Relay Selection Approaches for Wireless Cooperative Networks

Tauseef Jamal, Paulo Mendes
UITC, University Lusofona
Campo Grande, 376, Lisbon, Portugal
{tauseef.jamal, paulo.mendes}@ulusofona.pt

***Abstract*—Wireless networks are characterized by having limited resources accessed by a large number of mobile stations with distinct capabilities. In such challenged environment the dynamic control of resources is of major importance to mitigate the limitations of wireless networks, such as the impact of low data rate stations and wireless channel oscillations. Such augmented usage of wireless resources can be implemented based upon cooperative relaying schemes, which have the potential to support the desired system performance and network lifetime. However, the introduction of cooperative relay raises several problems such as the issue for relay selection and resource allocation. Due to the significant number of different cooperative relaying approaches, this article aims to provide a systematic analysis and classification of major relay selection procedures, and to identify open research directions as well as the most suitable evaluation methods for an efficient analysis of different approaches.**

***Index Terms*—Cooperative Communication, Relay Selection, Relaying, Routing, Performance**

I. Introduction

NEXT generation wireless networks are expected to provide services that need high performances as well as bandwidth efficiency. This means that as the number of wireless terminals increases, higher system capacity is needed to provide the required data rate levels. However, although wireless networks provide easy connectivity and fast deployment, they still present low performance levels. The major limitation of wireless networks comes from the shared medium, limited-resources devices, and unstable wireless channels. Channel conditions in wireless networks are subjected to fading variations, including interference that can affect both throughput and reliability. As a result, receivers may get multiple copies of the transmitted signal, each having travelled through a different path. Such multipath fading increases the number of errors in the transmission, requiring additional re-transmissions that decreases the network throughput. Nevertheless, the effects of multipath fading can be mitigated by using cooperative communications, which aims to take advantage of wireless diversity to provide efficiency levels equivalent to wired line communications and similar to wireless Multiple-Input Multiple-Output (MIMO) systems.

The application of cooperative communications ranges from ad-hoc self organizing networks to vehicular networks, sensor networks and dynamic spectrum management. Technological challenges increase when nodes have intermittent access to a network infrastructure, which can happen in the presence of low data rate stations and in mobile scenarios. In the former case, network performance may decrease since low-data rate devices may grab the radio spectrum for long periods of time. In such situation high-data rate devices may act as relays, helping low-data rate devices to release the spectrum earlier, contributing to increase the overall system performance.

In the case of mobile scenarios, two examples can be provided to show the benefits of applying cooperative communications: vehicular networks and pedestrian networks. In the former example, cars may often leave the range of an Access Point (AP) without terminating their communication sessions. With cooperative communications, cars can relay data to the AP via another car, minimizing packet losses [1] and increasing coverage. In the case of pedestrian mobile networks, mobile devices may perform ping-pong movements at the edge of an AP with high probability, where devices will spend too much time performing handovers between neighbor APs, leading to performance degradation. To avoid such situation, another device can act as relay allowing the moving node to stay always associated to the same AP, avoiding handovers. These examples show the advantages of deploying cooperative communications to improve the utilization of wireless spectrum while providing higher network performance.

In this paper, we focus on the application of cooperative communications, namely relaying, to increase spectrum and power efficiency, network coverage as well as to reduce outage probabilities. With the introduction of cooperative relaying, the relay selection process requires special attention since it has a strong impact on network and transmission performance.

This article provides an analysis of relay selection procedures proposed in recent years. The goal is to identify the most suitable relay selection mechanism to support the design of cooperative MACs and cooperative routing strategies. This study includes the creation of a taxonomy and the performance analysis of the most prominent proposals. This article ends with an analysis of open research issues.

II. Related Work on Relay Selection

Independently of operating only at the link layer or in combination with cooperative diversity schemes at the physical layer, the performance of cooperative relaying strongly depends upon the efficiency of the process used to select one or more relays.

In what concerns relay selection mechanisms, the basic mechanism proposed in [2] defines an opportunistic behavior in which overhearing nodes estimate their Channel State Information (CSI) 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. Another simple proposal [3] uses the measured Signal-to-Noise ratio (SNR), the overhearing nodes send out a busy-tone (the relay with best channel conditions sends longer busy tone). Such mechanisms present a high probability of collisions. Nevertheless, opportunistic relaying has been modified aiming to increase its efficiency [4], [5], [6].

In Chen et al. [5], the sources include their residual power level on Request-to-Send (RTS) packets, allowing all overhearing nodes to estimate CSI, making optimal power allocation. The relay selection decision depends upon the relay transmission power and CSI, as well as the residual power of source and relay nodes. Another proposal in [7] where the source sends its maximum transmit power in RTS packet. The overhearing nodes compete for selection on the basis of signal strength combined with the overheard power information. Both of these approaches contend similar to basic mechanism in [2], the difference is that [2] just consider the channel estimation and not energy considerations.

K. Hwang et al. [4] modified the basic opportunistic approach [2] by reducing the number of channel estimations. It defines a predefined SNR threshold and the relay can take part into selection only if it satisfies such threshold. The aim is to save power consumption, but it still relies on channel estimations. In the [8], the threshold at relay is set based on Bit-Error-Rate (BER). The relay can decode and forward the information only if the quality of received signal is above that threshold. But this does not guarantee that symbols are decoded correctly.

All previous relay selection approaches assume that relays are always needed. Adam et al. [6] proposes an opportunistic approach in which relay selection is only triggered by the destination when the estimated (by the destination) CSI is lower than a pre-defined threshold. This reduces energy consumption. However relay selection still relies on overhearing RTS and Clear-to-Send (CTS) frames, leading to an increase of the communication overhead, especially in multi-hop scenarios.

In all previous approaches relays are selected in a distributed way where relays do not know the channel information of other potential relays. In CoopMAC [9] and CODE [10], relays periodically broadcast their willingness for cooperation by sending their channel information, which is stored by sources. Sources select either a direct transmission or the transmission through a relay by look-up into the local table. However, the relay selection is based on historical information and may not work in mobile environments.

In PRO [11] a potential relay may retransmit on behalf of a source when it detects a failed transmission. In PRO the potential relays broadcast their channel information allowing other relays to set their priority level. Based on priority levels relays then select their contention window in order to increase chances of retransmission. Thus each node maintains a table to keep the channel information (priority levels) of neighbors, which maintenance consumes power, resources and affects the network capacity. Another problem is the occurrence of unnecessary retransmissions, if eligible relays do not overhear an Acknowledge (ACK) frame, due to failure in ACK transmission and not on data transmission.

N. Marchenko et al. [12] propose to select a relay selection based on channel conditions and spatial efficiency, which is achieved when relay selection results in few additional transmissions being blocked. An example is when a relay lies near the source or the destination (low distance towards the communicating nodes), in which case the relay shares a large part of the wireless resources with the source-destination direct link, presenting a low probability of blocking concurrent transmissions. In terms of spatial efficiency, although selecting relays closer to source reduces the probability of blocking other transmissions, it decreases the benefits brought by spatial diversity.

In the two-for-one cooperation approach [13] cross layering is used to provide routing information to the MAC layer in order to allow simultaneous relaying over two hops. The two-for-one cooperation is particularly suited to achieve high diversity with little bandwidth expansion. At a given Packet-Error-Rate (PER), the gain of the two-to-one approach can be used to reduce transmit power, improving network capacity. However, it presents the problem of unnecessary transmissions. Another multi-hop relaying approach is proposed by H. Adam el al. [14]. It exploits synergy between single-hop relays (helping only one transmission) and multi-hop relays (helping two transmissions simultaneously) taking into account information provided by a link-state routing protocol. The used scenario excludes a potential (even if weak) direct link between source and destination. Still, as occurred with the proposal presented by H. Lichte et al [13], the presented solution depends on a global topological view of the network provided by the routing protocol. Moreover, it is not justified why is the usage of a single-hop relay over the destination link, and not the source link, the best choice: considering that a bad channel from source to relay will jeopardize the effort applied from the relay to the destination, it could make sense to have the single-hop relay helping the source transmission.

III. Taxonomy for Relay Selection

It is clear that the major challenge in cooperative relaying is to select a node, or set of nodes, which can effectively improve data transmission. Although most of the current schemes envision operation under a single AP, relay selection mechanisms should be carefully defined thinking about large networks. One reason is the unsuitable performance of chaining relaying processes along multiple hops. Another reason in the impact that one relay may have on concurrent transmissions.

The first aspect that needs to be considered when analyzing relay selection mechanisms is related to the selection criteria. As seen in section II, the most common in the literature are: CSI, SNR and PER. Since such parameters need to be measured in both sender-relay and relay-receiver links, relay selection may require the exchange of meta-data, usually transported using RTS and CTS frames.

The second aspect is the impact on the overall network. Normally relays are selected to improve the performance of a source-destination communication (e.g. [2], [9]), but no consideration is taken about the impact over the overall network capacity. Such selfish behavior may lead to higher probability of transmission blocking and interference.

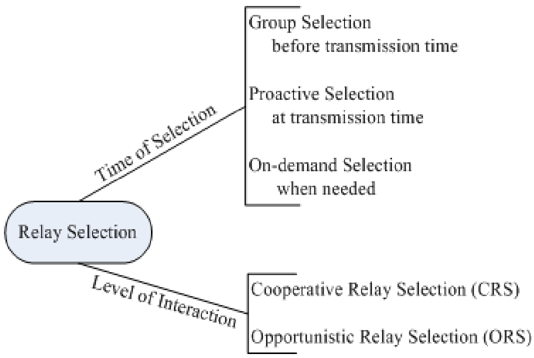

Figure 1. Relay selection taxonomy

For a better understanding of the utility of current relay selection approaches, we classify them in what concerns time of selection (three classes) and level of interaction (two levels), as shown in Figure 1.

In what concerns time of selection, we group approaches into the following three categories: i) *group selection*, in which relay selection occurs before transmission aiming to achieve certain pre-defined performance level; ii) *proactive selection*, in which relay selection is performed by the source, the destination, or the relay itself at transmission time ; ii) *on-demand selection*, in which relay selection is performed when needed, namely when direct channel conditions decrease below a pre-defined threshold.

In what concerns the level of interaction, we group relay selection mechanisms into two categories: *Opportunistic Relay Selection* and *Cooperative Relay Selection*. With the former each potential relay decides about forwarding packets, based on the information that it has about the network. This may lead to a high probability of selecting more than one relay whose transmissions will compete for the wireless medium. While opportunistic relay selection occurs in one phase, the cooperative relay selection process encompasses two phases: In the first phase relays broadcast willingness to relay and local information that will be useful for relay selection. Such information is overheard by other nodes, which can then participate in the selection of one or more relays in a second phase. One drawback of cooperative relay selection is the potential lack of synchronization between the two operational phases. As a consequence, packet relaying may not occur if a node that was selected as relay is not available when transmission is required, due to mobility or lack of energy.

IV. Relay Selection Classification

For a better understanding of the existing relay selection proposals, we analyze seven types of relay selection approaches, being the classification based on the taxonomy presented in section III (c.f. Figure 2). This study is helpful to identify similarities among existing proposals, supporting the decision about the relay selection mechanism that better suits novel cooperative relaying proposals.

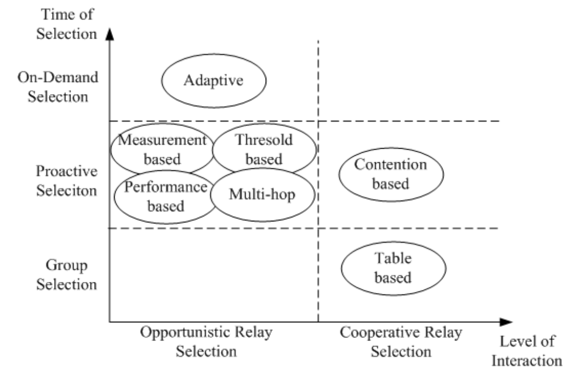

Figure 2. Classification of relay selection approaches

As an introduction to the analysis provided in this section, we may say that the basic opportunistic relay selection scheme is based on local measurements (measurement-based relay selection). Several other approaches aim to mitigate the limitations of measurement-based relay selection, by minimizing the overall transmission power (performance-based relay selection) and the channel estimation overhead (threshold-based relay selection). All these three approaches are opportunistic and follow a proactive selection approach, which means that a relay (or set of relays) is always selected. The on-demand selection category (e.g. adaptive relay selection) follows a different approach, in which the relay selection procedure is only triggered if needed.

Contrary to opportunistic relay selection, cooperative relay selection procedures require the exchange of information among the involved communication nodes. In this case we identify two categories. One (table-based relay selection) that leads to the selection of a controlled number of relays (one or two) based on information kept by the source, and a second category (contention-based relay selection) that leads to the selection of a set of a variable number of relays. In this case competition among relays may be reduced by making use of the contention windows.

All mentioned relay selection approaches only consider transmissions over a direct (probabilistically poor) source-destination link. This assumption restrict the scenarios over which cooperative relaying may be used. To expand the utility of cooperative relaying to multi-hop networks an extra category (multi-hop relay selection) considers that relays may also help source-destination communications even when such communications have to go other an intermediary node (identified by a routing protocol).

A. Measurement-based Relay Selection

Measurement-based relay selection approaches are characterized by requiring no topology information, being based only on local measurements of instantaneous channel conditions. An example is the opportunistic relaying approach proposed by A. Bletsas et al. [2]. Shan et al. [3] is another example.

In general the operation of measurement-based selection approaches is as follows: each potential relay estimates channel conditions (CSI in case of [2]) of source-relay and relay-destination channels by using RTS/CTS signaling. CSI estimation is based on fading amplitudes between source-relay and relay-destination and on the expected performance of the source-relay-destination channel. After CSI estimation, each relay sets a transmission timer to a value inverse to the estimated CSI value. The timer with the best suitable CSI expires earlier, qualifying that device as relay. Devices in listening mode will back off as soon as they overhear a short duration packet sent by the qualified relay. To avoid the case of "hidden" relays, the qualified relay may request the destination to notify all the other potential relays about its transmission.

Measurement-based approaches are able to select the best relay among N devices, but for this they may require 2N channel state estimations, which is in the same complexity order as conventional Distributed Space-Time Coding (DSTC) algorithms [15]. Nevertheless, DSTC algorithms require significant modifications of hardware to support complex signal processing at receiver.

B. Performance-based Relay Selection

Performance-based selection approaches rely on performance criteria (e.g. delay and energy efficiency etc) to select the most suitable relay, aiming to optimize measurement-based approaches. Approaches proposed in [5] and [7] are examples of performance-based relay selection.

In general the operation of performance-based selection approaches is as follows: in a first phase, sources transmit their required performance level, and in a second phase all potential relays estimates their channel conditions as well as performance level. For example, PARS approach [5] aim to reach an optimal power allocation.

However, estimation overhead may bring some limitations to performance-based approaches, and the transmission may still occur over the direct link if the performance conditions are not met.

C. Threshold-based Relay Selection

Threshold-based approaches rely of a certain threshold to reduce the number of competing relays, and thus reducing the overhead of channel estimations. This class of relay selection can follow any category of interaction (c.f. Figure 1). The relay selection involves two phases.

In general the operation of threshold-based selection approaches is as follows: in a first phase, each neighbor compares the quality of signal it received from the source with a threshold such as SNR (in case of [4]) or BER (in case of [8]). In a second phase, only relays who satisfied the threshold requirements will enter into relay selection according to the algorithm. For instance, in [4], the node with the maximum lower value of the SNR in the source-relay and relay-destination links is selected as relay.

This category of schemes may lead to some complexity, for instance, in K. Hwang et al. [4] when all M relays satisfy the threshold, there will be 2M channel estimations. Another problem is the choice of the threshold value; if it is fix then relay selection mechanism is unable to react to variations on channel conditions.

D. Adaptive Relay Selection

Due to variations on channel conditions the PER of the link from source to destination may decrease in a way that relaying over a helping node is not needed. Adaptive relay selection approaches propose to perform relay selection only if relaying is needed with high probability. An example of adaptive relay selection is Adam et al. [6].

In general the operation of adaptive relay selection approaches is as follows: in a first phase the destination compares the quality of received signal with a pre-defined threshold. If the quality of received signal is below that threshold, then the relay selection process is triggered. In case of the Adam et al. [6] relay is selected similar to basic opportunistic approach proposed in [2].

Nevertheless, adaptive schemes should address the transmission collision problem and should take more advantage of spatial diversity. Moreover, thresholds at destination need to be optimal to guarantee fast reaction to channel variations.

E. Table-based Relay Selection

Table-based approaches follow a cooperative relay selection process aiming to decrease the impact of relay selection on transmission time. In general the operation of table-based approaches such as CoopMAC and CODE is as follows: sources keep CSI information about the links between themselves and potential relays as well as about the links from potential relays and each potential destination. The CSI information is gathered using RTS/CTS frames as well as information collected from overheard transmissions. Relays are selected by the source by looking up in a table. A node may be selected as relay if the transmission time over the direct link to a destination is higher than the sum of the transmission time over the source-relay and relay-destination links. For instance, the CoopMAC proposal follows a cooperative relay selection approach by extending the RTS/CTS process with a Helper-ready To Send (HTS) frame.

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. Code proposes the cooperative-RTS which is sent by the source to the relays and by the latter to the destination to show their willingness to cooperate. If the destination finds that such cooperation is beneficial via both relays, it sends a cooperative-CTS to the source. Table-based approaches present degradation problems in the presence of moving nodes. Another problem with this class are the periodic broadcast and extra handshaking signals which can limit the efficiency.

F. Contention-based Relay Selection

Contention-based selection follows a cooperative approach making use of contention windows to increase the probability of selecting the best relay, aiming to achieve a good resource allocation. This class of relay selection works in two phases.

In general the operation of contention-based selection approaches is as follows: in the first phase relays estimate their qualification. The nodes estimates local conditions, which are the relay position and degree in case of [12], and the link quality of both relay channels with source and destination in the case of PRO. If these estimations satisfy certain threshold then such relays are qualified relays for selection. In the second phase the relays select their contention window on the basis of priorities. For instance, in PRO the potential relays broadcasts their qualification, allowing other overhearing qualified relays to construct a global map of qualified relays and source-destination pairs, setting the priority level of each node.

The limitation of this class is the influence that the size of the contention window has in the relay selection. Moreover, since it follows a cooperative approach, there is the problem of overhead due to broadcast of qualification/nomination messages.

G. Multi-Hop Relay Selection

The most common relaying approach in the literature is to select a relay (or a set of relays) to help a transmission from a sender to a destination over a direct poor wireless link. When applied to multi-hop networks, this method requires the repetition of the relay selection procedure for each hop from sender to destination. However, such hop-wise cooperation can reduce network capacity. One solution is to select relays that can help more than one link simultaneously Lichte et al. [13], Adam et al. [14]. Such higher diversity is not possible to achieve with 802.11 MAC protocols as they are not aware of following hops.

In general the operation of multi-hop relay selection approaches is as follows: potential relays access routing information (from the local network layer) creating a limited image of the network beyond the adjacent wireless links (typical two hops). By overhearing transmissions over the identified network, potential relays may decide to relay overheard information to potential destinations, even in the absence of a direct link between the source and destination of the packet. This means that relays may have received the information to be relayed directly from the source (as happens in single-relay selection) or from other relays or intermediary nodes (routers). This opportunistic behavior can be augmented by the exchange of meta-data among potential relays, tuning the relay selection and scheduling decisions.

In multi-hop relay selection, the destination node may receive more than two independent signals of the same packet (e.g. directly via the source, via the intermediary node identified by the routing protocol and via the selected relay node). This extra spatial diversity increases robustness and performance. However, the price to pay is the extra network overhead to transmit redundant information, and the cross layering needed to collect routing information, which may not be updated with the frequency require to react in environments with mobile devices.

V. Performance Analysis

Based on the proposed relay selection categories we performed a cross analysis of performance results using the approaches described in section II as examples. Our analysis shows that opportunistic relay selection approaches aim to reduce outage, while cooperative relay selection approaches try to increase transmission throughput (cf. Table 1).

Table I
PERFORMANCE OF RELAY SELECTION APPROACHES

Approach	**Outage reduction**	**Energy saving**	**Throughput increase**	**Blockage reduction**
Measurement-based	Yes	–	–	–
Performance-based	Yes	Yes	–	–
Threshold-based	Yes	Yes	–	–
Adaptive	Yes	Yes	–	–
Table-based	–	–	Yes	Yes
Contention-based	–	–	Yes	–
Multi-hop	Yes	–	Yes	–

In what concerns opportunistic relay selection, improvements of network lifetime are pursuit by increasing energy savings or by decreasing the overall overhead. To start with, measurement-based proposals, such as the one proposed by A. Bletsas et al. [2], present a significant decrease in outage probability, when compared to the direct transmission. As a function of SNR, i.e. $\frac{1}{SNR*m}$, where m is the size of the network. When compared to measurement-based approaches, performance-based and adaptive relay selection achieve higher improvements of network lifetime by increasing energy savings. For instance, the performance-based approach PARS [5] is able to increase network lifetime in 80% to 100%, by minimizing the overall transmission power, while the adaptive relay selection proposed by H. Adam et al. [6] achieves an improvement of 75% to 100% in energy savings. However, such improvements are highly dependent upon the used policies (PARS) or the used thresholds (H. Adam et al.).

Reduction of network outage and increase of network lifetime can also be achieved by decreasing the overall network overhead, which is major goal of threshold-based relay selection solutions [4], [8]. However, all of these approaches are still complex, since they rely upon channel estimations.

In what concerns cooperative relay selection, results show that throughput gains increase with the number of devices, since the probability of finding a suitable relay increases. In the case of table-based relay selection approaches, CoopMAC shows a throughout gain of 40% to 60% as compared to 802.11 standards. This gain can be improved by reducing collisions, overhead, and the impact of payload size. Although throughput gains of table-based relay selection approaches provide a good incentive to apply cooperative relaying techniques, the impact on the overall network performance, namely the probability of blocking resources, needs to be further analyzed. The problem of transmission blocking by relays is analyzed by contention-based relay selection approaches, as shown in Figure 3. With increasing nodes in the network, the probability of blocking concurrent transmissions increases 50% to 100%, depending upon the number of nodes and the contention window size. The impact of relay selection in concurrent transmissions may be reduced by employing a policy aiming to select relays that have lowest degree and are closest to the direct transmission.

But this strongly depends upon scenario/topology, and it is possible that an isolated relay that lies far away from both source and destination can be selected for cooperation.

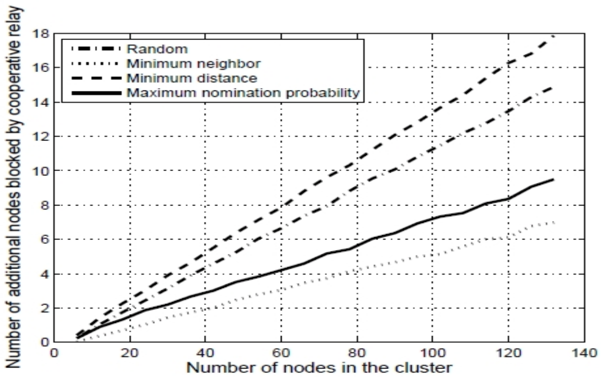

Figure 3. Number of additional transmissions blocked in a network [12]

When looking at realistic scenarios, performance analysis should also assume that relays may be used in multi-hop communications, due to the number of existing applicability scenarios such as vehicular networks. Hence, we analyze the performance of multi-hop relay selection approaches, namely the two-for-one cooperation approach [13] in two scenarios with four and fifty nodes, as illustrated in Figure 4. This figure shows that for Strong-Full Diamond (SFD) and Weak-Full Diamond (WFD) configurations, PER can be improved in about 45% (50 nodes with SFD) and 36% (4 nodes with SFD), when compared to Non-Cooperative-Relaying (NCR). These results show that SFD performs better in dense scenarios, since spatial re-usage provides maximum gain with lower transmit power regimes. However, the PER gain is worst in the WFD scenario with 50 nodes, due to the lower diversity order of WFD in relation to SDF.

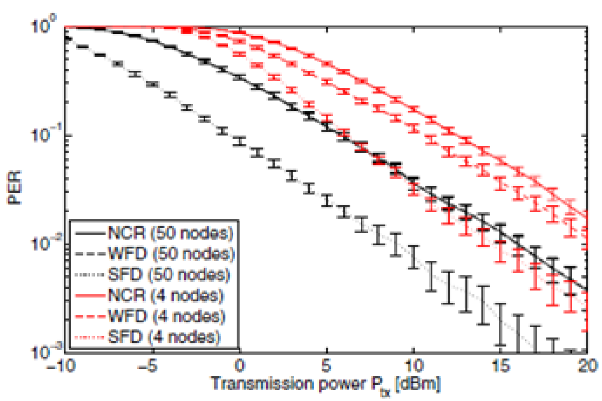

Figure 4. Multi-hop relaying performance [13]

Although current experimental results of the relay selection mechanisms already show the benefits of using cooperative relaying, our study shows that previous work has a generic lack of interest in analyzing the impact of relay selection in the overall network capacity, namely in realistic scenarios where relays may also operate as sources/destinations and where cooperation may not be reciprocal, in the sense that some potential relays may give highest priority to the transmission of their own data. One exception is the Fixed Priority Selection (FPS) approach [16] that investigates the effect of relay allocation policies on system performance, namely on the decoding probability at each receiver. With FPS each node must decide upon whom to cooperate with in the absence of any knowledge of who may be able to decode their data. Each node may help n other nodes, providing diversity n+1 over the network. A positive result of FPS is that, even without network knowledge, it is still possible for nodes to select partners so that full network-wide cooperative diversity is achieved. However, since n+1 nodes are involved in one transmission, the system complexity is considerably high. Moreover, FPS assumes that small scale fading is not dominated by path loss which points to networks with small coverage area.

VI. Observations and Open Research Issues

From the realized performance analysis we make two strong observations: i) all approaches assume static devices, small networks with high probability or a direct source-destination link usage, and the need to use always one relay; ii) there is no single approach that presents good behavior in terms of both transmission and network performance. In general, approaches try to increase network lifetime or transmission throughput. Multi-hop relay selection approaches are one exception. However, performance of multi-hop approaches depends upon the existence of link-state routing and the capability to create strong-full diamonds, which can only be constructed in dense stable networks. These observations lead to the identification of two important research issues: i) achieve a good balance between network lifetime and transmission throughput; ii) improve the capacity of large mobile networks.

Before investigating suitable solutions to achieve a good balance between network lifetime and transmission throughput, we need to answer the following question: when do we really need to use cooperative relaying? To answer this question we will need to compare the network lifetime and transmission throughput achieved by proposals that take advantage of spatial diversity (cooperative relaying), and by techniques that take advantage of time diversity over the direct link.

To devise a cooperative relay solution able to achieve a good balance between network lifetime and transmission throughput it is important to start by investigating what CSI accuracy levels can be ensured in relation to different levels of channel variation. Moreover, although all analyzed approaches make use of RTS/CTS mechanism, it would be important to investigate approaches agnostic to RTS/CTS, aiming to reduce overhead. In what concerns more realistic scenarios, it is necessary to analyze performance in the presence of asymmetric channels, since current approaches assume symmetric channels.

Moreover, with the exception of CODE, all analyzed proposals rely upon the usage of one relay to help one transmission. However, the advantage of selecting more than one relay to help the same transmission (even if in different time frames), as well as the time that nodes should be kept as relays should be further investigated. The presence of multiple relays over the same link requires the analysis of the gains that physical layer coding offers in comparison to a full link layer approach.

In order to investigate the most suitable solutions to improve the capacity of large mobile networks, we should start by revisiting two basic assumptions: i) devices are mostly mobile; ii) connectivity may be intermittent.

The majority of the analyzed approaches assume scenarios where nodes are static and where it is not difficult to find a direct link between source and destination. In the case of scenarios with multiple hops between source and destination, it would be beneficial to further exploit the selection of relays that can help over multiple hops simultaneously (multi-hop relay selection), namely trying to identify the most suitable relay/hops ratio. However, current multi-hop relay selection approaches rely on link-state routing information, which means that they are not suitable for scenarios with intermittent connectivity. Hence the investigation of the usage of multi-hop relay selection in the presence of more opportunistic routing [17] is an important research topic.

Besides the usage of multi-hop relays it is important to guarantee a good network capacity in the presence of concurrent relays. Hence, relay selection in large networks may benefit from a combination of opportunistic and cooperative relay selection approaches. On the one hand, we want to achieve the network lifetime levels assured by opportunistic relay selection approaches. And on the other hand we want to improve the overall throughput and reduce the probability of resource blocking, as achieved by cooperative relay selection mechanisms. This line of research is further analyzed in the next section.

VII. Future Direction on Relay Selection

From the observations provided in the previous section it is clear that cooperation brings benefits to the operation of wireless networks but its usage over large networks may introduce undesirable levels of overhead and complexity. The complexity is mainly due to the number of channel estimations, while the overhead is mainly due to the multiple copies of data messages and feedback signals.

When considering mobile scenarios, complexity may increase due to the number of times relay selection must be performed due to frequent link breakage. Moreover, waiting for optimal relay to assist one transmission degrades the overall performance of the network and decreases its capacity.

As happens with mobile scenarios, the presence of dense networks will also bring performance degradation, mainly due to the high interference levels. In this case, the interference caused by relay transmissions will be, in the best case, directly proportional to the relay degree. The situation may get worse in the presence of multi-hop networks, where the usage of hop-by-hop cooperation will increase the network cost e.g. number of transmissions. Figure 5 shows that by cleverly selecting a relay to assist several transmissions in a multi-hop scenario (Rm) we can reduce the number of relays (R1, R2 and may be R3) and consequently the number of transmissions. As Rm have the knowledge of the following hops from routing information.

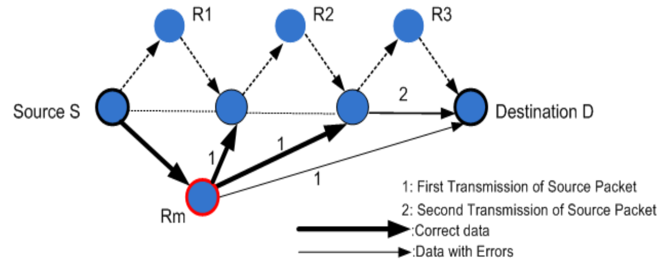

Figure 5. Multihop relay Rm

A. Opportunistic-Cooperative Relay Selection

A major conclusion of our investigation is that to avoid extra overhead and complexity, relays should be selected with limited feedback (opportunistically) in a distributed manner and by computing just local parameters. In addition inter-relay cooperation should be taken into account in order to improve spatial reuse, but we should have in mind that cooperation and exchange of information produces overhead and energy consumption. So, we may say that the usage of opportunistic relay selection schemes is a good choice in a collision free environment. But in a realistic scenario, scheduling and priorities are important to consider, which means that some cooperation level needs to be taken into account.

Hence it is our opinion that opportunistically once a node or set of nodes are selected as a relay(s), they should try to cooperate with the source, destination or even with other selected relays (Inter-relay cooperation) dynamically, to achieve better results with varying network conditions. This gives rise to a new level of interaction that we call "Opportunistic-Cooperative Relay Selection", in which multiple relays may have different roles (priorities). For example, when a relay fails to provide the required performance, its role can just be changed, and another relay can take its place without a new relay selection.

It is our opinion that the investigation of joint opportunistic cooperative relay selection schemes deserves some attention in the future.

B. Evaluation Parameters

To limit communication overhead, especially in large networks, it is important to investigate the intelligent usage of thresholds over local variables, since they can filter out poor relays as well as unwanted transmissions. Independently of the type of thresholds, they should be adaptive to cope with the varying nature of networks.

In what concern the parameters themselves, previous work uses local variables such as SNR, BER, CSI. Since these are very unstable parameters, we propose the usage of less volatile parameters, namely interference level, energy levels and stability. Interference level provides an indication about the probability of resource blockage. Node degree and queuing delay are examples of measures that can be used to estimate the interference level, without using physical layer measurements. Energy is an important parameter, especially in battery constraint networks. The last parameter, stability, is very most important and has not been considered by any prior work.

Stability is the measure of mobility, and can be obtained by estimating pause time or link duration. The more stable (less mobile) nodes are, the more suitable are they to operate and relays. So, our investigation lead us to the conclusion that the most suitable relay selection scheme for large scale networks is devised by using local parameters characterized by being less volatile than the usual SNR, BER and CSI parameters.

C. Evaluation of Scenarios

From our analysis it is clear that the performance of cooperative relaying greatly depends upon the used scenario. Hence, the analysis of relay selection schemes for large networks should be evaluated based on a basic scenario that encompasses the most useful aspects discussed in this paper. One of such scenario is what we call Double Full Diamond (DFD) as illustrated in Figure 6. This is multi-source multi-destination scenario including several concurrent transmissions and where at least three potential relays can be used. Each relay can help more than one transmission and relays can work in sequence, if needed, to increase network capacity as well as in parallel to increase diversity, depending on coordinating (cooperative) information which itself depends upon network conditions. Relays should be selected opportunistically but then can be coordinated (either by source or destination) to assign priorities (roles), which can stipulate that some relays will be active while others will be passive. Passive relays are like an assistant for active relay and can be utilized when needed. Relays should also be able to cooperate by exchanging local information and switching roles. The DFD scenario also gives an opportunity to exploit time diversity (e.g. in case of concurrent transmissions at R2), thus reducing spatial resource blockage and number of transmissions.

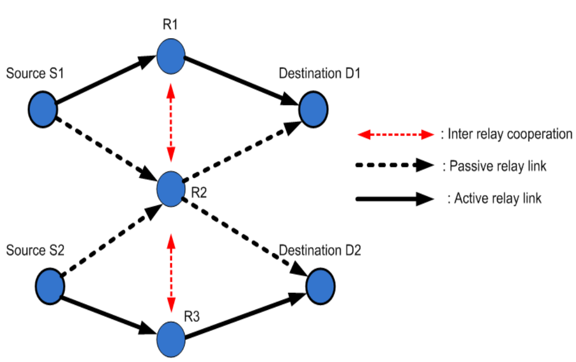

Figure 6. Basic evaluation scenario for relay selection schemes

VIII. Summary and Conclusion

This article provides an analysis of relay selection approaches for wireless cooperative networks, since a poor selection may considerable degrade the performance of the overall network. We propose a taxonomy for the evaluation of relay selection approaches, and an analysis of their performance. Based on such analysis, some observations are provided about topics that need to be further investigated to devise cooperative relaying systems able to optimize concurrent communications in large networks composed of mobile nodes. Based on a systematic analysis of relay selection approaches our initial conclusions are three-fold: i) relay selection should support systems able to achieve a good balance between the performance of individual transmissions and performance of the overall network; ii) relays should be selected based on stable parameters, avoiding the usual channel state, signal-to-noise ratio or packet error rate; iii) good relay selection schemes should be able to support multi-hop scenarios as well as scenarios with mobile nodes. It is our opinion that the investigation of relay selection schemes able to make the best out of local opportunities, with the support of inter-relay cooperation, is a fruitful research area. The usage of such opportunistic-cooperative relay selection schemes will provide the needed distributed intelligent to support relaying over large networks in the present of nodes with dynamic behavior.

References

[1] J. Morillo-Pozo, O. Trullols, J. M. Barceló, and J. García-Vidal, "A Cooperative ARQ for Delay-Tolerant Vehicular Networks," in *Proc. of IEEE ICDCS*, Beijing, China, Jun. 2008.
[2] 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.
[3] H. Shan, W. Z. P. Wang, and Z. Wang, "Cross-layer Cooperative Triple Busy Tone Multiple Access for Wireless Networks," in *Proc. of IEEE Globecom*, New Orleans, USA, Dec. 2008.
[4] K.-S. Hwang and Y.-C. Ko, "An Efficient Relay Selection Algorithm for Cooperative Networks," in *Proc. of IEEE VTC*.
[5] 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.
[6] H. Adam, C. Bettstetter, and S. M. Senouci, "Adaptive Relay Selection in Cooperative Wireless Networks," in *Proc. of IEEE PIMRC*, Cannes, France, Sep. 2008.
[7] Z. Zhou, S. Zhou, J. Cui, and S. Cui, "Energy-Efficient Cooperative Communications based on Power Control and Selective Relay in Wireless Sensor Networks," *IEEE Journal on Wireless Communications*, vol. 7, no. 8, pp. 3066–3078, Aug. 2008.
[8] W. P. Siriwongpairat, T. Himsoon, W. Su, and K. J. R. Liu, "Optimum Threshold-Selection Relaying for Decode-and-Forward Cooperation Protocol," in *Proc. of IEEE WCNC*, Las Vegas, USA, Apr. 2006.
[9] 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.
[10] K. Tan, Z. Wan, H. Zhu, and J. Andrian, "CODE: Cooperative Medium Access for Multirate Wireless Ad Hoc Network," in *Proc. IEEE of 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] N. Marchenko, E. Yanmaz, H. Adam, and C. Bettstetter, "Selecting a Spatially Efficient Cooperative Relay," in *Proc. of IEEE GLOBECOM*, Honolulu, Hawaii, Nov. 2009.
[13] 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.
[14] H. Adam, C. Bettstetter, and S. M. Senouci, "Multi-Hop-Aware Cooperative Relaying," in *Proc. of IEEE VTC*, Barcelona, Spain, Apr. 2009.
[15] J. N. Laneman and G. W. Wornell, "Distributed SpaceŰTime-Coded Protocols for Exploiting Cooperative Diversity in Wireless Networks," *IEEE Transactions on Information Theory*, vol. 49, no. 10, pp. 2415–2425, Oct. 2003.
[16] 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, pp. 369–378, Feb. 2007.
[17] Z. Zhang, "Routing in Intermittently Connected Mobile Ad-hoc Networks and Delay Tolerant Networks: Overview and Challenges," *IEEE Communications Surveys and Tutorials*, vol. 8, no. 1-4, pp. 24–37, Dec. 2006.