Cooperative Relaying In Wireless User-Centric Networks

Tauseef Jamal, Paulo Mendes

[1]

Abstract An ever-growing demand for pervasive Internet access has boosted the deployment of wireless local networks in the past decades. Nevertheless, wireless technologies face performance limitations due to unstable propagation conditions and mobility of devices. In face of multi-path propagation and low data rate stations, cooperative relaying promises gains in performance and reliability. However, cooperation procedures are unstable (dependency upon current channel conditions) and introduce overhead that can endanger performance, especially when nodes are mobile. In this paper we describe a novel protocol, called RelaySpot, able to implement cooperative relaying in dynamic networks, based upon opportunistic relay selection, and cooperative relay scheduling and switching. RelaySpot removes the need for estimation and broadcast of channel conditions, and is expected to improve the utilization of spatial diversity, minimizing outage and increasing the transmission capacity of wireless local networks.

Key words: Opportunistic Relay Selection, Cooperative Relay Scheduling, Cooperative Relay Switching, Wireless Resource Management, Space-Time Diversity.

1 Introduction

Over the past decade, Internet access became essentially wireless, with 802.11 technologies providing a low cost broadband support for a flexible and easy deployment.

Copelabs, University Lusofona, Lisbon, Portugal

However, channel conditions in wireless networks are subjected to interference and multi-path propagation, creating fading channels and decreasing the overall network performance [3]. While fast fading can be mitigated by having the source retransmitting packets, slow fading, caused by obstruction of the main signal path, makes retransmission useless, since periods of low signal power last for the entire duration of the transmission.

Cooperative networking can mitigate wireless performance constraints at the MAC layer. Cooperation occurs when overhearing nodes assist the communication between source and destination, by relaying different copies of the same frame from different locations, generating spatial diversity that allows the destination to get independently versions of the frame sent by the source. Hence, cooperative relaying allows a destination to get good frames with high probability. If all copies are corrupted, they can still be combined at the destination in order to obtain an error-free frame.

The development of cooperative relaying raises several research issues, including the performance impact on the relay itself, and on the overall network, leading to a potential decrease in network capacity and transmission fairness. Such research issues can be influenced not only by fading, but also by other performance constrains in wireless networks, such as the distance at which wireless nodes are from Access Points (APs), as well as the mobility of such nodes [8].

Due to the distance to an AP, a wireless node can observe a bad channel as compared to other nodes that are closer to such AP, leading to the use of 802.11 rate adaptation schemes. Figure 1 illustrates the transmission characteristics of wireless

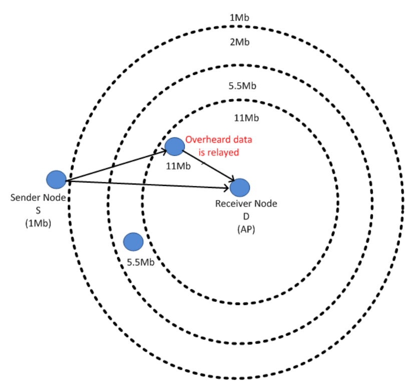

Fig. 1 802.11 rate adaptation and cooperative relaying.

nodes, as a result of the rate adaptation functionality of IEEE 802.11: nodes closer to the AP transmit at high data rates, while nodes far away from the AP decrease their data rate after detecting missing frames. Figure 1 also illustrates the role that cooperative relaying may have increasing the performance of the overall wireless network, helping low data rate nodes to release the wireless medium sooner, helping high data rate nodes to keep the desirable performance, and allowing the network to achieve a good overall capacity.

The problems posed by the presence of low data rate nodes are magnified in mobile scenarios, since the data rate of nodes change over time, due to their mobility, requiring faster and more accurate selection of potential relays. However, the selection of a helper can be problematic, since potential relays are also mobile, which means that their relaying conditions may change over time. This requires relaying methods able to switch among relays to make a better use of spatial diversity.

In this paper we present a cooperative relaying MAC protocol, called RelaySpot, that is able to mitigate the problems posed by shadowing and by the presence of low data rate nodes. In a clear breakthrough in relation to prior art, the proposed relaying protocol is aware of the mobility of potential relays, leading to an increase in the performance of dynamic wireless local networks.

With RelaySpot, wireless networks do not need complicated distributed routing algorithms, as in ad-hoc network to extend the coverage of wireless local networks, due to its capability to switch among relays as mobility patterns change over time. With RelaySpot, standard 802.11 networks are able to offer ubiquitous high data rate coverage and throughput, with reduced latencies.

The paper is organized as follows: Section II describes related work. In section III we describe RelaySpot, while section IV illustrates its operation. Section V presents the performance evaluation. Section VI presents a summary of our findings and our conclusions.

2 Related Work

With the purpose of offering effective and efficient interaction between the physical and higher protocol layers, research on cooperative communication has been exploring the MAC layer [9]. Cooperative relaying, at the MAC layer, comprises two phases: relay selection and cooperative transmission. In the first phase a relay or group of relays are selected, while in the latter phase the communication via relay(s) takes place. The relays can be selected either by the source (source-based), the destination (destination-based), or by the relay itself (relay-based). Node mobility can greatly affect the cooperative transmissions and the selection of the relays due to additional overhead (due to relay failure). The mobility of wireless nodes should be taken into consideration when developing cooperative MAC protocols, in order to minimize such additional overhead and to maximize cooperation gain. However, the impact of node mobility on cooperative relaying has not been addressed in the literature.

For a better analysis of cooperative relaying, we can split current proposals into two classes of cooperative MAC protocols: proactive and reactive. In proactive relaying the source, the destination or a potential relay replaces a slow direct communication with a faster relaying communication, aiming to improve the transmission performance. In the case of reactive relaying, relays forward data to the destination when the direct communication fails, avoiding retransmissions.

Source-based relaying approaches require the source to maintain a table of Channel State Information (CSI) that is updated by potential relays based upon periodic broadcasts. As an example, with CoopMAC [14], the source can use an intermediate node (called helper) that experiences a good channel with the source and the destination. Based on the CSI broadcasted by potential helpers, the source updates a local table (cooptable) used to select the best relay for each transmission. Another example of source-based relaying is CODE [17], which uses multiple relays based on network coding. If nodes find that they can transmit data faster than the source, they add the identity of the source and the destination to their willingness list. Once the source finds its address on the willingness list of potential relay(s), it adds those relay(s) into its cooperative table. In general source-based approaches undergo two main problems: channel estimation and periodic broadcasts, which introduce overhead that is problematic in mobile scenarios. These problems are mitigated with RelaySpot, whose behavior was previously compared to CoopMAC, highlighting its operational advantages [12].

The relay enabled DCF (rDCF) protocol developed by Zhu and Cao [4] based on DCF is an example of destination based proactive relaying. In this protocol relays maintain a willingness list that contains the identifiers of the source-destination pairs that a relay can help. Periodically, each potential relay advertises its willingness list, and the source picks a relay from such list. rDCF proposes a triangular handshake mechanism used by the destination to select a relay based on a set of *Relay Requests to Send* messages sent by the source and the relay: these messages allow the destination to get information about the quality of the source-relay and relay-destination channels. rDCF has poor performance in the presence of messages with small payload, due to its relatively high overhead, and increases the probability of collisions, situation that does not occur with RelaySpot. Enhanced relay-enabled DCF (ErDCF) [1] inherits some characteristics of rDCF such as triangular handshake. But it uses short Physical Layer Convergence Protocol (PLCP) preamble for dual-hop cooperative transmission, which provides higher throughput and reduced blocking time. In ErDCF the data frame forwarded by a relay includes the duration field, which can minimize the collision risks. However, it increases the frequency of periodic broadcast, which increases overhead.

While the mentioned proactive approaches rely upon broadcast, Opportunistic Relay Protocol (ORP) [13] does not. It also does not rely on CSI for relay selection: the source opportunistically makes a frame available for relaying and all potential relays try to forward that frame. ORP is similar to RelaySpot in the sense that both do not rely on CSI for relay selection. However with ORP the source does not know the availability of relays, and therefore, it does not know the rate of the source-relay and relay-destination channels, leading to poor relay selection. With RelaySpot the destination is aware of the relay diversity, as well as the rates of the used links.

Reactive cooperative methods such as PRO [15] rely on relays to decide to retransmit on behalf of the source when the direct transmission fails. With PRO [15], relays are selected among a set of overhearing nodes in two phases: the first phase leads to the identification of qualified relays; in the second phase, qualification information is broadcasted, allowing qualified relays to set scheduling priorities. Contrary to RelaySpot, PRO presents a high probability of collision, as well as low efficiency in mobile scenarios due to CSI measurements.

In general, our analysis of related work shows that proactive and reactive approaches have their pros and cons. RelaySpot combines reactive and proactive mechanisms to avoid CSI estimation and broadcasts, and to reach low probability of collision, and good selection of relay communication (due to awareness about the data rate of the source-relay and relay-destination links). Moreover most of the prior art only considers relaying in static wireless scenarios. There are some approaches (e.g. CoopMAC and PRO) whose performance is evaluated also in mobile networks, but they are still agnostic of the mobility patterns of the involved nodes. To the best of our knowledge, RelaySpot is the first cooperative MAC protocol that is able to augment the performance of dynamic wireless networks, by being aware of the level of mobility of potential relays, combining it with an analysis of interference and transmission success rate.

3 RelaySpot MAC Protocol

RelaySpot is a hybrid cooperative relaying protocol where relays self-elected under cooperation conditions are used to increase the performance of active transmissions (proactive behavior) or to replace failed transmissions (reactive behavior). RelaySpot comprises three building blocks: opportunistic relay selection; cooperative relay scheduling; cooperative relay switching [7, 11].

In order to be applied to dynamic scenarios, and unlike previous work, RelaySpot does not require the maintenance of CSI tables, avoiding periodic updates and consequent broadcasts. The reason to avoid CSI metrics is that accurate CSI is hard to estimate in dynamic networks, and periodic broadcasts would need to be very fast to guarantee accurate reaction to channel conditions in such scenarios.

Moreover, relay selection faces several optimization problems, meaning that the best relay may be difficult to find. Hence, for dynamic scenarios, the approach followed by RelaySpot is to make use of the best possible relaying opportunity, and to switch between relays qualified within the cooperation area, if necessary.

With RelaySpot each session competing for the wireless medium is identified by a source-destination pair. The destination node is assumed to be reachable via the direct link or via one-hop relay. During the lifetime of a session, the destination dynamically selects the best qualified relay, from the set of self-elected relays, aiming to maximize the network utility in terms of throughput and latency.

We make the following assumptions during development of RelaySpot protocol:

- Single-channel: to keep RelaySpot simple, we consider that all nodes are using the same wireless channel. Interference is not handle by switching wireless channels, which would bring more delay and performance uncertainty, but by relay switching, selecting relays with a low interference factor.

- One-hop relaying: the current usage scenario is of a wireless local network with one access point and several mobile stations, which can act as source of data, as a relay, or both simultaneously. The usage of multiple chained relays, as a simpler alternative to layer-3 routing will be investigated in the future, as a solution to expand wireless coverage and increase the utility of a relay.
- Simultaneous access to a channel: Multiple sessions are allowed to access the channel at any given time, including the ones that are being relayed, which increases the wireless interference. To mitigate the effect of interference, dynamic switching among qualified relays is implemented aiming to exploit the utility of each relay, ensuring that RelaySpot is able to increase the utility of the overall network, and not only of specific links.
- Multiple relay selection: Each node can be self-elected as relay for more than one session at the same time. Moreover, one communication session can be helped by one or more relays in each moment in time, leading to a system with wireless diversity of one or higher. If the destination selects more than one relay for a single session (diversity > 1) and gets corrupted frames from all relays, in a worse case scenario, it can perform frame combination in order to create a good frame. In this paper we consider a diversity of one during the experimental evaluation.

In the following, the components of RelaySpot are described followed by the formats used for frames.

3.1 Components

In the following, RelaySpot's building blocks are explained. First the relays are selected opportunistically, and then the destination schedules the potential relays for the following transmissions. If there are other better relays, then the relays can be switched.

3.1.1 Opportunistic Relay Selection

Relay selection is a challenging task, since it greatly affects the design and performance of a cooperative network. However, relay selection may introduce extra overhead and complexity, and may never be able to find the best relay in dynamic scenarios. Hence, the major goal of RelaySpot is to minimize overhead introduced by cooperation, with no performance degradation, by defining an opportunistic relay selection process able to take advantage of the most suitable self-elected relay.

This section describes the functionality proposed to allow self-elected relays to avoid high interference and to guarantee high data-rates to a destination, while preventing waste of network resources. Relay selection is performed in three steps: First, each node checks if it is eligible to be a relay by verifying two conditions, overheard a good frame sent by the source and be positioned within the so called cooperation area; Second, eligible nodes start the self-election process by computing their selection factor; Third, self-elected relays set their CW based on their selection factor, and send a qualification message towards the destination after the contention window expires, as shown in Figure 2. In [2] these steps are refered as negotiation phase, where the qualifications and elegibility of helping nodes (relays) are processed.

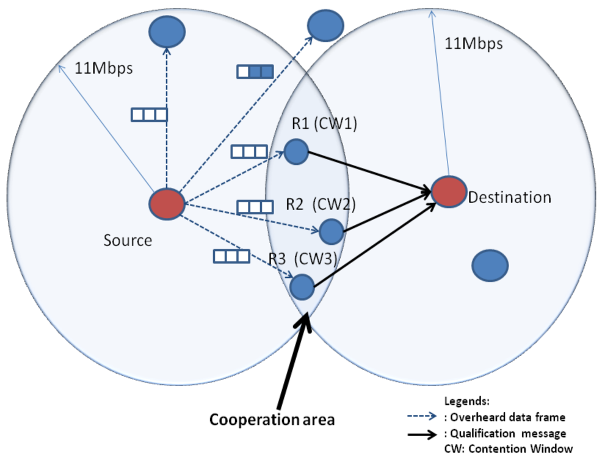

Fig. 2 Opportunistic relay selection.

The relay selection process is only executed by nodes that are able to successfully decode frames sent by a source. These relays start by verifying if they are inside the cooperation area by computing their Cooperation Factor (CF) as given in Equation 1, where R_{sr} is the rate of the source-relay channel, and R_{rd} of the relay-destination channel rate. The rate of the source-relay and relay-destination channel is computed by overhearing RTS and CTS frames exchanged between source and destination. The CF ensures that potential relays are closely bounded with the source while having good channel towards the destination: an eligible relay must have a CF that ensures a higher data-rate than over the direct link from source to destination.

$$CF = (R_{sr} * R_{rd}) \,/\, (R_{sr} + R_{rd}),\ CF \in [0,\infty[\quad (1)$$

The qualification of a node (that is able to decode the source frame and is within the cooperation area) as a relay depends solely upon local information related to interference (node degree plus load), mobility and history of successful transmissions towards the specified destination.

Node degree, estimated by overhearing the shared wireless medium, gives an indication about the probability of having successful relay transmissions: having information about the number of neighbors allows the minimization of collision and blockage of resources. However, it is possible that nodes with low node degree are overloaded due to: i) local processing demands of applications (direct interference); ii) concurrent transmissions among neighbor nodes (indirect interference). Hence, RelaySpot relies upon node degree and traffic load generated and/or terminated by the potential relay itself, to compute the overall interference level that each potential relay is subjected to.

Equation 2 estimates the interference level that a potential relay is subjected to as a function of node degree and load. Let N be the number of neighbors of a potential relay, T_d and T_i the propagation time of direct and indirect transmissions associated to the potential relay, respectively, and N_i and N_d the number of nodes involved in such indirect and direct transmissions. Adding to this, T_p is the time required for a potential relay to process the result of a direct transmission. The interference factor (I) affecting a potential relay has a minimum value of zero corresponding to the absence of direct or indirect transmissions.

$$I = \sum_{j=1}^{N_d} \left(T_{dj} + T_{pj}\right) + \sum_{k=1}^{N_i} T_{ik}, \; I \in [0, \infty[\tag{2}$$

Figure 3 shows a scenario where a node R is selected as a potential relay for nodes S and D. Node $N1$ is the direct neighbor of node R, while there are several other indirect neighbors ($N2$,$N3$,$N4$, X). Apart from R, node X also seems to be a relay candidate due to its low interference level. But it may be difficult to select R or X due to the similar interference levels: while R has a short transmission from a neighbor and a long transmission from the source, X is involved in an inverse situation. The selection of R or X as a relay can be done based on two other metrics of the RelaySpot framework: history of successful transmissions towards destination; stability of potential relays.

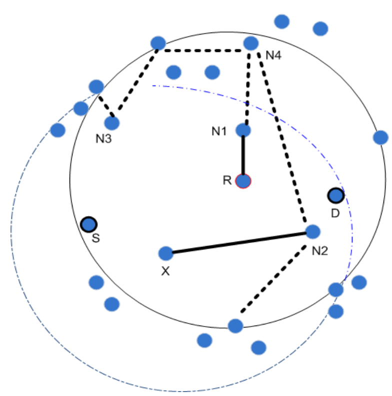

Fig. 3 Opportunistic relay selection: example scenario.

The goal is to select as relay a node that has low interference factor, which means few neighbors (ensuring low blockage probability), and fast indirect and direct transmissions (ensuring low delays for data relaying).

By using the interference level together with the history and mobility factors, the probability of selecting a node as a relay for a given destination is given by Equation

3: the Selection Factor (S) is proportional to the history of successful transmissions that a node has towards the destination and its average pause time, and inversely proportional to its interference level.

$$S = \frac{H * M}{1 + I}, \ S \in [0, 1[\tag{3}$$

The History Factor (H) is the ratio between the number of successful transmissions and the total number of transmissions towards destination, as given by Equation 4:

$$H = \frac{N_{successful}}{N_{total}}, \ H \in [0, 1[\tag{4}$$

If self-elected to operate as a relay, the node computes its CW, as shown in Equation 5. The CW plays an important role in scheduling relay opportunities. The goal is to increase the probability of successful transmissions from relays to the destination by giving more priority to relays that are more closely bounded to the destination, have less interference and have higher pause times.

$$CW = CW_{\min} + (1 - S)(CW_{\max} - CW_{\min}) \tag{5}$$

From a group of nodes that present good channel conditions with the source, the opportunistic relay selection mechanism gives preference to nodes that have low degree, low load, good history of previous communication with the destination, as well as low mobility. In scenarios with highly mobile nodes, opportunistic relay selection is expected to behave better than source-based relay selection (e.g., CoopMAC), since with the latter communications can be disrupted with a probability proportional to the mobility of potential relays, and relays may not be available anymore after being selected by the source.

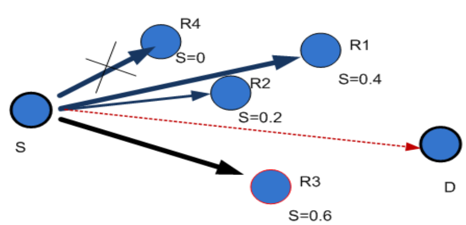

Fig. 4 Opportunistic relay election.

3.1.2 Cooperative Relay Scheduling

As illustrated in Figure 4 the selection mechanism may lead to the qualification of more than one relay (R1, R2, R3), each one with different values of *S*, leading to different sizes of CW (e.g., R3 transmits first). Selected relays will forward data towards the destination based on a cooperative relay scheduling mechanism.

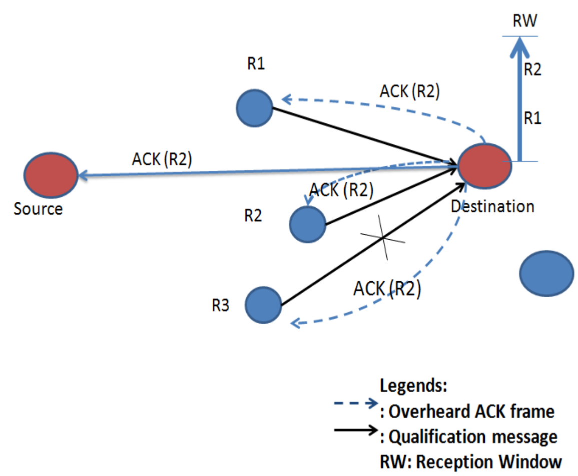

Fig. 5 Relay scheduling: example scenario.

Based on the CF (*i.e.,* R_{sr} and R_{rd}) of the qualification messages received from all self-elected relays, the destination estimates which of the involved relays are more suitable to help in further transmissions. To get multiple qualification messages the destination only processes the received qualification messages after a predefined time window, i.e., Reception Window (RW). As shown is Figure 5 the size of the reception window is of major importance, since it will have an impact on the number of qualification messages that will be considered by the destination.

After the expiration of the reception window the destination processes all the received qualification messages based on their received signal strength (R_{rd}) and R_{sr} (R_{sr} is carried by QM). Depending on the configured diversity level the destination will select one or more relays to help the current transmission. If diversity is set to one, the destination sends an ACK frame to the source including the ID (i.e., MAC address) of the selected relay, which will continue sending the frames to the destination.

When the destination is configured to operate with a diversity higher than one, the destination sends an ACK frame to the source including the MAC addresses of the selected relays. During data transfer, the destination sends the received data to the application as soon as a correct frame arrives from any of the selected relays. If the selected relays start sending corrupted frames (e.g., because they moved to a faraway position) the destination waits until a good frame is received, until it received data from all selected relays, or until a predefined timeout occurs. If the destination only got corrupted frames it will try to combine them to create a good frame. If such process is possible, the destination will send an ACK to the source including the MAC addresses of the relays that sent the frames which combined produced a good frame. As shown in Figure 6, where the primary relay R3 fails to relay the frame.

In this paper we consider a diversity of one during the experimental evaluation, which means that the transmission is diverted by the source to a unique relay selected by the destination.

RelaySpot solution (in proactive mode) is destination based, because the destination chooses the best set of relays via scheduler. In reactive mode (i.e., reaction to a failed link), the scheduler is not used, because the relay only forwards the failed data frame on behalf of source. Therefore, RelaySpot in reactive mode is relay-based, because decision about cooperation initiation and selection is taken on relays.

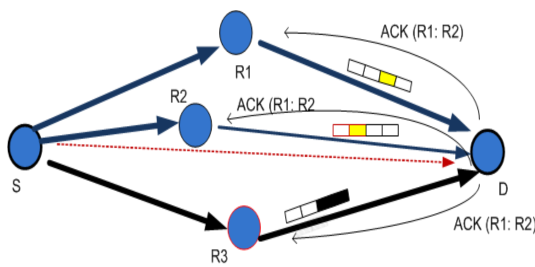

Fig. 6 Frame combining at destination by scheduler.

3.1.3 Relay Switching

Since relays are selected opportunistically, based on local information, there is the possibility that the best relay will not be able to compute a small contention window, losing the opportunity to relay the frame. In order to overcome this situation, as well as to support the failure of selected relays, RelaySpot includes a relay switching operation.

All potential relays are able to compute their own CF, as well as the CF of the selected relay. The former is possible by overhear the ongoing RTS/CTS, which are used to compute the cooperation factor from the signal quality. The CF of the currently selected relay can be computed based on its source-relay and relay-destination data-rate, that any other potential relay can collect by overhearing data and ACK frames.

If a potential relay is not selected in the relay selection procedure, it compares its CF with the CF of the selected relay. If its CF is better, which means that it can provide better gain, it sends a Switching Message (SM) to the destination, by means of a dummy data frame, informing it about its own CF. This way the current relay can be switched to the newly selected relay, since: i) by overhearing the frame sent by the new relay, the source will send the next data frame towards that relay: ii) by receiving the frame sent by the new relay, the destination knows that the next data frame will be sent by it.

Relay switching is suitable for dynamic scenarios where a previously selected relay may not be efficient at some stage, due to mobility, fading, or obstacles, for instance. Hence, unlike prior-art, relay switching can overcome such variations in network conditions making the deployment of cooperative relaying possible for dynamic networks.

While the use of relay switching can be used to improve the performance of a communication, by replacing a good relayed transmission by a better one, relays can be switched implicitly when a potential relay detects a missing ACK for an already relayed communication. In this situation, the relays try to forward the overheard data frame on behalf of the relay that failed the transmission. If successful, the destination notifies the source about the MAC ID of the new relay within and ACK frame.

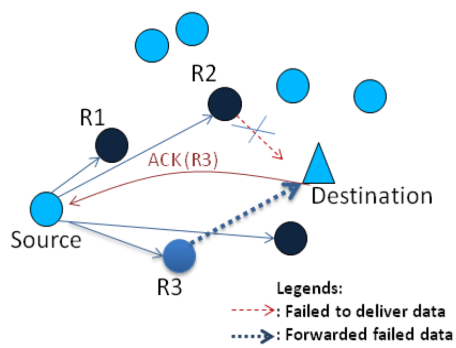

Fig. 7 Relay switching due to failure of current selected relay.

Figure 7 shows an example of implicit relay switching, where a previously selected relay, R2, fails to relay data to the destination. In this case, instead of retransmitting the failed data and re-selecting the relays, another potential relay (in this case R3) that has better cooperation factor than R2 reserves the channel for sending the failed data frame to the destination. If it is successful, the destination sends an ACK frame with indication of R3 as relay. This way the source switches from R2 to R3 starts from the next data frame.

3.2 Frames

After associating with an AP, nodes start by sending RTS/CTS frames to gain access to the shared medium, and all nodes start listening for control and data frames sent out by others on the shared channel: the overhearing process is required by 802.11's

DCF mechanism as all nodes in the network need to correctly update their Network Allocation Vector (NAV). In RelaySpot, potential relays are self-elected based on the state of data transmission from nodes to AP (destination). In the remaining of this section, we explain how RTS, CTS, DATA and ACK frames are used by RelaySpot.

As mentioned before, RelaySpot does not require any new frame, making use of the RTS, CTS, DATA and ACK frames already specified by the 802.11 standard. To ensure standard compatibility, the generic 802.11 frame structure is considered by RelaySpot (c.f. Figure 8).

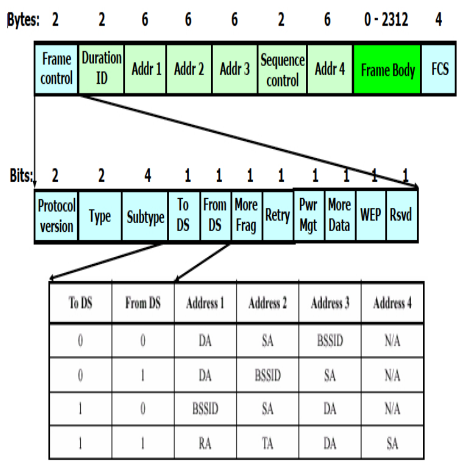

Fig. 8 802.11 frame structure used by RelaySpot.

During the operation of RelaySpot, a node may need to inform other nodes about the data reception rate. To exchange this information bits 11-13 of the frame control field are used to code the data-rate of the transmission link. Table 1 illustrates the codes used by RelaySpot to identify the data-rate in the 802.11b nodes (the number of codes is enough to identify also the data-rates in the 802.11g and 802.11n). The usage of these bits does not jeopardize the operation of nodes that do not execute RelaySpot, since it only use bits that are not used within control frames.

Table 1 Control frame bits to code rate information.

Bit 11	Bit 12	Bit 13	Code
0	0	0	No rate information
0	0	1	Link is 1Mb
0	1	0	Link is 2Mb
0	1	1	Link is 5.5Mb
1	0	0	Link is 11Mb

3.2.1 RTS Frame

The usage of RTS frame is different during the cooperative transmission phase and when reacting to failed transmissions. In each of these cases the RTS frame is used as follows:

• For cooperative transmissions: Duration field is set to accommodate two transmissions (source-relay and relay-destination), while address 4 accommodates the address of the relay. More-frag bit is set to 0 indicating cooperation phase.

• Reaction to failed transmissions (or implicit switching): Address 4 is set with the source address, and the More-frag bit is set to 1 indicating the retransmission of failed transmission from the specified source.

3.2.2 CTS Frame

Since RelaySpot is triggered by the relays themselves, these need to gather as much information as possible about the surrounding transmissions, in order to detect nodes that need to be helped. CTS frames allow overhearing nodes to get information about the data-rate of direct links. To provide this information bits 11-13 in the CTS frame control are used to code information about the data-rate of the direct link, as illustrated in Table 1.

3.2.3 ACK Frame

RelaySpot uses the address 4 in the ACK frame (marked as unused by the 802.11 standard) to allow the destination to inform the source about the address of the relay for the subsequent data frames. While bits 11-13 indicate the data-rate of the relay-destination channel, according to Table 1, as the source needs it to reserve the channel. If address 4 and/or relay-destination rate is not used, the source keeps using the direct transmission.

If the ACK indicates the reception of failed data via a relay, the destination sets the More-frag bit to 1.

3.2.4 Data Frame

DATA frames can be sent on the direct link, prior to relay selection, or via the relay node, after relay selection. Data frames sent over the direct link have a ToDS/FromDS code of (1:0). In this case the address code is defined as follows: Address 2 indicates the source address; Address 3 the destination address. Relayed data frames have a ToDS/FromDS code of (1:1) and are sent over the source-relay link and over the relay-destination link. In each of these two cases the address code is defined as follows:

• Over the source-relay link: Address 1 indicates the relay address; Address 2 the source address; Address 3 the destination address.

• Over the relay-destination link: Address 2 indicates the relay address; Address 3 the destination address; Address 4 the source address. The relay also sends the rate of the source-relay channel encoded in bits 11-13 of the frame control according to Table 1.

3.2.5 Qualification Message (QM)

If a node is able to elect itself as a potential relay, the self-elected relay uses a frame of 112 bits (of type CTS) to inform the destination about its willingness to operate as relay for that source-destination transmission. The QM contains information about the rate of the source-relay channel encoded in bits 11-13 of the frame control according to Table 1. Although relays compute their CF to participate in the selection phase, the destination needs to know those values to identify the most suitable relay. Since the destination already knows R_{rd}, it only needs information about R_{sr} to estimate the CF of a specific relay.

3.2.6 Switching Message (SM)

If a node is able to successfully decode a data frame sent by a relay (with ToDS/FromDS bits set to (1:1)), it can elect itself as a potential replacement of that relay if: i) detects a missing ACK from the destination; ii) detects that its source-relay and relay-destination links provide better data-rates than the current source-relay-destination path.

The node self-elected to replace the current relay uses an empty data frame to inform the destination about its willingness to relay data frames related to that source-destination transmission. This data frame has ToDS/FromDS bits set to (1:1) where address 2 indicates the relay address, address 3 the destination address and address 4 the source address. Moreover, the relay sends its CF (the rate information about source-relay and relay-destination channels) in bits 11-13 of the frame control. The more-frag bit in frame control is set to 1 to indicate that it is cooperation switching frame.

4 Example Illustrations

In this section we illustrate the operation of RelaySpot with examples to describe: i) Proactive operation, by selecting relays followed by a cooperative transmission to improve the direct transmission; ii) Reactive operation, by retransmitting on behalf of source; and iii) Sequence chart to show explicit and implicit switching.

4.1 Proactive: Relay Selection and Cooperative Transmission

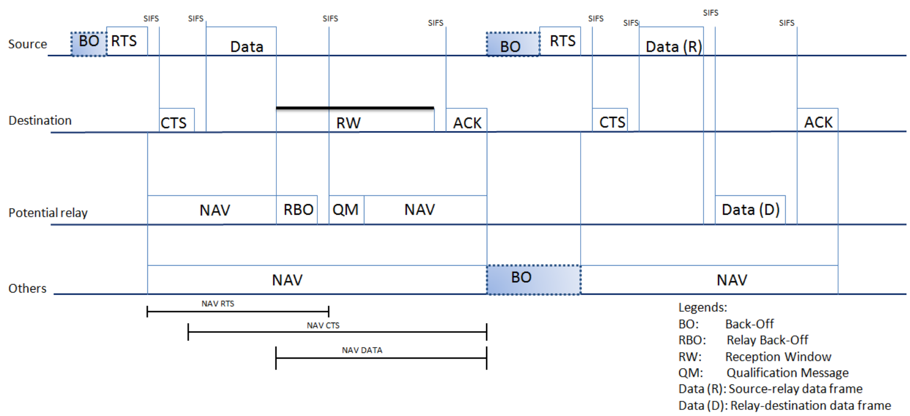

Fig. 9 An illustration of RelaySpot's proactive mode.

Figure 9, illustrates the RelaySpot operation in a scenario where we have a poor link between the source and the destination. If direct link exists, it means that RelaySpot can work in proactive mode. Within proactive mode, the slow direct link can be improved by being replaced by fast relayed links. The decision to initiate cooperation is taken by the destination, after detecting a poor direct link. In the 802.11b standard poor link means either 1 Mbps or 2 Mbps, which can be helped by relays. If the direct link has 5.5 Mbps, then it can not be helped, because the condition for cooperation is false (CF > R_{sd}). The destination implicitly indicates the need for cooperation within CTS frame. Destination also increases the duration within CTS frame by a RW amount, to allow relays to send their QMs. By overhearing CTS, all nodes update their NAV accordingly.

In this example, first the relay selection takes place. After overhearing a data frame from the source, the relays contend according to Equation 5 and try to send QMs to the source. It is assumed that the destination received at least one non colliding QM from a potential relay within RW, and the data frame from source was also received correctly. Hence, destination sends ACK with potential relay ID, after RW expires.

The cooperative transmission takes place after the relay has been selected. After the usual handshake, the data frame is forwarded to the selected relay, which relays the data frame to the destination without contention. The destination confirms the reception of data via the relay within ACK. This cooperative transmission continues until the last frame, or if the direct link gets better.

4.2 Reactive: Relay Selection and Retransmission

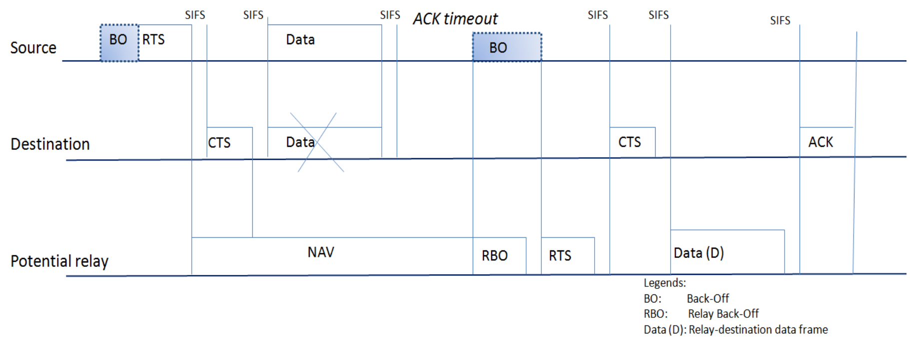

Fig. 10 An illustration of RelaySpot's reactive mode.

The reactive mode is triggered when the direct link fails. In short, RelaySpot can also operate in a reactive mode, aiming to replace a failed direct link, if potential relays detect a failed transmission (by missing ACK). In this case potential relays try to send the failed data frame to the destination on behalf of the source, based on their CW. If a potential relay gets the channel, it starts sending data by sending an RTS frame with address 4 set with the source ID (i.e., MAC address) and More-frag set to 1. By overhearing this RTS frame the source stops the retransmission process. In this case no scheduler is used at the destination.

In case of reactive relaying, the role of destination is not vital as in case of proactive relaying. Reactive relaying is initiated by relays themselves, followed by opportunistic relay selection. The example illustrated in Figure 10, shows that the destination did not receive the data frame from the source. As a result there is no ACK sent to the source. We assume that there is a potential relay that was successful accessing the medium before the source. In this case the relay forwards the frame on behalf of the source, avoiding retransmissions.

Another example of reactive mode is when relays react to failed relayed transmissions, i.e., implicit switching, which is discussed in next section.

4.3 Sequence Chart

Figure 11 illustrates the message exchange used by RelaySpot in a scenario with three potential relays (R1, R2 and R3), and one source-destination pair. In this scenario we assume a low data-rate direct link.

The destination uses CTS frames to piggyback the source-destination data-rate, since this is a low data-rate link that may need to be helped. Eligible relays compute their cooperation factor based on the rate information collected by overhearing RTS/CTS frames; if an eligible relay is qualified to help the direct channel, it sends a qualification message (QM) by setting its contention window based on the selection factor computed after overhearing a data frame from the source. After receiving a data frame from the source, the destination does not send an ACK immediately. Rather, it starts the RW in order to give opportunity to qualified relays to send QMs. After the RW expires, the destination selects the relay based on the received QM, and confirms the selected relay in an ACK message, which includes the relay-destination data-rate (R_{rd}).

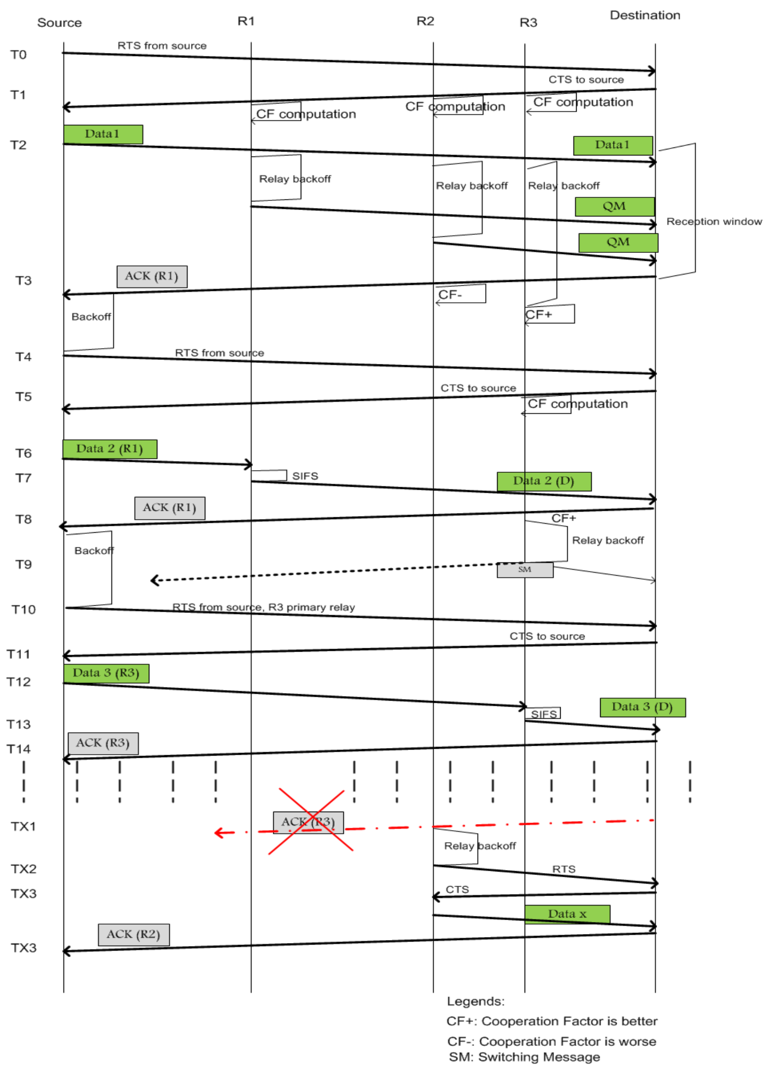

Fig. 11 RelaySpot sequence chart.

After relay selection and for the next data frames, the source sends an RTS message to the destination to reserve the channel for accommodating source-relay and relay-destination transmissions. After receiving the CTS frame sent by the destination, the source forwards a data frame to the selected relay, which sends the data frame to the destination after a Short Interframe Space (SIFS) amount of time. After successful reception of the relayed data frame, the destination sends an ACK message to the source.

In this example we assume that, due to mobility, R3 becomes a better relay than R1 in order to illustrate the proactive behavior (in term of explicit switching) of RelaySpot. In this case R3 sets its contention window according to Equation 5 after overhearing the ACK frame, and sends an SM to the destination carrying its CF. Upon overhearing this frame, the source start using R3 as a relay for the next data frames.

Now we assume that R3 fails to relay data at some instant in time to illustrate the reactive behavior (in term of implicit switching). If potential relays detect missing ACKs, they try to retransmit overheard data frames on behalf of R3. In this example, R2 tries to set its CW according to Equation 5. If R2 is successful to forward the failed data frame, the destination sends an ACK frame to the source with R2 ID and R2-destination data-rate (R_{rd}), while the source learns about R_{sr} from overhearing transmissions from R2. Then, the source switches to R2 for next data frames. This way implicit relay switching takes place.

5 Performance Evaluation

In this section, we evaluate the performance of RelaySpot by means of simulations, and compare it with the IEEE 802.11 standard, as well as two versions of RelaySpot: one that is not aware of mobility and another that does not use relay switching. The reason for not comparing RelaySpot with other cooperative MAC protocols is that RelaySpot is an hybrid protocol (reactive and proactive), that combines opportunistic and cooperative behavior, while the other proposals belong to different categories.

5.1 Simulation Environment

Evaluation is based on simulations run on the MiXiM framework of the OMNeT++ 4.1 simulator using 2D linear mobility model. Table 2 lists the simulation parameters. Each simulation has a duration of 300 seconds and is run ten different times in order to provide results with a 95% confidence interval.

Simulations consider a scenario based on a wireless local network with one static AP and up to 25 mobile nodes. Each mobile node is a source of data towards the AP, and can be a potential relay of the transmissions started by other mobile nodes.

Table 2 Simulation Parameters

Parameter	Values
Playground Size	$200x200m^2$
Path Loss Coefficient	4
Carrier Frequency	2.412e9 Hz
Max Transmission Power	100 mW
Signal Attenuation Threshold	-120 dBm
MAC Header Length	272 bits
MAC Queue Length	14 frames
Basic Bitrate	1 Mbps
Rts-Cts Threshold	400 bytes
Thermal Noise	-110 dBm
MAC Neighborhood Max Age	100 s
Speed	1 m/s
Reception Window Size	1504 us
Payload Size	1024 Bytes

Each simulation starts by randomly placing the group of mobile nodes (1 to 25) in a square of 200x200 m^2, having the AP at its center. Each node is equipped with only one half-duplex transceiver and has a unique MAC address. All the nodes in the network transmit control frames and data frames with the same power, and the network load is uniformly distributed among all nodes.

Wireless communications are done over one unique channel shared by all nodes. The used wireless channel supports four different data rates (1, 2, 5.5 and 11 Mbps) determined by the distance of the node towards the AP, while control frames are transmitted at a basic rate set to 1 Mbps [5].

To setup the mobile scenario with the most suitable configuration, we start by performing some experiments in a static scenario (1 AP and 25 nodes) to get the most suitable value for the frame size and the size of the reception window at the AP. The latter has an impact on the number of QMs that the AP can get from potential relays, which influences the selection of the most suitable relay. The frame size can have an impact on the quality of the number of successful transmissions.

In what concerns the frame size, simulation results (c.f. Figure 12) shown that the performance gets better as the frame size increases, since more bits are transmitted in each transmission opportunity. Since RelaySpot leads to a reduction of frame retransmissions, the potential bad impact of handling large frames is diminished.

In what concerns the size of the reception window, results (c.f. Figure 13) show that it is better to have a big reception window to allow the AP to grab a larger number of QMs, allowing it to select the best relay with high probability.

A very small reception window allows the AP to receive only one QM, which means that the destination has only one relay to select from. Such relay is with high probability a node closer to the source, since such nodes overhear good copies of source frames first. Moreover, in case of collision of QMs, the destination is not able to select a relay, leading to low throughput and high latency. Our findings show that a reception window of size 1504 us provides an overall network gain of

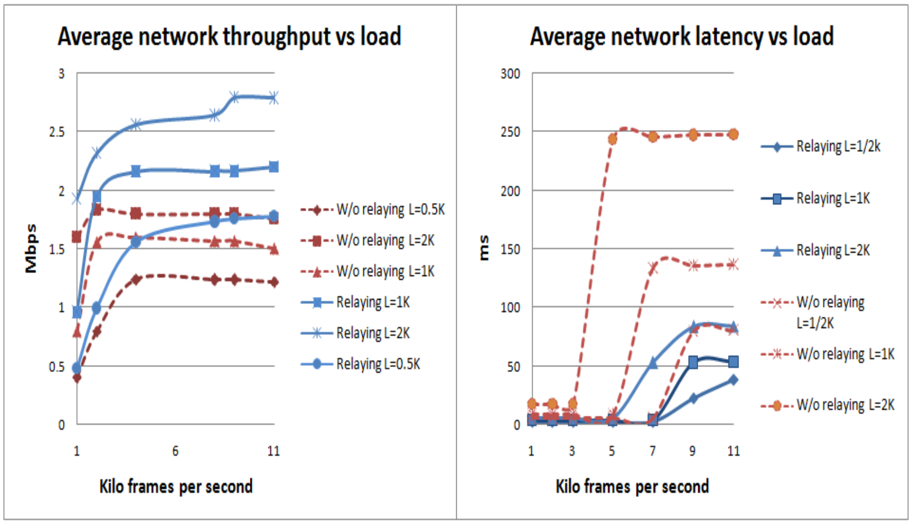

Fig. 12 Impact of frame size.

46% in terms of throughput and 154% in terms of latency, under a network load of 11K frames per second, and payload size of 1K bytes. Contrary to what could be expected, our findings show that latency decreases with a large reception window. The reason is that, although the reception window introduces a delay in the response of the destination, this only occurs during relay selection and not during the process of data relaying. A reception window of size 1504 us also provides highest gain under varying network density [6].

5.2 Network Capacity

In this section we analyze the performance of RelaySpot based on its impact on the overall transmission capacity of a wireless local network. This is done by measuring the overall network throughput and latency when all 25 mobile nodes transmit to the AP, while moving with random pause time between 10 to 100 seconds. The goal is to understand if RelaySpot can increase the transmission capacity of the network by increasing the overall throughput and decreasing the overall latency in the presence of nodes with different levels of mobility. Moreover, we also measure the tradeoff between the number of successful helped transmissions and the number of transmissions whose performance was degraded due to the action of a relay.

In this set of simulations the network load is uniformly distributed among all 25 nodes. Figure 14 compares the average network throughput achieved by RelaySpot (which is aware of mobility by means of factor M in equation 3), with a version

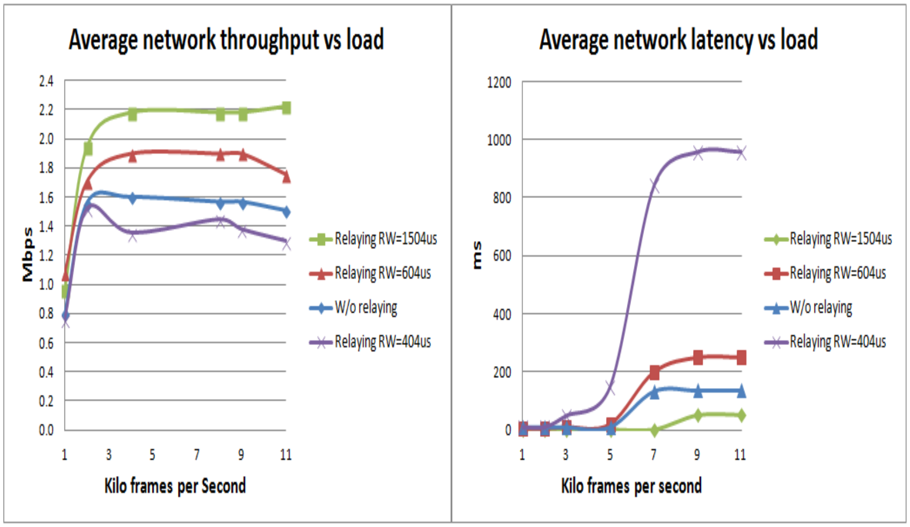

Fig. 13 Impact of reception window.

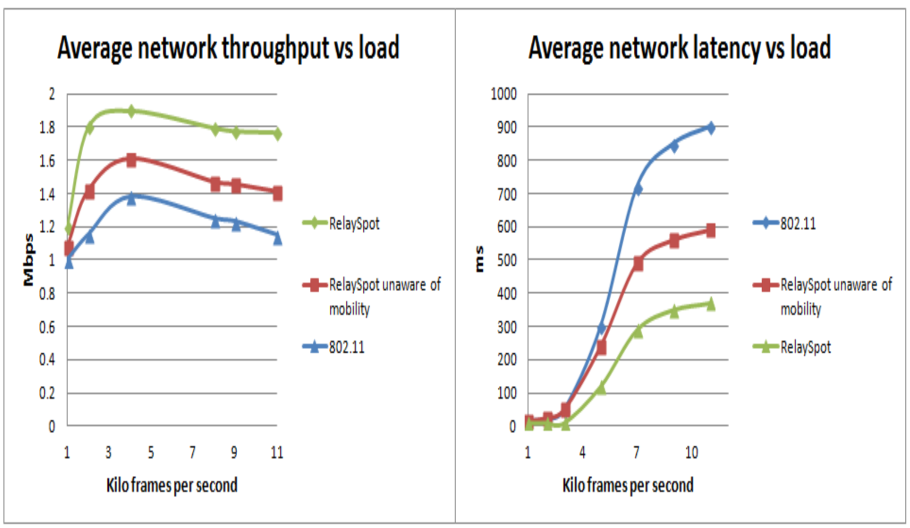

Fig. 14 Analysis of network capacity.

of RelaySpot without mobility-awareness and with the 802.11 standard, all under a series of different traffic load (frame size equal to 1K bytes). Simulation results show that RelaySpot can achieve higher throughput than the 802.11 standard and the mobility unaware RelaySpot even with high load, mainly because it is able to select stable relays (with low mobility), which are more likely to help for longer time. RelaySpot achieves an average throughput gain of 42% in relation to 802.11. RelaySpot without mobility-awareness can still achieve an average throughput gain of 17.6% in relation to 802.11, due to the scheduler at the destination, which is able to select a relay with a pair of channels (source-relay; relay-destination) with better throughput than the direct link.

In what concerns the overall network latency, Figure 14 shows that RelaySpot achieves an average gain of 152% in relation to a direct 802.11 transmission, while the mobility unaware RelaySpot achieves an average gain of 17.8% in relation to the direct transmission. The main reason for the gain that RelaySpot has in relation to 802.11 is the fact that with RelaySpot the selected relay does not contend, thus reducing the delay. What differentiates RelaySpot from its mobility unaware version is the fact that by selecting relays with high pause time RelaySpot reduces the overall communication delay, by avoiding re-selection of relays during the communication session. Furthermore, since RelaySpot allows low data rate nodes to release the wireless medium faster, other nodes can access the medium more frequently, leading to less overall network latency, even in scenarios with high mobility.

As is well known, the network load has a great impact on the performance of any MAC protocol. Figure 14 observes this effect for both RelaySpot and 802.11 protocols: the performance gets better as the load increases, since more bits are transmitted at each transmission opportunity. However, when the network is overloaded (4 kilo frames per second) then the margin gain is reduced mainly due to collisions. Since RelaySpot operation leads to a reduction of frame retransmissions, the potential bad impact of retransmissions in a heavy loaded network is diminished.

In comparison to static scenarios (Figure 12), it is clear that with RelaySpot the overall network capacity does not decrease significantly in the presence of mobility. Even the mobility unaware RelaySpot has gains over 802.11. The reason is that the overhead of relay failure due to mobility is smaller than the benefit achieved from helping poor communication sessions.

5.3 Impact of Relay Switching

The aim of this experiment is to analyze how much can relay switching contribute to a good network capacity, by rectifying the impact of relay failures. In this set of simulations we consider a scenario with one AP and 25 mobile sources, each one generating a traffic load of 10K bytes per second. Several simulations are run with different levels of mobility, from simulations where all nodes have 100 seconds of pause time to simulations where nodes pause time is of 600 seconds (static nodes, since the pause time equals the simulation time).

Figure 15 shows the benefits of RelaySpot over 802.11 and highlights the benefits of relay switching. The advantage of switching between relays during the lifetime of a communication session is analyzed by comparing RelaySpot with two benchmark versions of itself: a version without relay switching; a version where switching is done between two relays only (if one fails the other relay forwards the data).

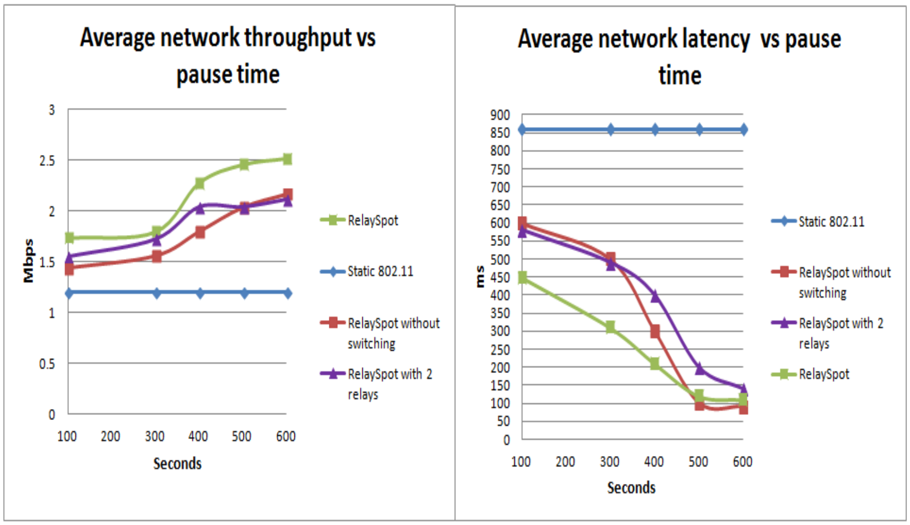

Fig. 15 Analysis of impact of switching.

Results illustrated in Figure 15 clearly show that RelaySpot has always better performance than 802.11. This performance gain is still clearer even when RelaySpot switches between two predefined relays only, or when RelaySpot does not switch at all.

In what concerns the analysis of relay switching, our first finding shows that the performance of RelaySpot increases with its capability to switch between any qualified relay: relay switching gives RelaySpot an average throughput gain of 20% in relation to the RelaySpot version that does not use switching at all. Moreover, it is also clear that the flexibility of being able to switch between any qualified relay brings additional performance to RelaySpot: Figure 15 shows that RelaySpot has an average throughput 13.5% higher than the RelaySpot version that uses only two predefined relays in the switching process.

In static scenarios (pause time of 600 seconds) the throughput gain of RelaySpot increases 16% and 19% in relation to RelaySpot versions without switching and with 2 relays only, respectively. These results show the advantage of switching even in scenarios without mobility: in these scenarios switching is mainly useful to overcome the impact of interference over relay operations: a relay can be subjected to different interference levels depending upon the number of neighbor nodes transmitting, and the amount of data generated and consumed by the relay itself.

In static scenarios, switching traffic between just two relays does not bring any major gain (c.f. Figure 15). The reason is that the usage of two relays brings some extra overhead that does not compensate the small throughput gain that comes from switching a communication session between two relays that may be under similar interference conditions with high probability. Such probability is lower when we increase the number of relays involved in the switching process, as happens with RelaySpot (which is evident from the results illustrated in Figure 15). Moreover, when compared with RelaySpot, the probability of non optimal relay selection is higher when we consider only two relays.

The problem of using only a small number of predefined relays to switch upon (two relays in this experiment) is also evident in terms of latency, as shown in Figure 15. The overall latency of the RelaySpot version with two relays is higher than the version not using switching for pause times higher than 300 seconds. These experiments show that for the majority of the scenarios, switching among two relays does not bring any advantage, due to the high probability of having the two relays under the same interference conditions.

The advantage of switching starts to be more evident when we use all the potential relays, as RelaySpot does. In relation to the version that does not use switching at all, RelaySpot brings better performance in terms of latency as soon as mobility increases (for pause time lower than 500 seconds). The reason is that by exploiting a significant number of potential relays (all qualified nodes) RelaySpot increases the probability of finding a node with low interference at a certain moment in time.

For more static scenarios the advantage of switching is not significant in this experiment (RelaySpot as a latency 16% lower than the RelaySpot version without switching) since all nodes have the same set of neighbor during the simulation and all nodes have the same traffic load.

6 Conclusions

In this paper, we present RelaySpot, the first cooperative MAC protocol that is able to increase the performance of dynamic wireless networks, by being aware of the level of mobility, interference and transmission success rate of potential relays. RelaySpot comprises three building blocks: opportunistic relay selection, cooperative relay scheduling, and cooperative relay switching. In order to operate in dynamic scenarios, and unlike previous work, RelaySpot does not require the maintenance of CSI tables, avoiding periodic updates and consequent broadcasts.

RelaySpot can effectively increase the transmission capacity of wireless local area networks, even in the presence of wireless interference and mobile nodes. Experimental results show that RelaySpot brings an overall average throughput and latency gains of 42% and 152%, respectively, in relation to 802.11, and of 17.6% and 17.8% in relation to a version of RelaySpot that is unaware of node mobility[16, 10].

In very dynamic scenarios, where a selected relay may not the best choice for the entire duration of a communication session, our experiments show that the relay switching capability of RelaySpot brings an overall average throughput and latency gains of 20% and 21%, respectively, in relation to a version of RelaySpot that does not perform relay switching. This shows RelaySpot capability to improve the utilization of spatial diversity by switching in real time to the relay that offers the best throughput and latency conditions within the cooperation area.

As future work, we plan to extend the operation of RelaySpot with the inclusion of a chain relaying capability, in which the operation of a poor relay is compensated by a second relay, located closer to the destination. We plan to compare the performance of this new functionality with the relay switching approach described in this paper.

References

1. R. Ahmad, F. Zheng, M. Drieberg, and S. Olafsson. An Enhanced Relay-Enabled Medium Access Control Protocol for Wireless Ad Hoc Networks. In *Proc. of IEEE Vehicular Technology Conference (VTC)*, Singapore, Singapore, May 2008.
2. A. Bogliolo, P. Polidori, A. Aldini, W. Moreira, P. Mendes, M. Yildiz, C. Ballester, and J. Seigneur. Virtual Currency and Reputation-Based Cooperation Incentives in User-Centric Networks. In *Proc. of IEEE IWCMC*, Cyprus, August 2012.
3. W. Elmenreich, N. Marchenko, H. Adam, C. Hofbauer, G. Brandner, C. Bettstetter, and M. Huemer. Building Blocks of Cooperative Relaying in Wireless Systems. *Electrical and Computer Engineering, Springer*.
4. Zhu Hao and Cao Guohong. rDCF: A Relay-Enabled Medium Access Control Protocol for Wireless Ad Hoc Networks. *IEEE Transactions on Mobile Computing*, 5, March 2006.
5. T. Jamal and P. Mendes. 802.11 Medium Access Control In MiXiM. *Tech Rep. SITILabs-TR-13-02 University Lusófona*, March 2013.
6. T. Jamal and P. Mendes. Analysis of Hybrid Relaying in Cooperative WLAN. In *Proc. of IFIP WirelessDays*, Valencia, Spain, November 2013.
7. T. Jamal and P. Mendes. Cooperative Relaying for Dynamci Networks. *EU Patent*, (EP13182366.8), August 2013.
8. T. Jamal and P. Mendes. Cooperative Relaying for Wirelesss Local Area Networks. *Accpted as Chapter in Springer LNCS WiNeMo (Wireless Networks Moving Objects) Book*, March 2014.
9. Tauseef Jamal and Paulo Mendes. Relay Selection Approaches for Wireless Cooperative Networks. In *Proc. of IEEE WiMob*, Niagara Falls, Canada, October 2010.
10. Tauseef Jamal, Paulo Mendes, and Andre Zúquete. Interference-Aware Opportunistic Relay Selection. In *Proc. of ACM CoNEXT student workshop*, Tokyo, Japan, Dec 2011.
11. Tauseef Jamal, Paulo Mendes, and Andre Zúquete. RelaySpot: A framework for Opportunistic Cooperative Relaying. In *Proc. of IARIA ACCESS*, Luxembourg, June 2011.
12. Tauseef Jamal, Paulo Mendes, and Andre Zúquete. Wireless Cooperative Relaying Based on Opportunistic Relay Selection. *International Journal on Advances in Networks and Services*, 05(2):116–127, June 2012.
13. L. M. Feeney, B. Cetin, D. Hollos, M. Kubisch, S. Mengesha, and H. Kar. Multi-rate Relaying for Performance Improvement in IEEE 802.11 WLANs. In *Proc. of WWIC*, Coimbra, Portugal, May 2007.
14. P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. Panwar. CoopMAC: A Cooperative MAC for Wireless LANs. *IEEE Journal on Selected Areas in Communications*, 25(2):340–354, February 2007.
15. Lu Mei-Hsuan, Steenkiste Peter, and Chen Tsuhan. Design, Implementation and Evaluation of an Efficient Opportunistic Retransmission Protocol. In *Proc. Of IEEE MobiCom*, Beijing, China, April 2009.
16. T. Jamal, P. Mendes, and A. Zúquete. Opportunistic Relay Selection for Wireless Cooperative Network. In *Proc. of IEEE IFIP NTMS*, Istanbul, Turkey, May 2012.
17. Kefeng Tan, Zhiwen Wan, Hao Zhu, and Jean Andrian. CODE: Cooperative Medium Access for Multirate Wireless Ad Hoc Network. In *Proc. of IEEE SECON*, California, USA, June 2007.