IEEE 802.11n MAC Mechanisms for High Throughput: a Performance Evaluation

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Abstract— **Nowadays IEEE 802.11 standard is the most widely used one in wireless LAN (WLAN) technology. One of the key reasons is the continuous amendments presented by the IEEE 802.11 working group. One of these amendments (IEEE 802.11n) was approved to enhance 802.11 for higher throughput operation. IEEE 802.11n is an ongoing next-generation wireless LAN standard that supports a very high speed connection with more than 100 Mb/s data throughput measured at the medium access control layer. In this paper we examine the major improvements introduced by IEEE 802.11n MAC: aggregation, block acknowledgement, and reverse direction. We show the impact of each parameter in the network performance.**

Keywords-component; IEEE 802.11n; aggregation; block ACK; reverse direction

I. INTRODUCTION

These days, the wireless LAN (WLAN) technology is usually deployed using the IEEE 802.11 standard. One of the main factors for the popularity of the IEEE 802.11 is the continuous amendments. The IEEE 802.11 working group has always strived to improve this wireless technology through creating new amendments to the base 802.11 standard. The amendments try to solve the low efficiency of its medium access control (MAC) and physical (PHY) layer protocols, which restrict its applications to support high data rate multimedia services. Current WLAN systems endure difficulties due to the increasing expectations of end users and volatile bandwidth Delay-boundary demands from new higher data rate services, such as high-definition television (HDTV), video teleconferencing, multimedia streaming, voice over IP (VoIP), file transfer, and online gaming.

In 2002, the IEEE 802.11 standard working group established the high-throughput study group (HTSG) with the aim to achieve higher data rate solutions by means of existing PHY and MAC mechanisms [2, 3]. Its first interest was to achieve a MAC data throughput over 100 Mb/s using the 802.11a standard. However, the objective proved to be infeasible. So, in September 2003, the HTSG set off the IEEE 802.11n ("n" represents next-generation) resolution to compose a high-throughput (HT) extension of the current WLAN standard would increase the transmission rate and would reduce the unavoidable overhead. The main goal of the IEEE 802.11n task group (TGn) was to define an amendment that had a maximum data throughput of at least 100 Mb/s (measured at the MAC layer) and at the same time, to allow coexistence with legacy devices. To achieve high throughput in 802.11 wireless networks, the most commonly used method is to increase the raw data rate in the PHY layer. For this propose IEEE 802.11n [4] include multiple input multiple output (MIMO) antennas with orthogonal frequency division multiplexing (OFDM) and various channel binding schemes. Moreover, IEEE 802.11n expands the channel bandwidth to 40MHz to increase the channel capacity.

However, higher PHY rates do not necessarily translate into corresponding increases in MAC layer throughput. Indeed, it is well known that the MAC efficiency of 802.11 typically decreases with increasing PHY rate [5], [6]. To solve this limitation, IEEE 802.11n defines new mechanisms to increase the network performance.

The main contribution of this work is to provide an understanding of the three IEEE 802.11n MAC layer major enhanced mechanisms: aggregation, block acknowledgement, and reverse direction. Most previous works on IEEE 802.11n performance evaluation only explored aggregation mechanism [7, 8]. In [9] the authors evaluate both physical and MAC enhanced.

The rest of this paper is structured as follows: in Section 2 we describe a brief outline of the current IEEE 802.11 standard, followed by a discussion of its maximal throughput limitations. We describe the IEEE 802.11n in Section 3. We carry out a performance evaluation in Section 4 by means of extensive simulation. Section 5 concludes this paper.

II. IEEE 802.11

A. *Overview of IEEE 802.11 PHY*

The IEEE 802.11 PHY layer specification concentrates mainly on wireless transmission. The original specification was first approved in 1997 [1] and includes a primitive MAC architecture and three basic over-the-air communication techniques with maximal raw data rates of 1 and 2 Mb/s. Because of their fairly low data bandwidths, further amendments have been proposed throughout the years: IEEE 802.11a [10], 802.11b [11], and 802.11g [12]. Both 802.11a and 802.11b were finalized in 1999 and support raw data rates up to 11 Mb/s and 54 Mb/s, respectively. In June 2003, a third PHY specification (802.11g) was introduced, with similar maximum raw data rate as 802.11a but operating in separate frequency bands. For this period, there were many

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amendments and countless research works for improved PHY specifications that mostly aim to provide reliable connections and higher data rates. This is mainly because there is a continuous rapid increase in user demand for faster connections. In spite of establishing novel techniques that theoretically can be used for higher data transmission rates, the throughput outcomes at the MAC data are surprisingly low and in most cases, half of what the underlying PHY rates can offer.

B. IEEE 802.11 MAC

The MAC architecture is based on the logical coordination functions, which determine who accesses to the wireless medium at each time. In the legacy IEEE 802.11 standard, there are two types of access schemes: the mandatory distributed coordination function (DCF), which is based on the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism; and the optional point coordination function (PCF), which is based on a poll-and-response mechanism. These MAC schemes are inadequate to resolve differentiation and prioritization between frames and multimedia applications such as VoIP and audio/video conferencing with strict performance constraints. Due to these applications have become widely popular, a new extension was vital. In late 2005, IEEE 802.11 TG approved the IEEE 802.11e amendment [13] to provide an acceptable level of quality of service (QoS) for multimedia applications. The 802.11e proposes the hybrid coordination function (HCF), which uses a contention-based channel access method, known as enhanced DCF channel access (EDCA). EDCA has the ability to operate simultaneously with a polling-based HCF controlled channel access (HCCA). In addition to the differentiation and prioritization that IEEE 802.11e offers, the transmission opportunity (TXOP) was introduced in order to improve MAC efficiency. A TXOP is an interval of time in which multiple data frames can be transferred from one station to another (also known as bursting). During a TXOP period the station can transmit multiple data frames without entering the backoff procedure, reducing the overhead due to contention and backoff period. Along with frame bursting, another type of acknowledgment (ACK), known as block ACK, was established. Receivers can acknowledge multiple received data frames efficiently by using just a single extended ACK frame.

C. Throughput Limitations

To understand the inefficiency of IEEE 802.11 over higher data rates, we must briefly describe the legacy DCF. A successful packet transmission in DCF is illustrated in Fig. 1. When a station has a data frame (MAC service data unit, MSDU) to transmit, MAC headers are added to form MPDUs. A station may start to transmit after having determined that the channel is idle during an interval of time longer than the distributed interframe space (DIFS). Otherwise, once the transmission in course finishes and in order to avoid a potential collision with other active stations, if the channel is busy, the station will wait a random interval of time (the backoff_time) before start to transmit. The station will be able to begin transmission as soon as the backoff counter reaches zero. In order to know if a transmission has been successful, the destination station should respond to the source station with an ACK in an interval of time equal to the short interframe space (SIFS).

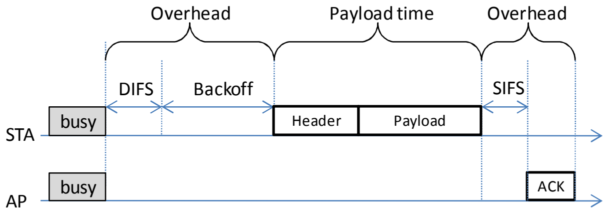


Figure 1. Legacy IEEE 802.11 operation.

By looking into the procedure of a packet transmission, we note that the channel is inefficiently used by the DCF. During the transmission procedure, transmission time is divided into a DIFS, a Contention Window backoff time, the PPDU transmission time, a SIFS, and the ACK frame transmission time. The PPDU transmission time can be further divided into two parts: 802.11 header and data payload transmission time. Other than the payload transmission portion is the overhead. The overhead of the DCF mechanism results in the inefficiency of the channel utilization, and thus limits the data throughput. When the payload is small, the overhead is relatively large and is less efficient. The percentage of the overhead among all usable airtime increases as the physical transmission rate increases. This fact causes that he overhead limits the achievable data throughput. In a higher data rate scenario, although the frame transmission time is reduced, the part of the overhead is unchanged due to the backward compatibility issue. As a result, to achieve higher throughput in 802.11 reducing the percentage of overhead is critical.

III. IEEE 802.11N

Although 802.11e adds the support of QoS, TXOP and block ACK, the inefficiency of channel utilization in legacy 802.11 MAC is not fully solved. To satisfy the current need of the high-speed wireless network access, the major target of IEEE 802.11n, is to provide a high throughput mechanism based on state of art design while allowing the coexistence of legacy 802.11 devices. To meet the requirements of “high throughput”, two possible methods can be applied. The first one is to increase the data rate in the PHY layer, and the second one is to increase the efficiency in the MAC layer. Based on the foundation of 802.11a/b/g/e, many new features in PHY and MAC layers are introduced to enhance the throughput of IEEE 802.11 WLAN.

A. MIMO-OFDM physical layer

To achieve high throughput in 802.11 wireless networks, the most commonly used method is to increase the raw data rate in the PHY layer. IEEE 802.11 uses two mechanisms to increase this data rate: MIMO technology and a channel bandwidth that is twice as size (from 20 MHz to 40 MHz). IEEE 802.11n expands the channel bandwidth to 40MHz in order to increase the channel capacity. However, IEEE 802.11n operates in OFDM scheme with MIMO technique [6]. MIMO can effectively enhance spectral efficiency with simultaneously multiple data stream transmissions. In theory, channel capacity gain could be up to the number of transmitting antennas without additional bandwidth or power. The power of the MIMO system relies on using space-time coding and the channel information for intelligent transmission. Multiple antennas could help to transmit and receive from multiple spatial channels simultaneously. Multipath wireless fading channel results in poor performance in legacy 802.11 PHY scheme. Hence, 802.11n PHY applies MIMO technique to improve performance over multipath environment. With this enhancement in the PHY layer, the peak PHY rate can be boosted up to 600 Mbps to meet the IEEE 802.11n high throughput requirement.

B. Aggregation

Increasing the data rate of PHY layer alone is not enough to achieve the desired MAC layer throughput of more than 100 Mbps due to rate independent overheads. We have described the overhead in legacy IEEE 802.11 MAC, which has been partly solved by the TXOP technique introduced by the 802.11e amendment. Aggregation may further enhance efficiency and channel utilization. The aggregation mechanism combines multiple data packets from the upper layer into one larger aggregated data frame for transmission. Overhead in multiple frame transmissions is reduced since the header overhead and interframe time is saved.

In IEEE 802.11n MAC, the aggregation mechanism is designed as two-level aggregation scheme, and hence two types of aggregation frames are defined: aggregate MAC protocol service unit (A-MSDU) and aggregate MAC protocol data unit (A-MPDU). The aggregation mechanism is able to function with A-MPDU, A-MSDU, or using both of them to form two-level aggregation. A-MSDU is composed of multiple MSDUs and is created when MSDUs are received by the MAC layer. To ease the de-aggregation process, the size of a MSDU, including its own subframe header and padding, must be multiple of 4 bytes. Two parameters are used to form an A-MSDUs: the maximum length of an A-MSDU (3839 or 7935 bytes by default), and the maximum waiting time before creating an A-MSDU. Aggregated MSDUs must belong to the same traffic flow (same TID) and have the same destination and source. Broadcasting and multicasting packets are excluded.

In the second level, multiple MPDUs are aggregated into an A-MPDU, which is created before sending the MSDU (or A-MSDU) to the PHY layer for its transmission. Unlike the A-MSDU, the MAC layer does not wait for additional time before the A-MPDU aggregation. It only uses the available MPDUs in the queue to create A-MPDUs. The TID of each MPDU in the same A-MPDU might be different. The maximum size limit of A-MPDU is 65535 bytes. In an A-MPDU, each MPDU has an MPDU delimiter at the beginning and padding bytes at the end. These bytes ensure that the size of each MPDU is multiple of 4 bytes. Delimiter is used to separate the MPDUs in an A-MPDU. The de-aggregation process first checks the CRC integrity. If the CRC check is passed, the MPDU will be de aggregated and sent to upper layer.

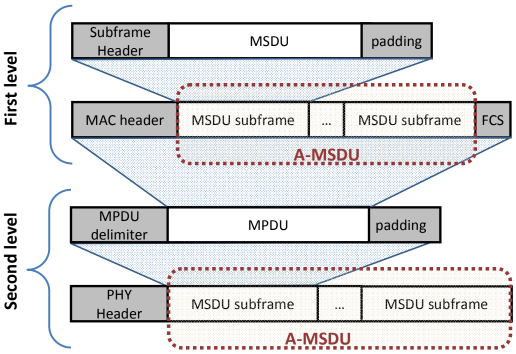


Figure 2. Aggregation in IEEE 802.11n.

The two-level aggregation mechanism is shown in Fig. 2. In the first level, MSDUs received by the MAC layer from the upper layer are buffered for a short time until A-MSDUs are formed according to their TID, destination, source, and the maximum size of A-MSDU. Then, the complete A-MSDUs and other non-aggregate MSDUs are sent to the second level to form an A-MPDU. Due to compatibility reasons, every MPDU in A-MPDU should not exceed 4095 bytes. It must be taken into account that 802.11n aggregation does not support frame fragmentation. Only complete A-MSDUs or MSDUs, not the fragments of A-MSDUs or MSDUs, could be contained in an A-MPDU. The whole aggregation mechanism completes when A-MPDU is created.

C. Block ACK

Originally, the block ACK operation incorporates the TXOP mechanism, as previously described in the 802.11e MAC design. The block ACK mechanism is further enhanced in 802.11n to be applied with the aggregation feature. Although a larger aggregation frame may significantly reduce the overhead in a transmission, the frame error rate is higher as the size of the frame increases. Large frames in a high bit-error-rate (BER) wireless environment have a higher error probability and may need more retransmissions. The network performance might be degraded. To overcome this drawback of the aggregation, the block ACK mechanism is modified in 802.11n to support multiple MPDUs in an A-MPDU. Fig. 3 shows the block ACK mechanism. When an A-MPDU from one station is received and errors are found in some of the aggregated MPDUs, the receiving node sends a block ACK which only acknowledges the correct MPDUs. The sender only must retransmit those non-acknowledged MPDUs. Block ACK mechanism resolves the drawback of large aggregation in the error-prone wireless environment and further enhances the performance of 802.11n MAC (Fig. 3).

Block ACK mechanism only applies to AMPDU, but not A-MSDU. That is, when an MSDU is found to be incorrect, the whole A-MSDU needs to be transmitted for error recovery. The maximum number of MPDUs in an A-MPDU is limited to 64 as one block ACK bitmap can only acknowledge at most 64. The original block ACK message in IEEE 802.11e contains a Block ACK bitmap field with 64 × 2 bytes. These two bytes record the fragment number of the MSDUs to be acknowledged. However, fragmentation of MSDU is not allowed in 802.11n A-MPDU. Thus, those 2 bytes can be reduced to 1 byte, and the block ACK bitmap is compressed to 64 bytes. This is known as compressed block ACK. Compared with 802.11e, the overhead of block ACK bitmap in 802.11n is reduced. Moreover, IEEE 802.11n introduces the use of implicit block ACK. With this mechanism is not necessary to request the sending of ACK block, reducing overhead.

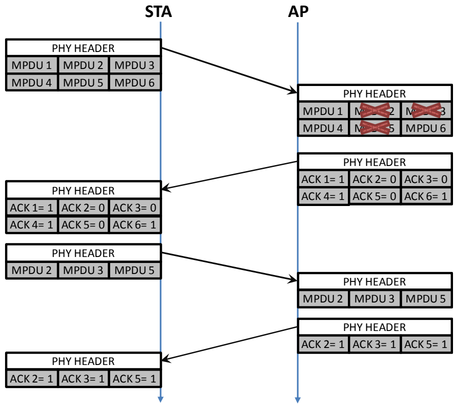


Figure 3. Block ACK with aggregation.

D. Reverse Direction

Reverse direction mechanism is a novel breakthrough to enhance the efficiency of TXOP. In conventional TXOP operation, the transmission is uni-directional from the station holding the TXOP, which is not applicable in some network services with bi-directional traffic like VoIP, videoconference and on-line gaming. The conventional TXOP operation only helps the forward direction transmission but not the reverse direction transmission. For application with bi-directional traffic, their performance is degraded by the random backoff and contention of the TXOP. Reverse direction mechanism allows the holder of a TXOP to allocate the unused TXOP time to its receivers and hence, enhancing the channel utilization and performance of reverse direction traffic flows.

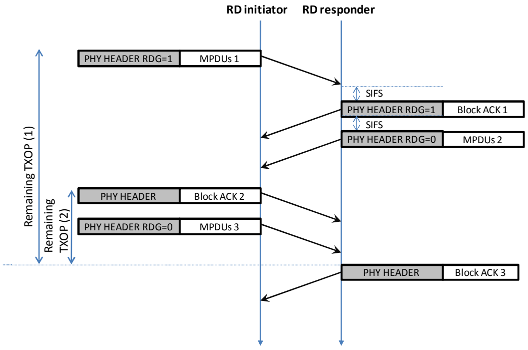


Figure 4. Reverse direction.

The reverse direction operation is illustrated in Fig. 4. In reverse direction operation, two types of stations are defined: RD initiator and RD responder. RD initiator is the station which holds the TXOP and has the right to send reverse direction grant (RDG) to the RD responder. RDG is marked in the 802.11n header and is sent with the data frame to the RD responder. When the RD responder receives the data frame with RDG, it responds with RDG acknowledgement if it has data to be sent, or without RDG if there is no data to be sent to the RD initiator. If the acknowledgement is marked with RDG, the RD initiator will wait for the transmission from the RD responder, which will start after a SIFS or a reduced inter-frame space (RIFS) once the RDG ACK is sent. RIFS can be used in the scheme when no packet is expected to be received after the transmission, which is the case here. If there is still data to be sent from the RD responder, it can mark RDG (which represents MORE DATA) in the data frame header to notify the initiator. The RD initiator still has the right to accept the request. To allocate the remaining TXOP, the initiator will mark the RDG in the acknowledge message or the next data frame. To reject the new RDG request, the initiator just ignores it.

The major enhancement of the reverse direction mechanism is the delay reduction in reverse link traffic. These reverse direction data packets do not need to wait in queue until the station holds a TXOP but can be transmitted immediately when the RD responder is allocated for the remaining TXOP. This feature can benefit a delay-sensitive service like VoIP. We will show a performance enhancement in the simulation section.

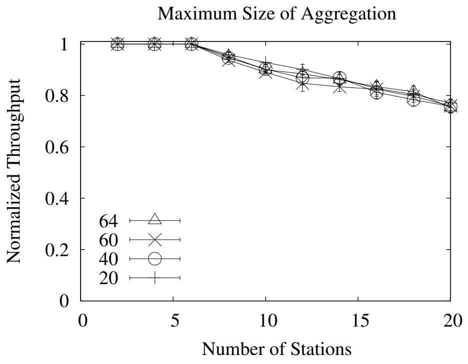
IV. PERFORMANCE EVALUATIONS

In this section, we carry out a performance analysis on the effectiveness of the IEEE 802.11n standard. We examine the major improvements introduced by IEEE 802.11n MAC: aggregation, block acknowledgement, and reverse direction. We show the impact of each parameter in the network performance.

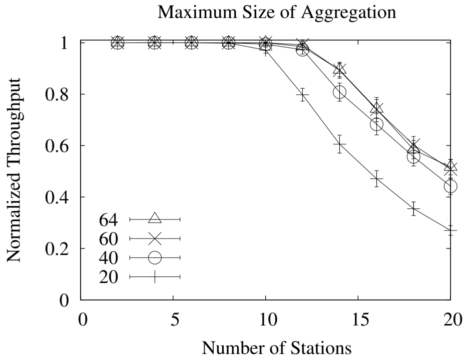
A. Scenario

In our simulations, we model an IEEE 802.11n wireless LAN using OPNET Modeler tool 10.0 [14]. We use a wireless LAN consisting of several wireless stations and an access point connected to a wired node, which serves as sink for the flows from the wireless domain. All the stations are located within a basic service Set (BSS), i.e., every station is able to detect a transmission from any other station. The parameters of the wired link have been chosen to ensure that the bandwidth bottleneck of the system is within the wireless LAN. Each wireless station operates at 300 Mbit/s IEEE 802.11n mode and we assume the use of an ideal channel. All the stations use a MIMO configuration with 2x2 antennas.

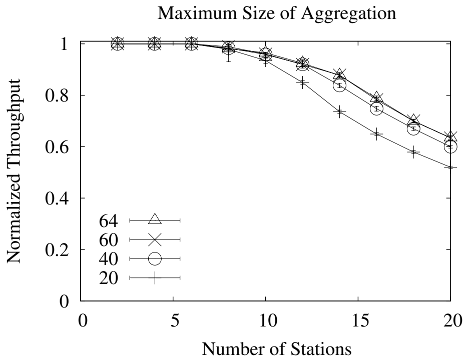
For all the scenarios, we have assumed a bi-directional and constant bit-rate application. This application has an average rate of 8 Mbps and a packet size equal to 1000 bytes. We start by simulating a WLAN consisting of two wireless stations. We then gradually increase the network load by adding the number of stations each time. We increase the number of stations 2 by 2 starting from 2 and up to 20. In this way, the offered load is increased from 32 Mbps (16 Mbps in the AP and 16 Mbps in the stations) up to 320Mbps. The traffic sources are randomly activated within of the interval [1,1.5] seconds from the start of the simulation. Throughout our study, we have simulated two minutes of operation of each particular scenario. Our measurements start after a warm-up period allowing us to collect the statistics under steady-state conditions. Each point in our plots is an average over thirty simulation runs, and the error bars indicate the 95% confidence interval.



(a) Stations



(b) AP

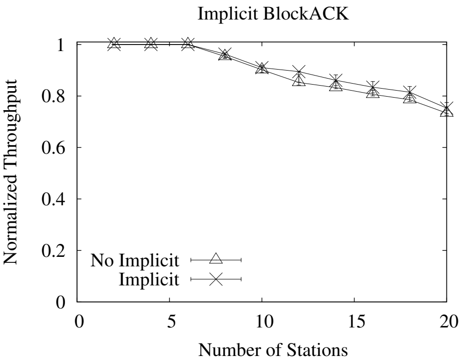


(c) Global Throughput

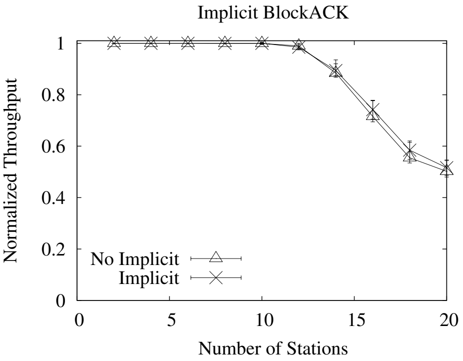
Figure 5. Performance evaluation for different sizes of aggregation.

For the purpose of our performance study we are selected the normalized throughput. The normalized throughput is calculated as the percentage of the offered load actually delivered to destination.

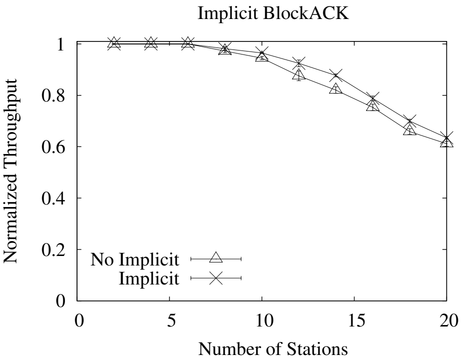
B. Results



(a) Stations



(b) AP

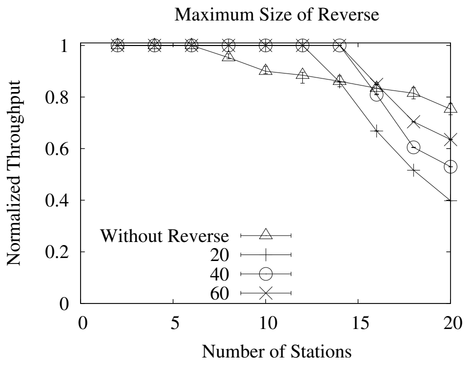


(c) Global Throughput

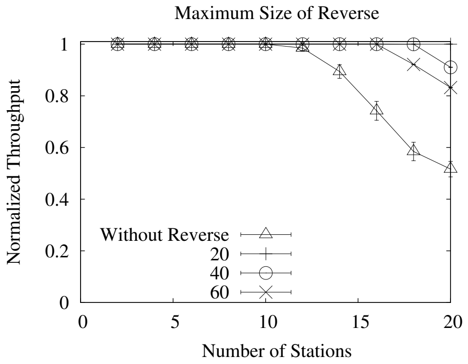
Figure 6. Performance evaluations with implicit block ACK..

Figure 5 shows the normalized throughput with different maximum size of aggregation. In this simulations we have fixed the first level of aggregation (A-MSDU) changing the second level of aggregation (A-MPDU). We evaluate several maximum sizes for the aggregated frames (20, 40, 60 and 64 packets). The figure shows that the larger the aggregation, higher performance is achieved. This improved performance is higher in the AP (see Figure 5.b). This is because the AP has more packets to transmit that the stations so the AP will use the higher size of aggregation. This result is expected since a higher aggregation size leads to a lower overhead.

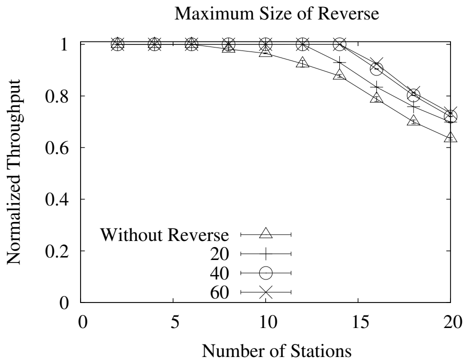
Figure 6 shows the effect of using the implicit block ACK. In these simulations, the maximum size of aggregation is fixed to 60. The figure shows that the normalized throughput increases when an implicit ACK block is used. This is due to the reduction in overhead. When the implicit block ACK is used, the station does not request confirmations.



(a) Stations



(b) AP



(c) Global Throughput

Figure 7. Performance evaluations for different sizes of reverse direction..

Finally, the impact of use the reverse direction is shown in Figure 7. This figure shows that the use of reverse direction improves network performance. This result also was expected because if bidirectional applications are transmitted, the destination station takes advantage of the TXOP that belongs to the sending station. However, the size of the reverse should not be too large, because it gives too much traffic to the destination station

V. CONCLUSIONS

We have investigated the performance of IEEE 802.11n MAC protocol. The three enhanced 802.11n MAC mechanisms: aggregation, block acknowledgement and reverse direction have been discussed. We have implemented an 802.11n module in Opnet Modeler. We designed several simulation scenarios in order to evaluate the influence of the different enhanced mechanisms. The simulation results have shown that the aggregations, implicit block ACK and reverse direction mechanisms reduce the overhead allowing an increase of the network performance.

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