RelaySpot: A Framework for Opportunistic Cooperative Relaying

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]IEETA / Dep. Electronics, Telecommunications and Informatics 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 paper we describe a framework, called RelaySpot, to implement cooperative wireless solutions in large mobile networks, based upon the combination of opportunistic and cooperative 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 relaying; Opportunistic relaying; 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 the entire duration of the transmission.

Extensive research has been done to mitigate the effect 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 [1].

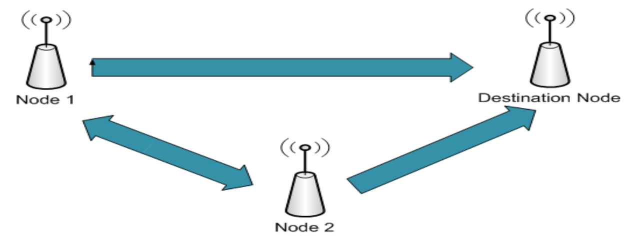

Figure 1. Cooperative Relaying

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. Because 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.

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 with an efficient cooperative *Medium Access Control* (MAC) layer achieved by modifying the DCF signaling scheme.

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

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reacting to network changes, mainly in the presence of mobile nodes.

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., CSI) collected over multiple links. We describe an 802.11 backward compatible cooperative relaying framework, called *RelaySpot*, that aims to ensure accurate and fast relay selection, posing minimum overhead and reducing the dependency upon CSI estimations, which is essential to increase the 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 combined utilization of opportunistic relay selection and cooperative scheduling. Intermediate nodes take the opportunity to relay in the presence of local favorable conditions (e.g., no concurrent traffic) and absence of relaying attempts by any other nodes. 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.

II. State Of The Art

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 cooperative MAC source-based cooperative relaying schemes are that use one relay [2], [3] or two relays in parallel [4]. Source-based relaying approaches require the source 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 packets 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. 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 [5], [6] rely on relays to retransmit on behalf of the source when the direct transmission fails. An example is PRO [5], where relays are selected 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 [7] 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 best relay in term of 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 [8] 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 cooperation 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 packet might be in need of help but also the next hop. An alternative approach may be to use two-in-one cooperation [6], 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.

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 [9]. 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 [10], [11]. For instance, with relaying on demand [12], the basic relay selection mechanism [9] was 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.

For better understanding of the different type of relay selection schemes, Jamal and Mendes [13] devised a comprehensive analysis and taxonomy.

III. 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 the 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 packets 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 no direct or indirect transmissions.

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

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 2 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.

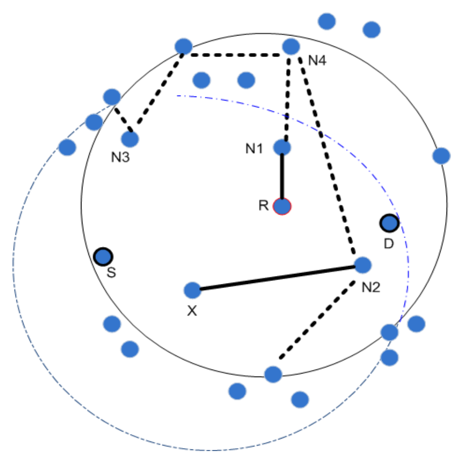

Figure 2. Opportunistic relay selection scenario

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 can be 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.

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

Lets go back to Figure 2 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 gives preference to node R, although it presents a higher mobility factor than X.

After overhearing data packets 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.

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

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 3 the selection mechanism may leads to the qualification of more than one relay each one with different values of S, depending on current conditions. Selected relays will forward data towards destination based on its cooperative relay scheduling mechanism.

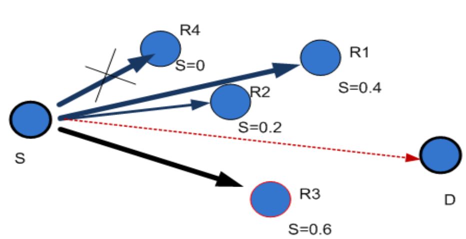

Figure 3. Opportunistic relay selection

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 Eq 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 packet, aims to construct error free packets while avoiding re-transmissions.

Based on the quality of the packets 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 receiver only process received packets after a predefined time window). By sending a list of priority relays embedded in ACKs 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 other 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.

Cooperation between selected relays, identified by the priority list embeded in ACK message, aims to ensure a high probability of selecting the best set of nodes as relays over time. Decision to switch relays is done as a consequence of a transmission. Figure 4 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 3). Based on the quality of the received packets, the destination is able to decode the data by combining the packets received from R1 and R2.

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. Cooperative scheduling allows to keep a source-destination transmission in a good shape even when the primary relay is not useful anymore.

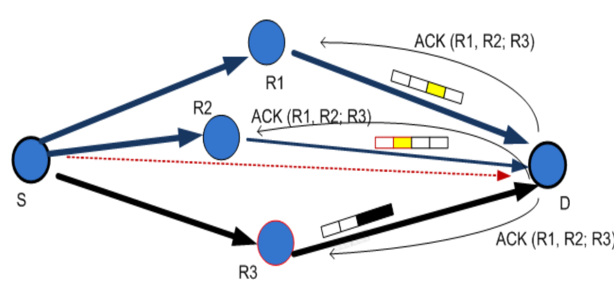

Figure 4. Cooperation relay scheduling

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

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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 5).

In a chain relaying, the relaying process is repeated for the relay-destination channel (R1-D and R2-D in Figure 5), 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 packets 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, which can be detected after overhearing of two recurring NACK messages (or the absence of ACKs/ NACKs) during a predefined time window. Chain relaying aims to minimize the outage and to increase the overall throughput by complementing the cooperative scheduling functionality.

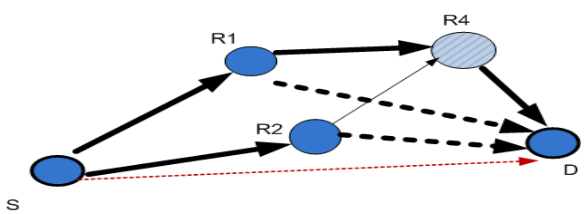

Figure 5. Chain relaying

IV. RelaySpot Algorithm in a Nutshell

The RelaySpot process is triggered by potential relays themselves (the ones with correct copies) if no ACK from the destination is overheard (c.f. Figure 6). RelaySpot operation, for a specific pair source-destination ends when there are no more packets to be send or when the destination informs the relays to stop relaying packets, after detecting that the number of damaged packets received through the direct channel from the source have decreased below a predefined threshold. This action aims to increase network capacity by allowing relays to help other endangered transmissions.

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 goal is to give higher priority to successful relaying operations in future transmissions.

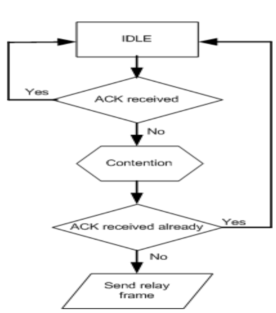

Figure 6. RelaySpot start-up flow

Due to the unpredictable conditions of relay-destination channels, the RelaySpot process can be repeated in a recursive process having relays as sources (Chain Relaying). Nodes that are able to successfully decode packets 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 ACKs/ 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) packet from any relay in contact with the source.

Figure 7 illustrates the operation 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 7 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 does local computations of I and M factors without any transmission.

At time T1 CoopMAC relays undergoes three way handshake by introduction of "Helper ready To Send" (HTS) message, 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, achieve higher diversity than CoopMAC. The destination notifies the relays (in ACK message), about priority order for future transmission i.e., ACK(R3; R1). After receiving the ACK, R1 will back-off since R3 seems to be suitable to provide reliable transmissions.

At time T3, R3, the primary relay, moves away. In such case CoopMAC will repeat from start the relay selection procedure after a maximum number of retries. While in RelaySpot, the secondary relay R1 (in this example) will try to help the transmission and will send data to destination on behalf of source after detecting the missing ACK for R3 transmission (or detecting NACK). If this is successful, destination will send ACK(R1).

At time T4 we suppose that R1 is unable to cooperate too. 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 will take place leading to outage.

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

V. Summary and Future Work

Most of the current cooperative relaying approaches use only one relay, selected based on CSI estimations, without

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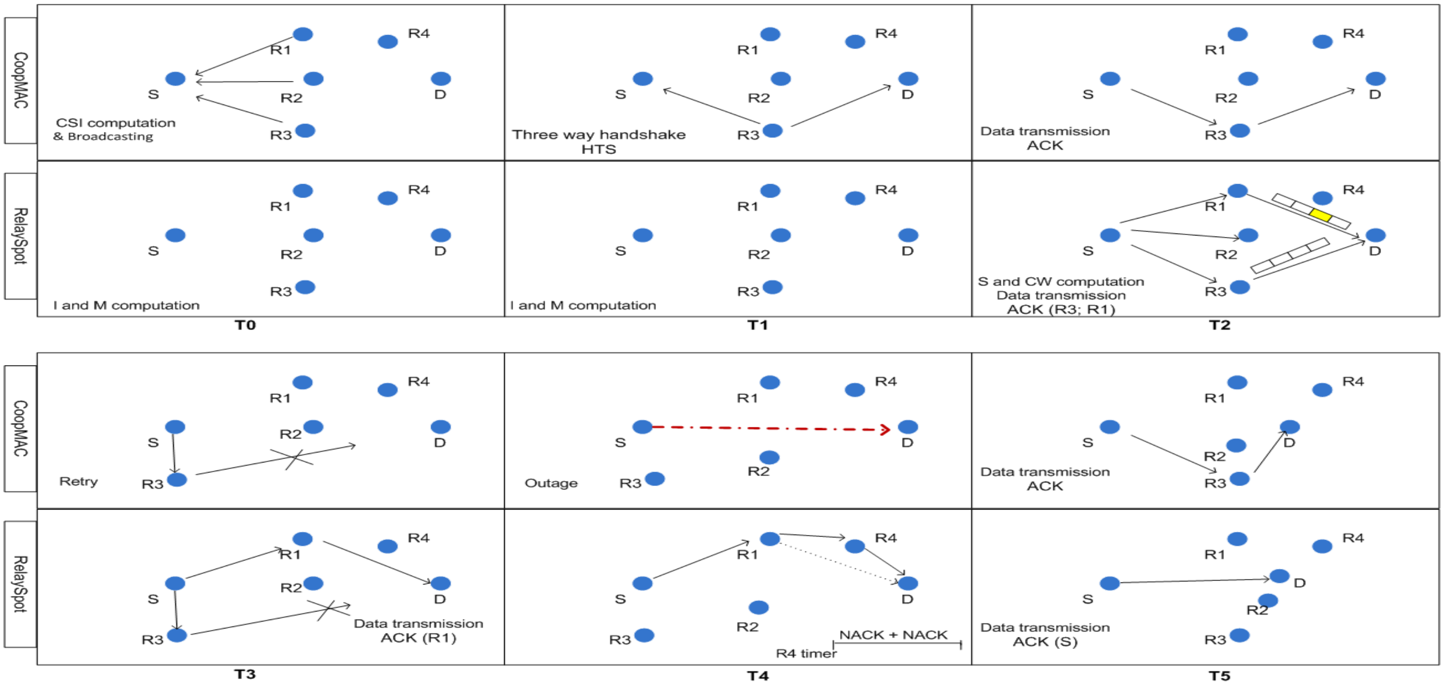

Figure 7. Illustration of the RelaySpot algorithm with chain relaying

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. With very dynamic channel conditions, it is expected that any solution based on the RelaySpot framework will have better performance than previous relaying proposals due to its combination of opportunistic and cooperation operations.

As future work, we aim to implement an instantiation of the RelaySpot framework in a test-bed aiming to prove the efficiency of this new type of cooperative relaying schemes. We expect to prove the potential of the RelaySpot achievements in terms of outage, delay and throughput, as well as to investigate the adjustment for the source retransmission, contention window and chain relaying timers. Finally, the impact of the hidden and expose node problems needs to be addressed, because the RelaySpot framework proposes to avoid RTS/CTS messages since their utilization depends on packet size and increasing overhead.

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