Wireless Cooperative Relaying Based on Opportunistic Relay Selection

Tauseef Jamal[1], Paulo Mendes[1], André Zúquete[2]
[1]SITI, R&D Unit of Informatics Systems and Technologies, Universidade Lusofona de Humanidades e Tecnologias (ULHT), COFAC, Campo Grande 376, Lisbon, Portugal
{tauseef.jamal,paulo.mendes}@ulusofona.pt
[2]Dep. Electronics, Telecommunications and Informatics, IEETA, University of Aveiro Campus Universitário de Santiago 3810–193 Aveiro, Portugal
andre.zuquete@ua.pt

***Abstract*—Advances in wireless technologies, including more powerful devices and low cost radio technologies, have potential to drive an ubiquitous utilization of Internet services. Nevertheless wireless technologies face performance limitations due to unstable wireless 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 (rely on current channel conditions) and introduce overhead that can endanger performance especially when nodes are mobile. In this article we describe a framework, called RelaySpot, to implement cooperative wireless solutions in large mobile networks, based upon opportunistic relay selection methods. RelaySpot based solutions are expected to minimize signaling exchange, remove estimation of channel conditions, and improve the utilization of spatial diversity, minimizing outage and increasing reliability.**

***Index Terms*—Cooperative Relay Scheduling, Opportunistic Relay Selection, Wireless Resource Management, Space-Time Diversity.**

I. 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. However, channel conditions in wireless networks are subjected to interference and multi-path propagation, creating fading channels and decreasing the overall network performance. 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 lasts for the entire duration of the transmission.

Extensive research has been done to mitigate the impact of shadowing in wireless networks, being mostly focused on *Multiple-Input Multiple-Output* (MIMO) systems. Recently, cooperative relaying techniques have been investigated to increase the performance of wireless systems by using diversity created by different single antenna devices, aiming to reach the same level of performance of MIMO systems.

Cooperation occurs when overhearing relays assist the transmission from source to destination, by transmitting different copies of the same signal from different locations, allowing the destination to get independently faded versions of the signal that can be combined to obtain an error-free signal.

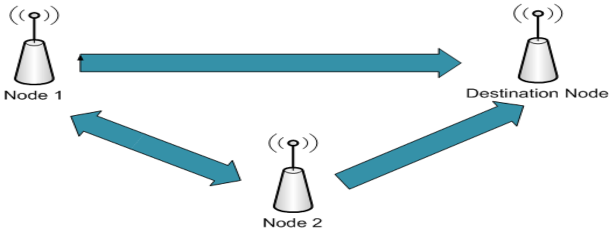

Figure 1. Cooperative relaying

Figure 1 shows a pair of single antenna devices able to act as relays of each other by forwarding some version of “overheard” packets along with its own data. Since the fading channels of two different devices are statistically independent, this generates spatial diversity. The development of cooperative relaying systems, of which Figure 1 illustrates a simple scenario, raises several research issues including the performance impact on the relay itself, and the interference on the overall network, leading to a potential decrease in network capacity and transmission fairness.

In this paper, we present our arguments in favor of a new type of cooperative relaying scheme based upon local decisions that do not rely on unstable information e.g., *(Channel State Information*) CSI collected over multiple links. We describe an 802.11 backward compatible cooperative relaying framework, called *RelaySpot* [1], which aims to ensure accurate and fast relay selection, posing minimum overhead and reducing the dependency upon CSI estimations, which is essential to increase system performance in scenarios with mobile nodes. The basic characteristic of any RelaySpot-based solution is the capability to perform local relaying decisions at potential relay nodes (can be more than one), based on a combination of opportunistic relay selection and cooperative relay scheduling. Intermediate nodes take the opportunity to relay in the presence of local favorable conditions (e.g., no concurrent traffic). Cooperative scheduling is used to compensate unsuccessful relay transmissions. To the best of our knowledge RelaySpot is the first framework that aims to create the basic conditions to allow relay selection to be done without relying on CSI estimation.

The remaining of this paper is organized as: section II describes the concept of cooperative relaying. Section III describes the prior-art. In sections IV and V we describe the proposed RelaySpot mechanism. Section VI provides an operational comparison with an example of source-based relaying approach (CoopMAC [2]) with RelaySpot. While RelaySpot implementation is discussed in section VII. Section VIII concludes the paper.

II. COOPERATIVE RELAYING

The basic problem of wireless communication systems is the delivery of information from one network node to another in a resource-efficient manner. While, wireless links always had orders of magnitude less bandwidth than their wired counterparts, newer technologies, such as multiple-input multiple-output (MIMO) systems, are starting to improve the performance of wireless network. However such improvements come at the cost of multiple Radio Frequency (RF). Furthermore, the size of mobile devices may limit the number of antennas to be deployed.

In 802.11 networks, the low quality (throughput and reliability) and short coverage of the direct link between a source and a destination are mainly due to the shadowing and fading effects of the wireless environment [3]. There are however other constrains in wireless networks such as limited power, size of devices, and distance. Due to the distance from the Access Point (AP), a mobile node can observe a bad channel as compared to other nodes that are closer to the AP. Figure 2 shows the transmission characteristics of some nodes, as a result of the rate adaptation functionality of IEEE 802.11: stations closer to the AP transmit at high data rates, while stations far away from the AP decrease their data rate after detecting missing frames.

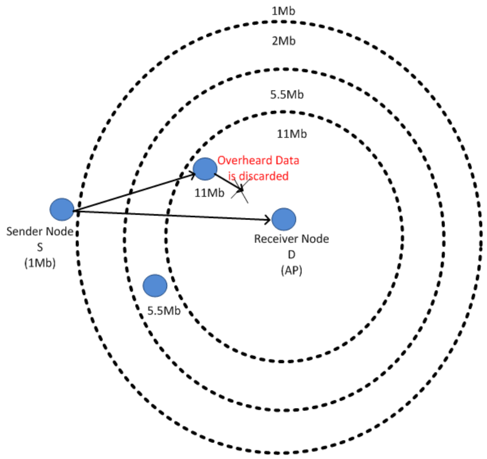

Figure 2. 802.11 rate adaptation

The usage of rate adaptation schemes results in a degradation of the overall network performance, since low data rate stations grab the wireless medium for a longer time. This occurs since each station has the same probability to access the channel, which means that high data rate stations will not be able to keep the desirable throughput.

As illustrated in Figure 2, the station at the cell edge adapts its data rate to 1Mbps, yet its frames are overheard by the high data rates stations. The latter ignores this overheard information and drops the frames. Cooperative relaying is a very simple, and yet effective solution, to mitigate the problems raised by the presence of low data rate stations. With cooperative relaying, high data rate stations help low data rate stations to release the medium earlier, by relaying their data over channels with higher data rates. This way high data rate stations will be able to transmit earlier, increasing the overall system performance. In cooperative communications, nodes in a wireless network work together to form a virtual antenna array.

The basic ideas behind cooperative communication can be traced back to the relay channel model in information theory extensively studied in the 1970s by Cover and El Gamal [4]. Recent research on cooperative communication [5], [6], [7] demonstrates the benefits of cooperative relaying in a wireless environment by achieving spatial diversity. Moreover, most of the research being done focuses on the physical layer (cooperative communications), by exploiting spatial diversity to increase system reliability of cellular networks. Recently, the exploitation of link-layer diversity (cooperative relaying) in cellular and multi-hop wireless networks has attracted considerable research attention. Cooperative techniques utilize the broadcast nature of wireless signals: the source node sends data for a particular destination, and such data can be "overheard" at neighboring nodes; these neighboring nodes, called relays, partners, or helpers, process the data they overhear and transmit it towards the destination; the destination receives the data from the relay or set of relays (on behalf of the source) enabling higher transmission rate, or combines the signals coming from the source and the relays enabling robustness against channel variations. Such spatial diversity arising from cooperation is not exploited in current cellular, wireless LAN, or ad-hoc systems. Hence, cooperative relaying is different from traditional multi-hop or infrastructure based methods. Therefore, for cooperation to be implemented at the link layer, link layer needs to be changed in order to allow indirect transmission between source and destination.

At the link layer, IEEE 802.11 uses the CSMA/CA algorithm to control medium access, being the *Distributed Coordination Function* (DCF) the most common operation mode. In scenarios with fading channels and low data rate stations, high throughput, reliability, and coverage may be possible to achieve with an efficient cooperative *Medium Access Control* (MAC) layer based on a modifying version of the DCF signaling scheme. Like Ethernet, it first checks to see that the radio link is clear before transmitting. To avoid collisions, stations use a random back-off after each frame, with the first transmitter (the one with shortest random time) seizing the channel. Carrier sensing is used to determine if the medium is available. Two types of carrier sensing functions in 802.11 manage this process: the physical carrier-sensing and virtual carrier-sensing functions [8]. If either carrier-sensing function indicates that the medium is busy, the MAC reports this to higher layers. Virtual carrier-sensing is provided by the Network Allocation Vector (NAV). Most 802.11 frames carry a duration field, which can be used to reserve the medium for a fixed time period. The NAV is a timer that indicates the amount of time the medium will be reserved. Stations set the NAV to the time for which they expect to use the medium, including any frames necessary to complete the current operation. Other stations count down from the NAV to zero. When the NAV is not zero, the virtual carrier-sensing function indicates that the medium is busy; when the NAV reaches zero, the virtual carrier-sensing function indicates that the medium is idle. Figure 3 shows the virtual carrier sensing with usage of optional RTS/CTS signaling.

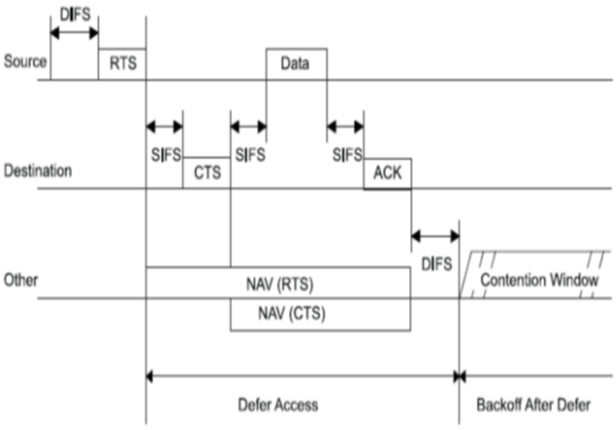

Figure 3. NAV propagation mechanism [8]

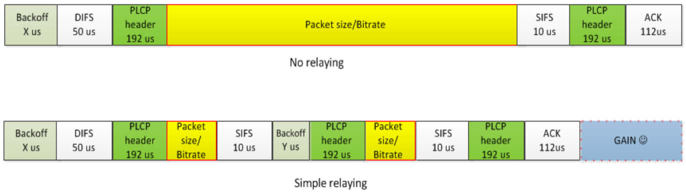

Figure 4. Simple relaying gain

Relaying involves transmission of two data frames separated in time and space; therefore, it introduces overhead, which increases due to additional control messages. However significant gain can be achieved by a careful selection of reservation duration and back-off timings. Figure 4 shows the gain of cooperative relaying in 802.11 (when there is no extra control message). As seen in Figure 4 a regular data transmission with acknowledgment takes longer to send data when compared to the data transmission based on a relay protocol. With a relay protocol the relatively slow stations would reserve the channel for a duration of *frame_size/(fast_data_rate=11Mbps)* instead of *frame_size/(slow_data_rate=1Mbps)* and the other stations will benefit from this with higher probability of accessing the channel.

Cooperative relaying can be divided into two major parts: i) relay transmission protocol (relaying protocol); ii) relay selection. Cooperative relaying protocols can be classified into proactive schemes and reactive schemes. In the former, the cooperation from relay(s) is always provided either by a prearranged or a random set of relay(s) before the acknowledgment (ACK or NACK) from the receiver. In the latter, the help from the relay(s) is initiated only when the direct transmission fails (lack of ACK or overheard NACK). Irrespective of the class of relaying protocol, the operation can be opportunistic or cooperative. Cooperative relaying protocols are normally initiated by source or destination, where relays are selected prior to data transmission. Such protocols require additional control/handshake messages which pose additional overhead. In the case of opportunistic relaying protocols, the relay(s) opportunistically forward the overheard data to destination, and the destination acknowledges the reception of data by sending ACK to the source. Source and destination may not have prior knowledge of selected relay(s). Such mechanisms are prone to collision as there is no coordination between nodes.

The definition of MAC cooperative schemes poses several challenges, specially in the presence of mobile nodes. A major challenge is related to relay selection, which aims to identify the most suitable relay(s) for assisting transmissions between any pair of nodes. Research is ongoing to devise efficient relay selection at MAC layer, being the proposed approaches mostly source or destination based. In the former case, the source maintains a table with *Channel State Information* (CSI) of neighboring devices to support relay selection. In destination-based approaches, the destination decides whether to use relaying or not, based on thresholds and CSI kept on the destination and on potential relays. Both approaches incur in some overhead (specially source-based) and are not efficient reacting to network changes, mainly in the presence of mobile nodes.

III. STATE OF THE ART

This section provides an analysis of the most significant contributions aiming to devise efficient cooperative relaying mechanisms, able to take advantage of available relay nodes. First of all, a study of backward compatible 802.11 cooperative MAC proposals (relay transmission protocol) is presented: such proposals can serve as a basic ground for further developments. Second, central aspects of cooperative relaying (relay selection) are analyzed.

A. *Cooperative MAC*

Initial work in cooperative networking was mainly focused on physical layer approaches aiming to achieve higher spatial diversity. Although previous work shows the benefit of cooperation in wireless networks, it does not define medium access methods that would support new cooperative schemes. To take full advantage of physical layer cooperative techniques, new MAC schemes must change the transmitter-receiver communication model to include a transmitter-relay(s)-receiver model. Common examples of MAC source-based cooperative relaying schemes are the ones that use one relay [2], [9] or two relays in parallel [10]. Source-based relaying approaches require the sources to maintain a table of CSI that is updated by potential relays based upon periodic broadcasts. As an example, with

CoopMAC [2], the source can use an intermediate node (called helper) that experiences relatively good channel with the source and the destination. Instead of sending frames directly to the destination at a low transmission rate, the source makes use of a two-hop high data rate path to the destination via a helper. In case of CoopMAC, potential helpers overhear ongoing RTS/CTS transmissions for measuring the source-helper and helper-destination CSI. Based on the CSI broadcasted by potential helpers, sources update a local table (cooptable) used to select the best relay for each transmission. Another example of source based relaying is CODE[10], which uses multiple relays based on network coding. In CODE all nodes overhear RTS/CTS frames, and if they find that they can transmit data faster than the source, they add the identity of source and destination to their willingness list. Once the source finds its address in the willing list of relay(s), it adds those relay(s) into its cooperative table. The major difference between CoopMAC and CODE is that with the latter, a source selects two relays with latest feedback time, forming a cooperative diamond. The usage of RTS-CTS frames is also different. Source-based approaches undergo two main problems: channel estimation and periodic broadcasts, which introduce overhead that is problematic in mobile scenarios.

While source-based proposals follow a proactive approach, reactive cooperative methods [11], [12] rely on relays to retransmit on behalf of the source when the direct transmission fails. An example is PRO [11], which selects relays among a set of overhearing nodes in two phases: first, a local qualification process takes place at potential relays, during which the link quality is compared with some predefined threshold, leading to the identification of qualified relays. In a second phase, qualification information is broadcasted, allowing qualified relays to set scheduling priorities. Reactive approaches face the same challenges of source-based methods. CoRe-MAC [13] is another reactive Cooperative MAC protocol. In CoRe-MAC, when a NACK is overheard, candidate relays send an AFR (Apply For Relay) message to the destination within a fixed number of slots. After receiving non colliding AFRs, the destination elects the best relay in term of the highest received SNR. However the destination does not know which is the suitable number of AFR messages to wait for, in order to reach a good decision. Moreover, the extra handshake messages introduce significant overhead in case of relay failure.

N. Marchenko et al. propose a mechanism [14] where all overhearing nodes estimate the *Signal-to-Noise Ratio* (SNR) for both source-relay and relay-destination channels, based on which they can nominate themselves as potential relays. Potential relays send a nomination message to the destination, by selecting a slot in the contention window, and the destination selects a most suitable relay among all the nominated nodes. This proposal has several drawback: i) geographic position of nodes is assumed to be known; ii) the size of the contention window has great influence in selecting the best relay; iii) the destination node is not aware of the number of nominated relays.

In the case of multi-hop networks the performance gain of cooperative relaying may be exploited by finding a node that assists the transmission for every hop. Although the gain achieved through cooperative diversity increases robustness, it requires retransmissions reducing network capacity. Such a hop base cooperation scheme neglects a crucial evidence: not only the destination of a data might be in need of help but also the next hop. An alternative approach may be to use two-in-one cooperation [12], in which a single retransmission can improve the success probability of two ordinary transmissions (source to next-hop and next-hop to destination), leading to a better usage of the network capacity. In two-in-one cooperation all potential relays react after detecting a missing *Acknowledgment* (ACK) from the destination. Although two-in-one cooperation can achieve a diversity gain of three, the most suitable relay selection scheme is not investigated.

B. *Relay Selection*

In what concerns relay selection mechanisms, the basic mechanism defines an opportunistic behavior in which all overhearing nodes estimate the CSI of sender-node and node-destination links, based on which they set a timer such that nodes with better channel conditions broadcast first their qualification as relays, or even data to be relayed [15]. Such mechanisms present a high probability of collision, as well as low efficiency in mobile scenarios due to CSI measurements. Nevertheless, opportunistic relaying has been modified aiming to increase its efficiency level [16], [17]. Although most of the related work considers opportunistic relaying, it may lead to data collision if more than one relay is selected [18]. Collisions may be avoided by using a suitable resource allocation scheme, or by using a relay only when needed, which lead to the need to devise a relay on demand mechanism. For instance, with relaying on demand [19], the basic relay selection mechanism [15] is modified with the introduction of a receiver threshold aiming to improve energy savings. With on-demand approaches nodes with bad channel conditions do not participate in relay selection. However, such approaches still rely upon RTS/CTS for channel estimation, leading to high overheads.

Other kind of relay selection mechanisms rely on geographical information [20]. Such approaches assume that users' location is known, based for example on information from GPS, and Packet Error Rate (PER) is used as metric for selecting relays. It relies on constant/known channel statistics in terms of fading Probability Density Function (PDF), fading auto correlation function, and path loss exponent. In scenarios where the users are moving fast such parameters cannot be assumed to be known, which limits the potential of this type of approaches.

A proposal to group and select set of relays for cooperative networks is presented by A. Nosratinia et al. [21], in which each node has data of its own to transmit, and cooperation may be non-reciprocal. The study of non-reciprocal approaches to relay allocation brings several benefits, since with distributed algorithms nodes make individual decisions about cooperation. A. Nosratinia et al. [21] investigate the effect of allocation policies on system performance, and how the cooperative gain scales with the number of cooperating nodes, such that each node can decode message with high probability. In terms of the outage probability, it assumes that each node may help n other nodes, and the selection strategy guarantees diversity n+1 for all transmissions. However, as n+1 nodes take part in one transmission, the system complexity is considerably high. Moreover, this work assumes that small scale fading is not dominated by path loss, which points to networks of up to a certain coverage area.

For better understanding of the different type of relay selection schemes, T. Jamal and P. Mendes [22] devised a comprehensive analysis and taxonomy.

IV. RELAYSPOT

Relay selection is a challenging task, since it greatly affects the design and performance of a cooperative network. On the one hand, cooperation is beneficial for the network, but on the other hand it introduces extra overhead (e.g., CSI estimation). The major goal of *RelaySpot* is to minimize overhead introduced by cooperation, with no performance degradation.

Unlike previous work, RelaySpot does not require maintenance of CSI tables, avoiding periodic updates and consequent broadcasts. The reason to avoid CSI metrics is that accurate CSI is even harder to estimate in dynamic networks, and periodic broadcasts would need to be very fast to guarantee accurate reaction to channel conditions. Moreover, relay selection faces several optimization problems that are difficult to solve, which means that the best relay may be difficult to find. Hence, for dynamic scenarios, the solution may be to make use of the best possible relaying opportunity even if not the optimal one (e.g., in terms of CSI). By achieving the best performance over the faced conditions, RelaySpot aims to target a fair balance between relay selection and additional resource blockage.

In summary, RelaySpot aims to select relay(s) based only on information local to potential relays, with minimum computational effort and overhead. The remaining of this section describes RelaySpot opportunistic relay selection, cooperative relay scheduling, and chain relaying mechanisms.

A. Opportunistic Relay Selection

The relay selection process only takes into account nodes that are able to successfully decode frames sent by a source. This ensures that potential relays are closely bounded with the source, with which they have good channel conditions. The qualification of a node as a relay depends upon local information related to node degree, load, mobility and history of transmissions to the specified destination, and not to CSI.

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 the collision risk as well as blockage of resources. However, it is possible that nodes with low degree are overloaded due to local processing demands, leading to delay.

Equation 1 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 involving such potential relay, respectively, and N_i and N_d the number of nodes involved in such indirect and direct transmissions (indirect transmissions are the ones overheard by the potential relay, and direct transmissions are the ones ending and starting at the potential relay). 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.

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

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

Figure 5 shows a scenario where node R is selected as a potential relay. 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.

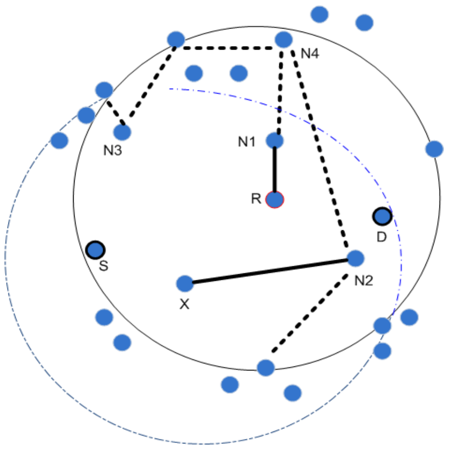

Figure 5. Opportunistic relay selection scenario

Although it is ensured that potential relays have good channel with the source, the quality of the relay-destination channel is unknown. Without performing measurement of CSI for the relay-destination channel, channel conditions are estimated based on the successful ratio of previous transmissions towards the destination (history factor) and the current stability of a potential relay (mobility factor). The history factor (H), is estimated as a ratio between an exponential moving average of the duration of successful transmissions and the maximum duration of any successful transmission (H_M), variable that is initiated to a time unit. The factor H aims to tell whether the intended relay has probabilistically a good channel with the required destination, without the need to estimate and broadcast channel information.

The mobility factor (*M*) is estimated as a ratio between an exponential moving average of the pause time of the node and the maximum detected pause time (M_M), which is initiated to a time unit. The factor M aims to select more stable nodes as relays.

Based on the interference factor of a node, as well as its history and mobility factors, the probability of selecting a node as relay for a given destination is given by Equation 2, which shows that the selection factor (*S*) is proportional to the history of successful transmissions to the destination and the pause time, and inversely proportional to the interference level of the node.

$$S = \frac{H * M}{1 + I}, \quad S \in [0, 1[\tag{2}$$

Lets go back to Figure 5 to illustrate the usage of Equation 2. Lets assume that R is a node that moves frequently around the destination with a good history of successful transmissions. While X is a node with long pause times but that is new near the destination. In this case, Equation 2 may give preference to node R, although it presents a higher mobility factor than X.

After overhearing data frames or RTS towards a destination, a potential relay uses the estimated selection factor (*S*) to compute the size of its contention window (*CW*), between a predefined minimum and maximum values of CW_{min} and CW_{max}, as given by Equation 3.

$$CW = CW_{\text{min}} + (1 - S)\,(CW_{\text{max}} - CW_{\text{min}}) \tag{3}$$

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, we expect opportunistic relay selection 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.

As illustrated in Figure 6 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.

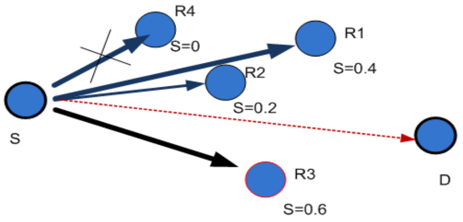

Figure 6. Opportunistic relay selection

B. Cooperative Relay Scheduling

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.

The contention window (computed in Equation 3) 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, while not neglecting the help that secondary relays may give. Increasing diversity, by allowing the destination to receive multiple copies of the same frame, aims to construct error free frames while avoiding re-transmissions.

Based on the quality of the frames 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 copies the destination only process received frames after a predefined time window). By sending a list of priority relays embedded in ACK messages, the destination allows potential relays to improve the accuracy of the back-off time computation in next transmissions (relay with highest priority sends and the others back-off but keep overhearing the transmission). This functionality leads to a space-time diversity, which leverage the space diversity used by prior art (e.g., CoopMAC). Space-time diversity is achieved by allowing the usage of different relays over time, helping the same source-destination communication.

Figure 7 illustrates the cooperative relay scheduling, in a situation where R1, R2 and R3 are self-elected as relays, with R3 having smaller CW than R1 and R2 (as illustrated in Figure 6). If the destination receives good frames from multiple relays during a predefined time window, it decides for priorities (primary and secondary relays) on basis of SNR between well decoded frames. As an example, Figure 7, shows a situation where the destination is only able to decode the data by combining partial frames received from R1 and R2, in a scenario in which no data is received in good shape.

In this situation the destination sends an ACK having R1 and R2 as primary relays and R3 as secondary one i.e., ACK(R1, R2; R3). This means that in the next transmission R1 and R2 will transmit (diversity 2) and R3 will back-off and overhear the transmission.

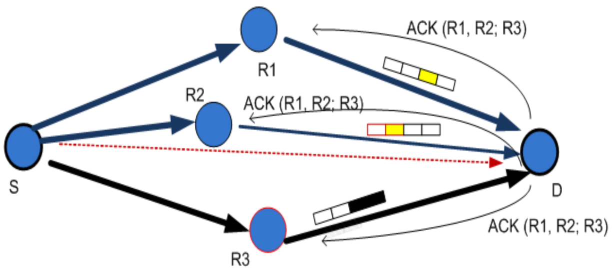

Figure 7. Cooperation relay scheduling

Cooperative scheduling allows to keep a source-destination transmission in a good shape even when the primary relay is not useful anymore. Cooperation between selected relays (primary and secondary), identified by the priority list embedded in ACK message, aims to ensure a high probability of having the best set of relays over time. This means that based on current conditions, primary and secondary relays may switch their priorities.

Figure 8 illustrates the relay switching operation between a selected primary relay (R1) and secondary relay (R2): Destination chooses R1 as primary relay on basis of signal strength, while R2 is a secondary relay; in the next transmission R1 will transmit (diversity 1) and R2 will back-off. Suppose that after some time R1 move away and detects a deterioration of the conditions of the Source-R1 channel. In this situation R1 notifies the secondary relay (R2) with a Relay-Switch message. This means that R2 will become a primary relay, starting to transmit frames received from source.

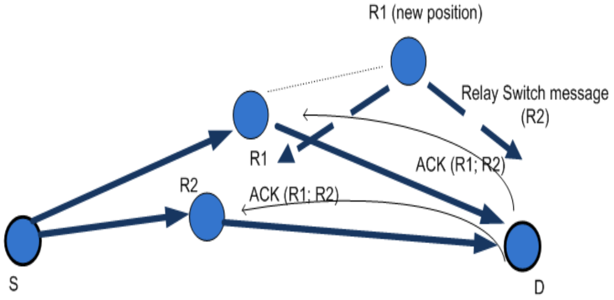

Figure 8. Cooperative relay switching

C. *Chain relaying*

The proposed opportunistic relay selection and cooperative relay scheduling mechanisms aim to increase throughput and reliability, as well as to reduce transmission delay by increasing the diversity adjusting the relaying order. Nevertheless, the presence of mobile nodes, as well as unstable wireless conditions, may require higher levels of diversity achieved based on nodes that are closed to the destination (higher probability of successful transmissions). Hence, RelaySpot includes the possibility of using recursive relay selection and retransmissions in case of poor performance. This functionality is called chain relaying (c.f. Figure 9). Nodes that are able to successfully decode MAC data frames sent by a relay to a destination may trigger the RelaySpot operation on that relay-destination channel in case the channel conditions are so bad that the node will overhear two consecutive NACK (or the absence of ACK's/ NACKs) during a predefined time window. This means that relays closer to the destination can help the transmission when the destination does not get any (acceptable) data frames from any relay in contact with the source.

With chain relaying, the relaying process is repeated for the relay-destination channel (R1-D and R2-D in Figure 9), by having another relay (R4) or set of relays helping the transmission from each of the previously selected relays to the destination. R4 may not receive correct frames from source, but it is closely bounded to R1 as well as to the destination. R4 can trigger chain relaying when both primary and secondary relays fail. Chain relaying aims to minimize the outage and to increase the overall throughput by complementing the cooperative scheduling functionality.

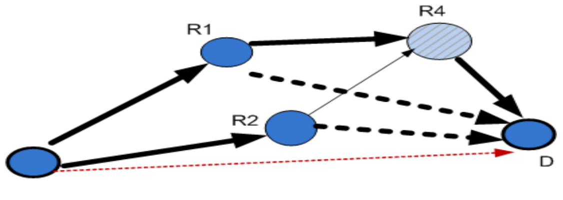

Figure 9. Chain relaying

V. RELAYSPOT ALGORITHM

RelaySpot is a hybrid relaying scheme, which means that it allows relays to retransmit data when: i) NACKs are overheard in the direct transmission; ii) relays detect that the performance of a direct link can be improved by relaying. RelaySpot operation, for a specific source-destination pair ends when there are no more packets to be send or when the destination informs the relays to stop relaying MAC data frames, after detecting a decrease in the number of damaged frames received through the direct channel below a predefined threshold. This action aims to increase network capacity by allowing relays to help other endangered transmissions.

RelaySpot operation has two modes: RelaySpot on potential relays and RelaySpot on destination (or gateway). Figure 10 shows the RelaySpot sequence of operations on potential relay nodes, which including the computation of the selection factor and relaying of MAC data frames.

Since the opportunistic relay selection process can lead to several relays being selected, self-elected relays may adjust their priority based on the information collected from the ACK sent by the destination. The primary relay (the one with highest priority) will continue sending frames, while other relays will back-off. Figure 10 shows that before sending data frames, the relay checks SNR for the signal received from source. If the SNR is below certain threshold (i.e., data rate is degraded) the relay stop participating as a relay by sending Relay-Switch message; otherwise it continue sending data frames until last frame. The primary relay then goes to back-off mode.

Figure 11 shows the RelaySpot operation at destination node. The destination keeps receiving good frames via relays until reception window expire. If the destination receives a good frame from a single relay it ACK with relay identification and send the frame to application to avoid further delays. However, if more than one good relay exists, the destination computes the priority list by using received SNR, acknowledging the priority list to self-elected relays. If there is not any good relay during reception window, the destination tries to combine the received partial frames. If the destination is able to decode the data by combining the received frames, it computes the priority list accordingly. However, if the destination is unable to decode the data even with combining, it sends NACK to indicate failure.

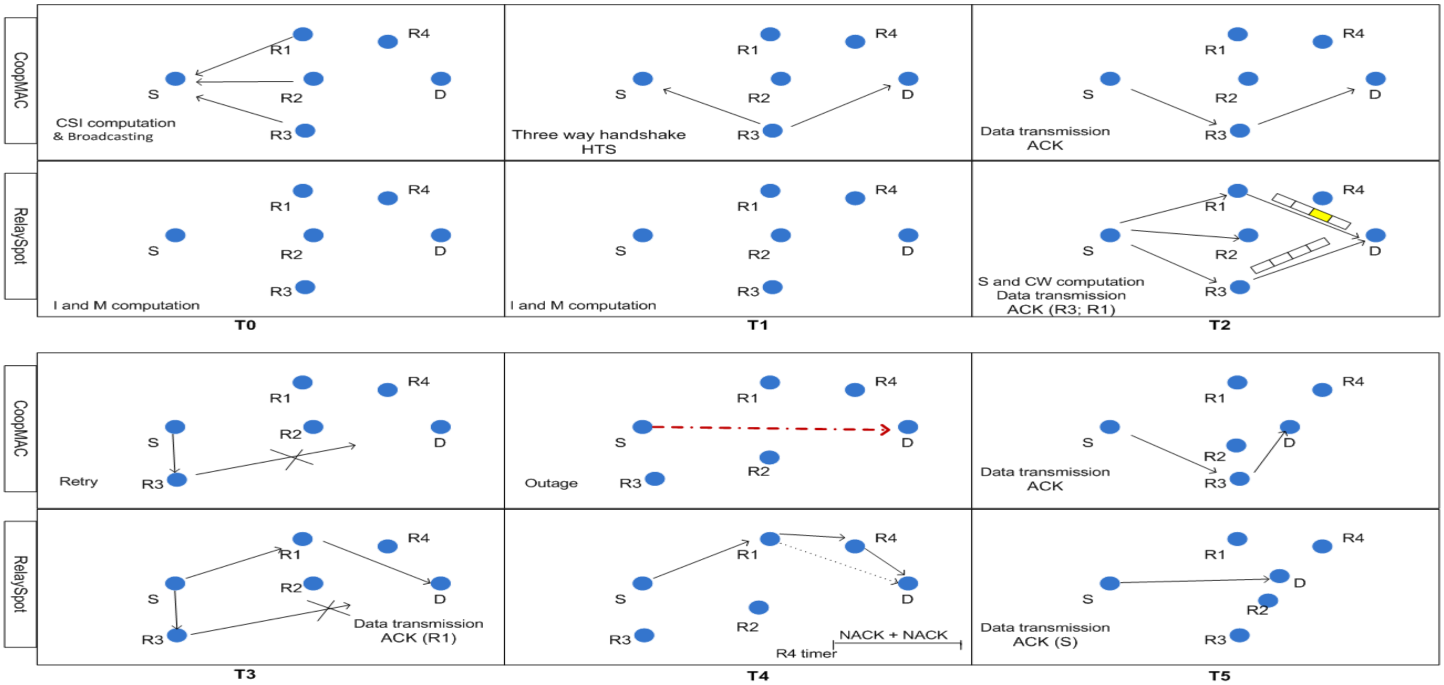

Figure 12. Illustration of the RelaySpot algorithm with chain relaying

VI. RELAYSPOT VS COOPMAC OPERATIONAL COMPARISON

Figure 12 illustrates the phases of the RelaySpot algorithm in comparison to CoopMAC. Lets consider that we have three potential relays (R1, R2, and R3), where R3 is the best (primary) relay. Figure 12 starts by showing that with CoopMAC at time T0 potential relays do some CSI computation and then broadcast it to source, while at that time RelaySpot potential relays do local computations of I and M factors without any transmission.

At time T1 CoopMAC relays undergo three way handshake using “Helper ready To Send” (HTS) messages, while RelaySpot potential relays updates local factors I and M without any transmission.

At time T2, CoopMAC sends data via the selected helper i.e., R3. RelaySpot potential relays first computes the selection factor S and CW after the reception of data from source, selecting R3 and R1 as relays, which then transmit data to the destination, achieving higher diversity than CoopMAC. The destination notifies the relays (in ACK message), about the priority order for future transmission i.e., ACK(R3; R1). After receiving the ACK, R1 backs-off since R3 seems to be suitable to provide reliable transmissions.

At time T3, R3, the primary relay, moves away. In such case CoopMAC repeats the complete relay selection procedure after a maximum number of retries. While in RelaySpot, the secondary relay R1 (in this example) tries to help the transmission and ends up sending data to destination on behalf of source, after detecting the missing ACK for R3 transmission (or detecting NACK). If this is successful, destination sends ACK(R1).

At time T4 we suppose that R1 is unable to cooperate. In this situation R4 overhears two consecutive NACKs during a predefined time frame. Thus chain relaying will occur as other nodes (R1, R2, and R3) are not suitable anymore. In case of CoopMAC, when there is no suitable relays, poor direct transmission takes place leading to outage.

At time T5 the destination moves closer to source and the direct link between source and destination becomes stronger. In RelaySpot when the destination starts receiving the correct frames from source, it notifies the relays to stop cooperation (i.e., ACK(s)) and continues receiving the direct data, while in CoopMAC the data will be still relayed over the selected relay (R3 in this example).

From this comparison it is clear that CoopMAC always uses additional control messages, such as periodic broadcast and HTS for handshaking. While RelaySpot does not have an overhead related to additional control messages. CoopMAC uses one relay only, while in RelaySpot multiple relays can be utilized in parallel or in sequence base on quality of received frames. CoopMAC does the CSI computation for relay selection, which incurs complexity; moreover the decision for relay is based on historic information. RelaySpot on the other hand, have fast reaction to network dynamics.

VII. IMPLEMENTATION AND ANALYSIS

In this section we start by describing the relaying protocol implementation in OMNET++, and then we discuss the simulation results: first we describe the initial analysis of RelaySpot, which serve as a reference point for further investigation; then we analyze the impact that interference has on relay performance. We also describe the analysis of the proposed cooperative relay switching.

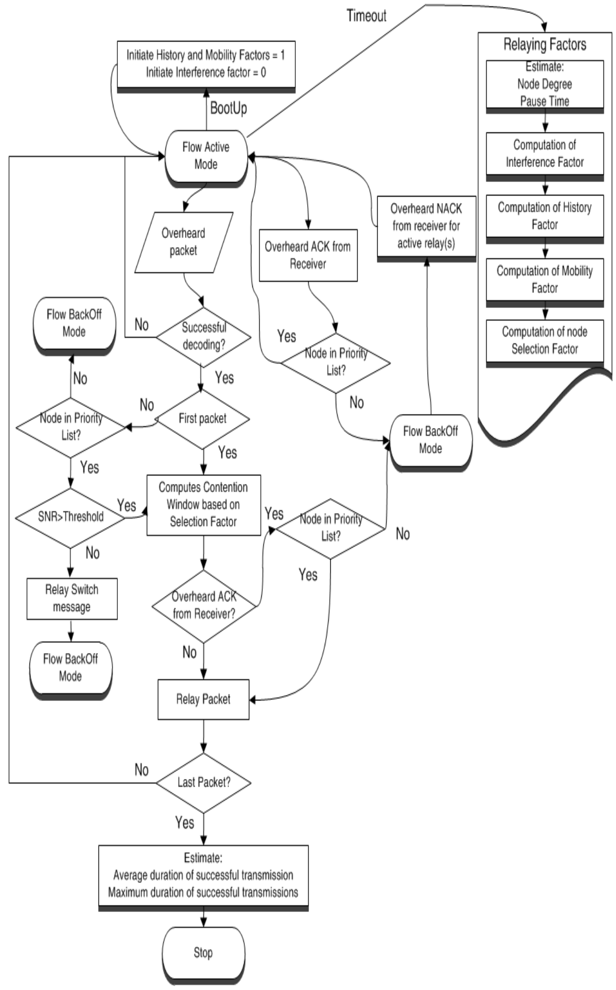

Figure 10. RelaySpot sequence of operations on potential relay nodes

A. RelaySpot implementation

In this section we describe the steps to implement the RelaySpot protocol, which is serving as a prototype for further implementation. We use OMNET++ 4.1 simulator and the MiXim 2.1 framework. As discussed before, relaying protocol is a MAC layer protocol. Therefore, most of the modifications were done in MAC layer. In MiXim framework, whenever a message arrives from physical layer (i.e., data is overheard), the MAC layer invokes a function “handleLowerMsg()”. This function analyzed the incoming message and passes the message to either msgForMe() or msgNotForMe(); if the message (overheard frame) is not for the node, it invokes msgNotForMe(). Normally a node discards data frames that are not intended for itself, but we modified this method to allow a node to keep and send data frames (to behave as a relay). Similarly, when a message arrives from upper layer (i.e., application layer), “handleUpperMsg()” is invoked. This function analyze the message and if it is a data frame to send, the node sends channel sense request and schedule the *Contention* timer. If the node wins contention it invokes sendDATAframe() to send down the data to physical layer, after which it set the MAC state to Wait For ACK (WFACK).

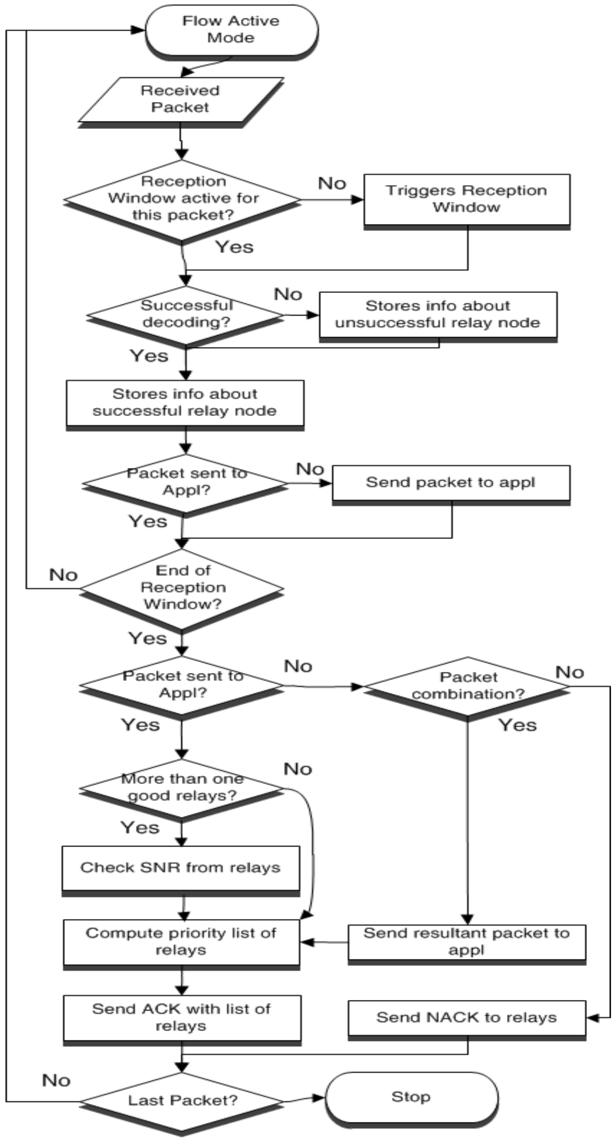

Figure 11. RelaySpot sequence of operations on destination nodes

We have added an additional timer “*RelayContention*”, which is used to schedule the contention period for the relay and to send down the channel sense request. The modifications to msgNotForMe() are as follows: when an overheard message arrives, first a node checks if it is a data frame or not. Then it checks the reservation duration (NAV timer) with message arrival time to be sure that it can relay the data frame. To start relaying, first a node adds its MAC address into address4 field of the data frame; it cancels the NAV timer as the node cannot send or receive data until NAV expires; then it schedules RelayContention timer and sends down a channel sense request. If there is no other ongoing transmission on channel, it calls sendDATAframe() to send the received frame to destination with necessary modification.

B. Initial Analysis

We start by performing an analysis to test the general relaying framework, in order to setup the performance reference points in what concerns throughput and latency in a scenario

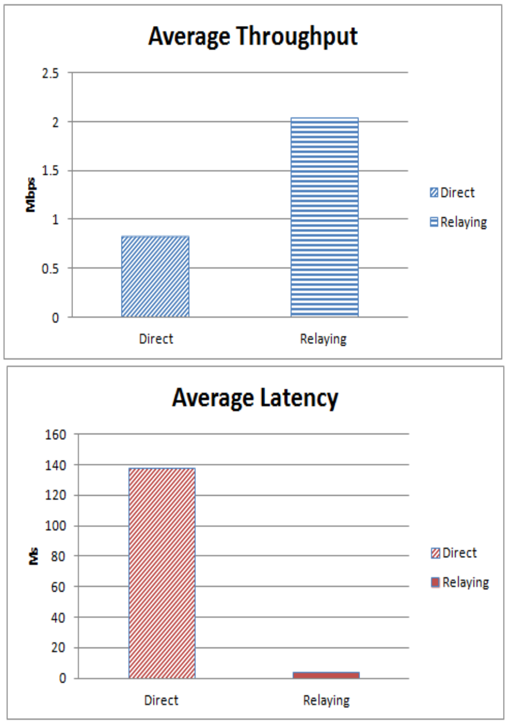

Figure 13. Throughput and latency gains of relaying

without interference, in which data frames can have different sizes. We also run simulations for a first evaluation of the impact of interference on relaying.

In order to test RelaySpot we create a scenario where source and destination is placed at a distance of more than 150 meter with a direct link of 1Mb. Figure 13 shows that when one relay is used improvements can be achieved in term of throughput and latency, reaching an average throughput near 2.1 Mbps and insignificant latency. In the same scenario the direct transmission provides only an average throughput of 0.82 Mbps, which is close to the average capacity of the direct link, and an average latency of 137.8 ms. The improvement in throughput and latency, illustrated in Figure 13, refers to a scenario that is free of interference. However the introduction of interference (different direct and indirect traffic) is expected to lead to a degradation of performance (we analyze this later on this article).

We also analyze the impact of frame size over gain in throughput. Figure 14 shows that RelaySpot has a gain in throughput for a frame of size of 1 Kbits or more in relation to the direct transmission. The gain is negative when the size of frame is less than 1 Kbit, however such frame size is rarely used. The frame size strongly influences the throughput as for smaller frame size the throughput drops due to the domination of the transmission overhead.

In order to have a first glimpse about the impact of interference over relayed data, we run a set of simulations with 25 nodes (other than relay) randomly generating between 1 and 10 Mbps of traffic (inducing indirect interference). Figure 15 shows that the throughput of relayed data dropped to a maximum of 1.8 Mbps instead of 2.1 Mbps as shown in Figure 13. In this situation the interfering node is in competition with the relay node. Therefore the throughput gain depends upon transmission opportunities. Figure 15 shows that at interference (traffic at interfering node) up to 2 Mbps the relay throughput drop linearly while throughput at interfering node reaches to its maximum. Further increase in interference (application traffic of interfering node) does not increase the throughput of interfering node because the relay is blocking this node. This benefits the relay throughput.

A node, when operating as a relay also has an impact on the system: on the relay node itself and on neighbor transmissions. Hence we also analyzed the impact that relaying data has on the data generated and consumed by the node acting as relay. Figure 16 shows that due to interference the number of frames dropped at the relay node increases significantly. Hence, by avoiding interference we can improve not only the performance of the flow being relayed, but also of the overall network performance. This motivates a further analysis about the impact that direct and indirect interference have on relaying based on RelaySpot, which uses interference-aware relay selection metrics.

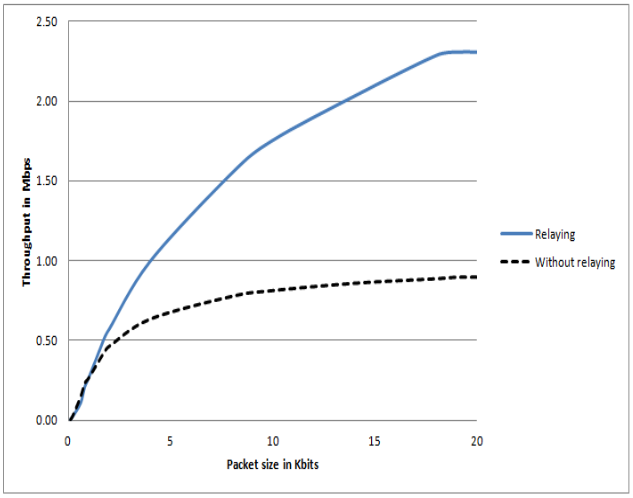

Figure 14. Frame size impact on throughput (with and without relaying)

C. Analysis of Impact of Interference

In this section we evaluate the performance of RelaySpot in the presence of different levels of direct and indirect interference. Several simulations are run based on the MiXim framework of the OMNET++ 4.1 simulator. Each simulation has a duration of 300 seconds and is run ten times, providing a 95% confidence interval for the results.

Simulations consider a scenario where all nodes are static and have similar stochastic history of transmissions among them, thus the mobility factor and history factors are assumed to be 1. The source and destination are at a distance of more than 150 meters from each other with a poor direct link, with an average of 1 Mbps. Depending on the level of interference needed in each simulation, potential relays may operate also as sources sending data to the same destination at different traffic rates.

First we did simulations by selecting a relay based on node degree and distance towards the destination in an interference

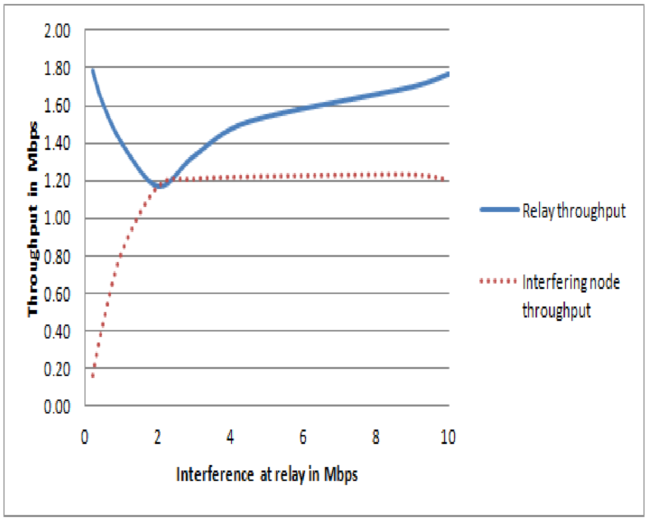

Figure 15. Relay throughput with indirect interference

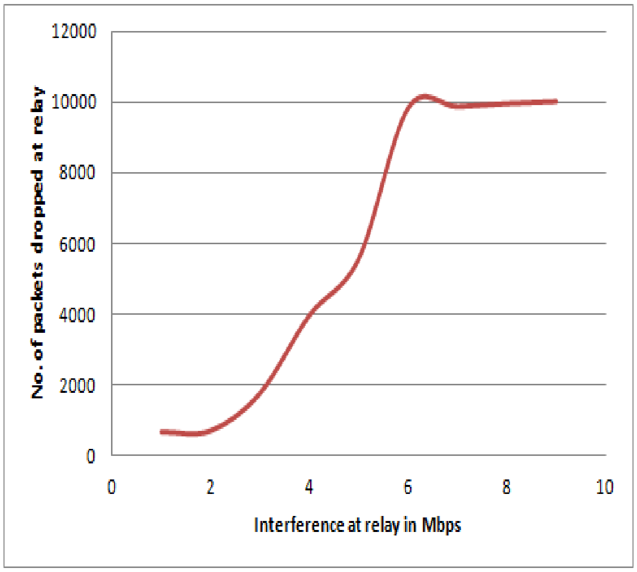

Figure 16. Number of frames dropped at relay node

free scenario. Using node degree as metric lead to the selection of isolated nodes, with high probability, being such nodes far away from the source and destination which were reflected in low throughput and big latency. Therefore, distance-based relay selection achieved significant improvement in term of both throughput and latency when compared to degree-based. Therefore, we consider distance-based as a reference point for our further evaluation of RelaySpot as an interference-aware relaying algorithm.

Figure 17 shows that by introducing interference, the performance of degree-based solutions starts degrading. As the direct interference increases, the relay starts blocking the source-destination communication, since it has its own processing delay. By using the proposed RelaySpot metric (Interference-aware) for direct interference, we achieved improvements in term of throughput and latency, as RelaySpot selects a relay which has less load. However, the gain is not considerable,

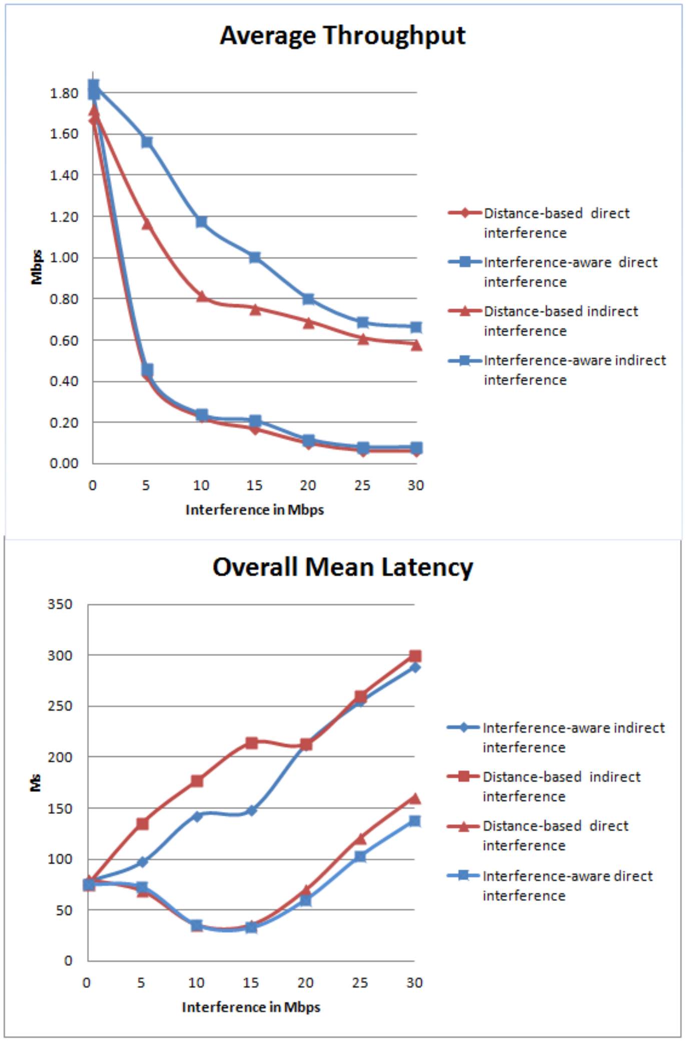

Figure 17. Throughput and latency analysis [23]

as the direct interference at other potential relay nodes is still affecting the source-destination pair. Therefore, it is always better to chose a dedicated relay (a relay without its own traffic). Figure 17 shows that the gain of the interference-aware approach with direct interference is more visible in the case of latency, since the interference-aware approach selects a relay from a set of nodes that present higher availability for retransmission (lower number of local generated traffic), even if placed further away from the destination, leading to lower latency. This gain is clearer with high traffic load, since distance-based approach keep selecting overloaded nodes near the destination.

In a scenario with indirect interference, the throughput gain of RelaySpot is significant (e.g., 33% with a load of 10 concurrent flows) because the indirect traffic does not affect the source-destination pair: only the chosen relay is affected. Nevertheless RelaySpot is able to choose a relay with low probability of being blocked by additional transmissions, leading to an improvement in performance. With an increase of traffic load this performance gain diminishes, because at some level of indirect interference it is hard to avoid interference, but it is always higher than the distance-based approach. The

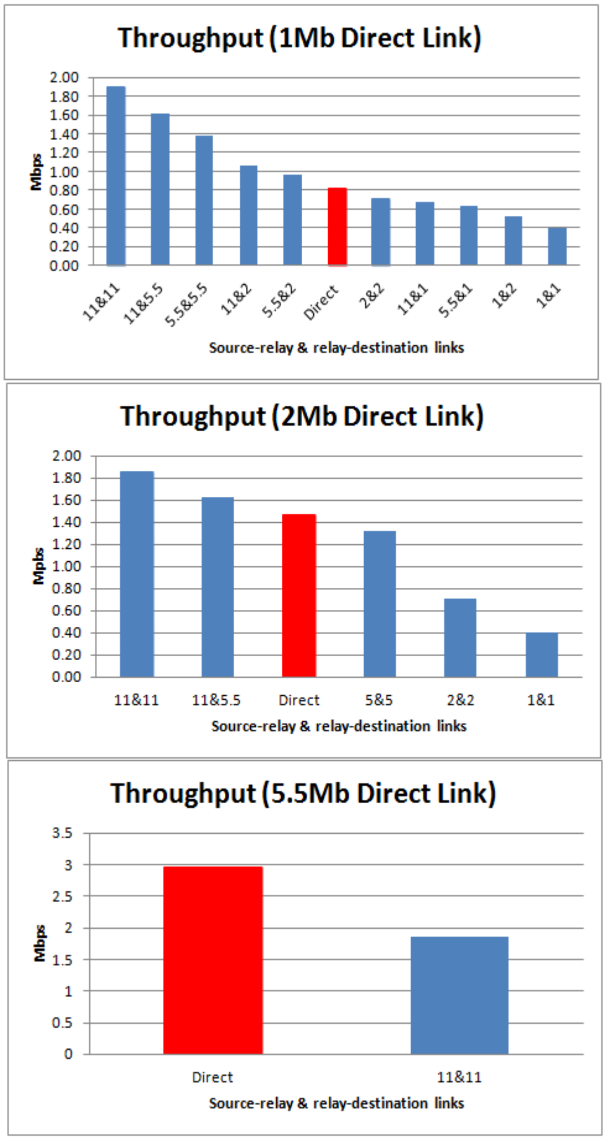

Figure 18. Analysis with different data rates

advantage of our interference-aware approach is also visible in terms of latency, since selecting a relay with low interference (lower number of concurrent neighbor flows) leads to higher transmission opportunities. The gain in latency decreases with a load of 20 concurrent flows, mainly due to increasing number of concurrent flows placed far away from the destination, which benefits distance-based approaches. Nevertheless, results show that even with a random placement of concurrent flows, the interference-aware solution keeps a lower latency with high traffic loads. By including the history factor we can achieve further improvement in both throughput and latency [24].

D. Cooperative Switch Analysis

In what concern the switching between relays as discussed in section IV-B, a relay can give up relaying if it does not ensure acceptable conditions anymore. To analyze this idea we run simulations with different source-destination pairs, relayed by relays in different location, and with different combination of data rates in the source-relay and relay-destination links. It is observed from Figure 18 that relaying is not always useful. In order to achieve performance improvement the direct link must be replaced by relays with both source-relay and relay-destination links that present a data rate higher than the direct link, and one of the links must have a data rate at least twice higher than the direct link. For instance, 1 Mbps direct links can be replaced by relays with 11 Mbps and 5.5 Mbps, or even with 5.5 Mbps and 2 Mbps, but not with 2 Mbps and 2 Mbps. For example if a direct link of 5.5 Mbps is replaced by relays with 11-11 Mbps links, the gain will be negative.

Hence, to ensure performance gain the cooperative relay switching operation of RelaySpot provides the following operation, as illustrated in Figure 10: in MiXim the data rates are decided on bases of received SNRs. Therefore, the primary relay collects SNRs of different links by overhearing to decide if switching is required or not. If a primary relay observe that its signal strength (SNR value) is below certain threshold (which means it does not support fast bit rate anymore), it notifies the secondary relay for help with a Relay-Switch message. The secondary relay starts relaying data while the primary relay goes to back-off mode.

VIII. CONCLUSIONS AND FUTURE WORK

Most of the current cooperative relaying approaches use only one relay, selected based on CSI estimations, without exploiting different relays in parallel or in sequence. The proposed *RelaySpot* framework provides a set of functional building blocks aiming to opportunistically exploit the usage of several relays to ensure accurate and fast relay selection, posing minimum overhead and reducing the dependency upon CSI estimations in scenarios with mobile nodes. The proposed building blocks are related to opportunistic relay selection, cooperative relay scheduling, and chain relaying. Moreover, RelaySpot does not have any additional control overhead and its functional blocks allow fast reactions to network conditions. We also observed that interference have great impact over relay network. After analyzing the behavior of RelaySpot in a scenario with interference our findings show that selecting a relay with low interference (lower number of concurrent neighbor flows) leads to higher transmission opportunities. The impact of direct and indirect interference is different in relation to throughput and latency: indirect interference has higher impact over latency, while direct interference leads to lower throughput. Interference-aware solution as RelaySpot ensures also low resource blockage.

As a future work, we will analyze the performance of a version of RelaySpot that would be aware of the type of traffic in order to further investigate the behavior of the cooperative relay switching and relay scheduling functionalities. We will also further evaluate how RelaySpot can contribute to increase the overall network capability in the presence of mobile nodes.

ACKNOWLEDGMENT

Thanks are due to FCT for PhD grant number SFRH/BD/60436/2009. The research leading to these results has received funding from the European Commission's Seventh Framework Programme (FP7) under grant agreement n° 257418, project ULOOP (User-centric Wireless Local Loop).

REFERENCES

[1] T. Jamal, P. Mendes, and A. Zúquete, "RelaySpot: A framework for Opportunistic Cooperative Relaying," in *Proc. of IARIA ACCESS*, Luxembourg, June 2011.

[2] 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*, vol. 25, no. 2, pp. 340–354, Feb. 2007.

[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*, vol. 125, no. 10, pp. 353–359, Oct. 2008.

[4] T. M. Cover and A. E. Gamal, "Capacity Theorems for the Relay Channel," *IEEE Trans. Info. Theory*, vol. IT-25, p. 57284, Sep. 1979.

[5] A. Sendonari, E. Erkip, and B. Aazhang, "User Cooperation Diversity-Part II: Implementation Aspects and Performance Analysis," *IEEE Journal on Selected Areas in Communications*, vol. 51, no. 11, pp. 1939–1948, Nov. 2003.

[6] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behavior," *IEEE Trans. Inform. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[7] E. Erkip, A. Sendonaris, A. Stefanov, and B. Aazhang, "Cooperative Communication in Wireless Systems," *Advances in Network Information Theory*, vol. DIMACS Series, 2004.

[8] M. Gast, "802.11: Wireless Networks: The Definitive Guide," *O'Reilly*, Apr. 2002.

[9] Z. Hao and C. Guohong, "rDCF: A Relay-Enabled Medium Access Control Protocol for Wireless Ad Hoc Networks," *IEEE Transactions on Mobile Computing*, vol. 5, Mar. 2006.

[10] K. Tan, Z. Wan, H. Zhu, and J. Andrian, "CODE: Cooperative Medium Access for Multirate Wireless Ad Hoc Network," in *Proc. of IEEE SECON*, California, USA, Jun. 2007.

[11] L. Mei-Hsuan, S. Peter, and C. Tsuhan, "Design, Implementation and Evaluation of an Efficient Opportunistic Retransmission Protocol," in *Proc. Of IEEE MobiCom*, Beijing, China, Apr. 2009.

[12] H. S. Lichte, S. Valentin, H. Karl, I. Aad, L. Loyola, and J. Widmer, "Design and Evaluation of a Routing-Informed Cooperative MAC Protocol for Ad Hoc Networks," in *Proc. of IEEE INFOCOM*, Phoenix, USA, Apr. 2008.

[13] H. Adam, W. Elmenreich, C. Bettstetter, and S. M. Senouci, "CoRe-MAC: A MAC-Protocol for Cooperative Relaying in Wireless Networks," in *Proc. of IEEE GLOBECOM*, Honolulu, Hawaii, Dec. 2009.

[14] N. Marchenko, E. Yanmaz, H. Adam, and C. Bettstetter, "Selecting a Spatially Efficient Cooperative Relay," in *Proc. of IEEE GLOBECOM*, Honolulu, USA, Dec 2009.

[15] A. Bletsas, A. Khisti, D. Reed, and A. Lippman, "A simple Cooperative Diversity Method Based on Network Path Selection," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 3, pp. 659–672, Mar. 2006.

[16] K.-S. Hwang and Y.-C. Ko, "An Efficient Relay Selection Algorithm for Cooperative Networks," in *Proc. of IEEE VTC*, Baltimore, USA, Oct. 2007.

[17] Y. Chen, G. Yu, P. Qiu, and Z. Zhang, "Power-Aware Cooperative Relay Selection Strategies in Wireless Ad Hoc Networks," in *Proc. of IEEE PIMRC*, Helsinki, Finland, Sep. 2006.

[18] Y. Zhao, R. Adve, and T. J. Lim, "Improving amplifying-and-forward relay networks: Optimal power allocation versus selection," in *Proc. of IEEE ISIT*, Seattle, USA, Jul 2006.

[19] H. Adam, C. Bettstetter, and S. M. Senouci, "Adaptive Relay Selection in Cooperative Wireless Networks," in *Proc. of IEEE PIMRC*, Cannes, France, Sep. 2008.

[20] Z. Lin, E. Erkip, and A. Stefanov, "Cooperative Regions and Partner Choice in Coded Cooperative Systems," *IEEE Transactions on Communications*, vol. 54, no. 7, pp. 1323–1334, Jul. 2006.

[21] A. Nosratinia and T. E. Hunter, "Grouping and Partner Selection in Cooperative Wireless Networks," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 2, Feb. 2007.

[22] T. Jamal and P. Mendes, "Relay Selection Approaches for Wireless Cooperative Networks," in *Proc. of IEEE WiMob*, Niagara Falls, Canada, Oct. 2010.

[23] T. Jamal, P. Mendes, and A. Zúquete, "Interference-Aware Opportunistic Relay Selection," in *Proc. of ACM CoNEXT student workshop*, Tokyo, Japan, Dec 2011.

[24] T. Jamal, P. Mendes, and A. Zúquete, "Opportunistic Relay Selection for Wireless Cooperative Network," in *Proc. of IEEE IFIP NTMS*, Istanbul, Turkey, May 2012.