster.

In this strategy the devices forms a cooperative cluster using the short range interface. The size of the cluster is determined by the range of the short-range link. After forming the cluster a cluster head is chosen, the cluster head collects any available data pending to be send to the AP within the cluster by using the Packet Aggregation strategy described earlier. The pending data are collected e.g. by using the token ring topology. The chosen cluster head then competes with other cluster heads in the network to access the AP. When a link to the AP is established the aggregated packets will then be sent and after a successful transmission the cluster head will respond to its own cluster with an ACK.

Another approach after forming the cluster is when each device in a cluster undertake the role of the cluster head in the reserved channel access time, this means that the pending message will not be aggregated by the cluster head, but instead each device will send its own message when it has the token and on a successful transmission it will pass the token to another device within the cluster. In this approach the cluster head reserves the channel in advance, knowing how many devices wanting to transmit. Finally these two approaches can be combined. This approach may seem relevant in scenarios where some device may decline the Packet Aggregation request from the current cluster head and may wish to send its packet directly to the AP. In Fig. 3 the three approaches are shown. [7]

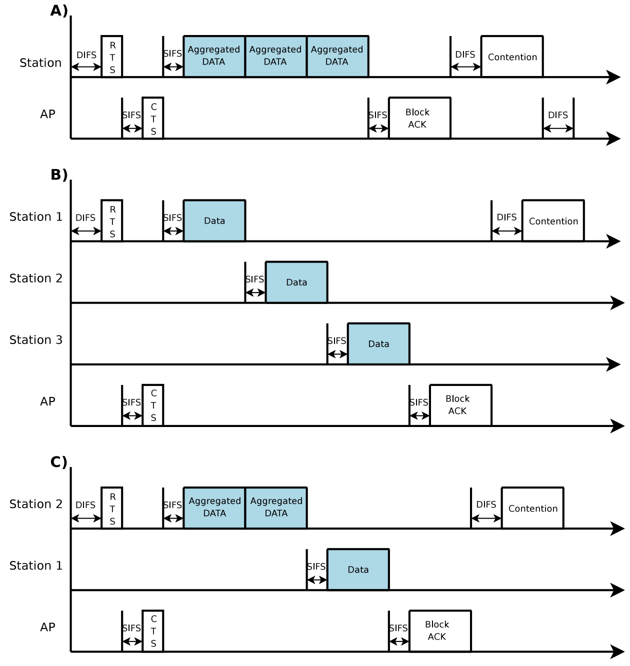

Fig. 3. Packet transmission in three different cooperative approaches where A) is using Packet Aggregation in the cluster, B) where each device in the cluster gets the channel and C) a combination of A) and B) is used.

D. Fairness in the protocols

Even though CSMA/CA should introduce fair sharing of the medium among the centending devices, this is not necessarily the case for a practical scenario. In a static setup where the locations of the devices and the AP is relatively fixed, some devices might experience better channel conditions than others, leading to unfair sharing of the medium. This can be seen whenever a collision in therory should occur, where the device with better channel condition will get the medium without collision. This unfairness will eventually be worsened for Packet Aggregation since the medium is obtained for longer periods. On the contrary the cooperative approach One4All is likely to offer a fair access to the medium due to the token ring approach, which will be elaborated further in the next section.

III. Cooperative MAC Design

The One4All approach does not apply for direct implementation in this project of the OpenSensor hardware platform only features one RF interface. Furthermore it is decided to focus on protocol types that applies to devices running IEEE 802.11 which typically only have one RF interface. The mechanisms of One4All will be used as inspiration for developing a new Cooperative MAC protocol. The following will describe the scenario of this protocol and point out which features is needed to insure reliable communication with minimum overhead.

The scenario is similar to the one of One4All shown in Fig. 2 where devices form clusters to relay data to the AP. When only one RF interface and one frequency is available, each transmission will block others. Thus packets are not relayed through the cluster head but transmitted directly to the AP. This approach will lead to better performance.

The scenario of the cooperative protocol is shown in Fig. 4 where devices are connected in clusters (dashed lines) and the data flow is going directly to the AP (solid lines).

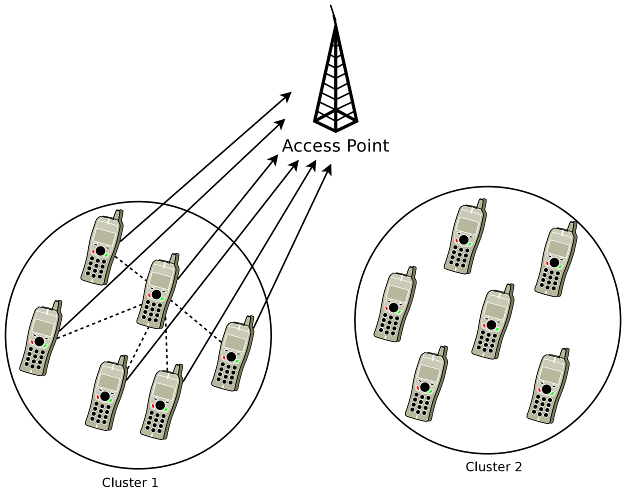

Fig. 4. Two cooperative clusters in the cooperative protocol.

The clustering of devices will not be investigated in this paper. It is assumed that the clusters are created and in a fixed state, i.e. no devices are entering or leaving a cluster. The following describes the events that occurs in the network under the assumption of saturation, i.e. all devices have a packet in the buffer immediately after transmitting the previous.

A. RTS/CTS Hanshake

The devices in the cluster have packets ready for transmission and they must enter a contention state to access the medium. The cluster head is responsible for negotiating with the AP. It will try to perform the RTS/CTS handshake as in CSMA/CA but like packet aggregation the RTS packet must tell how many packets or how long time the medium must be reserved for. Upon successful reception of an RTS, the AP replies with a CTS and the cluster head has access to the medium. Each device in the cluster must also know this and rather than having the cluster head telling them, they can just overhear the CTS sent from the AP.

B. Data Transmission

For simplicity the cluster head will be the first to transmit followed by the remaining devices in a token ring fashion. The cluster head now needs to pass on the token to another device. This can be done by sending a packet to the new device, but is more efficient to just overhear the transmission of the last one and in this way determine when it is time to transmit. An even more efficient approach is to make the token passing time based, i.e. when the CTS is received by the cluster nodes, they will take turns in a TDMA like fashion. This can save energy by letting the node enter sleep mode and not using energy on receiving packets from others, but it requires a fixed length of data packets and a way for the node to know its own priority in the token ring. The TDMA token ring is used in Cooperative MAC and is illustrated in Fig. 3 B).

Another advantage is that nodes are not dependent on hearing the transmission from the previous one to initiate its own transmission. This way the token passing is not jeopardized by interference or bit errors.

C. ACK

When the packets are received by the AP, ACK must be sent to acknowledge each packet. This can be done either by individual ACK to the devices after each packet or by a common block ACK to the cluster following the last data packet. The last approach is the obvious choice as it will minimize overhead. This is used in both Packet Aggregation and One4All.

IV. IMPLEMENTATION

The implementation of the Cooperative MAC protocol is done on the OpenSensor v3.0 [5] platform provided by Aalborg University. This section contains a short description of the platform and the parameters used in the implementation i.e. timing, packet sizes and data rate.

A. Testbed for the MAC Investigations

Each OpenSensor board contains a microprocessor, communication module and power supply. All of this is contained in a box typically about the same size as a mobile phone.

- RS-232 interface which can be used for serial communication with the device
- Microchip dsPIC30F3013 microprocessor for controlling the device
- 22.1 MHz oscillator as external clock source for the dsPIC
- PICkit2 programmer interface
- Bluetooth module (optional)
- nRF905 (Nordic Semiconductor) transceiver for communicating via the ISM band, 433 MHz, 50 kbit/s
- Loop antenna for the RF transceiver
- Programmable LED
- Easy connecter for external I/O equipment

The OpenSensor v3.0 platform can be seen in Fig. 5 by itself and in Fig. 6, where ten devices are mounted on a rack. The total testbed consists of five racks and a stand-alone OpenSensor as AP.

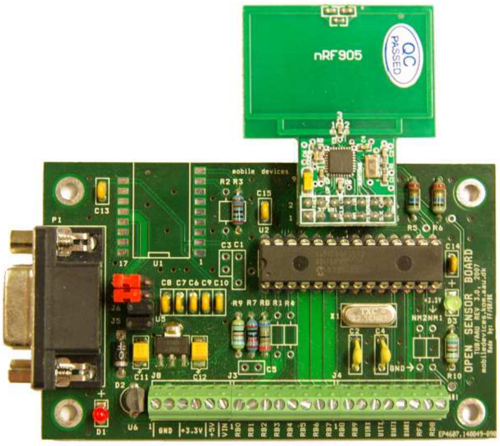

Fig. 5. The OpenSensor platform.

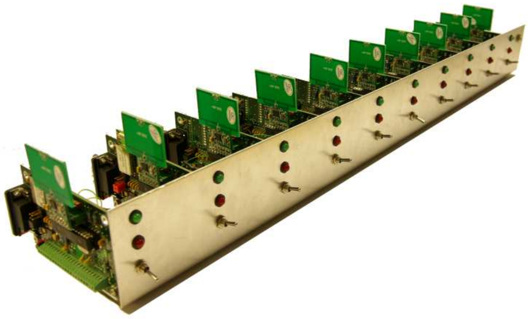

Fig. 6. The testbed for the implementation of the MAC protocols. Ten OpenSensors are mounted in each rack.

B. Parameters

To implement and analyze the protocols on the OpenSensor hardware some parameters needs to be defined. The parameters in Table I are chosen based on measurements performed on the sensor board.

V. NUMERICAL RESULTS

The protocols have been implemented using the parameters of Table I. The measurements have been obtained by the AP by logging the data packets of each device in the network. In order to analyze the performance of the the implemented protocols, some assumptions have been made. These assumptions are that the network must consist of n contending devices and each device has a new packet ready immediately after a successful transmission. Based on these assumptions the following performance metrics are described.

A. Performance Metrics

Throughput is defined as: *The ratio between the average time for a successful transmission in an interval and the average length between two consecutive transmissions.*

As described in [3] to calculate the throughput of the protocol it is assumed that each transmission is a renewal process for both successful and non-successful transmissions,

Notation	**Value**
nRF overhead	58 bits
Header	3 bytes + nRF overhead
Payload	28 bytes
ACK	4 bytes + nRF overhead
RTS	4 bytes + nRF overhead
CTS	4 bytes + nRF overhead
Max no. of stations	50
W - Init window size	32
m - Backoff stages	2
Slot time	1 ms
SIFS	1 ms
DIFS	4 ms
Channel Bit Rate	50 kbit/s
Aggregation level	4 packets
Cluster size	4 devices

TABLE I

Implementation parameters for the protocols

thus it is possible to calculate the saturated throughput in a single renewal interval between two consecutive transmissions.

The saturated throughput is defined in [3] as: *The limit reached by the system throughput as the offered load increases.* This corresponds to the assumption that all devices have a packet ready for transmission immediately after the previous packet is sent.

Channel access delay is defined as: *The time it takes when a frame is generated and ready for transmission until the medium can be accessed meaning that the device can start to transmit the frame.* From the moment where the frame is ready the device needs to contend with other devices and back–off and retry if there is collision or the medium is busy.

From [3], [4] and [7] the equations to derive saturated throughput and channel access delay are used to verify the measured results obtained from the implementation. These analytical results are compared with the results from the implementation in Fig. 7 and 9.

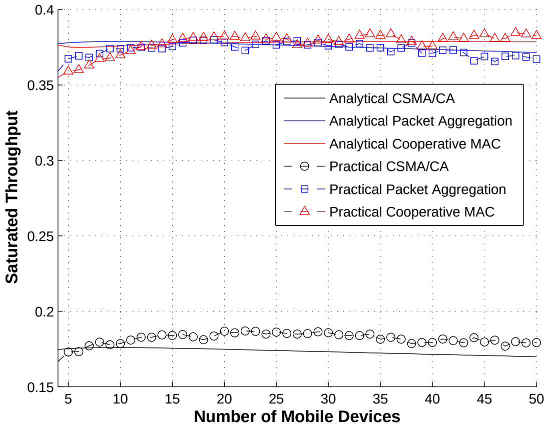

Fig. 7. Throughput of the CSMA/CA, Packet Aggregation and Cooperative MAC protocols

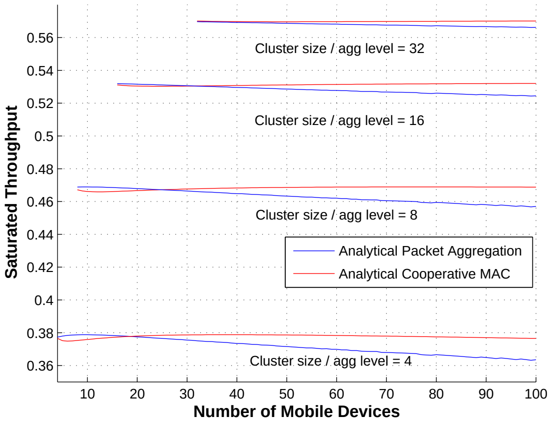

Fig. 8. Analytical model of the throughput of Packet Aggregation and Cooperative MAC extended up to 100 devices.

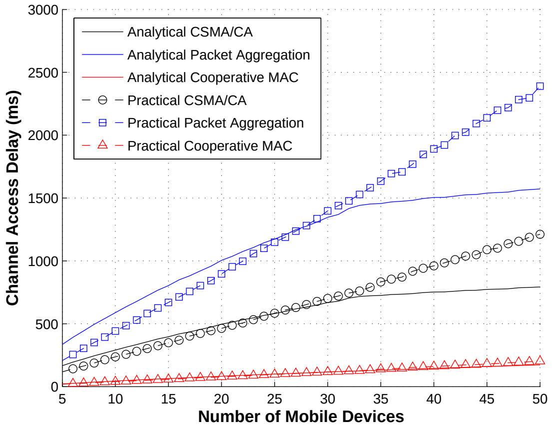

Fig. 9. Channel access delay of the CSMA/CA, Packet Aggregation and Cooperative MAC protocols

It can be seen that the saturated throughput for CSMA/CA is low because only one packet is sent after each contention period. Both Packet Aggregation and Cooperative MAC have great improvement in throughput compared to CSMA/CA. Packet aggregation and the cooperative protocol are transmitting the same amount of data packets in a given period of time except that the packets are split between devices in the cooperative case. The reason for Cooperative MAC having slightly lower throughput than Packet Aggregation for a low number of devices is that the contention period is less crowded when the number of clusters is small (approximately < 4) because only cluster heads are contending. This introduces more idle time per device in the system. As more clusters are introduced, the throughput of the Cooperative MAC will approach that of Packet Aggregation and outperform it when the number of devices is around 16 in case of cluster size and aggregation level equal to four. This can be seen in Fig. 8, where it also can be seen that for larger cluster sizes the throughput increases. It is obvious that the throughput does not double with the doubling of aggregation level / cluster size, but it seems that there exists an upper bound for aggregation level / cluster size where the throughput does not increase any further. This matter will not be investigated any further in this paper.

Cooperative MAC has a very low channel access delay which is far better than the channel access delay of Packet Aggregation and CSMA/CA. For the protocols, the analytical and practical results deviate slightly from each other. One reason for this deviation between the analytical and practical results is explained in the following: During the implementation and test of the system it was observed that some devices received CTS packets with wrong addresses after sending RTS packets. This occurred regularly on some devices, but there was always one device in the system which never received a wrong CTS packet. This phenomenon occurs when two or more devices send RTS at the same time. In this case the RTS packets, which is transmitted with the same power, should in theory collide and annihilate each other, but one of the RTS packets is correctly received by the AP which replies with a corresponding CTS. Hence the successful device gets channel access where it was not supposed to, which results in a lower average delay and better throughput. This observation shows how the channel conditions in a practical scenario can lead to unfair sharing of the medium as described previously.

The analytical model for channel access delay also deviates from the practical results for more than 32 devices, by having a lower and almost flat slope. This phenomenon must be interpreted in the following way: By introducing more devices into the system, almost no extra backoff is added and almost no more collisions occur. This bahavior may only occur if idle periods already exists in the system. At this point it is unclear whether it is the analytical model or the practical results that deviates.

VI. DISCUSSION AND CONCLUSION

In this paper the protocols CSMA/CA, Packet Aggregation and Cooperative MAC have been described and implemented on the OpenSensor v.3.0 platform. The aim was to compare the performance of the implementation to analytical models regarding saturated throughput and channel access delay. The results shows that aggregation of packets leads to higher throughput as the contention is lower per packet. In our measurements that corresponds with the analytical model, we show that the Packet Aggregation and Cooperative MAC were doubling the saturated throughput compared to standard CSMA/CA. The cooperative approach has significantly more saturated throughput than the standard CSMA/CA, but Packet Aggregation performs slightly better from 4 to 16 devices. The analytical model shows that from 16 devices the Cooperative MAC performs better.

The cooperative approach is outperforming both other approaches in terms of channel access delay. Compared to the standard CSMA/CA approach and the Packet Aggregation, the channel access delay for the cooperative approach is 1/6 and 1/12, respectively.

The results for saturated throughput obtained from the implementation is equivalent to the analytical models and thus it verifies the implementation. The results for channel access delay in the implemented protocols fits the models up to 32 devices. Further work will be carried out to determine the reason for the deviations above 32 devices.

It can be concluded that for a scenario with static clusters and minimal cluster maintenance the Cooperative MAC is a good solution to ensure fair access to the medium, high saturated throughput and low channel access delay at the same time. On the other hand the CSMA/CA and Packet Aggregation schemes might perform better in a scenario where it is not possible to maintain a clustered ad hoc network e.g. where devices are frequently entering or leaving, due to larger overhead introduced for maintenance. Furthermore the cooperative approach is much more suited for real time traffic than packet aggregation, as the cooperative approach is not dependent on the fact that a device needs multiple packets itself, but only packets within the cluster.

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