Cooperative Relaying in Dynamic Wireless Networks under Interference Conditions

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An ever-growing demand for pervasive Internet access has boosted the deployment of wireless local networks in the past decades. Nevertheless, wireless technologies face performance limitations due to unstable propagation conditions and mobility of devices. In face of multi-path propagation and low data-rate stations, cooperative relaying promises gains in performance and reliability. However, cooperation procedures are unstable, due to their dependency upon current channel conditions, and introduce overhead that can endanger performance, especially when nodes are mobile. This paper presents an introduction to cooperative relaying, and describes a novel link layer protocol, called RelaySpot, able to implement cooperative relaying in dynamic networks, based upon opportunistic relay selection, cooperative relay scheduling and switching.

I. Introduction

The growth of wireless networks in the last decades is motivated by their ability of supporting communications anywhere and anytime. Boosted by the importance that such pervasive communications have on modern society, a high proliferation of wireless services and devices, such as WiFi or cordless phones has emerged. The increasing deployment of wireless systems, namely by end-users (e.g. wireless home gateways, smart-phones, wireless embedded devices), brings new challenges to the deployment of reliable wireless systems due to variations in the density of wireless networks, the unpredictable coverage of such networks, and the unstable availability of wireless devices (e.g. due to users' mobility and patterns of use).

User-centric networking is a new trend that aims to support efficient communications in such dynamic wireless environments by exploiting the role that end-users may have in the networking process by sharing network services and resources. This user-centric perspective of networking opens new possibilities for the development of novel wireless technologies able to sustain reliable and cost efficient wireless transmissions, even when wireless nodes are pervasive and mobile, and wireless communications are subjected to correlated interference conditions. One of such wireless technologies is cooperative relaying.

Cooperative relaying aims to bring several improvements to wireless networks, from increasing network capacity and coverage, to enhancing transmission reliability and throughput even in scenarios where mobile devices communicate under different wireless interference conditions.

In this paper, we start by providing an introduction of the role that cooperative relaying may have in the development of efficient user-centric wireless networks. In such networks cooperation occurs when overhearing wireless devices (called relays) assist the communication between source to destination, by transmitting different copies of the same frame from different locations, generating spatial diversity that allows the destination to get independently faded versions of the transmitted message. The literature reveals different cooperative approaches, depending on the role that sources, relays and destinations have on the cooperation process. In this paper we argue that the most suitable approach is the one that presents more self-organized properties in order to be efficient in dynamic wireless scenarios. For this propose, we present RelaySpot as a solution to mitigate the problems posed by wireless fading and by low data-rate mobile devices. With RelaySpot, relays are self-elected if within a cooperation area, defined for a source-destination pair, when they overhear a good frame transmitted by the source. Destination nodes are able to select the best set of relays based on the information provided by the latter during a predefined time period.

This paper is organized as follows: Section II provides an introduction to cooperative relaying in general. In section III we provide an analysis of cooperative relaying approaches, while in Section IV we describe the proposed RelaySpot protocol. Section V presents experimental analysis. Finally Section VI presents our conclusions.

II. Cooperative Relaying: Advantages and Limitations

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 fading, decreasing the overall network performance [1]. While fast fading can be mitigated by having the source retransmitting frames, slow fading, caused by obstruction of the main signal path, makes retransmission useless, since periods of low signal power last for the entire

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duration of the transmission. Moreover, the interference from other transmitters also affects the communication quality. Due to continuous changes related to interference conditions and mobility of devices (transmitter, receiver or relay) the wireless signal is scattered over many objects in the surroundings. Such channel impairments can be mitigated by exploiting cooperative diversity [2].

Besides the limitations inherent to the wireless channel, wireless networks suffer among other issues from scarcity of bandwidth, which limits the network throughput and requires efficient utilization of this resource. One example is the system impairment caused by the presence of low data-rate devices. The 802.11 standard makes use of rate adaptation schemes to allow low data-rate devices to adapt their modulation and coding scheme according to the quality of the radio channel, improving the bit rate and robustness of their data transmission. However, the usage of rate adaptation schemes results in the degradation of the overall network performance, since low data-rate devices grab the wireless medium for a long time. This occurs since each device has the same probability to access the wireless channel, which means that high data-rate devices are not able to keep the desirable throughput. Cooperative relaying may mitigate this problem by allowing low data-rate devices to finish their transmission faster by using a pair of wireless links (via a relay) that provide better wireless conditions than the direct channel to the destination. High data-rate devices have a high incentive to cooperate by relaying messages from low data-rate devices, since such cooperation may increase their probability to grab the wireless channel faster.

In general terms cooperative relaying at link layer comprises two phases: relay selection and cooperative transmission. In the first phase a relay or group of relays are selected, while in the latter phase the transmission via relay(s) takes place. The relays can be selected either by source (source-based), destination (destination-based), or by the relay itself (relay-based). At the link layer we can classify cooperative protocols as proactive and reactive. With proactive relaying, cooperation is set up to improve the performance of the direct link, even if the latter is operational [3]. In proactive relaying the cooperation process can be controlled by the source, destination or potential relay. Proactive relaying is time critical and incurs in higher overheads: frequent information exchange for timely delivery of data is required. In reactive relaying the cooperation is initiated when the direct link is not operational, which can be detected by any device receiving or overhearing a negative acknowledge message, or a lack of communication, which can occur due to collision or transmission errors [4]. Reactive relaying incurs in lower overhead, but is only appropriate for applications that are tolerant to delays or disruption.

For a better understanding of the role of cooperation in wireless networks, Figure 1 shows a basic 802.11b system where devices have different transmission rates at different distance from the Access Point (AP). Although cooperative relaying may improve the performance of such heterogeneous system, such improvement can only be ensured if the relay device is within a cooperation area that rectifies the impact of low rate nodes. Figure 1 provides an example where a source placed at a distance from the AP that only allows it to transmit at 2 Mbps, can actually transmit at 11 Mbps, by making use of any relay placed in the suitable cooperation area. Such cooperation area is identified as the interception of R_{11}, referred to the distance at which the AP can receive at 11 Mbps, and r_{11}, which is the distance at which the source can transmit at 11 Mbps.

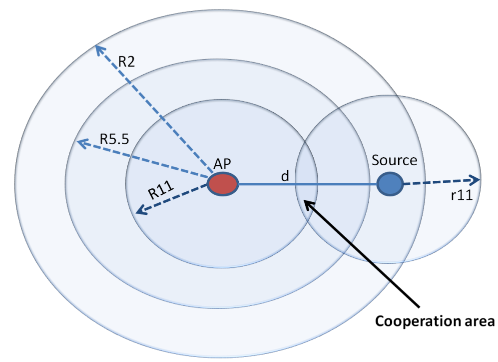

Figure 1. Cooperation conditions in wireless networks.

Although cooperative relaying brings advantages for wireless networks, it is necessary to analyze the potential drawbacks: one is related to the additional interference caused by the relaying operation, since it involves additional transmissions via relays. Thus, the benefits brought by cooperation can be diminished if relaying mechanism is not cleverly designed. Other potential constrains are concurrent transmissions and mobility, which can affect the performance of cooperative networks [4]. Therefore, there are design issues that must be taken into account while developing cooperative systems aiming to exploit wireless diversity at link layer, such as relay selection, cooperation decision, cooperation notification, cooperative transmission and cooperation management [4].

From all the design issues, relay discovery and selection is of high importance. In what concerns relay selection, most of the existing protocols require some devices, normally the source, to have a neighborhood map related to channel conditions. Such map is normally updated based on a broadcast mechanism: broadcasts need to be very frequent to cope with network variations, which limits the performance of the wireless system.

Besides the decision about the best relay, or set of relays, to use, it is necessary to keep cooperation efficiency. This aspect is of high importance in dynamic scenarios where mobile devices face variant interference conditions. In what concerns relay management, most of the protocols use additional control messages in a centralized manner. Such explicit notifications affect the cooperation gain, due to extra overhead. Moreover, in some scenarios, it is infeasible to have a centralized coordination [5]. The challenge here is the development of a distributed relay switching mechanism that allows the wireless system to take advantage of the most suitable relaying conditions.

As described in this section, the limitations of the cooperation process can be as significant as its advantages. Therefore, cooperative network design needs to be performed carefully in order to achieve the full gains of cooperation while ensuring that cooperation does not cause degradation of system performance. The next section provides an analysis of different type of proposals aiming to identify the most suitable approach for relaying in dynamic networks facing variant interference conditions.

III. Analysis of Cooperative Relaying Approaches

As mentioned in the previous section, cooperative relaying approaches can be classified as proactive and reactive: proactive relaying aims to improve the performance of an existing direct link; reactive relaying aims to replace a broken direct link to decrease degradation by avoiding retransmissions.

Proactive and reactive relaying can be further divided into broadcast-based, and opportunistic, as illustrated in Figure 2. Broadcast-based approaches represent a relatively simple strategy by making use of the broadcasting nature of the wireless medium. While broadcast-based relaying offers more control due to its centralized nature, with opportunistic relaying devices can make cooperation decisions on their own, within certain time and spatial constraint. As a general property, opportunistic relaying does not require extra control messages. The remaining of this section aims to highlight the differentiation factor of applying a broadcast or opportunistic approach to relaying.

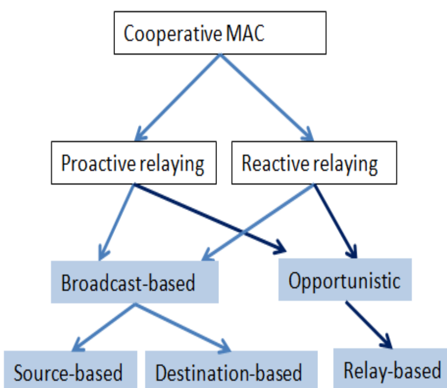

Figure 2. Taxonomy of cooperative relaying.

A. Broadcast-based Relaying

Broadcast-based relaying relies on the existing of a neighborhood map of channel conditions, normally at the source or the destination. The major drawback of broadcast-based relaying refers to the periodic broadcasts required for maintaining the neighborhood map and the consequent extra control overhead, which affects the performance. As mentioned before, broadcast-based approaches can be implemented in a proactive or reactive fashion. These approaches are normally source-based or destination-based.

One example of proactive source-based cooperative relaying scheme at the link layer is the Cooperative MAC protocol (CoopMAC) [6]. With CoopMAC the source selects (source-based) an intermediate devices (relay) that has a relatively good channel with the source and the destination. Based on the Channel State Information (CSI) broadcasted by potential relays, sources update a local table (cooptable) used to select the best relay for each transmission. CoopMAC performs a 3-way handshake, which requires the selected relay to send a control message, called Helper ready To Select (HTS), between the Request To Send (RTS) and the Clear To Send (CTS) messages: first, the source sends a Cooperative RTS (CoopRTS) message with the selected relay ID. If the selected relay is willing to cooperate, it then sends an HTS message back to source. If destination overhears an HTS message, it transmits a CTS. After receiving CTS, the source sends the data frame to destination via selected relay.

B. Opportunistic Relaying

One advantage of opportunistic relaying is its independency from any neighbor map maintained by means of extra exchange of message. This property allows a relay to forward data opportunistically without prior coordination among a set of devices. Hence, such approaches are normally relay-based. Opportunistic relaying is suitable for the deployment of cooperative relaying in dynamic scenarios. However, opportunistic relaying presents some drawback, such as: relays back-off every time they forward; the source ignores the availability of potential relays, and so it does not know the data-rates of source-relay and relay-destination channels.

One example of opportunistic (reactive) relaying is the Cooperative Communication MAC (CMAC) [7]. In case of CMAC each device stores the data frames sent by source. If no Acknowledge (ACK) is overheard the relay forwards the stored data frame on behalf of source. Due to usage of additional queues and channel estimations, CMAC introduces extra overhead.

IV. RelaySpot: Hybrid Relaying Solution

RelaySpot is a hybrid cooperative relaying protocol where relays are self-elected under certain cooperation conditions. Selected relays are used to increase the performance of active transmissions (proactive behavior) or to replace failed transmissions (reactive behavior). RelaySpot comprises three building blocks: opportunistic relay selection; cooperative relay scheduling; relay switching [2].

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

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

The remaining of this section provides a description of RelaySpot functional components that allow relays to be opportunistically selected, and the destination to schedule the potential relays for the forthcoming transmissions. Some of these transmissions may use different relays if a relay presents better conditions than the current one.

A. Opportunistic Relay Selection

Relay selection is a challenging task, since it greatly affects the performance of a cooperative network. Relay selection may introduce extra overhead and complexity, and may never be able to find the best relay in dynamic scenarios. Hence, the major goal of RelaySpot is to minimize cooperation overhead, with no performance degradation, by defining a relay selection process able to take advantage of the most suitable self-elected relay [8].

With RelaySpot, relay selection is performed in three steps: First, verification of eligibility of devices to become relays, which occurs if devices are able to overheard a good frame sent by the source and are positioned within the cooperation area; Second, computation of the Selection Factor (SF) of eligible devices; Third, computation of the Contention Window (CW) of eligible devices based on their SF. At the end of the self-election process, eligible relays send a Qualification Message (QM) towards the destination after the expiration of their CW.

During the first phase, potential relays verify if they are inside the cooperation area by computing their Cooperation Factor (CF), which is related to the effective rate of the source-relay channel (R_{sr}) and relay-destination channel (R_{rd}). These rates are computed by overhearing RTS and CTS frames exchanged between source and destination. The CF ensures that potential relays are closely bounded with the source, while having good channel towards the destination: an eligible relay must have a CF that ensures a data-rate higher than the data-rate achieved when using the direct link.

During the second phase, the computation of the SF of a relay depends solely upon local information related to interference (node degree and load), mobility and history of successful transmissions towards the specified destination. Node degree, estimated by overhearing the shared wireless medium, gives an indication about the probability of having successful relay transmissions: having information about the number of neighbors allows the minimization of collision and blockage of resources. However, it is possible that devices with low device degree are overloaded due to: i) processing demands of local applications (direct interference); ii) concurrent transmissions among neighbor devices (indirect interference). Hence, RelaySpot relies upon node degree and traffic load generated and/or terminated by the potential relay itself, to compute the overall interference level that each potential relay is subjected to. The goal is to select as relay a device that has low interference factor, which means few neighbors (ensuring low blockage probability), and fast indirect and direct transmissions (ensuring low delays for data relaying).

By using the interference level together with the history and mobility factors, the probability of selecting a certain device as a relay for a given destination is proportional to the history of successful transmissions that such device has towards that destination plus its average pause time, while being inversely proportional to the interference level that such device is subjected to.

During the third phase (CW computation), the goal is to increase the probability of having successful transmissions from relays to the destination by giving more priority to relays that are more closely bounded to the destination, have less interference and have higher pause times.

B. Cooperative Relay Scheduling

The relay selection mechanism may lead to the qualification of more than one device as relay, each one with different values of SF, leading to CWs with different dimensions.

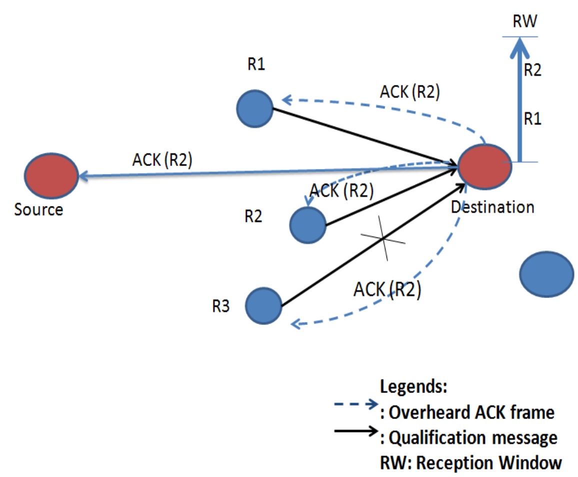

Figure 3. Relay scheduling example.

The destination schedules the self-elected relays after the expiration of a Reception Window (RW), in order to receive as much QMs as possible, as illustrated in Figure 3. The size of the RW is of major importance: on the one hand a large window increases the probability of scheduling a good relay, based on a large set of received QMs; on the other hand a small window introduces a lower delay in the communication session.

After the expiration of the RW the destination schedules all the eligible relays by checking the R_{rd}, (by means of the received signal strength) and the R_{sr}, (by means of the information carried in the QM).

After the scheduling process, the destination sends an ACK message to the source including the MAC address of the selected relay, which will be responsible for forwarding all the forthcoming frames of the communication session to the destination. The ACK frame also piggybacks the CF information.

This cooperative scheduling procedure supports RelaySpot proactive operation, by having the destination only scheduling relays that present a combination of R_{sr} and R_{rd} with better data-rate than the direct link. In RelaySpot the proactive operation is complemented with a reactive procedure, in which the decision of the cooperative scheduling mechanism is overtaken by having another relay, in the cooperation area, replacing the relay previously selected by the destination, when the latter fails. This relay switching mechanism is described in the next sub-section.

C. Relay Switching

Since relays are selected opportunistically based on local information, there is a probability of having good relays computing CWs that are not small enough to allow them to send a QM before the expiration of the RW. In order to overcome this situation, as well as to support the failure of selected relays, RelaySpot includes a relay switching operation, able to select one relay, among a set of potential relays able to cooperate at time when needed.

All potential relays are able to compute their own CF, as well as the CF of the selected relay: by overhearing ACK frames.

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

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

Relay switching can be used either to improve the performance of a communication session, by replacing a good relayed transmission by a better one, as well as to implement a reactive operation. The latter is implemented by having relays being switched implicitly when a potential relay detects a missing ACK frame for an already relayed communication. In this situation, the potential relays try to forward the overheard data frame on behalf of the relay that failed the transmission. In case of success, the destination notifies the source, by means of an ACK frame, about the MAC address of the potential relay that first reacted to the failure of the relayed communication.

V. Experimental Analysis

RelaySpot evaluation is based on simulations run on the MiXiM framework of the OMNeT++ 4.1 simulator using 2D linear mobility model. Simulations consider a scenario with one static AP and up to 25 mobile devices in a area of 200x200m^2. In this section we start by presenting a study of the performance of RelaySpot in scenarios with different level of interference and mobility. This study is done against standard 802.11 and a mobility unaware version of RelaySpot. Secondly, we present a comparative study of RelaySpot against broadcast-based and opportunistic relaying approaches.

A. Impact of Interference

Figure 4 illustrates the advantages of using RelaySpot as a complement of the normal 802.11 operation in scenarios with high interference. In this experiment, we consider a scenario where one static source is placed at a distance from the AP enough to observe poor data-rate; interference is added by randomly placing transmission pairs (each with 5 Mbps in average) among the available 25 static devices. In this experiment RelaySpot is configured without relay switching, since the propose is to analyze the efficiency of RelaySpot in selecting and scheduling a good relay in the presence of interference.

Simulation results show that in the presence of interference, RelaySpot has better performance than IEEE 802.11 (147% higher throughput than the standard 802.11 in average), by avoiding selecting overloaded devices as relays, and selecting relays with low blockage probabilities and with good transmission success rate towards the destination [9].

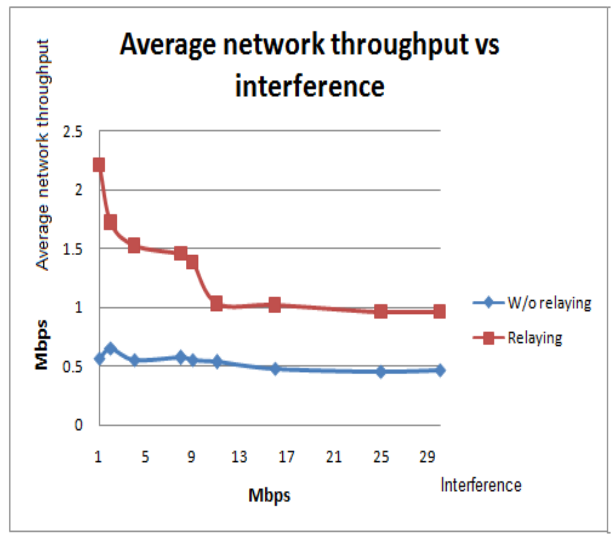

Figure 4. Analysis of impact of interference.

B. Network Capacity Analysis

In this section we analyze the performance of RelaySpot based on its impact on the overall transmission capacity of a wireless network. In this experiment we consider a scenario with 25 mobile devices moving with random pause time between 10 to 100 seconds. The goal is to understand if RelaySpot can increase the transmission capacity of the network by increasing the overall average throughput in the presence of devices with different levels of mobility. In this experiment, we compare the average network throughput achieved by RelaySpot, with a version of RelaySpot without mobility-awareness, and with the 802.11 standard.

Simulation results (c.f. Figure 5) show that RelaySpot can achieve higher throughput than the 802.11 standard and the mobility unaware RelaySpot even with high load. The main reason being the fact that RelaySpot is able of selecting relays with high pause time, which reduces the overall communication delay by avoiding re-selection of relays during the communication session.

RelaySpot achieves an average throughput gain of 42% in relation to 802.11, and of 21% in relation to the RelaySpot version that is unaware of mobility. Without mobility

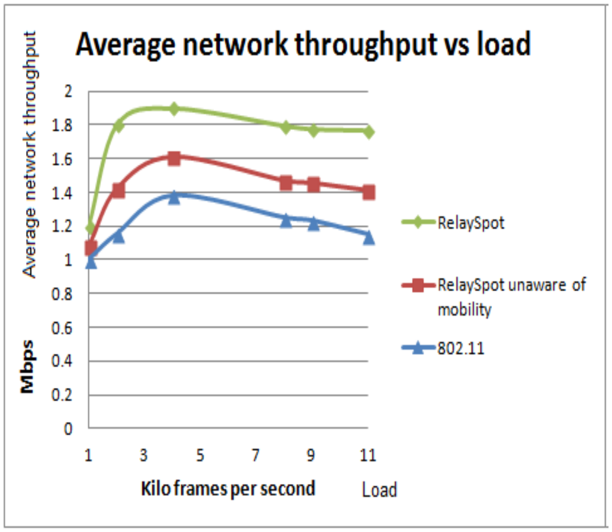

Figure 5. Impact of RelaySpot on the overall network capacity.

awareness, RelaySpot can still achieve an average throughput gain of 17.6% in relation to 802.11, due to the scheduler at the destination, which is able to select a relay with a pair of channels (source-relay; relay-destination) with better throughput than the direct link, even in the presence of mobile devices.

C. Comparative Analysis

This section provides an analysis of the hybrid relaying approach, followed by RelaySpot, against two generic implementations of proactive opportunistic and broadcast-based approaches [10].

Figure 6 shows a clear advantage of using a hybrid approach in dynamic networking scenarios, due to its capability to react to relay failures by exploring a relay switching functionality. Relay switching is able to decrease the overall contention by avoiding relay re-selection and replacing relays with poor performance.

Broadcast-based relaying includes additional control messages for handshake to avoid collisions and to guaranty correct channel reservations. This is why it achieves an average throughput gain of 40% in relation to 802.11. However, the gain decreases with the increase of network density, since relay failure increases due to collisions.

Both hybrid (RelaySpot) and broadcast-based relaying achieve better throughput gain when compared with opportunistic-based relaying: Figure 6 shows that opportunistic relaying achieves an average throughput gain of only 24% in relation to 802.11. Such low gain is due to the fact that the source and destination do not know the availability of relays, leading to a high probability of failed relay attempt, and of collision.

Figure 6 shows that hybrid relaying, such as RelaySpot, are able to increase the overall network performance, while decreasing the impact of relaying overhead. While broadcast-based and opportunistic relaying lead to a decrease of the overall network throughput with an increasing of density. The main reason being its capability to select good relays at a first attempt (e.g. relays with low interference and low mobility), as well as its capability to quickly replace relays that start to present a poor performance.

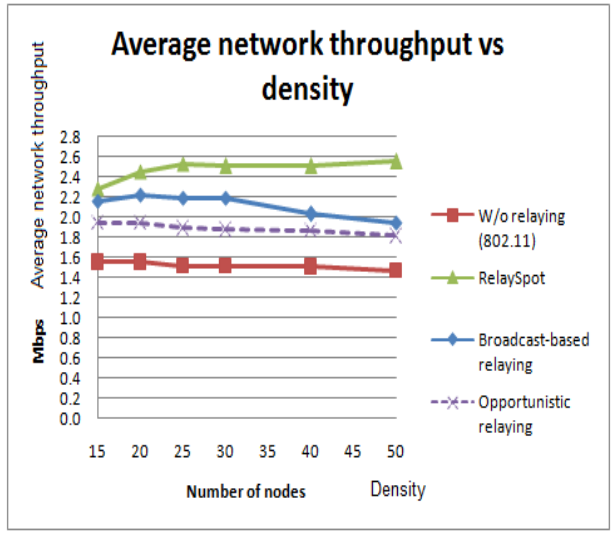

Figure 6. Comparative Analysis of Hybrid, Broadcast and Opportunistic Relaying.

VI. Conclusion

User-centric networking is a new trend that aims to support efficient communications in dynamic wireless environments by exploiting the role that end-users may have in the networking process. This user-centric perspective of networking opens new possibilities for the development of novel technologies able to sustain reliable and cost efficient wireless transmissions, such as cooperative relaying. Cooperative relaying aims to bring several improvements to wireless networks, from increasing network capacity and coverage, to enhancing reliability and throughput even in scenarios where mobile devices communicate under different wireless interference conditions.

In this paper we argue that hybrid cooperative relaying is the most suitable approach for such dynamic scenarios, due to its self-organized properties. To justify our argumentation, we present RelaySpot as a solution to mitigate the problems posed by fading and by the presence of low data-rate mobile nodes. Experimental results show that RelaySpot can effectively increase the transmission capacity of wireless local area networks, even in the present of mobile nodes communicating under different interference conditions. The proposed approach achieves an average throughput gain of 32% and 18% in relation to proactive opportunistic and broadcast-based relaying respectively.

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