Throughput Performance of Two-way Relaying in IEEE 802.11 Networks

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***Abstract*— Conventional half-duplex relaying suffers from a pre-log factor of ½ in the capacity equation which reduces the spectral efficiency significantly. On the other hand half-duplex two-way relaying, which can compensate this spectrum efficiency loss and could be a suitable substitute for conventional relaying, requires two nodes to transmit at the same time and frequency. Therefore to realise two-way relaying a modification of the current IEEE 802.11/e Medium Access Control (MAC) is necessary. In this paper we propose an appropriate MAC scheme for two-way relaying. The main objective is to investigate for realistic network configurations how much the throughput is improved by two-way and semi-two-way relaying under the proposed MAC compared to conventional relaying.**

I. Introduction

By applying relaying schemes one can enhance the coverage range of a system or increase the data rate within a given range. So far no explicit relaying function has been defined in IEEE 802.11 medium access protocols except for the cases in which an access point (AP) acts as a relay between two stations (STAs). This is indeed the only possible setup in an infrastructure mode based on the legacy IEEE 802.11 [1]. One of the main existing problems is the additional delay added by each extra hop and subsequently the degradation in the throughput. In [2] delay and throughput in a multihop IEEE 802.11 network are estimated via analytical models while in [3] throughput is studied through simulations. The authors in [4] proposed a MAC protocol to support cooperation among nodes. In [5] we proposed three different MAC schemes for relaying in wireless local area network (WLAN) based on the IEEE 802.11e [6]. In [7] we investigated the outage probability performance of two-way relaying in a WLAN and discussed the appropriate MAC scheme briefly. In this paper we extend our studies to include throughput analysis of two-way and semi-two-way relaying for realistic network configurations with different traffic load and priorities.

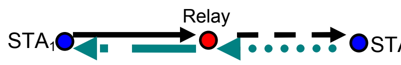
II. Contribution

We consider three different relaying methods, i.e. *two-way* (2W), *semi-two-way* (semi-2W) and *conventional* relaying as described in the next section. The last two techniques can be supported with the actual IEEE 802.11/e MAC protocols while the first one needs an extension. In this paper we propose an appropriate MAC scheme for the two-way relaying and first investigate the throughput performance of the three relaying methods in a low-loaded network having different traffic priorities. Then we study the impact of additional load and asymmetric traffic and specify the conditions/applications in which two-way relaying improves performance.

III. Scenario

We consider half-duplex *decode and forward* (DF) relays. A DF relay decodes the received data from the source and after re-encoding sends it to the destination. We consider two nodes STA_1 and STA_2 which are communicating with each other via the AP. In this case the AP acts as a relay. As it will be mentioned in section IV when non-AP STAs act as relays the MAC scheme proposed in section IV cannot be applied. We consider three relaying methods, i.e. conventional, 2W and semi-2W relaying as follows:

Conventional relaying (cf. Fig. 1): four timeslots are required to transmit data from a source to a destination and vice versa.



Timeslot	1	2	3	4
STA₁	TX			RX
Relay	RX	TX	RX	TX
STA₂		RX	TX	

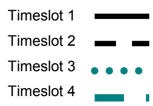
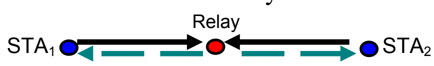


Fig. 1 Conventional DF relaying using half-duplex relays

2W relaying (cf. Fig. 2): just two timeslots are enough for the same data transmission [8]. In the first phase both nodes STA_1 and STA_2 transmit their data streams to the relay in the same timeslot (timeslot 1) and the same bandwidth. The relay, i.e., AP needs to have at least as many antennas as the number



Timeslot	1	2
STA₁	TX	RX
Relay	RX	TX
STA₂	TX	RX

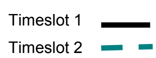


Fig. 2 Two-way DF relaying using half-duplex relays

of streams transmitted by the two STAs in order to be able to successfully decode all streams with high probability. For example in our scenario each STA_i has one antenna and transmits one stream; i.e. $\mathbf{x_i}$, to the AP while the AP has two antennas. Therefore the AP is able to decode the two received streams and transmits two streams in timeslot 2 during the second phase. This is compatible with the MIMO WLAN standard, i.e. IEEE 802.11n which allows APs to transmit up to four independent streams at the same time [9]. The received signal at the AP is $\mathbf{y_r}$:

$$\mathbf{y_r} = \mathbf{H_{r1}x_1} + \mathbf{H_{r2}x_2} + \mathbf{n_r} \quad (1)$$

where $\mathbf{H_{ri}}$ is the channel matrix between STA_i and AP for one OFDM subcarrier and $\mathbf{n_r}$ is the noise vector at the AP. In our example $\mathbf{H_{ri}}$ is a 2×1 vector. In the second phase AP can either transmit each stream from one antenna separately or combine the streams (symbol-wise or bit-wise) and in both cases multicast them to both stations. In the latter case for the single-antenna stations AP needs at least two antennas for decoding in the first phase however for the transmission during the second phase it only needs to use one of its antennas. The second antenna can also be used to improve the performance. Here we consider the first option which is the simplest setup and compatible with the IEEE 802.11n standard. In this configuration the AP transmits $\mathbf{X} = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T$ in the second phase using two antennas; e.g. x_1 from the first antenna and x_2 from the second antenna. T is the transpose operator. Assuming that each node knows which antenna in the AP is used for each stream, in the second timeslot the interference does not impair the transmission since each node knows its own transmitted signal and can cancel its back-propagating self-interference prior to decoding. Assume STA_i receives $\mathbf{y_i}$:

$$\mathbf{y_i} = \mathbf{H_{ir}X} + \mathbf{n_i} \quad (2)$$

where $\mathbf{H_{ir}}$ is the channel matrix between AP and STA_i (in our case 1×2 vector) and $\mathbf{n_i}$ is the noise at STA_i. In our example STA_1 receives $y_1 = h_{11}x_1 + h_{12}x_2 + n_1$, since STA_1 knows its own transmitted signal during the first phase; i.e. x_1 and can estimate the channel coefficients h_{11} and h_{12} it can decode with high probability (clearly depending on the level of received signal to noise ratio) the transmitted signal from STA_2; i.e. x_2.

However the current 802.11 MAC is not able to support the two-way relaying. To realise a 2W relaying scenario, two STAs have to be able to transmit at the same time and frequency during the first phase. This is not possible within the contention period (CP), because it is based on carrier sense multiple access with collision avoidance (CSMA/CA), which requires the nodes to sense the channel prior to their transmissions and thus tries to avoid collisions [1].

Semi-2W relaying: it has the same first phase as the conventional method and same second phase as the 2W. In the first phase STA_1 and STA_2 transmit the data streams to the AP in two different timeslots. In this case if each STA is equipped with one antenna the AP also needs only one antenna to decode each received data stream. Assuming a superposition coding at the AP, one antenna at the AP would be enough to transmit both streams in the third timeslot. However as we assumed that the AP is equipped with two antennas it is able to transmit each stream from one of its antennas at the same time; i.e. the third timeslot as a multicast transmission. As three timeslots are used the spectral efficiency is higher than that in the conventional relaying scheme, where four timeslots are needed, but lower than that in the 2W relaying scheme. Again perfect interference cancellation at the stations is assumed as explained before. In contrast to 2W, the semi-2W approach is nearly compatible with the existing MAC and the only necessary modification is that the AP has to wait to receive both packets from STA_1 and STA_2 and only then multicasts them to those STAs. Without any changes in the actual MAC the AP tries to access the channel as soon as it has a packet to transmit without collecting packets from two stations.

IV. MAC Schemes for Two-Way Relaying

There are mainly two different channel access methods supported by IEEE 802.11 MAC protocol [1]: the distributed mode based on CSMA/CA and the centralised method based on polling. In this paper we consider the MAC scheme defined in amendment IEEE 802.11e which enhances some of the legacy features to support quality-of-service (QoS) [6]. According to IEEE 802.11e each beacon interval may consist of contention free period (CFP) and CP. In CFP the hybrid coordinator (HC) which is collocated with the AP allocates timeslots to terminals by a polling mechanism under hybrid coordination function controlled channel access (HCCA). During CFP the HC receives add traffic stream (ADDTS) requests from non-AP QSTAs (QoS stations) and it may accept or deny the requests according to an admission control policy. In CP stations contend to get the channel according to the enhanced distributed channel access (EDCA).

Since the CSMA/CA tries to avoid collisions and within CP it is not possible to guarantee that a node transmits in a specific timeslot we assume the use of HCCA for the first phase of the 2W scheme. Prior to transmission there should be a handshake between each station and AP so that stations request from the AP for a two-way relaying setup and announce to the AP the required transmission data rate. In general the relay could be either an AP or a non-AP STA. When the relay is an AP it should poll both STAs at the same time, because then the STAs transmit simultaneously in the following timeslot (i.e. the first timeslot of the 2W relaying). However concurrent polling of two STAs requires an extension of the current IEEE 802.11e MAC. When a non-AP STA acts as relay, polling cannot be handled by the relay anymore. In this paper it is assumed that the relay is always an AP. In the second phase the AP multicasts both streams within the CP. As it will be explained in section V if the stations transmit with different data rates the AP polls them in proportion to the higher rate and whenever the station with lower transmission rate has no data packet to send, it sends a QoS (+)Null frame [6].

The semi-2W relaying can be totally handled by EDCA since during the first phase each STA transmits in a separate timeslot. However the AP needs to wait for the packets from both stations to multicast those packets afterwards.

V. SIMULATION RESULTS

For the simulations it is assumed that the nodes are perfectly synchronised and that the signal processing is performed without any error. The processing time at the AP in 2W and semi-2W scenarios is neglected.

We use QualNet [10] to simulate our scenarios. Fig. 3 shows conventional, semi-2W and 2W relaying throughput values under saturation condition when STA_1 and STA_2 communicating via an AP. Each STA transmits UDP (user datagram protocol) packets of size 512 bytes to the other one. The maximum data rate of each link is limited to 6 Mbps. The queue size at each node is large enough and there is no packet loss due to the overloaded queue. The channel is perfect and errors occur only due to collisions. The Beacons are transmitted within 100 time unit (TU) intervals while each time unit is 1024μs long. The simulation time is long enough so that all packets are transmitted. The EDCA parameter values are the ones defined for the IEEE 802.11a. In the conventional relaying mode the AP relays packets from each STA to the other one. In the semi-2W scenario each STA transmits its packet to the AP and the AP multicasts packets to STA_1 and STA_2. The channel access in both conventional and semi-2W setups are based on EDCA. In the 2W scheme the first phase is coordinated by HCCA while it is assumed that both stations transmit the first packet at the same time and the second phase is coordinated by EDCA. In our setup HC always accepts the ADDTS requests. In this paper the multicast link is always handled in EDCA mode [6]. Perfect interference cancellation is assumed at the STAs. The throughput is calculated by dividing the number of bits received at each STA_i (b_i) to the time required for the transfer (t_i):

$$S_i = \frac{b_i}{t_i} \quad \text{in which} \quad t_i = t_{li} - t_{fj} \qquad (3)$$

where t_{li} is the time when the last packet is received at STA_i and t_{fj} is the time when the first packet destined for STA_i is transmitted by STA_j. The average throughput of STA_1 and STA_2 having conventional, semi-2W and 2W relaying setups for different traffic priorities is depicted in Fig. 3. Both STA_1 and STA_2 are transmitting with the lowest priority at the first point denoted by "1" in the X-axes while they have the highest priority, i.e. priority 7 at the fourth point. As it is seen for the conventional and 2W relying the throughput is slightly improved by increasing the traffic priority because of shorter contention window and interframe spaces (IFS) in the higher priorities. However for semi-2W scheme higher priorities result in a slightly lower throughput. This is due to the fact that shorter backoff causes more collisions and in the Semi-2W setup the transmission in the second phase is performed as multicast which in contrast to the unicast (e.g. in conventional relaying) has no MAC-level recovery [1]. In the 2W scenario the situation is different; due to use of HCCA in the first phase only the second phase transmission (multicast packets) is handled during the CP and the AP does not need to compete with any other node for the data packet transmission. Essentially higher priorities in a loaded network with a large number of nodes competing for the same channel may degrade the system performance compared to the same system with lower traffic priorities due to more collisions occurred [11].

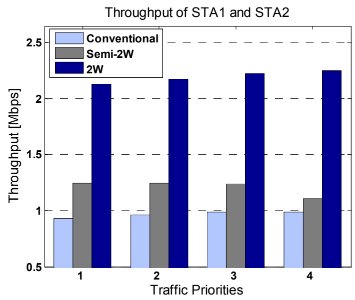


Fig. 3 Throughput of conventional, semi-2W and 2W relaying

From now on we consider the setup for the 3rd group, i.e. STA_1 and STA_2 have a traffic priority of 4 (which belongs to the third access category: AC_VI [6]). For the 2W scheme as the first phase is coordinated by HCCA and its second phase by EDCA, the controlled access phase (CAP) duration is an important parameter. CAP is defined as a time period when the HC maintains control of the medium [6]. In Fig. 3 the CAP duration was set to 60 TU. In Fig. 4 average throughput of STA_1 and STA_2 having different values for maximum CAP is depicted. It is clearly seen that allocating only a small fraction of the beacon interval to HC delays the first phase and consequently the second phase of 2W relaying. On the other hand by increasing this parameter the second phase is deferred. As it is seen in our scenario a maximum CAP with length of 60 TU is large enough. We choose this value as the maximum value for CAP throughout this paper.

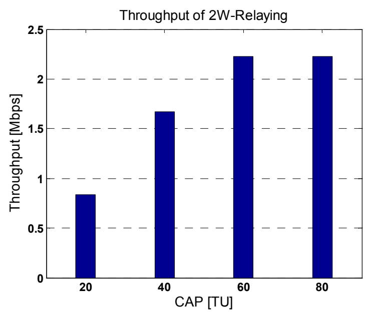


Fig. 4 2W relaying throughput for different maximum duration of CAP with beacon interval of 100 TU

A. *Impact of Additional Traffic*

So far we considered a low loaded network consisting of only two stations associated to one AP. To investigate the performance of different relaying methods in a realistic environment we extend our scenario to cases in which in addition to the STA_1 and STA_2 there are 4, 8 or 12 extra STAs associated to the same AP. The total traffic load is kept the same for all four cases. Again STA_1 and STA_2 transmit to each other UDP packets of size 512 bytes via the AP as explained before. We consider two scenarios:

***Scenario A* - Background traffic:** extra nodes transfer background traffic with the lowest priority (access category of background, AC_BK [6]) under EDCA. During the transmission between STA_1 and STA_2 each extra node transmits packets of size 512 bytes to the AP directly (single-hop transmissions). Considering again STA_1 and STA_2 we depicted in Fig. 5 their average throughput under saturation condition when they communicate with each other in the conventional, semi-2W and 2W relaying modes as explained earlier. As it is seen by increasing the number of nodes with background traffic, the throughput of all relaying methods only slightly decreased. The reason is that STA_1 and STA_2 communicate with a higher priority than other nodes and as a result their performance is not much influenced by other

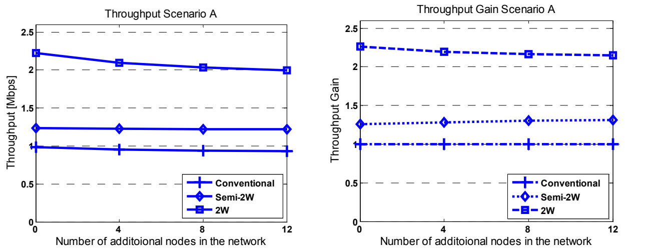


Fig. 5 Throughput (left plot) and throughput gain of semi-2W and 2W to conventional relaying (right plot) for STA_1 and STA_2 vs. number of additional nodes in scenario A

nodes. However in this setup the lower-priorities nodes highly suffer from low throughput.

To be able to compare different relaying methods better we have also depicted the throughput gain of semi-2W and 2W to conventional relaying as defined in the following equation (Fig.5 right-hand side plot). We calculate the throughput gain *G* by dividing average throughput of STA_1 and STA_2 in the semi-2W and 2W at each point to that in the conventional relaying mode:

$$G = \overline{R_{12-j}} / \overline{R_{12-\text{conventional relaying}}}, \qquad j=\text{semi-2W, 2W} \qquad (4)$$

where $\overline{R_{12}}$ is the average throughput of STA_1 and STA_2. The gain is slightly larger than 2 for the 2W and around 1.3 for semi-2W method. It is important to note that the performance gain is impacted not only by relaying method but also by multicast which has less signalling overhead, and by coordination function features. In contrast to conventional and semi-2W relaying which have totally been handled under EDCA the 2W method benefits from HCCA during the first phase. It is also important to note that the process time at the AP between the first and second phase has been neglected in semi-2W and 2W models.

***Scenario B* - Large relayed traffic:** now we investigate performance of different relaying methods when each node in the network has a two-hop traffic using the AP as relay. Each extra node transmits the same type of packets as in scenario A this time to one of the non-AP stations in the same way as STA_1 and STA_2 communicate with each other; i.e. with the same priority as well as same relaying technique. This is done by having once the conventional relaying and other times the semi-2W and the 2W structure for all STAs. In the semi-2W case STA_k transmits the data stream intended for STA_{k+1} to the AP and STA_{k+1} transmits the data stream intended for the STA_k to the AP. Afterwards the AP multicasts the received streams from STA_k and STA_{k+1} back to themselves. In the 2W setup the AP polls STA_k and STA_{k+1} simultaneously during the first phase and then multicasts the packets back to STA_k and STA_{k+1}. Scenario A modelled networks which include both two-hop as well as single-hop transmissions with low-priority traffic while scenario B represents a pure relaying setting (e.g. communication between each pair of STAs which are associated to the same AP).

Fig. 6 shows the throughput (left-hand plot) and the throughput gain, *G*, as defined in Eq. 4 (right-hand plot). As it is expected by increasing the number of nodes the throughput in all three methods is reduced. However the pure 2W and semi-2W network outperform the pure conventional relaying setup even for a large number of nodes. Comparing the three schemes shows a gain factor of about 1.19 to 1.25 for the semi-2W and about 2.25 to 2.35 for the 2W compared to the conventional relaying. As it has been mentioned before contrary to conventional and semi-2W methods in the 2W scheme in the first phase each node transmits packets within CFP and consequently AP does not need to compete for the

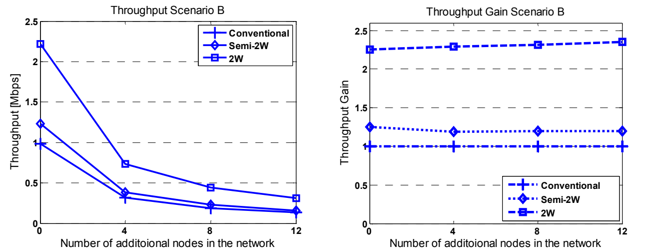


Fig. 6 Throughput (left plot) and throughput gain of semi-2W and 2W to conventional relaying (right plot) for STA_1 and STA_2 vs. number of additional nodes in scenario B

channel during the CP with any other node.

B. Impact of Asymmetric Traffic

So far we considered symmetric traffic under saturation condition, i.e., STA_1 and STA_2 transmitted same amount of packets with same data rate to each other and the rate was large enough to bring the network in the saturated condition.

To investigate how 2W relaying handles an asymmetric traffic case and compare it with the conventional relaying case we consider the following scenario. STA_1 transmits P_1=20000 UDP packets of 512 bytes size with the data rate R_1 of 2.56 Mbps to the STA_2 while STA_2 transmits P_2 UDP packets of size 512 bytes with data rate R_2 less than R_1 to the STA_1. R_1/R_2 is a positive integer and number of transmitted packets by STA_2 is chosen in a way that $P_1/R_1 = P_2/R_2$. For example when STA_2 transmits packets with data rate of 1.28 Mbps it transmits only P_2=10000 packets. The left-hand side plot in Fig. 7 shows the throughput of STA_1 and STA_2 having conventional relaying as the relaying method versus ratio of R_1 to R_2. The throughput is calculated as defined in Eq. 3 in the receiver side. As it is shown by decreasing the transmission rate of STA_2, STA_1 is able to access the channel more often and consequently transmits with a higher rate. In other words the received throughput at STA_2 improves. As expected the throughput at STA_1 is limited by the transmission rate at STA_2. It is important to note that in this scenario we do not have saturation condition anymore.

Fig. 7 right-hand side plot shows the same scenario but for the 2W relaying scheme. In this case the AP polls both STAs with a rate proportional to the higher rate but as one STA transmits with a lower rate AP's multicast rate is limited by the lower rate. As there are more packets transmitted from STA_1, AP multicasts only P_2 packets and unicasts the rest of the packets; i.e., P_1-P_2 packets, directly to STA_2 with a rate R which is adapted to R_1-R_2.

As it is shown the 2W relaying has used the resources more efficiently from the beginning (e.g. R1/R2 of 2 or 3). The small difference between the throughputs at the point with R_2=0 (R1/R2 goes to infinity) comes from a different model and channel coordination functions in the 2W and the conventional relaying case.

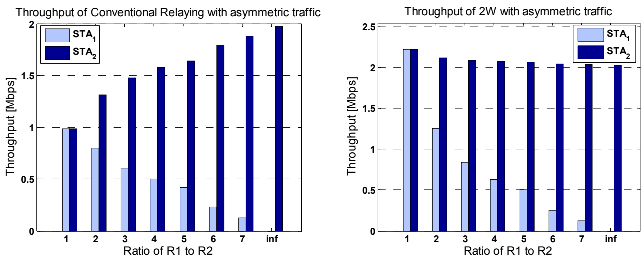


Fig.7. Throughput of STA_1 and STA_2 with asymmetric traffic for conventional relaying (left plot) and 2W relaying (right plot)

In the considered scenarios the 2W relaying has shown better throughput performance than the conventional relaying. However it is important to note that in this paper we assumed a perfect synchronisation and signal processing and the asymmetry is introduced only with having different data rate requirements. Asynchronous transmission might have significant impact on the outcomes. In practice asymmetry may occur due to many different factors. For example due to different applications the packet size or the coding types can be different. The channel status can also introduce the asymmetry to the system. For example one side might suffer from a weaker channel and might transmit with a more robust modulation and consequently lower rate. In [7] we looked at the outage probability for an asymmetric scenario in which STA_2 had a larger distance to the AP than STA_1 and we could improve the outage probability by a proper power allocation at the AP.

Another restriction is that in a WLAN, the 2W relaying is only suited for the transmissions among the nodes which are in the same basic service set (BSS) and cannot be applied to the nodes which communicate via different APs over the backbone. It is also important to note that the proposed MAC scheme for the 2W relaying can be applied only when the relay is a QoS-AP. Besides in this paper we assumed that the relay has a large buffer and we did not analyse the time a certain packet stays in a buffer, but this delay in highly loaded networks may increase and consequently relaying in such a scenario might not be appropriate for delay critical applications.

VI. Summary

In this paper we evaluated the proposed MAC schemes for 2W and semi-2W relaying by investigating the throughput values. In order to investigate the conditions in which 2W relaying is an appropriate alternative, we estimated throughput for the 2W, semi-2W and conventional relaying methods having different traffic priorities and network loading with symmetric and asymmetric links. The performance is affected not only by different access schemes but also by multicasting in which the transmission is not as reliable as unicasting. In general for the bi-directional links even in a highly loaded network the spectral efficiency of 2W and semi-2W relaying is higher than that of the conventional relaying. For the considered setups the throughput gain remained almost the same for different amount of load in the network. Compared to the conventional relaying method the cost of 2W relaying will be the required MAC modification, extra antenna in the AP and self interference cancellation feature at the STAs. The last two requirements are provided in a MIMO WLAN system based on IEEE 802.11n. Further work is required to investigate the impact of imperfect synchronisation and delay.

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