Universidade de Aveiro Departamento de Eletrónica, Telecomunicações e Informática
2013

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Conceção e Desempenho de Retransmissões Sem Fios Cooperativas

Design and Performance of Wireless Cooperative Relaying

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palavras-chave

Comunicações sem fios, redes sem fios de próxima geração, redes locais sem fios, redes sem fios cooperativas, controlo de acesso ao meio cooperativo, seleção de retransmissores, gestão de recursos, DCF, diversidade.

resumo

Nos últimos anos foi proposto um novo paradigma de comunicação, chamado de comunicação cooperativa, para o qual estudos iniciais de teoria da informação demonstraram ter potencial para melhorias na capacidade em redes sem fios tradicionais *multi-hop*. Uma extensa pesquisa tem sido realizada para mitigar o impacto da atenuação em redes sem fios, tendo-se debruçado principalmente em sistemas *Multiple-Input Multiple-Output* (MIMO). Recentemente têm sido investigadas técnicas de retransmissão cooperativas para aumentar o desempenho de sistemas sem fios, usando a diversidade criada por diferentes antenas individuais com o objetivo de atingir o mesmo nível de desempenho dos sistemas MIMO com dispositivos de baixo custo.

A comunicação cooperativa é um método promissor para atingir uma elevada eficiência na ocupação espectral e melhorar a capacidade de transmissão em redes sem fios.

A comunicação cooperativa tem por ideia base a junção de recursos de nós distribuídos para melhorar o desempenho global de uma rede sem fios. Em redes cooperativas os nós cooperam para ajudarem-se mutuamente. Um nó cooperativo que ofereça ajuda estará agindo como um intermediário ou mediador, podendo transmitir mensagens da origem para o destino.

A comunicação cooperativa explora a natureza da transmissão em difusão das comunicações sem fios para formar antenas múltiplas virtuais com vários nós de rede independentes e com antenas únicas. Esta investigação visou contribuir para a área científica das redes sem fios cooperativas. O foco da pesquisa foi nos protocolos de controlo de acesso ao meio (MAC) com retransmissão cooperativa. Especificamente, proponho uma arquitetura para enquadrar a retransmissão cooperativa, chamada RelaySpot (ponto de retransmissão), que explora a seleção oportunista de retransmissores, o escalonamento de retransmissores cooperativos e a comutação entre retransmissores. As comunicações baseadas na RelaySpot deverão ter uma troca de sinalização reduzida, não usam estimativas das condições do canal e melhoram o aproveitamento da diversidade espacial, minimizando a interrupção e aumentando a fiabilidade.

keywords

Wireless communications, next generation wireless networks, wireless local area networks, wireless cooperative networks, cooperative MAC, relay selection, resource management, DCF, diversity.

abstract

In recent years, a new paradigm for communication called cooperative communications has been proposed for which initial information theoretic studies have shown the potential for improvements in capacity over traditional multi-hop wireless networks. Extensive research has been done to mitigate the impact of fading 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 with low cost devices.

Cooperative communication is a promising method to achieve high spectrum efficiency and improve transmission capacity for wireless networks.

Cooperative communications is the general idea of pooling the resources of distributed nodes to improve the overall performance of a wireless network. In cooperative networks the nodes cooperate to help each other. A cooperative node offering help is acting like a middle man or proxy and can convey messages from source to destination.

Cooperative communication involves exploiting the broadcast nature of the wireless medium to form virtual antenna arrays out of independent single-antenna network nodes for transmission. This research aims at contributing to the field of cooperative wireless networks. The focus of this research is on the relay-based Medium Access Control (MAC) protocol. Specifically, I provide a framework for cooperative relaying called RelaySpot which comprises on opportunistic relay selection, cooperative relay scheduling and relay switching. 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.

Contents

List of Figures

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Main Contributions

Following are the scientific outcome during development of my thesis:

Articles:

- T. Jamal, P. Mendes, and A. Zúquete, “Wireless Cooperative Relaying Based on Opportunistic Relay Selection,” International Journal on Advances in Networks and Services, vol. 05, no. 2, pp. 116-127, Jun. 2012.

Patents:

- Tauseef Jamal (PK); Paulo Mendes (PT); “Cooperative Relaying for Dynamic Networks”, EU Patent No. EP1318236, Aug. 2013.

Book Chapters:

- T. Jamal and P. Mendes, “Cooperative Relaying for Dynamic WLAN,” Chapter abstract submitted to WiNeMO Book (Springer LNCS Editor), Dec. 2013.

- T. Jamal, and P. Mendes,“Cooperative Relaying In Wireless User-Centric Networks,” contribution to Book Chapter in User Centric Networking - Future Perspectives (Springer LNSN) Dec. 2013.

- P. Mendes, W. Moreira, C. Pereira, T. Jamal, A. Bogliolo, H. Haci, and H. Zhu, “Cooperative Networking In User-Centric Wireless Networks,” contribution to Book Chapter in User Centric Networking - Future Perspectives (Springer LNSN) Dec. 2013.

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- T. Jamal, P. Mendes, and A. Zúquete, “Analysis of Hybrid Relaying in Cooperative WLAN,” in Proc. of IEEE/IFIP WirelessDays, Nov. 2013.

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- T. Jamal and P. Mendes, “Cooperative Wireless Relaying, Key Factors for Relay Selection,” in 1st MAP-Tele Workshop, Porto, Portugal, Dec. 2009.

Nomenclature

AF	Amplify and Forward
AP	Access Point
BER	Bit-Error-Rate
CACK	Cooperative ACK
CCTS	Cooperative CTS
CD-MAC	Cooperative Diversity MAC
CF	Cooperation Factor
CMAC	Cooperative Communication MAC
CoopMAC	Cooperative MAC
CoopRTS	Cooperative RTS
CRS	Cooperative Relay Selection
CRTS	Cooperative RTS
CSI	Channel State Information
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear To Send
CW	Contention Window
DCF	Distributed Coordination Function
DF	Decode and Forward
ErDCF	Enhanced relay-enabled DCF
HTS	Helper ready To Select
MAC	Medium Access Control
MIMO	Multi-Input Multi-Output
NAV	Network Allocation Vector

ORP	Opportunistic Relaying Protocol
ORS	Opportunistic Relay Selection
PCF	Point Coordination Function
PDAs	Personal Digital Assistants
PER	Packet-Error-Rate
PHY	Physical layer
PLCP	Physical Layer Convergence Protocol
PRO	Opportunistic Retransmission Protocol
QM	Qualification Message
QoS	Quality of Service
RAMA	Relay-Aided Medium Access
RCONTEND	Relay CONTEND
RCTS	Relay Clear To Send
rDCF	Relay-enabled DCF
RRTS	Relay Request To Send
RTS	Request To Send
RW	Reception Window
SF	Store and Forward
SIFS	Short Interframe Space
SM	Switching Message
SNR	Signal to Noise Ratio
STBC	Space-Time Block Coding
WFACK	Wait For ACK
WFCTS	Wait For CTS
WFDATA	Wait For DATA
WLANs	Wireless Local Area Networks
WWRF	World Wireless Research Forum

Chapter 1

Introduction

The success of wireless networks in the last decade has made our life so convenient and hassle free that even imagining a life without this technology seems to be a nightmare. Users are so much used to modern wireless devices such as mobile phones, laptops, Personal Digital Assistants (PDAs), navigators, cordless phones, gaming consoles, etc., that their demand for higher bandwidth is increasing exponentially. This trend is supported by the World Wireless Research Forum (WWRF) forecast which shows that by 2017, we will have seven trillion wireless devices serving seven billion people [2].

The increasing trend is the main motivating factor for development of novel wireless technologies for reliable and cost efficient transmissions. The introduction of Multi-Input Multi-Output (MIMO) systems [22, 20] is a remarkable advancement in the field of communication theory during the last decade. Numerous practical schemes, such as spatial multiplexing and space-time coding, are designed using multiple antennas on transmitter and/or receiver side. These schemes provide considerable improvement in spectral efficiency and signal reliability on the links. MIMO techniques and their variations are very popular in wireless applications. For instance, various standards, such as IEEE 802.11, IEEE 802.16, and IEEE 802.20 use these techniques. However, multi-antenna systems have their inherent limitations. For instance, deployment of complex antenna systems at user device becomes inappropriate due to size, cost and power limitations.

Cooperative communication is an innovative technique that takes the advantage of broadcast nature of wireless channels and can achieve spatial diversity gain without deploying multiple antennas at the nodes. This new transmission paradigm forms an efficient virtual multi-antenna system in a wireless network. Consequently, significant performance gains can be achieved in terms of link reliability, system capacity and coverage [25].

1.1 Motivation

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. The most actively researched area is the Medium Access Control (MAC) layer, responsible for the efficient coordination of access to the shared wireless medium. The 802.11 standard specifies a common MAC layer, which manages and maintains communication between 802.11 stations by coordinating access to shared wireless channel. The IEEE

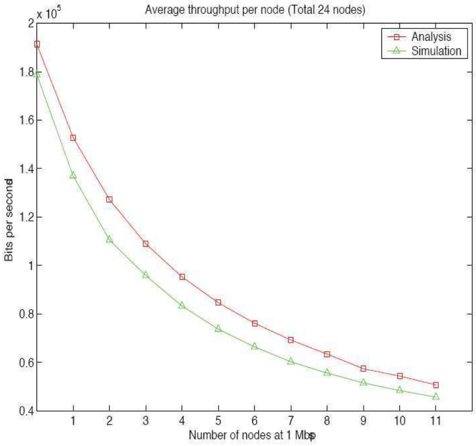


Figure 1.1: Effect of slow node in IEEE 802.11 [51].

802.11 MAC specifies two access mechanisms: the polling-based Point Coordination Function (PCF) and the contention-based Distributed Coordination Function (DCF). PCF is not widely deployed because of its complexity, inefficient polling schemes and limited Quality of Service (QoS) provisioning.

However, channel conditions in wireless networks are subjected to interference and fading, decreasing the overall network performance [18]. Fading effects in a wireless environment can be classified as either fast or slow [71]. 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 duration of the transmission. Moreover, the interference from other transmitters also affects the communication quality severely. Because of the constant change of the environment and the mobility of the terminals (transmitter or receiver or both) the signal is scattered over many objects in the surroundings [59]. Such channel impairments can be mitigated by exploiting cooperative diversity [45].

In what concerns Wireless Local Area Networks (WLANs), among other issues they suffer from scarcity of bandwidth, which limits the network throughput and requires efficient utilization of this valuable resource. One example of these issues is from the existing WLANs, where the performance of the whole system degrades greatly once low data-rate nodes become dominant. The usage of rate adaptation schemes results in a degradation of the overall network performance, since low data-rate nodes grab the wireless medium for a longer time. This occurs since each node has the same probability to access the channel, which means that high data-rate nodes will not be able to keep the desirable throughput.

In the 802.11 protocol, nodes far from its Access Point (AP) observe low data-rate, which cause fairness problems within the network as shown in [26]. If all nodes have uniform traffic to/from the AP, then the low data-rate nodes will use much more channel time than the high data-rate nodes. This has two negative effects: not only do the low data-rate nodes get poor service, but they also reduce the bandwidth of high data-rate nodes. This reduces the effective throughput of the network. Other proposals, such as [60] also demonstrated that the overall throughput of the network decreases significantly due to the presence of low data-rate nodes.

The negative effect of nodes operating at a lower data-rate on the average throughput per node for an 802.11 system is shown in Figure 1.1. As can be seen in the figure, the presence of nodes at 1 Mbps reduces the average throughput of all the nodes in the network. This is because a 1 Mbps node takes roughly 11 times more transmission time than a 11 Mbps node to transmit the same number of bits [51]. This multi-rate capability can be further exploited by enabling cooperative transmission at MAC layer to mitigate effects of low data-rate nodes.

Currently, cooperative relaying is considered in different usage models, encompassing different MAC algorithms such as 802.11 and 802.16. In what concerns the 802.16 standard, analysis of usage models for cooperative relaying is ongoing in the 802.16j group [1]. The usage models are categorized according to where coverage is provided. There is already a considerable effort being applied in the specification of multi-hop relaying in 802.16j, aiming to provide a certain level of service to a given number of users over a given coverage area.

The standardization effort being done in the IEEE 802.16j group aiming to specify cooperative relaying, and the lack of a similar initiative in IEEE 802.11, added by the huge deployment of 802.11 networks, motivates further research on cooperative relaying for 802.11 networks. Such motivation is further sustained by the potential benefits in terms of system throughput, reliability and coverage.

1.2 Problem Statement

Although, wireless networking provides easy connectivity and fast deployment, it still presents low performance level. These limitations come from the shared medium and the unstable wireless channel. There are many other constrains in wireless networks such as limited power, Quality of Service (QoS), deployment, size of devices, and distance from the AP.

Extensive research has been done to achieve better throughput and reliability in wireless networks, being mostly focused on MIMO systems. Recently, cooperative networking techniques have been investigated to increase the performance of wireless systems by using the diversity created by different single antenna devices. In cooperative networking, intermediate nodes (relays) help source-destination transmission forming dual-hop communication. This unique solution provides a response to the majority of the above concerns in an efficient way. However, most of the cooperative solutions rely upon Channel State Information (CSI), explicit notifications and additional broadcast information, which incur overheads and complexity.

Current cooperative networking proposals are characterized by their limited focus. Most of the research being done focuses on the physical layer, by exploiting spatial diversity to increase system reliability of cellular networks [57]. In its simplest version, a terminal trying to reach a base station is assisted by a relay terminal. Due to the broadcast nature of the wireless channel, the relay can overhear the sender's transmission, decode it, and, if correctly received, repeat it. The base station combines these two copies of the same transmission, reducing the packet error-rate. This provides larger reliability gains than simple retransmission due to the exploitation of spatial diversity, in addition to time diversity [45].

The development of cooperative relaying systems, 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 [67].

As cooperative transmissions involve additional transmissions via relays, therefore, it always introduces some additional overhead and interference as compared to non-cooperative transmission. Thus, the benefits brought by cooperation can be diminished if relaying mechanism is not cleverly designed. There are many other constrains such as concurrent transmissions and mobility etc., which can affect the performance of cooperative networks [14].

Cooperative communications require unique features from MAC, which should be distributed and cooperative for a multipoint-to-multipoint environment. There are noteworthy issues that must be taken into account while designing cooperative diversity MAC: relay selection, cooperation decision, cooperation notification and cooperative transmission design [65].

In what concerns the relay selection, there is broad horizon of selection parameters, mostly based on channel information. Such parameters are complex and unstable. Moreover, the selected relay may be the best for the transmission pair that is helped but may be the worst in terms of the overall network capacity. Therefore, there is need to design hybrid techniques that allow simultaneous optimization over several parameter domains. In what concerns the relay failure issues, there are many situations when the relay may fail or when the poor relay is selected.

In what concerns the cooperative transmission design: the first issue is the relay discovery. Most of the protocols require an image of neighborhood implemented in a table, normally based on channel qualities. Most of the protocols use periodic broadcast for this purpose. Such periodic broadcast needs to be very frequent to cope with network variations, in any case it limits the performance of cooperative system. Another issue is coordination with relays; most of the protocols use additional control messages for relay management in a centralized manner. Such explicit notifications affect the gain of cooperation. Yet, in some scenarios, it is infeasible to have such a centralized coordination [63, 58]. The challenge is how to identify the cooperation capabilities of the possible relays in a distributed manner.

Cooperation in wireless networks may not be beneficial or even necessary. Therefore, the decisions when to start cooperation and when to stop cooperation are very important to avoid unnecessary cooperation.

As a summary, MAC layer is most important for cooperative networks, since it can devise alternative ways of transmission within a network. However, advantages of cooperation are only possible if the MAC layer is able to efficiently select and coordinate relays with reasonable cost, with efficient cooperative transmission protocol.

1.3 Thesis Contribution

The primary aim of the research work conducted during the PhD was to investigate and propose solutions to improve the performance of existing 802.11 wireless networks. One solution arises from the advent of dual-hop relay-based, MAC protocols, which uses cooperative communication at the MAC layer, to resolve the issues in throughput and delay. In cooperative networking solutions, the MAC layer will be concerned with more than one-hop communication, being distributed and cooperative in a multipoint-to-multipoint communication. Consequently, this thesis investigated a cooperative 802.11

MAC protocol. The main focus of the research done is on the relay-based MAC layer: design of cooperative MAC protocols, to address relay selection, cooperation decision, relay failure and cooperative transmission issues. In July 2009, I presented the pre-thesis proposal [30] about the proposed research, followed by yearly progressions reports [32, 38, 39].

This research highlights the design and issues of dual-hop MAC protocols and introduces several improvements to existing protocols. I proposed a framework called RelaySpot. The RelaySpot framework allows any node to perform local relaying decisions. This solution allows the creation of dual-hop communication paths aiming to augment the quality of the wireless transmission and reduce the problem posed by low data-rate nodes. This solution reduces additional overhead, resource blockage and dependency over CSI.

The first contribution of this thesis is dedicated to the analysis of prior art that aids MAC protocol developers in the design phase to devise efficient protocols and relay selection solutions. In the related work analysis I analyzed the relay selection approaches [31] and cooperative MAC protocols by classifying the existing solutions and proposed taxonomies.

As a next contribution, I propose a framework, RelaySpot, which uses high data-rate nodes to work as relays for the low data-rate nodes. RelaySpot is a cooperative MAC protocol for WLANs while being backward compatible with 802.11. RelaySpot is a hybrid relaying protocol which aims to improve the poor links as well as responding to failed links. With RelaySpot, a relay is chosen for a cooperative transmission opportunistically, without any broadcast overhead. Through overhearing Request To Send (RTS) and Clear To Send (CTS) control frames exchanged by the source and destination nodes, nodes can acquire related rate information used to calculate their cooperation factor used to determine if they are eligible to become potential relays. Eligible relays are then able to self-elect themselves as qualified relays by computing their selection factor based on local information such as interference, history and mobility factors. The proposed protocol can effectively choose a suitable relay among all qualified relays, increasing the performance gain in relation to 802.11, even in the presence of interference. Thus, RelaySpot is an opportunistic cooperative relaying solution. To overcome with situations when the selected relay may fail, or a better relay is available later on, a relay switching functionality is proposed. Relay switching tries to react to relay failures and poor selections, by allowing transmissions to take advantage of more than one relay.

RelaySpot achieves higher throughput, and lower delay when compared to conventional 802.11 DCF. The performance of RelaySpot was evaluated under interference and it was proved that the gain of RelaySpot can still be maintained. Finally, RelaySpot was evaluated under multiple relays (relay switching) and the results confirm the advantage of relay switching.

As a summary: i) relays offer their services to source-destination pair by overhearing transmissions that can be helped; ii) each relay decides by itself without any global management and without use of any explicit messages (even if direct transmission is impossible); iii) relaying gets automatically adjusted to new relaying offers.

1.4 Dissertations Overview

The thesis is organized as follows:

This Chapter 1 presents the introduction to thesis and issues related to wireless technologies which motivates the cooperative networks.

Chapter 2 presents an introduction of cooperative networks and cooperative MAC. It also presents the comprehensive analysis of existing cooperative relaying solutions.

Chapter 3 surveys the relay selection mechanisms and discuss the issues related to relay selection in cooperative networks.

Chapter 4 presents the framework for cooperative relaying called RelaySpot. It further describes the various building blocks of the proposed framework.

Chapter 5 describes the experimental setup details for analysis of the relaying protocol. It also describes the relay-based protocol implementation.

Chapter 6 shows the evaluation of RelaySpot protocol, in term of opportunistic relay selection algorithm, relay scheduling and relay switching with its performance analysis which is an improvement on the IEEE 802.11 networks.

Some concluding remarks and future issues are presented in Chapter 7.

Chapter 2

Wireless Cooperative MAC

The theory behind cooperative communications has been studied in depth, and significant improvement of system performance has been demonstrated in terms of Signal to Noise Ratio (SNR) gains, network coverage and energy efficiency [57]. However, when it comes to the implementation of cooperative communications in a network, cooperative MAC protocol design is of indispensable significance as well. Therefore, to take full advantage of cooperative techniques, new MAC schemes must change the transmitter-receiver communication model to include a transmitter-relay(s)-receiver model.

Cooperative MAC protocols define the access method and data forwarding method via relays, and may request necessary information from the Physical layer (PHY) [52]. It also defines the relay selection methods which will be explained in Chapter 3.

This chapter focuses on the application of cooperative communications, namely relaying MAC protocols, to increase spectrum efficiency, network coverage as well as to reduce outage probabilities.

2.1 Cooperative Communications

The basic ideas behind cooperative communication can be traced back to the groundbreaking work of Cover and El Gamal [13] on the information theoretic properties of the relay channel. The transmission of different copies of the same signal from different locations, generating spatial diversity allows the destination to get independently faded versions of the signal that can be combined to obtain an error-free signal.

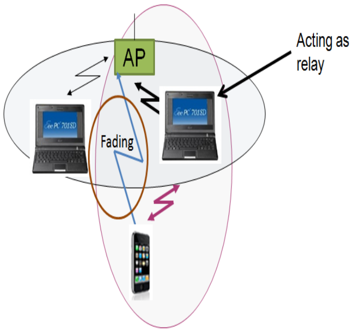


Figure 2.1: Mitigating fading effects by relaying.

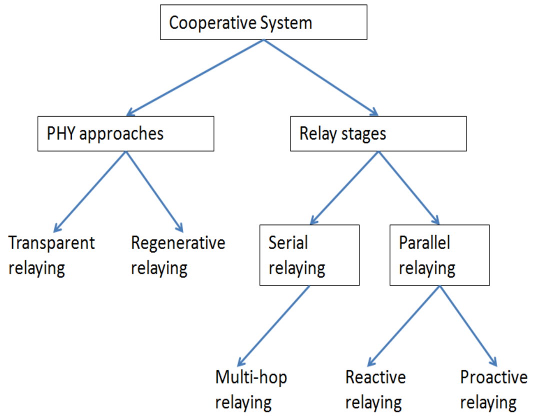


Figure 2.2: Classification of cooperative systems.

In a cooperative communication system, each wireless user is assumed to transmit its own data as well as acting as a relay for another user. Figure 2.1 shows single antenna devices able to act as relays of each other by forwarding some version of "overheard" data along with its own data. Since the fading channels of two different devices are statistically independent, this generates spatial diversity.

In the following sections the classifications, benefits and limitations of cooperative system are presented.

2.1.1 Taxonomy

From an implementation perspective, cooperative systems can be classified accordingly to different ways of utilizing relays, as shown in Figure 2.2. Cooperative systems can be designed with physical layer approaches or with higher layers (relay stages). At PHY layer, cooperative diversity is usually modeled as a MIMO system. Some designs aim at full diversity: For N-antenna virtual array, the outage probability decreases asymptotically with SNR^{-N}. Other designs set their performance criteria according to the well-known trade-off between diversity and multiplexing gain: for N-antenna array, the multiplexing gain r and the diversity gain d, as defined in [6], are complementary and upper bounded by $d(r) \leq N+1-r$.

The choice of relay stages is very important, because, relays can operate either in series or in parallel. On the one hand, increasing the number of serial relaying nodes reduces the path-loss along each transmission hop. On the other hand, increasing the number of parallel relaying nodes increases potential diversity gains. Parallel relaying is implemented at PHY/MAC layers (single-hop), while serial relaying can be implemented with combination of both MAC and routing layers (multi-hop). There are two types of approaches for implementing parallel relaying, i.e., proactive and reactive relaying, which will be explained in Section 2.2. In case of multi-hop relaying, the relays help more than one transmission requiring routing information.

There are two main categories of PHY relaying approaches, i.e., transparent and regenerative relaying. In transparent relaying the relay does not decode data from the signal received from the direct link; examples are Amplify and Forward (AF) and Store and Forward (SF) [61, 62]. In regenerative relaying, relays decode received packets, re-

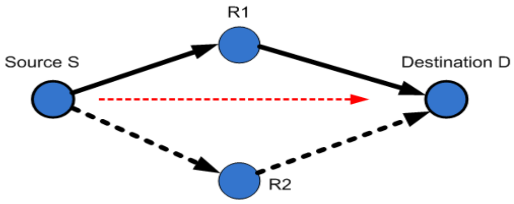


Figure 2.3: Increasing diversity order.

code the information and forward it to the destination; example is Decode and Forward (DF) [44].

2.1.2 Benefits of Cooperative Communications

From a network perspective, cooperation can benefit not only the nodes involved, but the whole network in many different aspects. For illustration purposes, only a few potential benefits are explained below.

Higher Spatial Diversity: Spatial diversity is the main advantage provided by cooperative communications. This property can be expressed in terms of increased diversity order.

As a simple example (c.f. Figure 2.3), if the channel quality between source node S and destination node D degrades severely, a direct transmission between these two nodes may experience an error, which in turn leads to retransmissions. Alternatively, S-D can exploit spatial diversity by having a relay R1 overhear the transmissions and forward the frame to D. The source S may also use another relay R2 for helping in forwarding the information, or use both relays together. So, compared with direct transmission, the cooperative approach enjoys a higher successful transmission probability. Therefore, cooperative communications have the ability to mitigate the effects of shadow fading better than MIMO since, unlike MIMO, antenna elements of a cooperative virtual antenna array are separated in space and experience different shadow fading.

Higher Throughput-Lower Delay: At the physical layer, rate adaptation is achieved through adaptive modulation. Many MAC protocols have introduced rate adaptation to overcome adverse channel conditions. For instance, when a high channel error-rate is encountered due to a low average SNR, the wireless LAN standard IEEE 802.11 switches to a lower transmission rate. The power of cooperation is evident when it is applied in conjunction with any rate adaptation algorithm. Due to its distance from the AP, a wireless node can observe a bad channel as compared to other nodes that are closer to the AP, leading to the use of 802.11 rate adaptation schemes. Figure 2.4 illustrates the transmission characteristics of wireless nodes, as a result of the rate adaptation functionality of IEEE 802.11: nodes closer to the AP transmit at high data-rates, while nodes far away from the AP decrease their data-rate after detecting missing frames. Figure 2.4 also shows the role that relaying may have increasing the performance of the overall wireless network, helping low data-rate nodes to release the wireless medium sooner, helping high data-rate nodes to keep the desirable performance, and the network to achieve a good overall capacity.

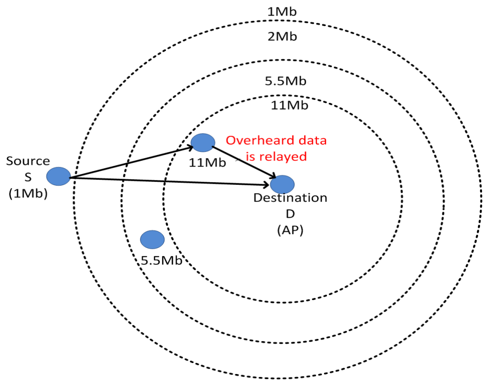


Figure 2.4: Helping low data-rate nodes by cooperative relaying.

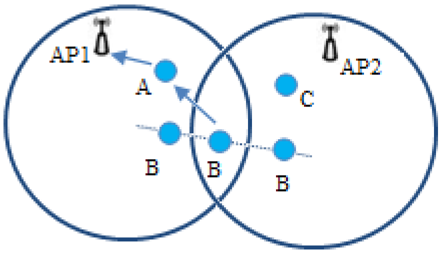


Figure 2.5: Avoiding unwanted handovers.

In this case the total transmission time for the dual-hop transmission is smaller than that of the direct transmission, cooperation readily outperforms the legacy direct transmission, in terms of both throughput and delay perceived by the source S.

Extending Range of Network: Due to cooperation, a node can reach to AP even via a relay, extending range and avoiding handovers. In the case of pedestrian mobile networks, mobile devices may perform pendular 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 (c.f. Figure 2.5). These examples show the advantages of deploying cooperative communications to improve the utilization of wireless spectrum while providing higher network performance and guaranty balance QoS to all users.

Cooperative communications also ease the roll-out of a system that has no infrastructure available prior to deployment. For instance, in disaster areas, relaying can be used to facilitate communications even if existing communication systems such as cellular systems are out of order.

2.1.3 Limitations of Cooperative Communications

The limitations of cooperative communications can be as significant as the advantages. Therefore, cooperative system design needs to be performed carefully in order to achieve the full gains of cooperative communications and at the same time to ensure that cooperation does not cause degradation of system performance.

Spatial diversity benefits come with some cost. Since at least one relay terminal retransmits the transmission overheard from a source terminal, cooperative transmissions are consuming more resources than a direct transmission. Resources can be expressed in terms of time slots, frequency bands, battery, spreading codes, or space time codes.

Moreover, the implementation of cooperative communications implies additional design constraints so that cooperative transmissions do not interfere with other direct transmissions.

Due to extra relay traffic, cooperative relaying will certainly generate extra interference, which potentially causes deterioration of system performance.

In cooperative systems, not only the traffic of different sources but also the relayed traffic needs to be scheduled. Thus, more sophisticated scheduling is required.

Cooperative communications involve the reception and decoding of data frames before being re-transmitted by relays. Therefore, extra latency is introduced by relaying.

2.2 Cooperative Communication at MAC Layer

Both the telecommunications operators and the end-users would reject a wireless network with cooperative diversity if the PHY layer required manual configuration. So the role of the MAC layer is essential. In addition to cooperation control, the MAC layer must support error recovery, dynamic optimization, mobility support, relay selection and cooperation decision [14].

Cooperative relaying at MAC layer comprises two phases: relay selection and cooperative transmission. In the first phase a relay or group of relays are selected, while in the latter phase the communication via relay(s) takes place. The relays can be selected either by source (source-based), destination (destination-based), or by the relay itself (relay-based). At MAC layer we can classify cooperative protocols as proactive and reactive. In the proactive protocols, the cooperation is based on some pre-arranged optimal or random format. In proactive relaying the source, destination or potential relay replaces the slow direct communication with a fast, one-hop relayed communication, aiming to improve the data-rate [65]. These protocols are time critical and incur higher overheads. They require frequent information exchange for timely delivery of data. Whereas, in reactive protocols [16], the cooperation is initiated with a Negative ACK (NACK) due to collision or error. Reactive protocols are appropriate for applications that are delay tolerant and incur lower overhead.

In what concerns the 802.11 MAC, Figure 2.6 shows a basic 802.11b system where nodes have different transmission rates at different distance from AP. Cooperation at MAC enables source node to find a relay node and transmit via that relay. The relay node must be within the cooperation area to rectify the impact of low rate nodes. In Figure 2.6, R_{11} is the distance from AP to transmit at 11 Mbps, while r_{11} is the distance from a source node to transmit at 11 Mbps. The cooperation area is the intersection of two circles (R_{11} and r_{11}), defined as follows [82]:

$$CooperationArea = r^2cos^{-1}(\frac{d^2+r^2+R^2}{2dR}) + R^2cos^{-1}(\frac{d^2+R^2+r^2}{2dR}) - \frac{1}{2}\sqrt{(-d+r+R)(d+r-R)(d-r+R)(d+r+R)} \tag{2.1}$$

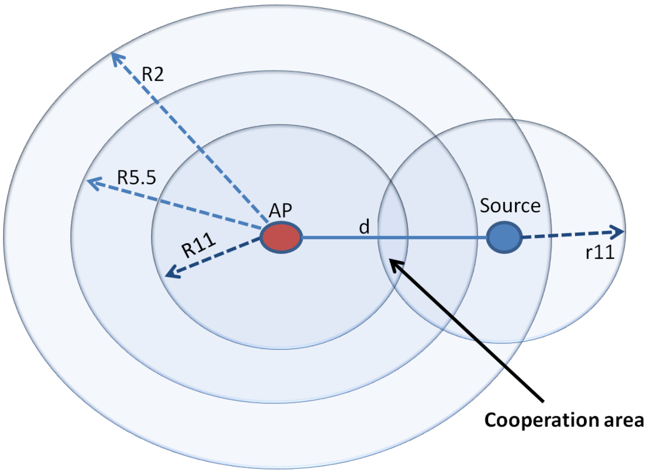


Figure 2.6: Sample 802.11b network.

Such cooperation may also bring some extra overhead, 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).

2.3 Classifications of Cooperative MAC Protocols

As discussed, cooperative MAC can be classified as proactive and reactive. Proactive protocols work if the direct link between source and destination exists. Whereas, reactive protocols are initiated when the direct link fails. Hence, proactive relaying aims to increase the throughput of wireless networks while reactive relaying aims to decrease degradation by avoiding retransmissions. Proactive relaying can be further split into 1) broadcast-based protocols, and 2) opportunistic protocols, as illustrated in Figure 2.7. Broadcast-based protocols represent a relatively simple strategy by utilizing the broadcasting nature of the wireless medium. While broadcast-based protocols offer more control due to its centralized nature, opportunistic relaying is the one where nodes can independently make cooperation within certain time constraint under some conditions. Such relaying does not require extra control messages. The reactive protocols can be further classified as 1) broadcast-based protocols, 2) opportunistic protocols, and 3) multi-hop protocols.

From the classification of cooperative MAC protocols shown in Figure 2.7, it is apparent that most of the literature focuses on the broadcast-based protocols due to their easy implementation and backward compatibility. Multiple relay broadcast protocols, though not very well researched, require better coordination among the multiple relays, thus increasing the complexity. In the next section, I provide details of some existing protocols.

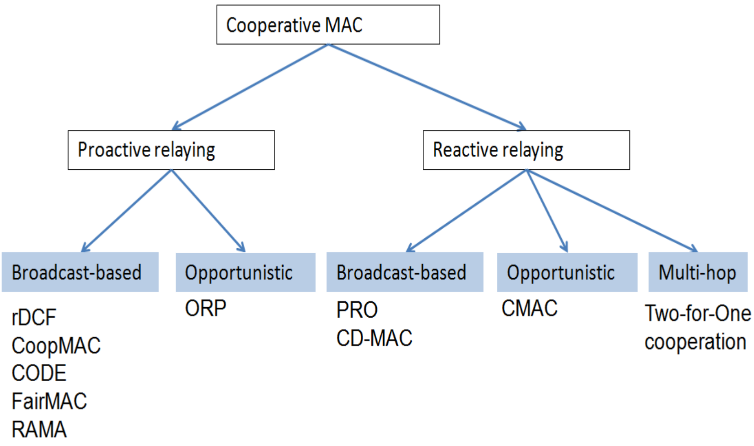
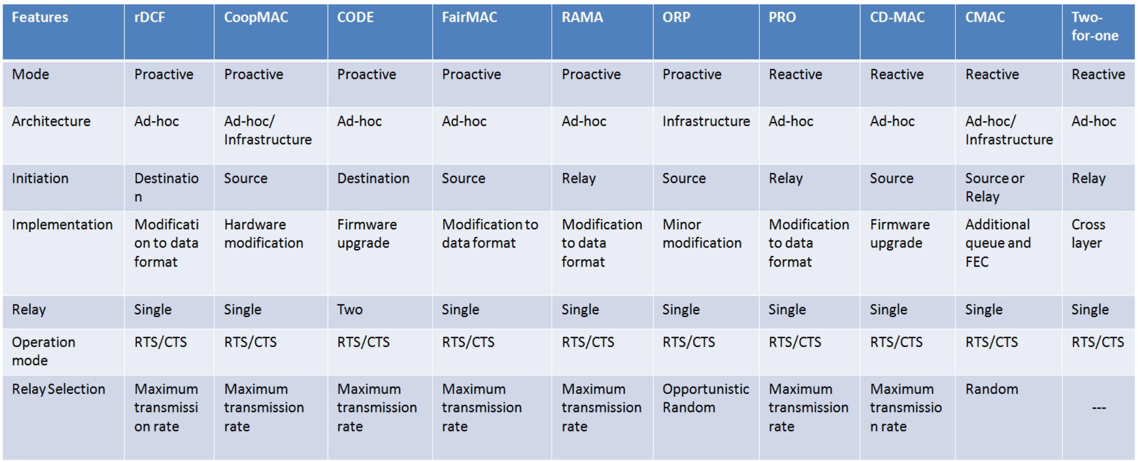


Figure 2.7: Cooperative MAC classifications.



Features	rDCF	CoopMAC	CODE	FairMAC	RAMA	ORP	PRO	CD-MAC	CMAC	Two-for-one
Mode	Proactive	Proactive	Proactive	Proactive	Proactive	Proactive	Reactive	Reactive	Reactive	Reactive
Architecture	Ad-hoc	Ad-hoc/ Infrastructure	Ad-hoc	Ad-hoc	Ad-hoc	Infrastructure	Ad-hoc	Ad-hoc	Ad-hoc/ Infrastructure	Ad-hoc
Initiation	Destination	Source	Destination	Source	Relay	Source	Relay	Source	Source or Relay	Relay
Implementation	Modification to data format	Hardware modification	Firmware upgrade	Modification to data format	Modification to data format	Minor modification	Modification to data format	Firmware upgrade	Additional queue and FEC	Cross layer
Relay	Single	Single	Two	Single	Single	Single	Single	Single	Single	Single
Operation mode	RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS
Relay Selection	Maximum transmission rate	Maximum transmission rate	Maximum transmission rate	Maximum transmission rate	Maximum transmission rate	Opportunistic Random	Maximum transmission rate	Maximum transmission rate	Random	---

Table 2.1: Comparisons of cooperative MAC protocols.

2.4 Existing Protocols

In general, both proactive and reactive approaches have their pros and cons, which greatly depends on individual mechanisms. Therefore, it is important to study individual protocols irrespective of their class. Table 2.1 provides comparisons of some of existing protocols. Following I describe cooperative MAC protocols grouped into families as mentioned in Figure 2.7.

2.4.1 Broadcast-based Protocols

In this type of protocols normally sources or destination or potential relays maintain a table which is updated periodically based on broadcasting. The limitations of this subclass are periodic broadcasts, maintenance of table and extra control overhead which effect the performance. These protocols can be proactive as well as reactive.

Relay-enabled DCF (rDCF) protocol was developed by Zhu and Cao [87, 86] based on DCF, where a high data-rate dual-hop path is used instead of a low data-rate direct path between the source and destination. For a given flow between a pair of sender and receiver, with the measured channel quality, if a relay finds that the data can be transmitted faster, it adds the identity (e.g., MAC address) of the sender and the receiver into its willing list. Periodically, each relay node advertises its willing list to its one-hop neighbors, from where the source picks a relay. rDCF proposed a triangular handshake mechanism for source-relay-destination transmission. First source node send Relay Request To Send (RRTS), after reception of RRTS, the relay and destination can measure the quality of the channel. The relay then sends another RRTS to destination with a piggybacked measurement information of source-relay channel. The destination measures the quality of relay-destination channel and sends Relay Clear To Send (RCTS) to the source including rate information of source-relay and relay-destination channels.

According to the results presented in [87], rDCF is only suitable if the frame size is larger than 400 bytes. Otherwise, rDCF gives worse performance when compared to DCF because of its relatively higher overhead. Another drawback of rDCF is that when the relay is forwarding the data frame, it does not include the duration field, which increases the probability of collisions. Following the success of rDCF, a lot of research was devoted to improving its performance [50, 5].

Enhanced relay-enabled DCF (ErDCF) [5] inherits some characteristics of rDCF such as triangular handshake. But it uses short Physical Layer Convergence Protocol (PLCP) preamble for dual-hop cooperative transmission, which provides higher throughput and reduced blocking time. In ErDCF the data frame forwarded by a relay includes the duration field, which can minimize the collision risks. However, it increases the frequency of periodic broadcast which increases the overhead.

In Cooperative MAC (CoopMAC) [51], the source uses an intermediate node (relay) that experiences relatively good channel with the source and the destination. Instead of sending frames directly to the destination at a low transmission rate, the source makes use of a two-hop high data-rate path to the destination via a relay. Based on the CSI broadcasted by potential helpers, sources update a local table (cooptable) used to select the best relay for each transmission. CoopMAC performs 3-way handshakes, which require the selected relay to send a control message Helper ready To Select (HTS) between RTS and CTS messages. First, 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.

There are other versions of CoopMAC for cooperative diversity based on IEEE 802.11 DCF [77, 47, 56, 78] and for IEEE 802.16 [48]. All proposals are similar, just changing some of the features, such as usage of Space-Time Block Coding (STBC).

The solution CODE [73] uses two relays to form the virtual antenna array and additionally makes use of the physical layer network coding technique to achieve the gain. For bidirectional traffic between the source and destination, network coding is applied at the relay node to increase system throughput. In CODE all nodes overhear RTS/CTS frames, and if they find that they can transmit data faster than the source, they add the identity of source and destination to their willingness list. Once the source finds its address in the willing list of relay(s), it adds those relay(s) into its cooperation table.

FairMAC, presented in [8] concerns about the energy cost of cooperation, since there is a trade-off between energy per transmitted bit and achieved throughput. FairMAC, allows the selection of the desired cooperation factor, which represents the limit of frames to be relayed for each own frame transmitted. In this protocol each relay node maintains an additional infinite queue to store the frames to be relayed.

Relay-Aided Medium Access (RAMA) protocol proposed the relay-based transmission to improve the performance and reduce the transmission time. RAMA consists of two parts: first is the invitation part which is used to configure the relay and second is the transmission part. RAMA allows only one relay in a transmission and in case of collision of the invitation, the relay node does not need to transmit and wait for the next transmission.

In Opportunistic Retransmission Protocol (PRO) [54] 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 level 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 ACK frame of successful transmission.

In Cooperative Diversity MAC (CD-MAC) [55], when the direct link fails, retransmission takes place via a relay. First the source and its preselected relay send a Cooperative RTS (CRTS) to the destination. Destination and its preselected relay respond with Cooperative CTS (CCTS). After receiving a CCTS, the source and its relay cooperatively transmit the data frame to destination and its relay. After receiving data frame, destination and its relay cooperatively transmit Cooperative ACK (CACK). There is high overhead of control frames as source, destination and relay repeat the whole control and data frames in different codes.

2.4.2 Opportunistic Protocols

These protocols do not maintain tables, therefore, a relay can relay data opportunistically without prior coordination.

Opportunistic Relaying Protocol (ORP) [19] is a relaying solution where nodes are able to increase their effective transmission rate by using dual-hop high data-rate links. ORP does not rely on the RSSI for relay selection. It opportunistically makes a frame available for relaying and all nodes try to forward that frame within the time constraint. However, the relays back-off every time they forward. Another drawback of this approach is that the source does not know about the availability of a relay, so it does not know rates of source-relay and relay-destination channels.

Cooperative Communication MAC (CMAC) [66] introduces spatial diversity via user cooperation. In case of CMAC each node stores the source node data frame. If no ACK is overheard the relay forwards the stored data frame on behalf of source. Due to usage of additional queues and channel estimations, CMAC faces the challenges of overhead.

2.4.3 Multi-hop Protocols

In the two-for-one cooperation approach [49] 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-for-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. [4]. 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 [49], 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.

2.5 Discussion

From the realized analysis I 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 capacity. These observations lead to the identification of two important research issues: i) achieve a good balance between interference and transmission throughput; ii) improve the capacity of large mobile networks.

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), 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. Another important issue is handshaking mechanism, almost all of the proposals, with the exception of ORP, are using additional messages for coordination/notifications.

From the analysis of cooperative MAC protocols, 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. The complexity may increase due to the number of times relay transmission fail. Moreover, waiting for optimal relay to assist one transmission degrades the overall performance of the network and decreases its capacity.

Before investigating suitable solutions, we need to answer the following questions: i) when do we really need to use cooperative relaying? ii) how to coordinate? and iii) whom to cooperate with? For cooperation to be triggered, we need to compare the transmission throughput achieved by proposals that take advantage of spatial diversity (cooperative relaying) over the direct link. The coordination between cooperative nodes can be done implicitly or with minimum feedback. To devise a cooperative relay solution able to achieve a good balance between interference and transmission throughput it is important to start by investigating the choice of relay selection parameters, as well as consideration of evaluation scenarios. The performance of cooperative relaying greatly depends upon the used scenario, on the other hand it gives opportunity to analyze various aspects, such as concurrent transmissions.

2.5.1 Choice of 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.

In what concern the parameters themselves, previous work uses local variables such as SNR, Bit-Error-Rate (BER), CSI. Since these are very unstable parameters, I propose the usage of less volatile parameters, namely interference level, 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. Another parameter is stability, which 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 as relays. So, this investigation leads to the conclusion that the most suitable parameters for large scale networks are devised by using local parameters characterized by being less volatile than the usual SNR, BER and CSI parameters. Detailed analysis about relay selection approaches is provided in the next chapter.

2.6 Conclusions

The MAC layer is the most important for a cooperative relaying system, as this relies on identifying alternative ways of transmission within a networked context. The advantage of cooperative relaying is possible if MAC layer is cleverly designed.

This chapter surveyed the existing relaying protocols at MAC layer and devised a taxonomy. Most protocols rely on handshake messages, modifying the DCF of 802.11 MAC, either in cooperative or opportunistic way. All proposed solutions have their benefits and drawbacks, and none of them is completely superior to the others. In general, most of the prior art only consider relaying in static wireless scenarios. There are some approaches (e.g., CoopMAC and PRO) which performance is evaluated also in mobile networks, but the proposals are still agnostic of the mobility patterns of the involved nodes. The choice of scenarios is very important to understand the impact of relaying on the overall network, because relaying can also introduce extra interference. Therefore, such issues need to be taken into account for devising an efficient relaying system.

Chapter 3

Relay Selection Mechanisms

Introduction of cooperative relaying raises several problems such as relay selection and resource allocation. With cooperative relaying, the relay selection process requires special attention, since it has a strong impact on network and transmission performance. 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.

Due to the significant number of different cooperative relaying approaches, this chapter aims to provide a systematic analysis and classification of the 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. 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.

3.1 Relay Selection Taxonomy

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. A reason is 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. The most common in the literature are: CSI, SNR and BER. 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 within 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 [7, 51], 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.

For a better understanding of the utility of current relay selection approaches, I classify them in what concerns time of selection (three classes) and level of interaction (two levels), as shown in Figure 3.1.

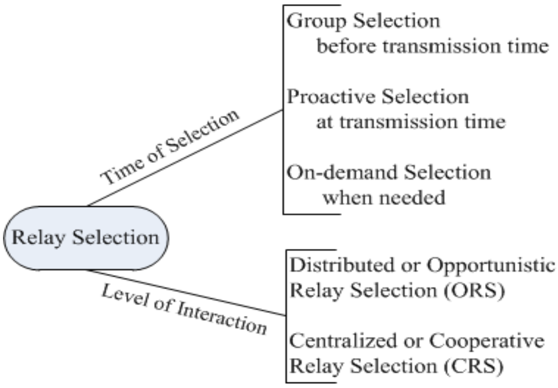


Figure 3.1: Relay selection taxonomy.

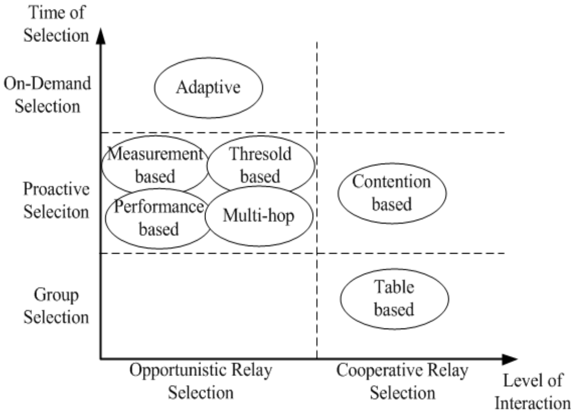


Figure 3.2: Classification of relay selection approaches.

In what concerns time of selection, I 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; iii) *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, I group relay selection mechanisms into two categories: *Distributed or Opportunistic Relay Selection* (ORS) and *Centralized or Cooperative Relay Selection* (CRS). For a better understanding of the existing relay selection proposals, I analyze seven types of relay selection approaches, being the classification based on the taxonomy (c.f. Figure 3.2). This study is helpful to identify similarities among existing proposals, supporting the decision about the relay selection mechanism that better suits cooperative relaying.

3.2 Opportunistic Relay Selections

With the distributed or opportunistic relay selection each potential relay decides about forwarding frames, 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 end up competing for the wireless medium. Such mechanisms present a high probability of collisions.

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 (such as 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.

Measurement-based Selection: These 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. [7]. Another example is presented by Shan et al. [64].

In general the operation of measurement-based selection approaches is as follows: each potential relay estimates channel conditions (CSI in case of [7]) of source-relay and relay-destination channels. 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 node as relay. In [64], the overhearing nodes send out a busy-tone (the relay with best channel conditions sends longer busy tone).

Measurement-based approaches are able to select the best relay among N nodes, but they may require 2N channel state estimations, which is in the same complexity order as conventional Distributed Space-Time Coding (DSTC) algorithms [46]. Nevertheless, DSTC algorithms require significant modifications of hardware to support complex signal processing at receiver.

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. 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 receives from the source with a threshold such as SNR (in case of [27]) or BER (in case of [69]). In a second phase, only relays that satisfy the threshold requirements enter into relay selection according to their algorithm. For instance, the work presented in [27], the node with the maximum lower value of the SNR in the source-relay and relay-destination links is selected as relay.

On Demand 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 proposed by Adam et al. [3].

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, the relay selection process is triggered. In case of the work presented by Adam et al. [3], relays are selected in a process similar to the basic opportunistic approach proposed in [7].

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.

Performance-based Selection: Performance-based selection approaches rely on performance criteria (e.g., delay and energy efficiency) to select the most suitable relay, aiming to optimize measurement-based approaches. Approaches proposed in [11] and [85] 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 [11] aims to reach an optimal power allocation.

In the work presented by Chen et al. [11], sources include their residual power level on RTS frames, 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. In the work presented by Zhou et al. [85], the source sends its maximum transmit power in RTS frame. 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 proposed in [7], the difference is that it just consider the channel estimation and not energy considerations.

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.

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 [49, 4]. 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.

3.2.1 Performance Analysis

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. [7], present a significant decrease in outage probability, when compared to the direct transmission. 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 [11] 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. [3] 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 a major goal of threshold-based relay selection solutions [27, 69]. However, all of these approaches are still complex, since they rely upon channel estimations.

3.3 Cooperative Relay Selections

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, relaying may not occur if a node that was selected as relay is not available when transmission occurs, due to mobility or lack of energy. Another problem with this class are the periodic broadcast and extra handshaking signals which can limit the efficiency.

Contrary to opportunistic relay selection, cooperative relay selection procedures require the exchange of information among the nodes involved in the communication. In this case I 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.

Table-based 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 [51] and CODE [73] 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. Relays are selected by the source by looking up in the table.

Contention-based 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 [53], and the link quality of both relay channels with source and destination in the case of PRO [54]. If these estimations satisfy certain threshold then such relays are qualified for selection. In the second phase the relays select their contention window on the basis of priorities. The limitation of this class is the influence that the size of the contention window has in the relay selection.

3.3.1 Performance Analysis

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 throughput 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. 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 lower degree and are closer 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 may be selected for cooperation.

3.4 Conclusions and Directions

This chapter provided so far an analysis of relay selection approaches for wireless cooperative networks, since a poor selection may considerably degrade the performance of the overall network. I proposed a taxonomy for the evaluation of relay selection approaches, and analyzed 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 the initial conclusions are three-fold: i) relay selection should allow systems 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 CSI, SNR or PER; iii) good relay selection schemes should be able to support multi-hop scenarios as well as scenarios with mobile nodes.

The analysis shows that opportunistic relay selection approaches aim to reduce outage, while cooperative relay selection approaches try to increase transmission throughput (cf. Table 3.1).

Table 3.1: Benefits 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	–

Although the discussed relay selection mechanisms already show the benefits of using cooperative relaying. However, there is 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.

It is my opinion that the investigation of relay selection schemes that are 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 intelligence to support relaying over large networks in the present of nodes with dynamic behavior.

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.

It is my 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 called "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 (relay switching).

Therefore, the investigation of joint opportunistic cooperative relay selection schemes deserves some attention in the future.

Chapter 4

RelaySpot Framework

An ever-growing demand for higher data-rates has fuelled the growth of wireless networks in the past decades. 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 nodes, cooperative relaying promises gains in performance and reliability. However, cooperation procedures are unstable (may rely on current channel conditions) and introduce overhead that can endanger performance, especially when nodes are mobile.

This chapter describes an 802.11 backward compatible cooperative relaying framework, called RelaySpot [41, 37], that does not rely on neighborhood mapping, CSI estimation and consequent periodic broadcasts, which are the source of overhead in cooperative systems. It implicitly starts and stops cooperation under certain conditions (i.e., data-rate) and switch relays in case of failure. Therefore, RelaySpot is expected to minimize signaling exchange, remove estimation of channel conditions, and improve the utilization of spatial diversity, minimizing outage and increasing reliability even in mobile environments.

RelaySpot aims to ensure accurate and fast relay selection, posing minimum overhead and reducing the dependency upon CSI estimations. The basic characteristic of any RelaySpot-based solution is the capability to perform local relaying decisions at potential relay nodes (can be more than one), based on a combination of opportunistic relay selection and cooperative relay scheduling and switching. To the best of my 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, additional handshake messages and back-off during relaying.

Figure 4.1 illustrates a simple example of cooperative relaying systems, RelaySpot considered issues related to such cooperative systems including decrease in network capacity and transmission fairness. With RelaySpot, wireless networks do not need complicated distributed routing algorithms, as in ad-hoc networks to extend the coverage of wireless local networks, due to its capability to, switch among relays as mobility patterns change over time. With RelaySpot, standard 802.11 networks are able to offer ubiquitous high data-rate coverage and throughput, with reduced latencies.

In the following, I start by describing generic RelaySpot architecture, followed by building blocks, frame formats, and finally explains the detail operation.

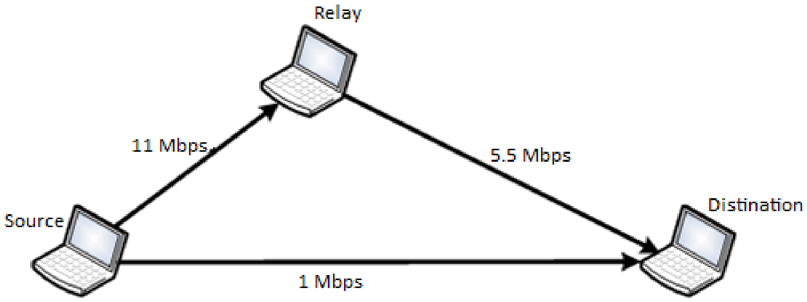


Figure 4.1: Cooperative relaying.

4.1 Architecture

The definition of MAC cooperative schemes poses several challenges, especially 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 approaches at MAC layer, being the proposed approaches mostly source or destination based. Both approaches incur in some overhead and are not efficient reacting to network changes, mainly in the presence of mobile nodes.

In a clear contrast to the prior art, RelaySpot is a hybrid cooperative relaying protocol (proactive and reactive) where relays self-elected under certain cooperation conditions are used to increase the performance of active transmissions or to replace failed transmissions. RelaySpot comprises three basic building blocks: Opportunistic relay selection, cooperative relay scheduling and cooperative relay switching. It also defines a forth building block, chain relaying, which is the focus of future work.

In order to fit dynamic scenarios, and 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 hard 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 approach followed by RelaySpot is to make use of the best possible relaying opportunity even if not the optimal one, and to switch between self-elected relays during transmission, if necessary.

The RelaySpot framework allows any node to perform local relaying decisions. This solution allows the creation of few-hop communication paths aiming to augment the quality of the wireless transmission and reduce the problem posed by low data-rate nodes. At the link layer, IEEE 802.11 uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm to control the access to the wireless medium. In RelaySpot the DCF scheme has been modified, such that RelaySpot is 802.11 backward compatible in the sense that it: i) does not create any new frame, making only use of all fields present in the 802.11 frames; ii) allows the same AP to be shared by RelaySpot nodes and nodes that only implement the 802.11 standard. In the following the generic operation of a RelaySpot node is described.

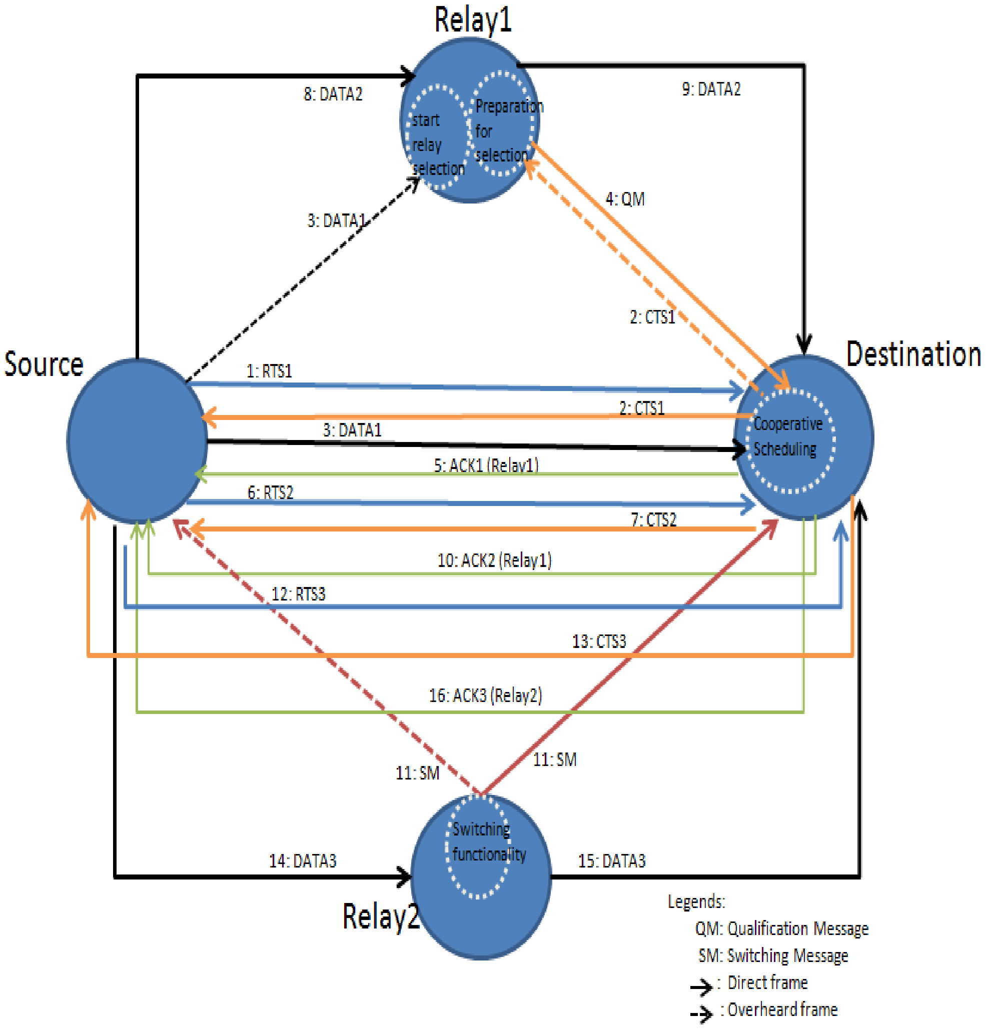


Figure 4.2: RelaySpot proactive functionality.

4.1.1 Node Design

This section describes the general functionality of a node running RelaySpot, in which case the node can operate as a potential relay or as a source/destination for each flow. RelaySpot can be used when the direct link between source and destination exists (proactive mode), or when the direct link fails (reactive mode), being all the major operations done by the three components mentioned before, which are: opportunistic relay selection; cooperative relay scheduling; relay switching, as described below: While chain relaying will be described in Section 4.6.2.

- Opportunistic relay selection: Intermediate nodes may take the opportunity to relay in the presence of local favorable conditions (e.g., no concurrent traffic) after detecting one of two situations: i) a broken communication; ii) a poor direct transmission, by analyzing the wireless data-rate;
- Cooperative relay scheduling: The destination node will be able to cooperate in the relay selection procedure by electing one over several potential relays, based on

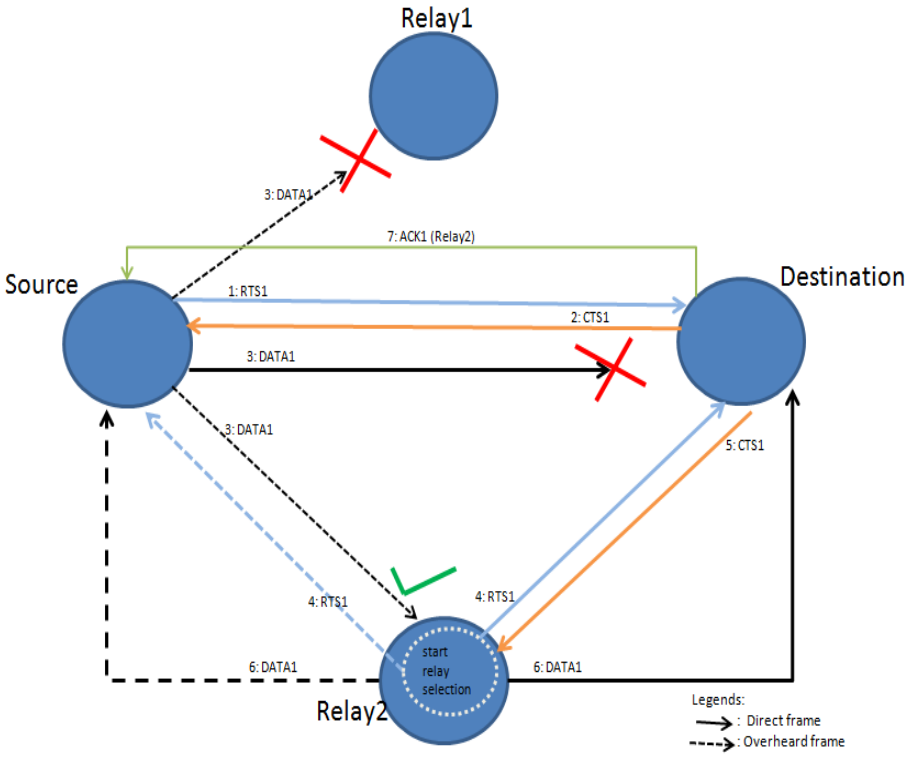


Figure 4.3: RelaySpot reactive functionality.

the quality of the relays. In a second version of RelaySpot, the cooperative scheduling mechanism will be augmented to create diversity higher than two, by selecting more than one relay.

- Relay switching: This functionality aims to compensate unsuccessful relay transmissions. Relay selection faces several optimization problems that are difficult to solve, which means that the best relay may be difficult to find by the destination based on the set of potential relays. Hence, aiming to be suitable for dynamic scenarios, RelaySpot allows the destination to select the best possible relaying opportunity even if not the optimal one (e.g., in terms of CSI). In order to keep a good quality level in case of a bad decision from the destination, RelaySpot allows potential relays to take over the control of the relay operation, by asking the source to switch the relay for the subsequent data frames.

Figure 4.2 illustrates the proactive operation of a RelaySpot node, based on an example with one source, two potential relays and one destination (the numbers before the messages refer to the order in which the frames are sent).

As shown in Figure 4.2, the operation starts as in a normal 802.11 network with the source starting an RTS/CTS procedure with the destination in order to gain access to the wireless medium. In the process, Relay1 (the potential relay present in the vicinity) overhears the CTS message and estimates the quality of the direct link. When the source transmits the data frame, this is overheard by Relay1, which activates the opportunistic relay selection mechanism in this node. As a result Relay1 transmits a Qualification Message (QM) to the destination aiming to notifying it of Relay1 availability to relay data from the source. Based on the information received from Relay1,

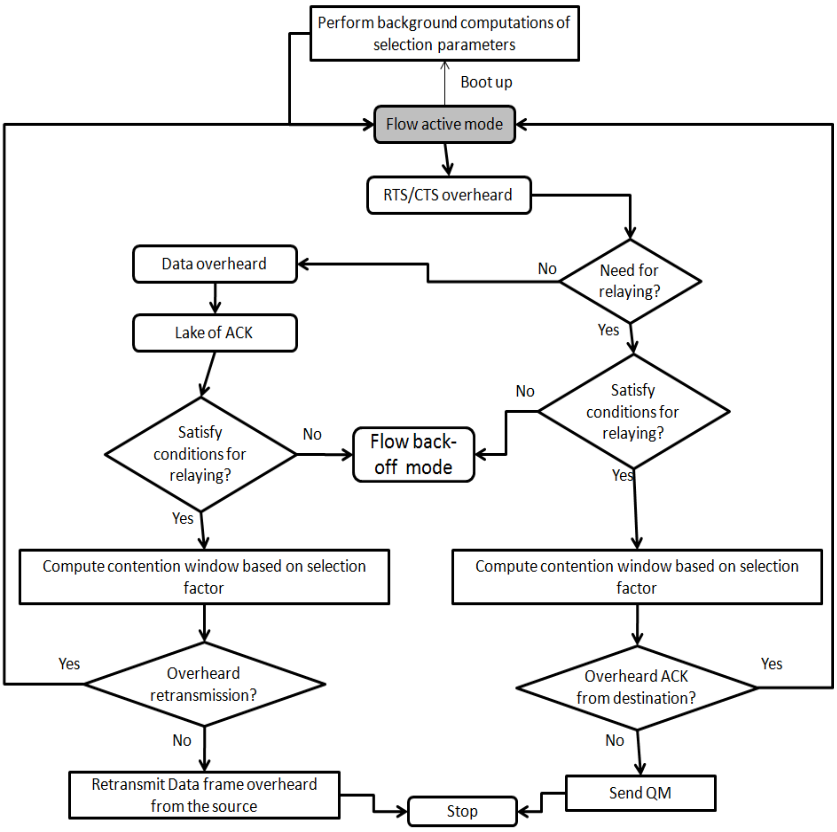


Figure 4.4: Opportunistic relay selection operation at relay node.

the destination acknowledges the reception of the data frame and notifies the source that subsequent data frames should be sent via Relay1, since this offers better quality transmission. As a result, the source sends the next data frame through Relay1, after gaining again access to the wireless medium by executing the RTS/CTS operation with the destination. The reception of this message is acknowledged by the destination, informing the source that frames should keep being send via Relay1. This acknowledgment message is overheard by a new potential relay in the vicinity (Relay2), which, after comparing its own cooperation factor with the one from Relay1, notifies the source and destination that it is a better relay than Relay1. As a consequence, the next time that the source gains access to the wireless medium (through a RTS/CTS procedure) it will send the data frame through Relay2.

Figure 4.3 illustrates the reactive operation of a RelaySpot node. In this scenario, the transmission between source and destination end up without acknowledgment, meaning that the data frame was not delivered successfully. In such situation, the potential relays start opportunistic relay selection process, after detecting a missing ACK to an overheard data frame. As a consequence, the first relay to gain access to the wireless medium (the one with best selection factor c.f. Section 4.2) will resend the overheard data frame to the destination (Relay2 in Figure 4.3).

While this section provides information about the generic functionality of a RelaySpot node, the interaction between RelaySpot nodes are done based on the message frames and the flowcharts presented in following sections.

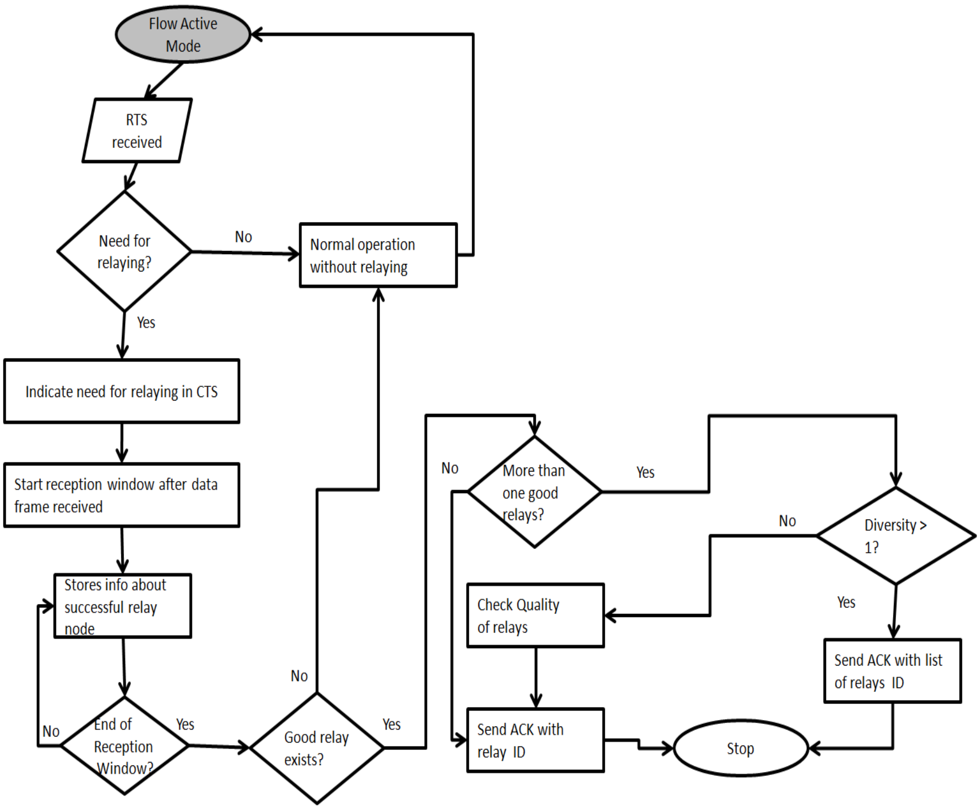


Figure 4.5: Cooperative scheduling functionality at destination node.

4.1.2 Flowcharts

Figures 4.2 and 4.3 gave an overview of RelaySpot in general. In this section I further expand these figures to present the flowcharts for the three building blocks. Figure 4.4 provides a flowchart describing the opportunistic relay selection operation in general for one flow (RelaySpot starts parallel processes to handle each active flow). This opportunistic relay selection is performed on the relay node. The relay performs some background computation to estimate how good it is to help an active flow, namely by computing its selection factor. In the presence of an active flow, it starts preparation for relay selection by checking its eligibility (previously computed value in background).

After overhearing the RTS/CTS exchange related to an active flow, the potential relay starts operating in a proactive mode, if *need for relaying* is indicated within CTS frame. In proactive mode, if the relay is eligible to improve the performance of the active flow (i.e., cooperation factor better than direct link), it starts the Contention Window (CW) based on the computed selection factor, in order to become a relay. After the expiration of the CW, and if ACK is not overheard for that flow, the relay perform relaying action by sending a QM to the destination.

The relaying action is different for reactive relaying (broken link). In this case if the potential relay does not overhear the acknowledgment of a previously overheard data frame. After the expiration of the CW, the potential relay sends the overheard data to the destination (instead of QM) if it satisfies some relaying conditions (and if it does not overhear another relay performing retransmission). Figure 4.4 also shows that

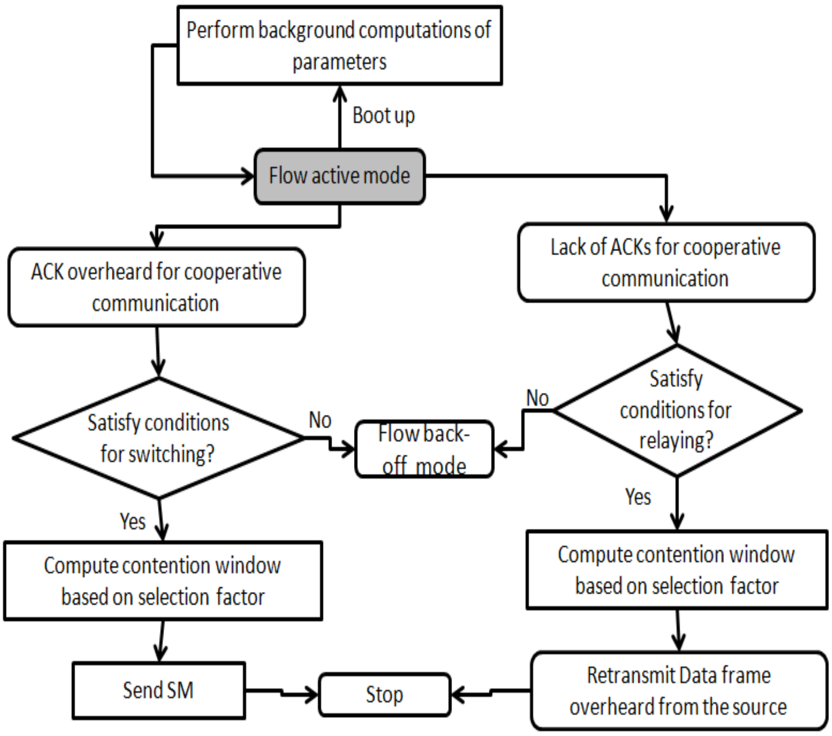


Figure 4.6: Relay switching operation at relay node.

opportunistic relay selection is activated due to lack of ACK in case of reactive mode.

Figure 4.4 described the operation of opportunistic relay selection only, which is executed on a potential relay node only, while the relaying process (transmission via relay) will be described in Section 4.4.

The role of the relay scheduler at the destination is to select the best relay among opportunistic relays based on received QMs. Figure 4.5 illustrates the scheduling operation, which starts a parallel scheduling process for each active flow, if there is the need for relaying. For each active flow the destination checks the need for relaying if the quality of the direct transmission is below a pre-configured threshold. If there is a need for relaying, this information is communicated in the CTS, allowing potential relays to pay attention to this specific flow. After this the destination starts a reception window as soon as the data frame is received in order to collect the QMs from potential relays. At the end of the reception window, the destination sends an ACK message to the source with the identification of the relay or relays (if diversity is configured to a value higher than 1) selected to help this flow, if there is one or more relays that can improve the quality of the direct link. Hence, RelaySpot solution (in proactive mode) is destination-based, as the destination is choosing the best set of relays via scheduler.

If there is no need for relaying, the destination enters in a normal procedure without relaying, although the data frames that it can get would be relayed by a relay operating in reactive mode, and not directly from the source. Therefore, the scheduler is not used in reactive mode. In this case the ACK is sent to the source, as in a normal 802.11 procedure.

Switching between relays, as described before, is performed when there is a potential relay that can improve the quality of the source-destination communication to a value higher than the one provided by the current relay. This situation can occur as a consequence of a bad estimation of the best relay by scheduler, or when a new relay comes to the vicinity of the source-destination link.

As shown in Figure 4.6, after overhearing the ACK sent by the destination to a relayed communication, a potential relay checks if it satisfies the conditions for relay switching: this happens if it has a cooperation factor higher than current relay. If so, the potential relay sends an SM to the destination after the expiration of its CW (this message is overheard by the source).

Relay switching is also used to keep data being relayed in the presence of a failed relay. If a potential relay detects that the cooperative transmission via a relay is failed, potential relay tries to retransmit the failed data frame, leading to relay switching (implicitly). This will be explained further in Section 4.2.3.

4.2 Components

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

4.2.1 Opportunistic Relay Selection

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

This section describes the functionality proposed to allow self-elected relays to avoid high interference and to guarantee high data-rates to a destination while preventing waste of network resources. Relay selection is performed in three steps: First, each node checks if it is eligible to be a relay by verifying two conditions, overheard a good frame sent by the source and be positioned within the so called cooperation area; Second, eligible nodes start the self-election process by computing their selection factor; Third, self-elected relays set their CW based on their selection factor, and send a qualification message towards the destination after the contention window expires, as shown in Figure 4.7.

The relay selection process is only executed by nodes that are able to successfully decode frames sent by a source. These relays start by verifying if they are inside the cooperation area by computing their Cooperation Factor (CF) as given in Equation 4.1, where R_{sr} is the rate of source-relay channel, while R_{rd} is the relay-destination channel rate. The rate of the source-relay and relay-destination channel is computed by overhearing RTS and CTS frames exchanged between source and destination. The CF ensures that potential relays are closely bounded with the source while having good channel towards the destination: an eligible relay must have a CF that ensures a higher data-rate than over the direct link from source to destination.

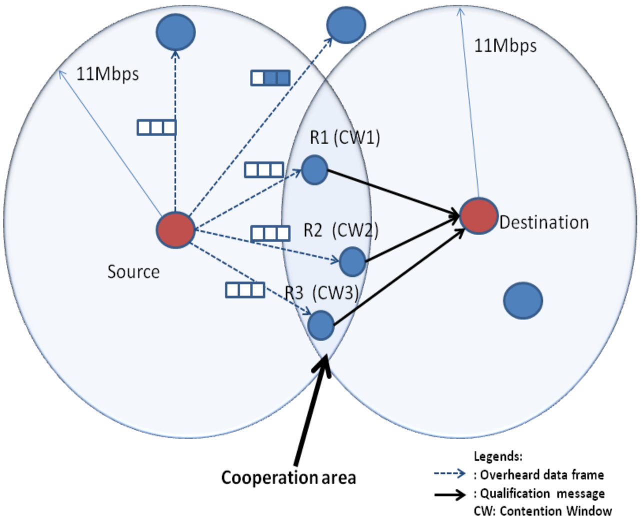


Figure 4.7: Opportunistic relay selection.

$$CF = \left(R_{sr} * R_{rd}\right) / \left(R_{sr} + R_{rd}\right), \quad CF \in [0, \infty[\tag{4.1}$$

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

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

Equation 4.2 estimates the interference level that a potential relay is subjected to as a function of node degree and load. Let N be the number of neighbors of a potential relay, T_d and T_i the propagation time of direct and indirect transmissions associated to the potential relay, respectively, and N_i and N_d the number of nodes involved in such indirect and direct transmissions. Adding to this, T_p is the time required for a potential relay to process the result of a direct transmission. The interference factor (I) affecting a potential relay has a minimum value of zero corresponding to the absence of direct or indirect transmissions.

$$I = \sum_{j=1}^{N_d} \left(T_{dj} + T_{pj}\right) + \sum_{k=1}^{N_i} T_{ik}, \quad I \in [0, \infty[\tag{4.2}$$

Figure 4.8 shows a scenario where node R is selected as a potential relay for nodes S and D. Node $N1$ is the direct neighbor of node R, while there are several other indirect neighbors ($N2$,$N3$,$N4$, X). Apart from R, node X also seems to be a relay candidate

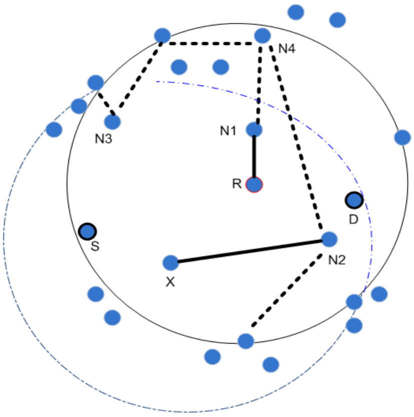


Figure 4.8: Opportunistic relay selection: example scenario.

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.

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

By using the interference level together with the history and mobility factors, the probability of selecting a node as a relay for a given destination is given by Equation 4.3: the Selection Factor (S) is proportional to the history of successful transmissions that a node has towards the destination and its average pause time, and inversely proportional to its interference level.

$$S = \frac{H * M}{1 + I}, \quad S \in [0, 1[\tag{4.3}$$

The History Factor (H) is the ratio of number of successful transmissions to the total number of transmissions towards destination as given by Equation 4.4:

$$H = \frac{N_{successful}}{N_{total}}, \quad H \in [0, 1[\tag{4.4}$$

If self-elected to operate as a relay, the node computes its CW, as shown in Equation 4.5. The CW plays an important role in scheduling relay opportunities. The goal is to increase the probability of successful transmissions from relays to the destination by giving more priority to relays that are more closely bounded to the destination, have less interference and have higher pause times.

$$CW = CW_{\min} + (1 - S)\,(CW_{\max} - CW_{\min}) \tag{4.5}$$

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

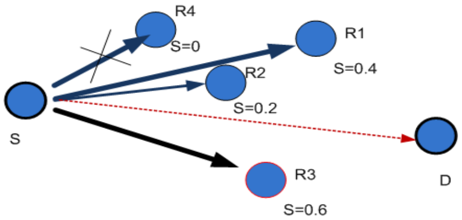


Figure 4.9: Opportunistic relay election.

4.2.2 Cooperative Relay Scheduling

As illustrated in Figure 4.9 the selection mechanism may lead to the qualification of more than one relay (R1, R2, R3), each one with different values of S, leading to different sizes of CW (e.g., R3 transmits first). Selected relays will forward data towards the destination based on a cooperative relay scheduling mechanism.

Based on the CF (*i.e.,* R_{sr} and R_{rd}) of the qualification messages received from all self-elected relays, the destination estimates which of the involved relays are more suitable to help in further transmissions. To get multiple qualification messages the destination only processes the received qualification messages after a predefined time window, i.e., Reception Window (RW). As shown is Figure 4.10 the size of the reception window is of major importance, since it will have an impact on the number of qualification messages that will be considered by the destination.

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

When the destination is configured to operate with a diversity higher than one, the destination sends an ACK frame to the source including the MAC addresses of the selected relays. During data transfer, the destination sends the received data to the application as soon as a correct frame arrives from any of the selected relays. If the selected relays start sending corrupted frames (e.g., because they moved to a faraway position) the destination waits until a good frame is received, until it received data from all selected relays, or until a predefined timeout occurs. If the destination only got corrupted frames it will try to combine them to create a good frame. If such process is possible, the destination will send an ACK to the source including the MAC addresses of the relays that sent the frames which combined produced a good frame. As shown in Figure 4.11, where the primary relay R3 fails to relay the frame.

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

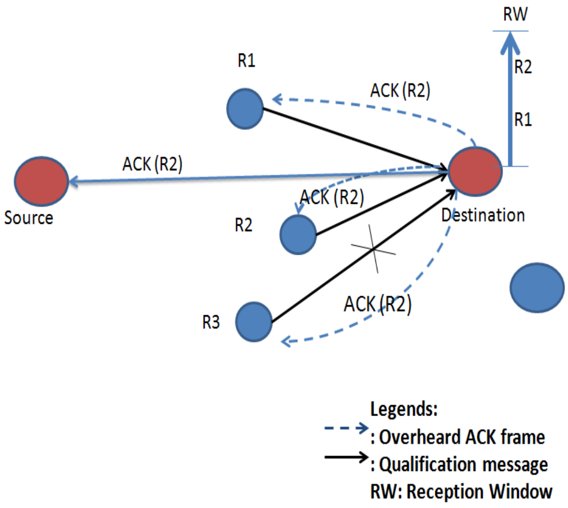


Figure 4.10: Relay scheduling: example scenario.

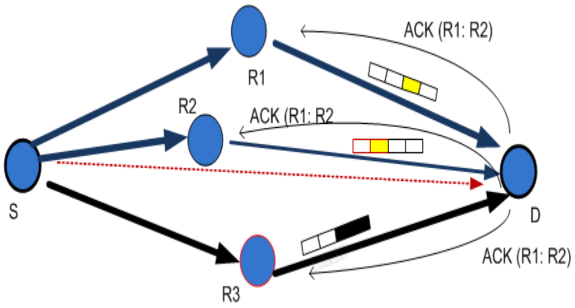


Figure 4.11: Frame combining at destination by scheduler.

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

4.2.3 Relay Switching

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

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

If a potential relay is not selected in the relay selection procedure, it compares its CF with the CF of the selected relay. If its CF is better, which means that it can provide

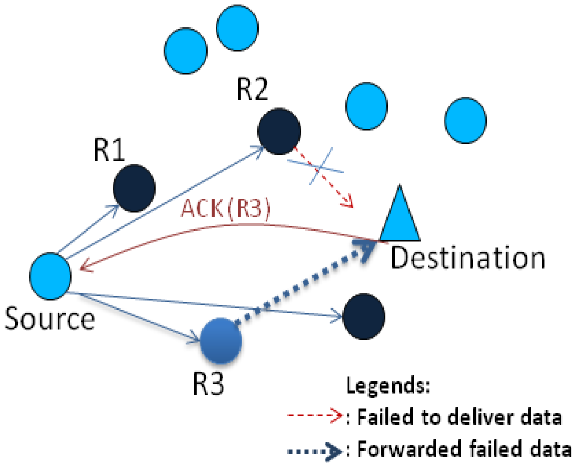


Figure 4.12: Relay switching due to failure of current selected relay.

better gain, it sends a Switching Message (SM) by sending a dummy Data frame to the destination informing it about its own CF. This way the previously selected relay can be switched to the newly selected relay, since: i) by overhearing the frame sent by the new relay, the source will send the next data frame towards that relay: ii) by receiving the frame sent by the new relay, the destination knows that the next data frame will be sent by it.

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

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

Figure 4.12 shows an example of implicit relay switching, where a previously selected relay, R2, fails to relay data to destination. In this case, instead of retransmitting the failed data and re-selecting the relays, another potential relay (in this case R3) that has better cooperation factor than R2 reserves the channel for sending the failed data frame to destination. If it is successful, the destination sends ACK with indication of R3 as relay. This way the source switches from R2 to R3 for the next data frame.

4.3 Frames

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

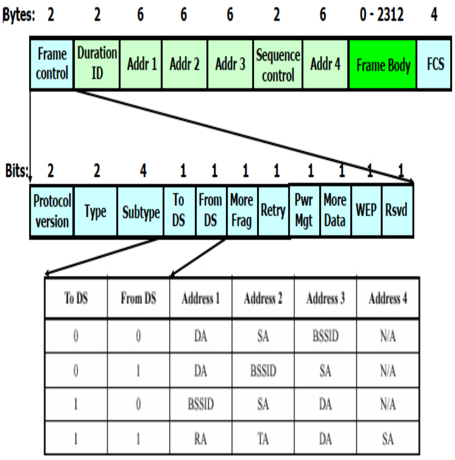


Figure 4.13: 802.11 frame structure used by RelaySpot.

Table 4.1: Control frame bits to code rate information.

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

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

As mentioned before, RelaySpot does not require any new frame, making use of the RTS, CTS, DATA and ACK frames already specified by the 802.11 standard. To ensure standard compatibility, the generic 802.11 frame structure is considered by RelaySpot (c.f. Figure 4.13).

During the operation of RelaySpot, a node may need to inform other nodes about the data reception rate. To exchange this information bits 11-13 of the frame control field are used to code the data-rate of the transmission link. Table 4.1 illustrates the codes used by RelaySpot to identify the data-rate in the 802.11b nodes (the number of codes is enough to identify also the data-rates in the 802.11g and 802.11n). The usage of these bits does not jeopardize the operation of nodes that do not execute RelaySpot, since it only use bits that are not used within control frames.

4.3.1 RTS Frame

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

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

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

4.3.2 CTS Frame

Since RelaySpot is triggered by the relays themselves, these need to gather as much information as possible about the surrounding transmissions, in order to detect the ones that need to be helped. CTS frames allow overhearing nodes to get information about the data-rate of direct links. To provide this information bits 11-13 in the CTS frame control are used to code information about the data-rate of the direct link, as illustrated in Table 4.1.

4.3.3 ACK Frame

RelaySpot uses the address 4 field in the ACK frame (marked as unused by the 802.11 standard) to allow the destination to inform the source about the address of the relay for the subsequent data frames. While bits 11-13 indicate the data-rate of the relay-destination channel, according to Table 4.1, as the source needs it to reserve the channel. If address 4 and/or relay-destination rate is not used, the source keeps using the direct transmission.

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

4.3.4 Data Frame

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

- Over the source-relay link: Address 1 indicates the relay address; Address 2 the source address; Address 3 the destination address.
- Over the relay-destination link: Address 2 indicates the relay address; Address 3 the destination address; Address 4 the source address. The relay also sends the rate of the source-relay channel encoded in bits 11-13 of the frame control according to Table 4.1.

4.3.5 Qualification Message (QM)

If a node is able to elect itself as a potential relay, the self-elected relay uses a frame of 112 bits (of type CTS) to inform the destination about its willingness to operate as relay for that source-destination transmission. The QM contains information about the rate of the source-relay channel encoded in bits 11-13 of the frame control according to Table 4.1. Although relays compute their CF to participate in the selection phase, the destination needs to know those values to identify the most suitable relay. Since the destination already knows R_{rd}, it only needs information about R_{sr} to estimate the CF of a specific relay.

4.3.6 Switching Message (SM)

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

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

Table 4.2 lists all of the fields used by RelaySpot.

4.4 Operation

In this section I describe the state diagrams and flowcharts of the three types of nodes involved in the operation of RelaySpot: source, relay and destination nodes. At the link layer, IEEE 802.11 uses the CSMA/CA algorithm to control the access to the wireless medium. These diagrams correspond to 802.11 DCF.

The relaying operation has two phases, first the relay is selected (relay selection phase) and then cooperative communication via selected relay starts (cooperation phase). The relay selection always takes place on the relay node, while the cooperation phase always started by having the source node sending data to the destination via the selected relay. However, in case of reaction to failed transmissions, the cooperative communication is started by the relay by sending failed data on behalf of source.

4.4.1 Source Node Operation

Figure 4.14 shows the state diagram at source node. All the illustrated states are already used for an operation already described in the 802.11 standard, which means that RelaySpot does not impose any fundamental change in the standard, since there is no new state required at source node. On a level of a state diagram the only changes required by RelaySpot are two new state switching conditions, represented by green lines on Figure 4.14.

In normal 802.11 operations (without cooperation) the source sends an RTS (in CONTEND state) and switches to the Wait For CTS (WFCTS) state where it stays until CTS is received. After this event the source sends a Data frame and switches to Wait For ACK (WFACK) state until an ACK is received. If the source has more data to send it switches back to the CONTEND state.

If the source is configured to operate in RelaySpot mode, while in CONTEND state the source sends an RTS and switches to WFCTS state (if a relay is already selected for this flow, means that the data should be transmitted via a relay, therefore, this RTS

Operation Fields		Direct 802.11	Relay Selection	Proactive	Reactive	Implicit switching	Explicit switching
RTS	Duration	Normal	Normal	Updated (to accommodate dual hop transmission)	Normal	Normal	
	Address 4	Normal	Normal	Relay address	Source address	Source address	
	More Frag	Normal	Normal		1	1	
CTS	Duration	Normal	Increased (by amount of RW)	Normal	Normal	Normal	
	Bits 11-13	000	Rate information	Rate information	000	000	
ACK	Duration	Normal	Normal	Normal	Normal	Normal	
	Bits 11-13	000	Rate information (Rrd)	Rate information (Rrd)	000	Rate information (Rrd)	
	More Frag	Normal	Normal	1	1	1	
	Address 4	Normal	Relay address	Relay address	Relay address	Relay address	
DATA	ToDS/FromDS	1:0	1:0	1:1	1:1	1:1	
	Duration	Normal	Increased (by amount of RW)	Normal	Normal	Normal	
	Address 1	Normal	Normal	Relay address over source-relay link	Normal	Normal	
	Address 2	Source address	Source address	Source address over source-relay link Relay address relay-destination link	Relay address	Relay address	
	Address 3	Destination address	Destination address	Destination address	Destination address	Destination address	
	Address 4	Normal	Normal	Source address over relay-destination link	Source address	Source address	
QM	Bits 11-13	----	Rate information (Rsr)	----	----	----	
SM	Bits 11-13	----	----	----	----	----	CF
	ToDS/FromDS	----	----	----	----	----	1:1
	Address 2	----	----	----	----	----	New relay address
	Address 3	----	----	----	----	----	Destination address
	Address 4	----	----	----	----	----	Source address

Table 4.2: 802.11 frame fields in RelaySpot.

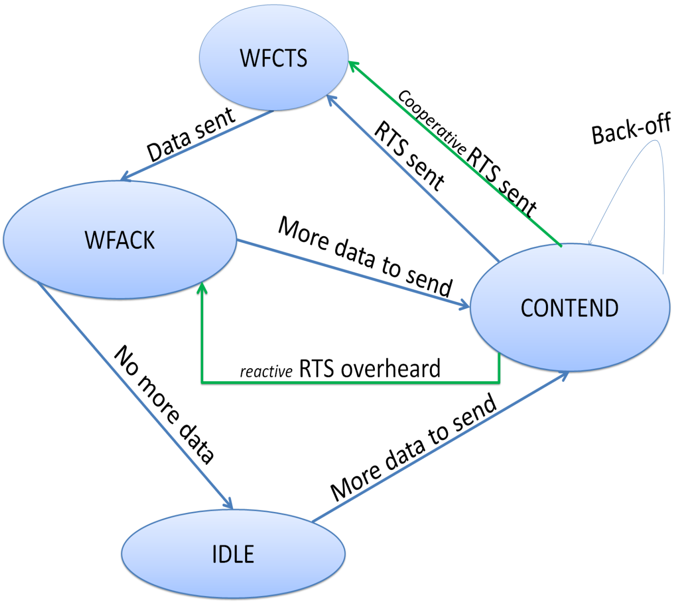


Figure 4.14: State diagram at source node.

should be a cooperative RTS frame as described in Section 4.3). After source receives cooperative CTS in the WFCTS state, it switches to the WFACK state after sending a data frame to the relay. While in this state the source overhears data forwarded by relay to destination, but it remains in the same state. In a situation when the source did not receive ACK, it tries to retransmit failed data by switching to CONTEND state. But if the source overhears that a potential relay is retransmitting the failed data frame on his behalf, the source switches back to WFACK state when the reactive RTS sent by another relay is overheard.

Cooperative RTS/CTS/ACK are not any new kind of frames; rather this terminology is just an indication of operation in the cooperation phase. Similarly, reactive RTS/CTS/ACK are just an indication of operation within reactive mode, during a failed data is forwarded by a relay.

The state diagram is further explained with the help of supporting flowcharts given below, which describe the operation of a source within the WFACK, CONTEND, and WFCTS states. The flowcharts show the normal 802.11 process in blue and the new RelaySpot operations in green.

Figure 4.15 described the operations within the WFACK state. If the source does not receive ACK, it will switch to CONTEND state to retransmit data. If the received ACK is a reactive ACK (more-frag=1, as a result of failed data forwarded by another relay), then the source discards the retransmission. In any case, the source checks the address 4 and R_{rd} within ACK frame: if these exist, the next data transfer will be via relay (cooperation phase), otherwise data will be sent by using the normal 802.11 operation. If there is a frame to send, the source switches to CONTEND state.

To send a frame a source needs to reserve the channel by sending an RTS, as in a normal 802.11 operation. In case of cooperation phase the source sets the duration field to accommodate source-relay and relay-destination data transfer according to data-rates R_{sr} and R_{rd} to reserve channel for cooperative transmission, as shown in Figure 4.16.

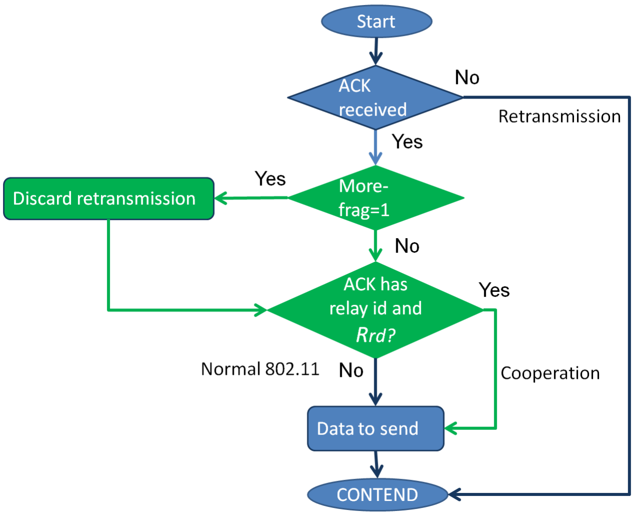


Figure 4.15: WFACK state flowchart at source.

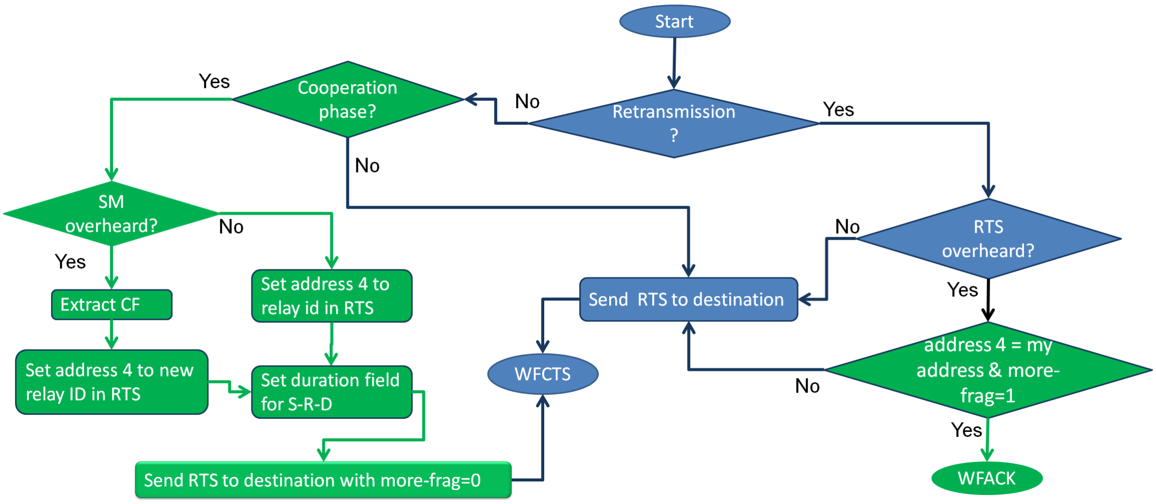


Figure 4.16: CONTEND state flowchart at source.

If in meanwhile the source overheard an SM, it sets the cooperative RTS according to new relay ID and R_{rd}.

If the source is trying to retransmit a frame, it will switch to the WFACK state if it overhears a reactive RTS with its ID in the address 4 field. Otherwise the source will continue normal 802.11 operations by sending an RTS.

Figure 4.17 describes the flowchart of the WFCTS state. In cooperation phase, it sends data frame to relay (instead of destination as occur in normal operation) when it receives a CTS from the destination. In case of direct normal transmission, the source checks if the received CTS include the R_{sd} and duration field is updated. If so, the source updates the ACK timeout and its duration field to reflect the duration field in the CTS frame, in order to be synchronized with the destination (to allow potential relays to transmit qualification messages towards the destination).This corresponds to relay selection phase at source node. The source sends the data frame and switches to

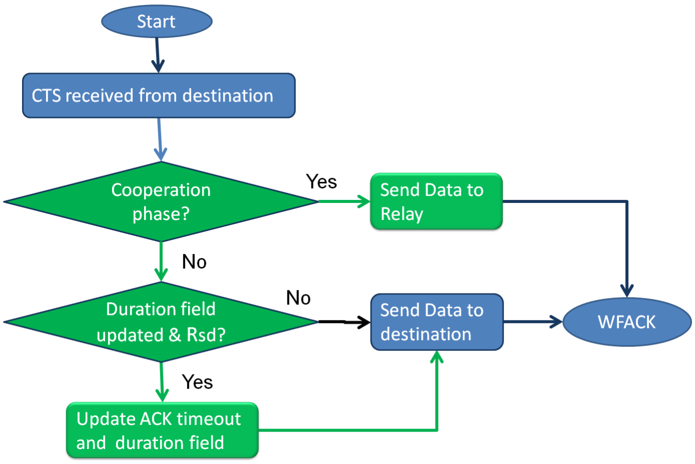


Figure 4.17: WFCTS state flowchart at source.

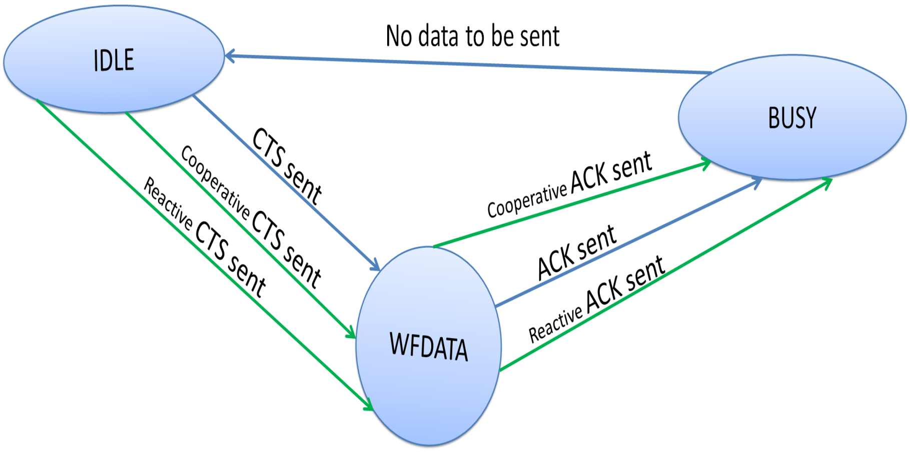


Figure 4.18: State diagram at destination node.

WFACK.

4.4.2 Destination Node Operation

Figure 4.18 shows the state diagram at destination node. As in the case of the source node, RelaySpot does not require any change to the normal 802.11 state diagram on the destination. In a normal 802.11 operation, if the destination receives an RTS within IDLE state, it sends CTS to source and switches to the Wait For DATA (WFDATA) state. After reception of data the destination send an ACK to the source and switches to BUSY state to check if it has its own data to send, after which the destination return to the IDLE state (because a node configured as destination has no data to send).

While in the IDLE state if the destination verifies the need for relaying, the destination indicates this situation within CTS (as described in Section 4.3) and switches to the WFDATA state. In the WFDATA state the destination sets the RW after the reception of the data frame. When RW expires, the destination sends an ACK (with relay indication if relay is selected) and switches to BUSY state, and then to IDLE.

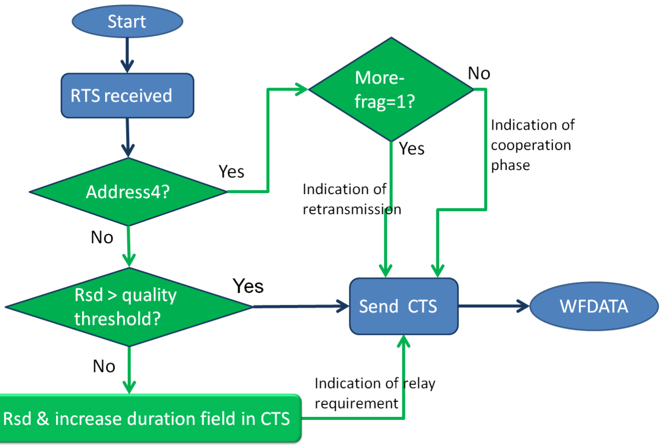


Figure 4.19: IDLE state flowchart at destination.

While in the IDLE state, if the received RTS indicate cooperation phase, the destination sends cooperative CTS, and wait for data to be arrived from relay. During WFDATA state, the destination also overhears data frame for source-relay link, but it stays in WFDATA. After arrival of data, it sends cooperative ACK to source.

While in the IDLE state, if the received RTS indicates reactive mode, the destination sends a reactive CTS, and waits for data to be arrived from the relay. After arrival of data, it sends reactive ACK to source.

Figure 4.19 shows the flowchart for the IDLE state. When an RTS is received, the destination ends up always sending CTS to the source and switching to the WFDATA state. In case of normal RTS (address 4 field is empty), the destination checks the data-rate of the source-destination link and verifies if relaying is required by checking if the data-rate of the direct link is below a configured threshold. If the performance of the direct link does not need to be improved, the destination sends CTS as in the normal 802.11 operation. However, if the direct link can be improved by relaying, the destination sends a CTS frame piggybacking the R_{sd} rate and increases the duration field in the frame by the RW size. This means that the scheduler is triggered, which allows the relays to send QM after overhearing data frame.

If the destination receive an RTS frame with an indication on the address 4 field that means that a relay is being used. In this case the destination check the more-frag bit to check if this is a cooperative or reactive RTS.

Figure 4.20 shows the destination operation at the WFDATA state. In a normal 802.11 operation, the destination gets a data frame directly from the source (To/FromDS =1:0), does not trigger the scheduler and send an ACK back to the source. However, if the data frame collected from the source requires relaying, the destination starts the RW timer (if scheduler was triggered for this flow). Before the expiration of the RW, the destination collects any qualification message that is addressed to it. After the expiration of the RW, the destination chooses the best relay based on the CF, and sends an ACK frame with the MAC ID of the selected relay and R_{rd}. This information is used by the source to perform channel reservation.

When the destination gets a data frame from a relay and is operating in the cooperation phase, it sends ACK to source with the relay ID and R_{rd}. However, if the quality

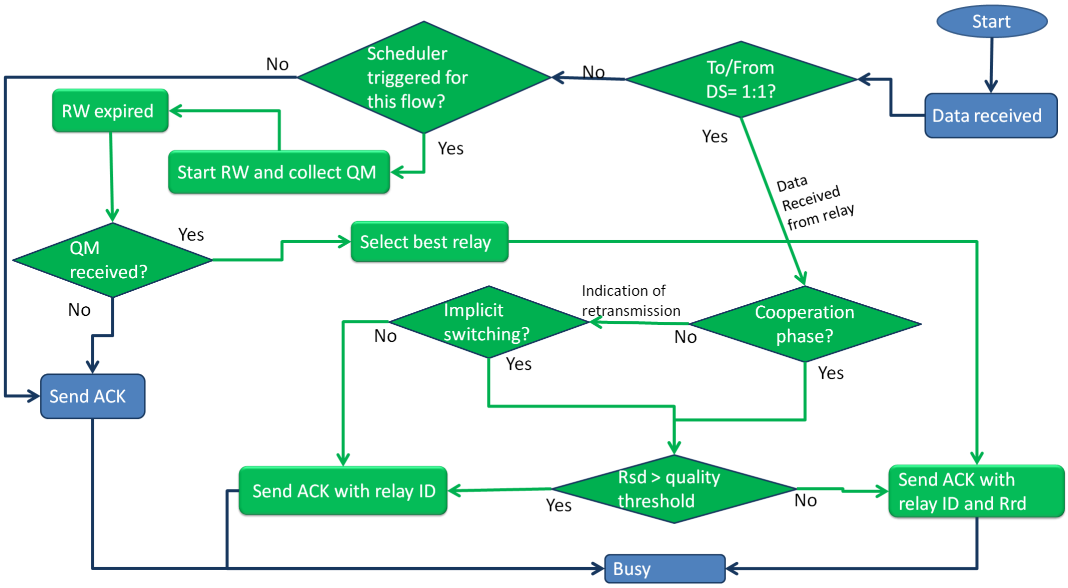


Figure 4.20: WFDATA state flowchart at destination.

of direct link has been improved, and there is no need of cooperation, the destination sends ACK without R_{rd} to implicitly inform the source that the cooperation phase should be stopped.

In case the received data frame is forwarded by the relay for a broken direct link (reactive phase), the destination sends an ACK to source, including the relay ID. (In this case the source will not enter to cooperation phase for the following frames rather direct transmission will take place.)

In case the received data frame is forwarded by relay for a broken relayed link (i.e., relay failure during cooperation phase), the destination first check if cooperation phase needs to be continue or not (as it check for normal cooperation phase). The destination sends ACK to source with relay ID, with or without R_{rd} accordingly.

4.4.3 Relay Node Operation

Figure 4.21 shows the state diagram at relay node. In relation to the normal 802.11 the operation of a relay needs the implementation of three new states. In a normal 802.11 operation, when a node overhears a transmission which is not intended for it, it switches to QUIET state; it will remain in QUIET state until the expiration of NAV. If the NAV expires it goes back to the IDLE (its original) state.

During cooperation phase (where the relay is already selected by the destination), the relay switches from IDLE state to the WFDATA state after overhearing cooperative RTS directed to it. After receiving data frame from source, it sends back the frame to destination (i.e., do not send frame to upper layers), and switches back to the IDLE (original) state.

There are three situations when the relay switches to (Relay CONTEND) RCONTEND state: i) when switching is required, ii) when failed link is detected and iii) when the relay selection is required.

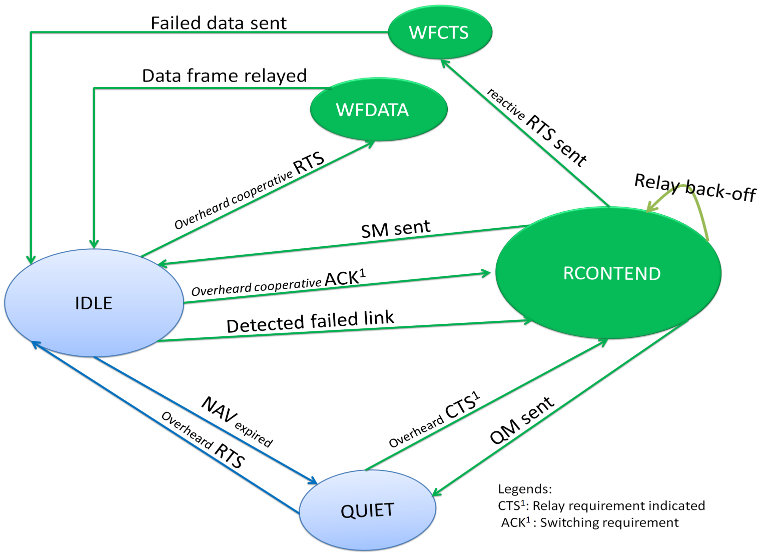


Figure 4.21: State diagram at relay node.

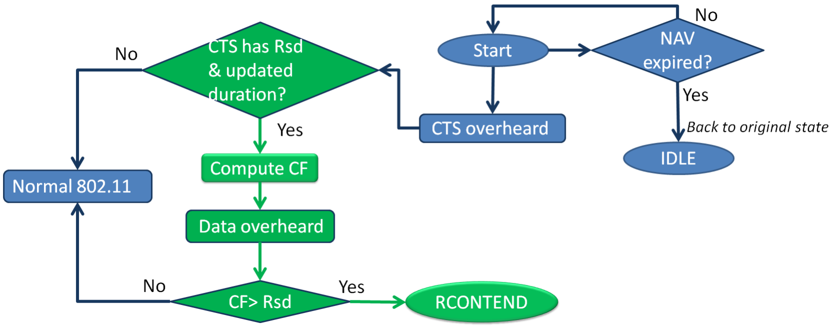


Figure 4.22: QUIET state flowchart at relay.

While in the RCONTEND state, the potential relay computes its contention window based on selection factor. When the contention window expires, the relay sends QM, SM or reactive RTS to the destination. In case of QM and SM, relay switch back to its original state. In short, the relay switches to RCONTEND state when it needs to contend for the medium.

In a case when switching is required, the relay switches to RCONTEND state, sends SM, and after that switched back to its original state (IDLE). In case a relay detects a failed transmission, it switches to RCONTEND state to send the data frame on behalf of source. Upon expiration of CW, it sends RTS to destination with more-frag bit set to 1 and address 4 set to source address (reactive RTS). Upon reception of CTS the data is forwarded to destination and the relay switches back to its original (IDLE) state. Such retransmission can also occur when the relay fails during cooperation phase.

With RelaySpot, any potential relay has a background process to periodically update its selection factor. When a potential relay overhears a transmission (of RTS), it switches to QUIET state; it will remain in QUIET state until the expiration of NAV. However, if the potential relay overhears a CTS frame with R_{sd} while in the QUIET state, it starts by checking if it is eligible for relaying. The verification is done by com-

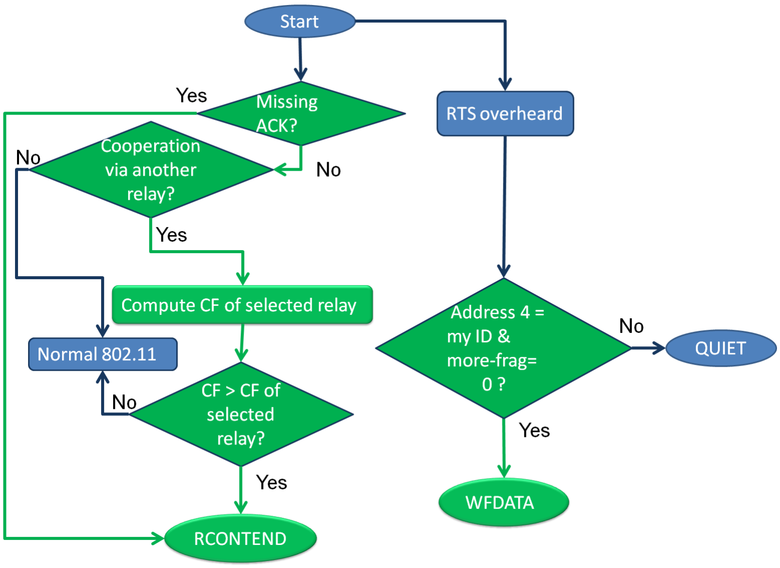


Figure 4.23: IDLE state flowchart at relay.

puting the CF based on the R_{sr} and R_{rd} values estimated by the strength of RTS and CTS respectively, and comparing it with the R_{sd} that is extracted from the CTS frame. If the relay is eligible, then after overhearing a data frame from a link that needs help, it switches to RCONTEND state, as shown in Figure 4.22.

Figure 4.23 explain the IDLE state at relay. If the relay detects a failed link - missing ACK (reactive mode), it tries to retransmit the failed data on behalf of source. Therefore, it will switch to RCONTEND state.

If an ACK is overheard for cooperative transmission via other relay, the relay computes the CF of the selected relay and if it has better CF than the selected relay, it switches to the RCONTEND state aiming to become the new relay.

While, the cooperation phase at relay starts by overhearing cooperative RTS from source with the relay MAC address included in address 4 field. In this case the relay switches to WFDATA state if the more-frag bit is set to zero meaning that the selected relay will forward the data received from source; otherwise the relay will switch to QUIET state as explained in state diagram.

4.5 Example Illustrations

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

4.5.1 Proactive: Relay Selection and Cooperative Transmission

Figure 4.24, illustrates the RelaySpot operation in a scenario where we have a poor link between source and destination. If direct link exists, it means RelaySpot can work in proactive mode. Within proactive mode, the slow direct link can be improved by fast

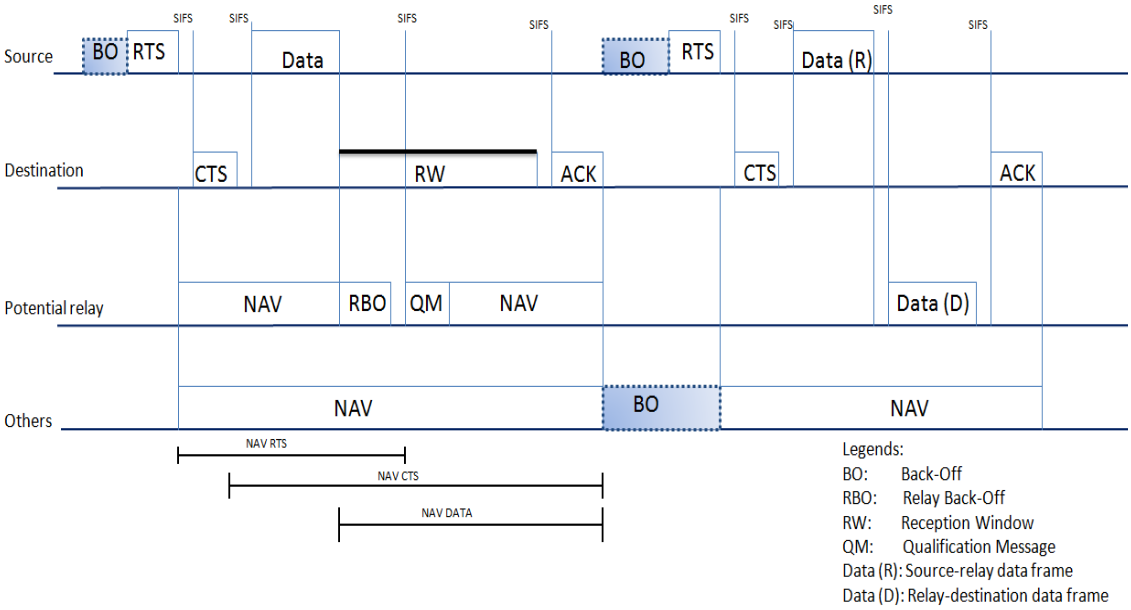


Figure 4.24: An illustration of RelaySpot's proactive mode.

relayed links. The decision to initiate cooperation is taken by destination, after realizing the poor link. In the 802.11b the poor links mean either 1 Mbps or 2 Mbps, which can be helped by relays. If the direct link is 5.5 Mbps, then it can not be helped, because the condition for cooperation is false (CF $> R_{sd}$). The destination implicitly indicates the need for cooperation within CTS frame. Destination also increases the duration within CTS frame by RW amount, to allow relays to send their QM. By overhearing CTS, all nodes updates their NAV accordingly.

In this example, first the relay selection takes place. After overhearing data frame from source, the relays contend according to Equation 4.5 and try to send QM to source. It is assumed that destination received at least one non colliding QM from a potential relay within RW, and the data frame from source also received correctly. Hence, destination sends ACK with potential relay ID, after RW expires.

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

4.5.2 Reactive: Relay Selection and Retransmission

Reactive mode is triggered when the direct link fails. In short, RelaySpot can also operate in a reactive mode, aiming to replace failed direct, if potential relays detect a failed transmission (by missing ACK) and try to send the failed data frame to the destination on behalf of the source, based on their CW. If a potential relay gets the channel, it starts sending data by sending an RTS frame with address 4 set with the source ID (i.e., MAC address) and More-frag set to 1. By overhearing this RTS frame

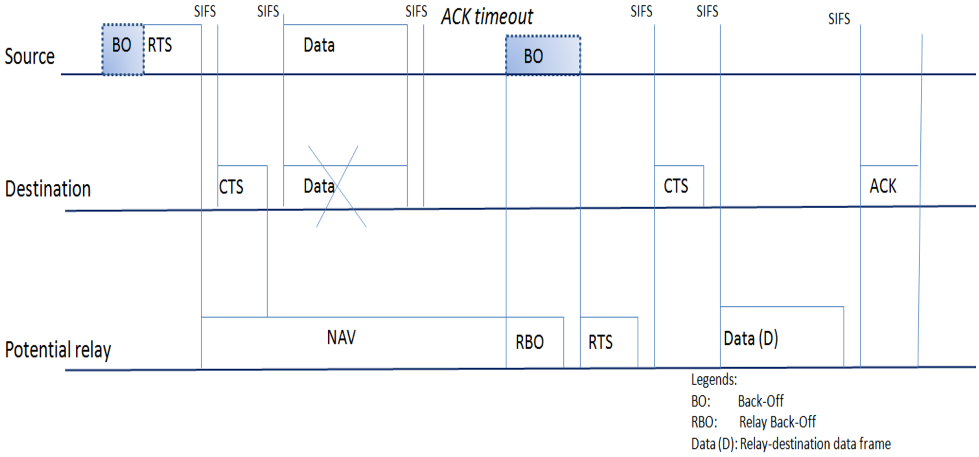


Figure 4.25: An illustration of RelaySpot's reactive mode.

the source stops the retransmission process. In this case no scheduler is used at the destination.

In case of reactive relaying, the role of destination is not vital as in case of proactive relaying. Reactive relaying is initiated by relays itself, followed by opportunistic relay selection. The example provided in Figure 4.25, shows that the destination did not receive the data frame from source. As a result there is no ACK sent to source. I assume that there is a potential relay which got successful to access the medium before the source. In this case the relay will forward the frame on behalf of source, thus avoiding retransmissions.

Another example of reactive mode is to react to failed relayed transmission, i.e., implicit switching, which will be discussed next.

4.5.3 Sequence Chart

Figure 4.26 illustrates the message exchange used by RelaySpot in a scenario with three potential relays (R1, R2 and R3), and one source-destination pair. In this scenario I assume a low data-rate direct link.

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

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

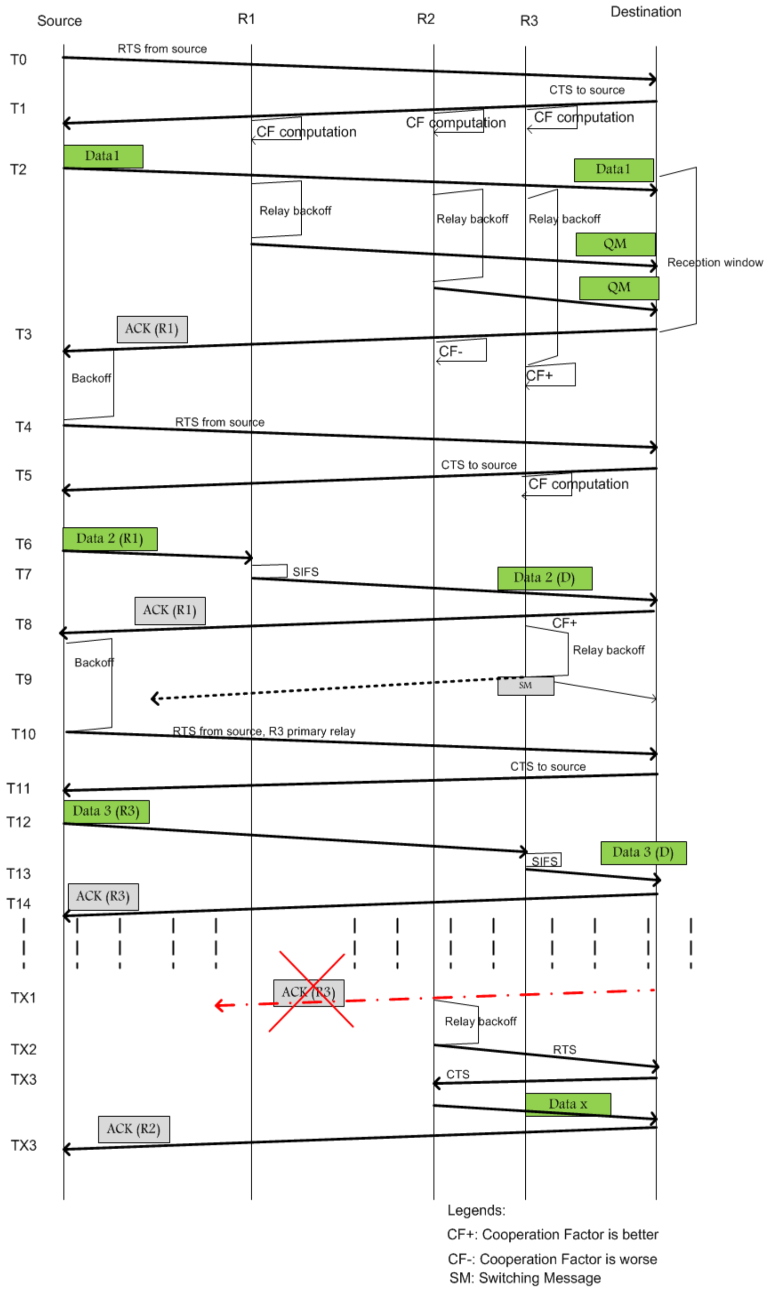
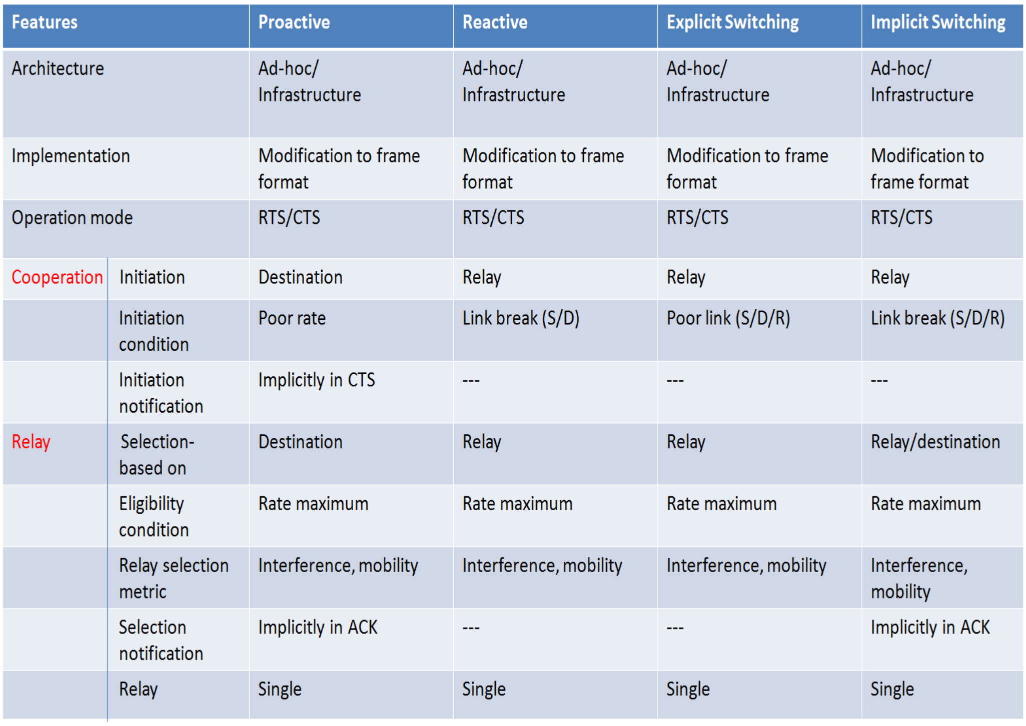


Figure 4.26: RelaySpot sequence chart.

In this example I assume that, due to mobility, R3 becomes a better relay than R1 in order to illustrate the proactive behavior (in term of explicit switching) of RelaySpot. In this case R3 sets its contention window according to Equation 4.5 after overhearing the ACK frame, and sends an SM to the destination carrying its CF. Upon overhearing



Features		Proactive	Reactive	Explicit Switching	Implicit Switching
Architecture		Ad-hoc/ Infrastructure	Ad-hoc/ Infrastructure	Ad-hoc/ Infrastructure	Ad-hoc/ Infrastructure
Implementation		Modification to frame format	Modification to frame format	Modification to frame format	Modification to frame format
Operation mode		RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS
Cooperation	Initiation	Destination	Relay	Relay	Relay
	Initiation condition	Poor rate	Link break (S/D)	Poor link (S/D/R)	Link break (S/D/R)
	Initiation notification	Implicitly in CTS	---	---	---
Relay	Selection-based on	Destination	Relay	Relay	Relay/destination
	Eligibility condition	Rate maximum	Rate maximum	Rate maximum	Rate maximum
	Relay selection metric	Interference, mobility	Interference, mobility	Interference, mobility	Interference, mobility
	Selection notification	Implicitly in ACK	---	---	Implicitly in ACK
	Relay	Single	Single	Single	Single

Table 4.3: RelaySpot features.

this frame, the source start using R3 as a relay for the next data frames.

Now I assume that R3 fails to relay data at some instant in time to illustrate the reactive behavior (in term of implicit switching) of RelaySpot. In this case if potential relays detect missing ACKs, they try to retransmit overheard data frames on behalf of R3. In this example, R2 tries to set its CW according to Equation 4.5. If R2 is successful to forward the failed data frame, the destination sends an ACK frame to the source with R2 ID and R2-destination data-rate (R_{rd}), while the source learns about R_{sr} from overhearing transmissions from R2. The source will then switch to R2 for next data frames. This way implicit relay switching will take place.

4.6 Conclusions and Summary

In this chapter, I presented RelaySpot, the cooperative MAC protocol that is able to increase the performance of dynamic wireless networks, by being aware of the level of mobility, interference and transmission success rate of potential relays. RelaySpot comprises four building blocks: opportunistic relay selection, cooperative relay scheduling, cooperative relay switching, and chain relaying. Table 4.3 lists some of the features of proposed protocol.

4.6.1 Advantages

In clear contrast to the scientific prior art, the solution proposed in this chapter is the combination of cooperative and opportunistic relaying, where the relays are selected opportunistically and then scheduled cooperatively, and when the selected relay fails there is option for relay switching.

While compared with the prior art, the solution proposed in this thesis aims to:

- Avoid the maintenance of CSI tables, avoiding periodic updates and consequent broadcasts.
- Reduce dependency over CSI.
- Avoid overhead of additional control messages.
- Target a fair balance between relay selection and additional resource blockage.
- Allow multiple relays to be utilized in parallel or in sequence based on quality of received frames.
- Trigger chain relaying in case of outage at relay (future work).
- Trigger relay switching in case of deterioration of the conditions of relay's channel.
- Support reaction to relay failures (implicit switching).
- Support multiple diversity levels based on channel conditions.
- Support both proactive and reactive types of relaying.

Contrary to broadcast based solutions, RelaySpot presents a lower probability of collision, due to the fact that CTS is immediately sent by destination after reception of RTS. This way the nodes exposed to destination are informed in shorter time. ORP is similar to RelaySpot in the sense that both do not rely on CSI for relay selection. However, with ORP the source does not know the availability of relays, and therefore, it does not know the rate of the source-relay and relay-destination channels, leading to poor relay selection. With RelaySpot the destination is aware of the relay diversity as well as the rates of the used links.

4.6.2 Future Deployment

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

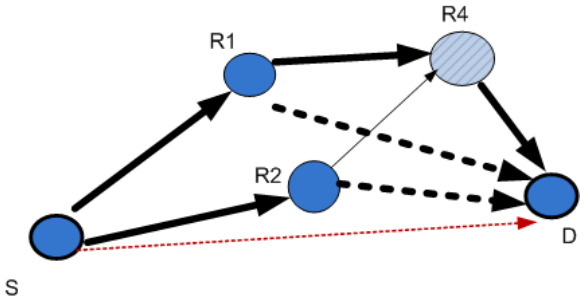


Figure 4.27: Chain relaying.

The proposed opportunistic relay selection and cooperative relay scheduling mechanisms aim to increase the throughput and reliability, as well as to reduce transmission delay by increasing the diversity adjusting the relaying order. Nevertheless, the presence of mobile nodes, as well as unstable wireless conditions, may require higher levels of diversity achieved based on nodes that are closed to the destination (higher probability of successful transmissions). Hence, RelaySpot includes the possibility of using recursive relay selection and retransmissions in case of poor performance. This functionality is called chain relaying (c.f. Figure 4.27). Nodes that are able to successfully decode MAC data frames sent by a relay to a destination may trigger the RelaySpot operation on that relay-destination channel in case the channel conditions are so bad that the node will overhear two consecutive NACKs (or the absence of ACK's) during a predefined time window. This means that relays closer to the destination can help the transmission when the destination does not get any (acceptable) data frames from any relay in contact with the source.

With chain relaying, the relaying process is repeated for the relay-destination channel (R1-D and R2-D in Figure 4.27), by having another relay (R4) or set of relays helping the transmission from each of the previously selected relays to the destination. R4 may not receive correct frames from source, but it is closely bounded to R1 as well as to the destination. R4 can trigger chain relaying when both primary and secondary relays fail. Chain relaying can be extended to multi-hop by R4 forwarding frame to next hop.

Chapter 5

Experimental Setup and Implementation

RelaySpot was implemented using OMNeT++ and MiXiM framework. This chapter describes the basic setup of implementations for analysis.

5.1 Experimental Setup

Evaluation is based on simulations run on the MiXiM framework of the OMNeT++ 4.1 simulator using 2D linear mobility model. Table 5.1 lists the simulation parameters. Each simulation has a duration of 300 seconds and is run ten different times in order to provide results with a 95% confidence interval.

Simulations consider a scenario based on a wireless local network with one static AP and up to 25 mobile nodes. Each mobile node is a source of data towards the AP, and can be a potential relay of the transmissions started by other mobile nodes. Each simulation starts by randomly placing the group of mobile nodes (1 to 25) in a square of 200x200 m^2, having the AP at its center. Each node is equipped with only one half-duplex transceiver and has a unique MAC address. All the nodes in the network transmit control frames and data frames with the same power, and the network load is uniformly distributed among all the nodes.

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

5.1.1 Network Model and Assumptions

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

I make the following assumptions during evaluation:

- Single-channel: to keep RelaySpot simple, I consider that all nodes are using the same wireless channel. Interference is not handle by switching wireless chan-

Table 5.1: Simulation Parameters.

Parameter	Values
Path Loss Coefficient	4
Carrier Frequency	2.412e9 Hz
Max Transmission Power	100 mW
Signal Attenuation Threshold	-120 dBm
MAC Header Length	272 bits
SIFS	10 us
DIFS	50 us
PLCP header	96 bits
MAC Queue Length	14 frames
Basic Bit-rate	1 Mbps
Maximum Bit-rate	11 Mbps
Rts-Cts Threshold	400 bytes
Thermal Noise	-110 dBm
MAC Neighborhood Max Age	100 s
Speed	1 m/s
Reception Window Size	1504 us
Payload Size	1024 Bytes

nels, which would bring more delay and performance uncertainty, but by relay switching, selecting relays with a low interference factor.

- One-hop relaying: the current usage scenario is of a wireless local network with one AP and several mobile nodes, which can act as source of data, as a relay, or both simultaneously. The usage of multiple chained relays, as a simpler alternative to layer-3 routing will be investigated in the future, as a solution to expand wireless coverage and increase the utility of a relay.

- Simultaneous access to a channel: Multiple sessions are allowed to access the channel at any given time, including the ones that are being relayed, which increases the wireless interference. To mitigate the effect of interference, dynamic switching among qualified relays is implemented aiming to exploit the utility of each relay, ensuring that RelaySpot is able to increase the utility of the overall network, and not only of specific links.

- Multiple relay selection: Each node can be self-elected as relay for more than one session at the same time. Moreover, one communication session can be helped by one or more relays in each moment in time, leading to a system with wireless diversity of one or higher. If the destination selects more than one relay for a single session (diversity > 1) and gets corrupted frames from all relays, in a worse case scenario, it can perform frame combination in order to create a good frame. In this thesis I consider a diversity of one during the experimental evaluation.

5.2 Implementation

OMNeT++ is a discrete event simulation environment, mainly focused in communication networks. OMNeT++ is a flexible and generic simulation framework [75]. One can simulate anything that can be mapped to active components that communicate by passing messages. OMNeT++ represents a framework approach, instead of containing explicit and hardwired support for computer networks or other areas, it provides an infrastructure for writing such simulations.

OMNeT++ has a good variety of models for simulating computer systems, Ethernet, or 802.11 systems etc., lags behind the ns-2 simulator on availability of communication protocol models. ns-2 has a rich set of communication protocol models too but mainly focused on TCP/IP.

OMNET module consists of three parts: NED language, Message definitions and Simple modules [74]. NED language defined the topology and its files are with *.ned* extension. Message definitions are with *.msg* extensions. Simple modules are implemented in C language as *.cc* files. Configuration and input data for the simulation are in a configuration file usually called omnetpp.ini.

OMNeT++ based network simulators and simulation frameworks are: Mobility framework for mobile and wireless simulations, INET framework for wired and wireless TCP/IP based simulations, Castalia for wireless sensor networks, MiXiM for mobile and wireless simulations. MiXiM (mixed simulator) is a simulation framework for wireless and mobile networks using the OMNeT++ simulation engine. MiXiM is a merger of several OMNeT++ frameworks written to support mobile and wireless simulations such as Mobility framework, Mac simulator [76] etc. Therefore, OMNet++ using MiXiM provides a perfect platform for analysis relay based network in 802.11.

5.2.1 802.11 MAC Implementation in MiXiM

In this dissertation, I looked into the IEEE 802.11 DCF which is the most prevalent MAC protocol. The IEEE 802.11 protocol is based on CSMA/CA. DCF mechanism has an optional RTS/CTS four-way handshaking mechanism used to combat the effects of collisions and to facilitate transmission of large data frames.

In the MiXiM framework, PHY and MAC layers are grouped into a Network Interface Card (NIC) module. The 802.11 MAC is implemented in term of messages [43]. Whenever an event occurs, a message is passed to concern module to be handled. The events are defined as timers. When the timeout occurs it means that an event has occurred (i.e., message has arrived) and then it is passed to appropriate method to handle.

MiXiM uses two type of messages, self messages and messages that come from other layers [83]. Messages which come from other layers are handled by two methods, which are MessageForMe() and MessageNotForMe(), while messages which are from inside module are handled by SelfMessage() method. In addition, within the code, all messages and timers are classes and MiXiM uses pointers to call any handler (method). Figure 5.1 shows the sequence of handler in reaction to any event occurs.

MAC state machine is very important for any implementations, since most of the modifications and protocol implementation must take the states into account. It has a state machine with seven states. Details about all message passing, state diagram and complete implementation can be found in [33].

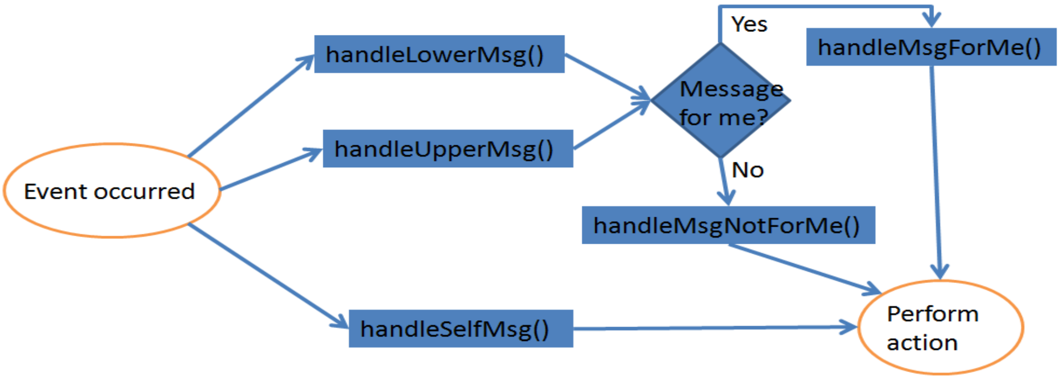


Figure 5.1: Message handling in MiXiM at MAC layer.

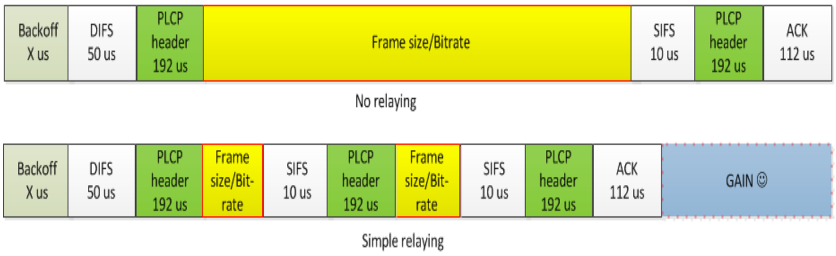


Figure 5.2: Simple relaying gain.

5.2.2 Relay Implementation

Relay protocol is a MAC layer protocol. Therefore, most of the modifications were performed in the Mac80211.ned. Mac80211.cc and Mac80211.h files of the 802.11b module.

In order to implement relaying in 802.11, we need to change the MAC state machine as shown already in Chapter 4.

Relaying protocols will benefit from RTS/CTS messages. Hence, let's consider a basic relaying scenario in which the relay has already been selected and the source has to perform a cooperative communication. A source node sends an RTS message with a duration request of two fast transmission times + 1 extra SIFS + CTS + ACK time. And destination approves this with a CTS message with the same duration information so that other nodes in the network (basic service set) update their NAV (they learn how long the channel is occupied). Then source performs the transmission of data frame with the desired higher data-rate (11 or 5.5 Mbps). Upon reception of data frame, the relay first cancels its NAV timer [29], change its radio state to Transmit (Tx), sense the medium if IDLE for SIFS amount of time, and forwards the data frame to destination. After transmission, the relay node goes back to its original state again with original back-off and NAV values. Transmission via relay does not affect relay's own transmission, because this is performed when the channel is already reserved by source and all other nodes including relay have set their NAV.

Relaying involves transmission of two data frames separated in time and space; therefore, it introduces overhead, which increases due to additional control messages. However, significant gain can be achieved by a careful selection of reservation duration

Figure 5.3: Data-rate vs distance in 802.11b.

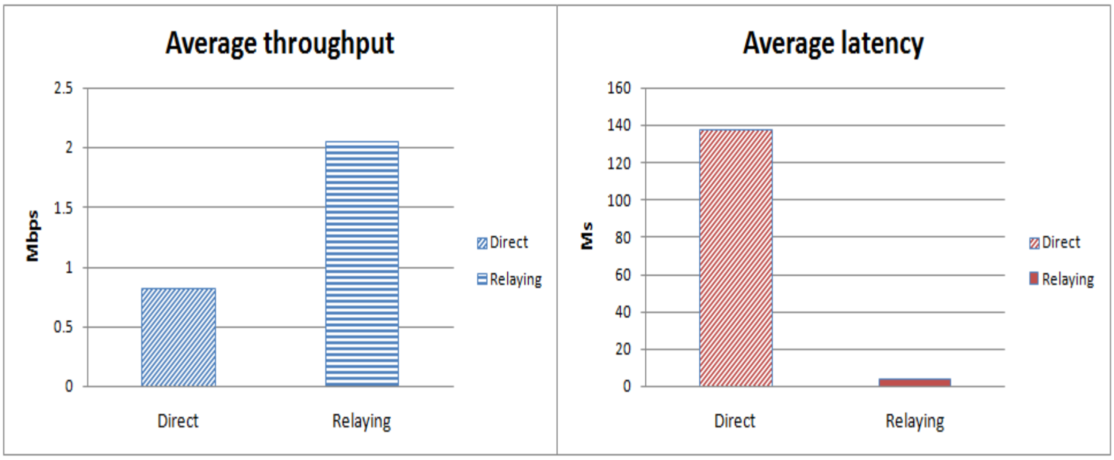


Figure 5.4: Basic relaying test.

and back-off timings. Figure 5.2 shows the gain of cooperative relaying in 802.11 (when there is no extra control message). As seen in Figure 5.2 a regular data transmission with acknowledgment takes longer to send data when compared to the data transmission based on a relay protocol. With a relay protocol the relatively slow nodes would reserve the channel for a duration of $frame\_size/(fast\_data\_rate{=}11Mbps)$ instead of $frame\_size/(slow\_data\_rate{=}1Mbps)$ and the other nodes will benefit from this with higher probability of accessing the channel.

The aim of basic relay implementation is to perform some background tests, to verify if the simulator complies with the standard and to test the basic operation of the proposed relaying protocol. Figure 5.3 shows that MAC 802.11b is using four data-rates which are decreasing with the increase in distance, which is according to standard. Figure 5.4 shows that a significant gain can be achieved by relaying.

Chapter 6

RelaySpot Performance Analysis

This chapter explains the analysis of RelaySpot mainly in term of three basic building blocks. First I performed some initial analysis to work as a performance benchmark, and then I analyzed the relay selection metrics. In order to perform these basic tests I create a scenario where source and destination is placed at a distance of more than 150 meters with a direct link of 1Mb.

I run simulations with different source-destination pairs, relayed by relays in different location, and with different combination of data-rates in the source-relay and relay-destination links. It is observed from Figure 6.1 that relaying is not always useful. In order to achieve performance improvement the direct link must be replaced by relays with both source-relay and relay-destination links that present a data-rate higher than the direct link (and one of the links must have a data-rate at least twice higher than the direct link). For instance, 1 Mbps direct links can be replaced by relays with 11 Mbps and 5.5 Mbps, or even with 5.5 Mbps and 2 Mbps, but not with 2 Mbps and 2 Mbps.

I also analyze the impact of frame size over gain in throughput. Figure 6.2 shows that RelaySpot has a gain in throughput for a frame of size of 1 Kbits or more in relation to the direct transmission. The gain is negative when the size of frames are less than 1 Kbits, however such frame size is rarely used. The frame size strongly influences the throughput as for smaller frame size the throughput drops due to the domination of the transmission overhead.

The improvement in throughput and latency, illustrated in Figure 5.4, refers to a scenario that is free of interference. However, the introduction of interference (different direct and indirect traffic) is expected to lead to a degradation of performance.

In order to have a first glimpse about the impact of interference over relayed data, I ran a set of simulations with a pair of nodes (other than relay) randomly generating between 1 and 10 Mbps of traffic (inducing indirect interference). Figure 6.3 shows that the throughput of relayed data dropped to a maximum of 1.3 Mbps instead of 2.1 Mbps as shown in Figure 5.4. In this situation the interfering node is in competition with the relay node. Therefore, the throughput gain depends upon transmission opportunities. Figure 6.3 shows that due to the action of relay the throughput at interfering node also drops. Although this gain in throughput or latency depends upon the load at network, it is proved that relay can cause additional resource blockage.

A node, when operating as a relay also has an impact on the system: on the relay node itself and on neighbor transmissions. Hence I also analyzed the impact that

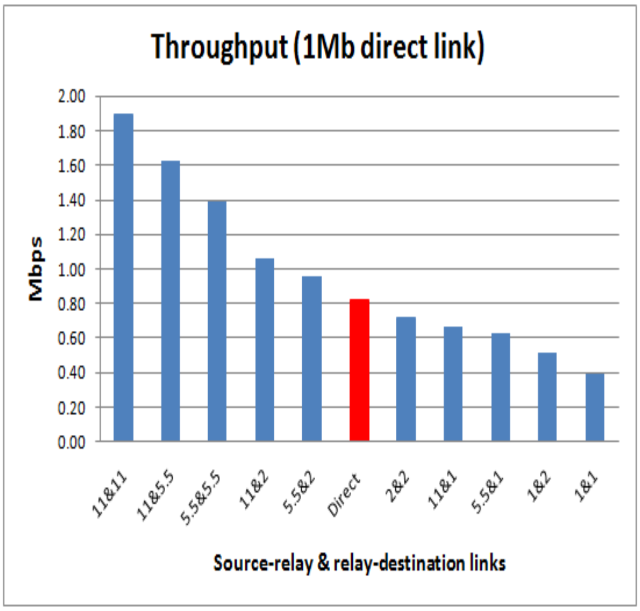


Figure 6.1: Analysis with different data-rates.

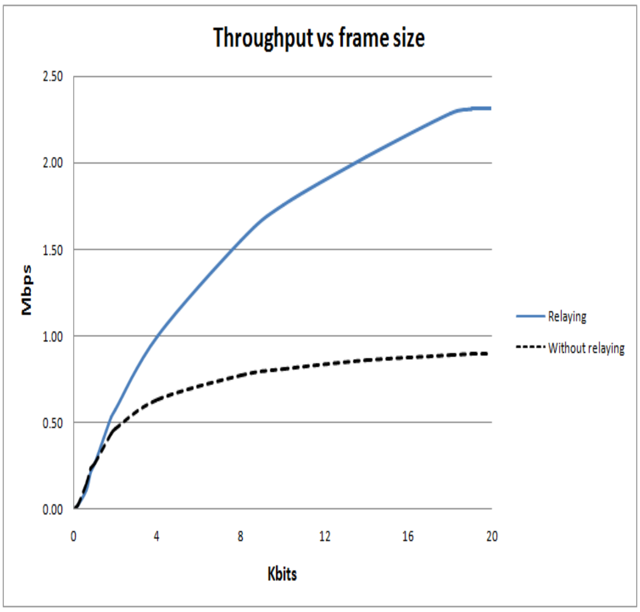


Figure 6.2: Impact of frame size on throughput (with and without relaying).

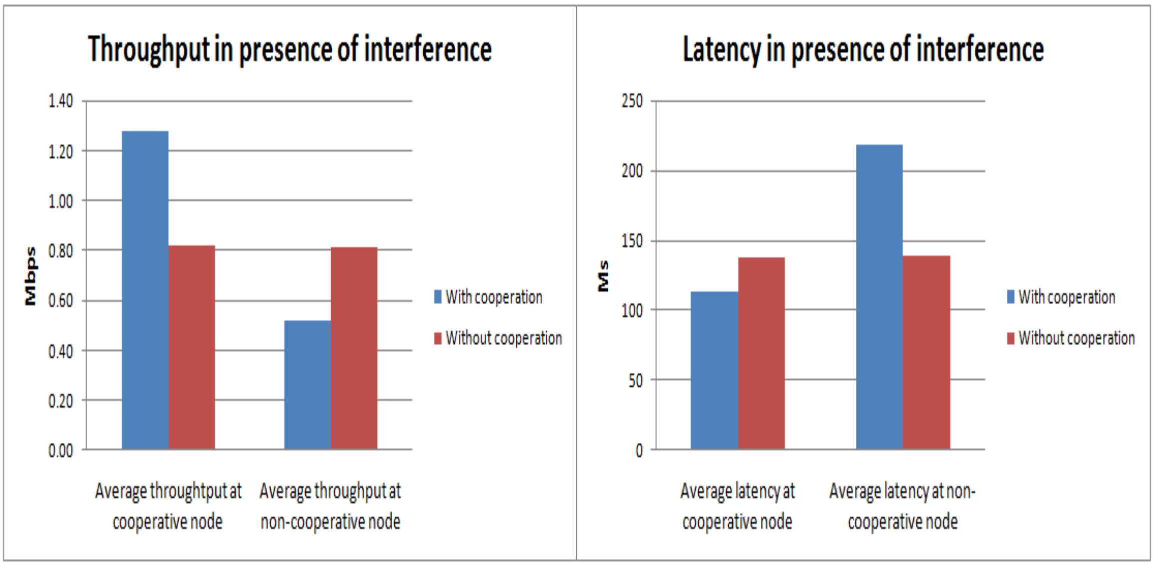


Figure 6.3: Effect of indirect interference.

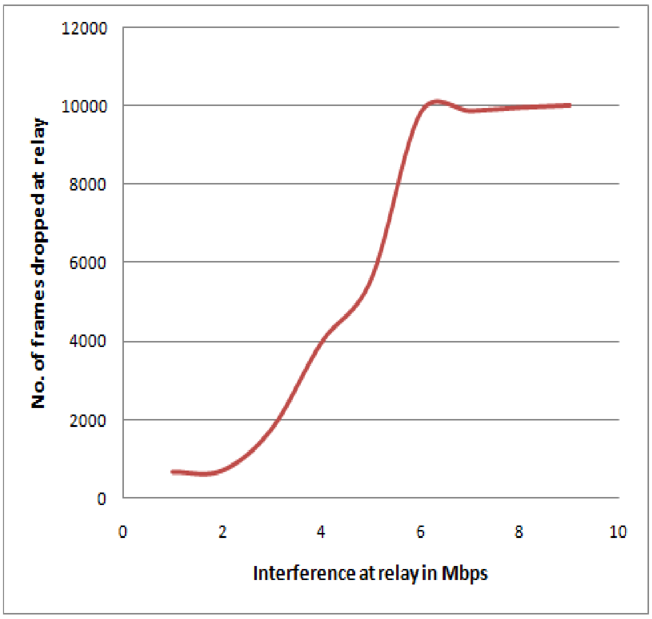


Figure 6.4: Number of frames dropped at relay node.

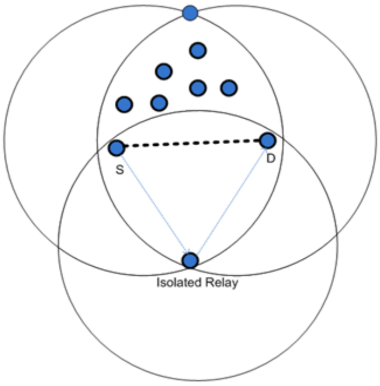


Figure 6.5: Isolated relay node.

relaying data has on the data generated and consumed by the node acting as relay. Figure 6.4 shows that due to interference the number of frames dropped at the relay node increases significantly. Hence, by avoiding interference we can improve not only the performance of the flow being relayed, but also of the overall network performance. This motivates a further analysis about the impact that direct and indirect interference have on relaying based on RelaySpot, which uses interference-aware relay selection metrics.

6.1 Relay Selection Analysis

Apart from rate and delay-based relay selection, there are other parameters which can be used while selecting relays such as interference, degree, distance and history. Most of the relay selection metrics are based on rate measurements, such relaying can give advantage to one source-destination pair but may not be useful for some other source-destination pairs, as discussed before. Therefore, in this section I analyze some of the relay selection parameters, using average throughput and delay of relayed link as metrics.

6.1.1 Degree-based and Distance-based Selection

N. Marchenko et al. [53] propose 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.

Node degree is the measure of interference too. Although selection based on degree can decrease the possibility of collisions due to relay action, we may end up with an isolated relay, if a relay is selected only base on node degree, as shown in Figure 6.5.

Distance is an important parameter for a node to be a relay. Several researchers proposed to use distance. Hence distance-based relay selection should provide optimal

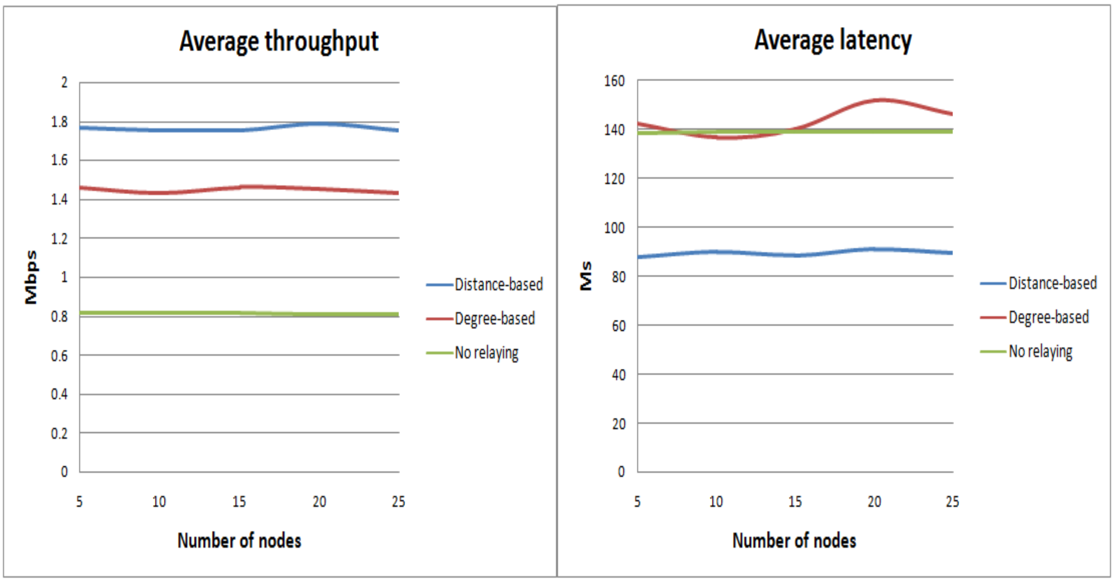


Figure 6.6: Degree and distance-based relay selection.

solution for relaying problem. In fact, how to measure the distance is important. In real, we can not measure the distance unless one node explicitly sends its position information. In what concerns the degree of effectiveness, distance is important because a node lies closer to both source and destination can help better than those which are located far. But there is a trade-off between overhead and effectiveness. If there is fixed network where all nodes are stationary, then measuring distance is easy. Distance can also be measure via GPS or received power. But in dynamic networks it may not be very accurate.

Even distance as the only parameter for selection may not be very useful, since we may select an overloaded relay. In case of work presented in [53], if a node is selected as relay based on distance to destination, then any node closer to destination will try to help, which is the wastage of radio resources. Another drawback using distance is that, radio range is normally spherical, unless we use directional antennas. Thus every node has a specific radius where it have fast bit-rate. Thus distance parameter does not tell us if the node lies in the cooperative area or not.

Since some prior relay selection proposals are based on node degree and relay distance towards the destination, I also analyze the performance of these approaches in an interference-free scenario with an increasing number of potential relays (1 to 25). Results show that distance-based approaches have better performance than degree-based ones (e.g., in average with 20% and 63% improvements in throughput and latency, respectively) as shown in Figure 6.6, since in an interference-free scenario the best performance can be achieved by selecting as relay a node closer to the destination, even if such node has not the smallest neighbor set. Hence, I use the distance-based approach as a benchmark in scenarios with interference for analyzing RelaySpot's relay selection parameters.

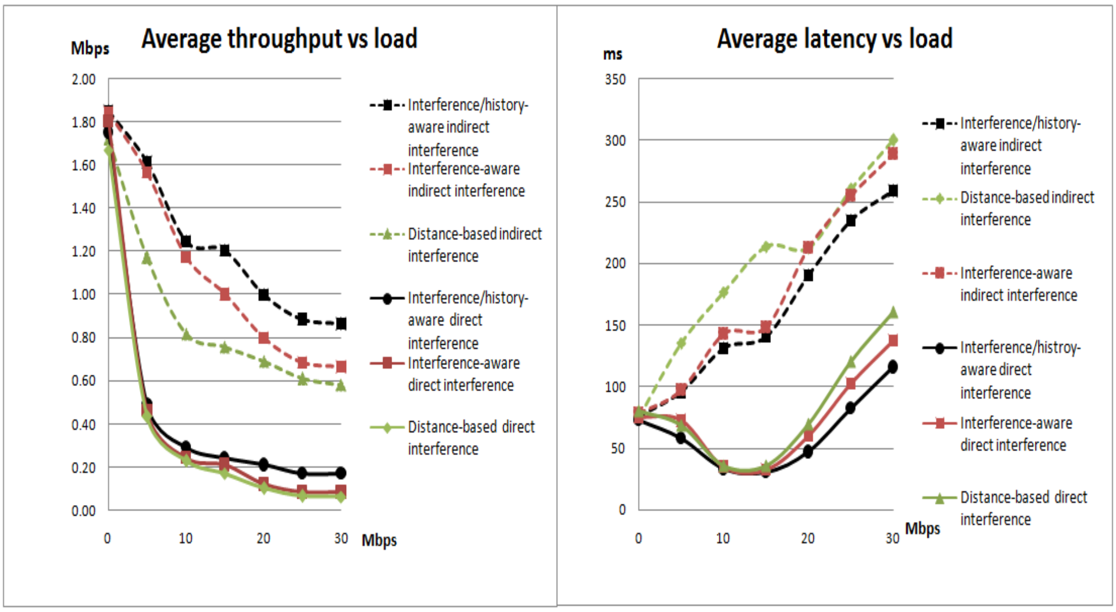


Figure 6.7: Throughput & latency analysis with direct and indirect interference.

6.1.2 Direct and Indirect Interference

As discussed, considering only node degree is not a useful parameter, therefore I use node degree in relation to traffic, as relay selection parameter. I divide traffic as direct and indirect. Direct is the traffic at relay while indirect traffic is background traffic. First I analyze the impact of adding direct and indirect interference. Direct interference is added by randomly installing a source of traffic, with an average data-rate of 5 Mbps, in a set of 25 potential relays. Indirect interference is added by randomly placing transmission pairs (5 Mbps in average) among the available 25 nodes.

Figure 6.7 shows that the RelaySpot's relay selection approach has better performance than distance-based approaches, with different traffic load (direct and indirect interference). As shown in Figure 6.7, direct interference has a significant impact on throughput, mostly due to the low probability of finding dedicated relays [36]. Nevertheless, results show that interference/history-aware relay selection achieves the highest throughput (e.g., 100% gain in relation to distance-based approaches with a load of 30 Mbps), due to its capability to select, among the set of overloaded nodes, the ones with better transmission success rate towards the destination.

Throughput performance improves for all approaches in the presence of indirect interference, due to the fact that all nodes are potential dedicated relays. Nevertheless, throughput still decreases with an increase of indirect interference. However, Figure 6.7 clearly shows the performance improvement that RelaySpot (relay selection based on interference and history) can reach in relation to distance-based approaches: with an interference load of 30 Mbps, relay selection based on RelaySpot presents a throughput gain of 14.3% and 48.8%, without and with history factor, respectively. Moreover, RelaySpot with history factor has a throughput always higher that the 0.82 Mbps of the interference-free direct transmission, even with an interference load of 30 Mbps.

In terms of latency, Figure 6.7 shows that indirect interference has the highest impact over the system. The reason for this overall effect is the high load of concurrent neighbor flows, which leads to a lower number of retransmission opportunities. Nevertheless, in such situation RelaySpot's relay selection is able to reach lower latency due to its capacity of selecting relays with a low load of concurrent neighbor flows, leading to a higher number of transmission opportunities: with a load of 30 Mbps RelaySpot (relay selection) with history factor has a gain of 11.5% and 16% in relation to RelaySpot without history and distance-based approaches, respectively. The reason for this better performance is the fact that RelaySpot (relay selection) with history factor is aware of the ratio of successful transmissions towards the destination, allowing the selection of nodes with higher probability to reach the destination, when the majority of nodes are affected by high interference. The RelaySpot (interference-aware relay selection) gain in latency decreases with a load of indirect interference of 20 Mbps, mainly due to the lower probability of having a significant load of concurrent flows closer to the destination, which benefits distance-based approaches.

The overall latency decreases without concurrent traffic (only direct interference), since the lower load of concurrent neighbor flows leads to higher number of retransmission opportunities for nodes that have enough CPU resources (low direct interference) to receive a perfect copy of frames sent by the source. In such scenarios, RelaySpot's relay selection proves to be more fit than distance-based approaches, due to its capability to select nodes with higher availability for retransmission (lower number of local generated traffic), and nodes with a higher number of successful transmission, among the ones with significant degree. RelaySpot biggest gain in latency is visible with a load of 30 Mbps: with history factor it has a gain of 19% and 39% in relation to RelaySpot without history and distance-based approaches respectively. This gain is due to the fact that distance-based approaches keep selecting overloaded nodes near the destination. Moreover, with history factor, RelaySpot is able to have a latency level always lower that the 137.8 ms of the interference-free direct transmission, even with a direct interference load of 30 Mbps.

6.1.3 Relay Selection in Combined Interference

Results based on direct and indirect interference show the performance gain of RelaySpot's relay selection. By comparing such results with the performance in the presence of combined interference (direct+indirect), as shown in Figure 6.8, I got to the conclusion that the performance gain of RelaySpot can be improved if the system would be aware of the type of traffic. Such conclusion is supported by findings that the impact of direct and indirect interference is different in relation to throughput and latency: indirect interference has higher impact over latency, due to a lower number of relaying/transmission opportunities, while direct interference leads to lower throughput, due to the high number of retransmissions needed for a potential relay to get an error-free frame sent by the source. A more detailed analysis of these findings will be done as future work. For now, I aim to study the performance of relay selection based on RelaySpot in a scenario where nodes may be subjected to simultaneous direct and indirect interference.

Figure 6.8 shows that in the presence of combined (direct + indirect) interference, RelaySpot's relay selection has better performance than distance-based relaying. It has a throughput gain of 50% and 150% in relation to distance-based approaches with a load of 30 Mbps, without and with history factor respectively. In terms of latency, RelaySpot with history factor has always a lower latency than RelaySpot without the

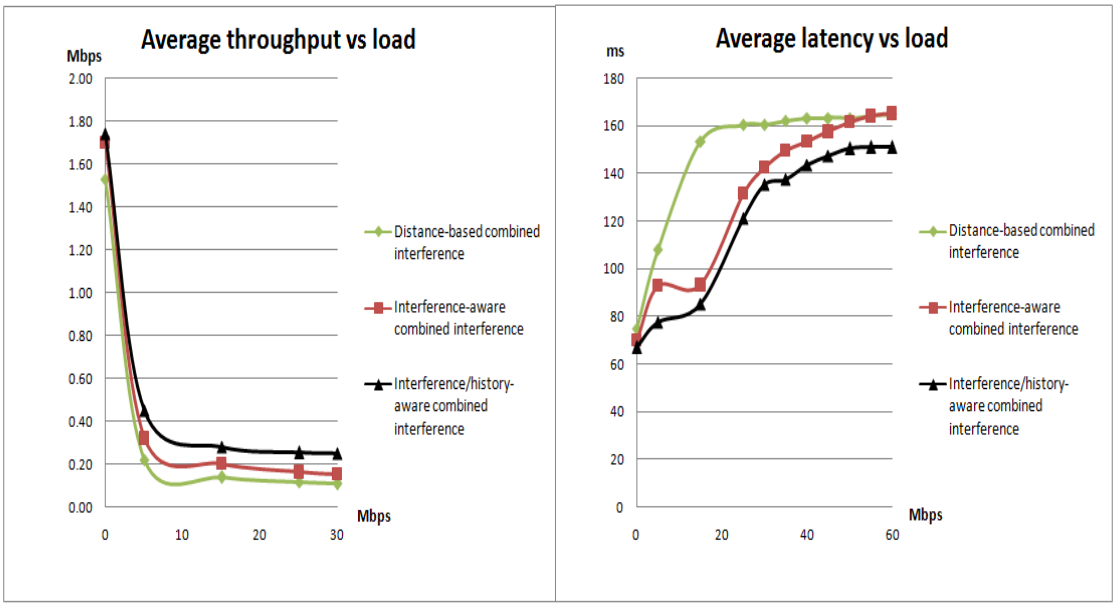


Figure 6.8: Throughput & latency with combined (direct+indirect) interference.

history factor and distance-based relaying approaches (10% gain with 60 Mbps load). Even without the history factor, the performance gain of RelaySpot is significant: equal latency to distance-based relaying with a load of 60 Mbps, and 13% lower with a load of 30 Mbps.

6.1.4 Conclusions

Cooperative relaying has potential to improve the performance of low-cost single antenna systems. However, most of the cooperation procedures are agnostic of interference induced by simultaneous transmissions. Therefore, in this set of experiments, I analyzed the interference and history parameters of RelaySpot's opportunistic relay selection mechanism.

The experimental findings show that RelaySpot's opportunistic relay selection (using interference and history parameters) has always better performance (throughput and latency) than distance-based relaying systems: 48.8% throughput gain in the presence of indirect interference, and 39% latency gain in the presence of direct interference with a load of 30 Mbps. In the presence of combined interference (direct+indirect), the performance gain of RelaySpot is still evidence: 150% in throughput (at load of 30 Mbps) and 10% in latency (at load of 60 Mbps). These findings also reveal that the impact of direct and indirect interference is different in relation to throughput and latency: indirect interference has higher impact over latency, while direct interference leads to lower throughput.

A major conclusion of this 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, I may say that the usage of opportunistic relay selection scheme 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.

6.2 Relay Selection and Scheduling Analysis

The opportunistic relay selection may not always be the best one due to lack of coordination. It also presents the probability of collisions, in this case the radio resources may be wasted due to unsuccessful relay initiation attempt. This is the major problem with prior art using opportunistic relay selection. As said in Section 6.1.4, some level of cooperation is always required, which is provided by scheduler. Due to such cooperation, a delay may be imposed, but as a result we may reach to better relay choice faster. Therefore, this section provides the analysis of relay selection with cooperative scheduling block of RelaySpot, while performance metrics are average throughput and latency. In contrast to the prior art related to broadcast-based relaying, RelaySpot only perform cooperative scheduling at time of relay selection. For this purpose, a time window i.e., RW is introduced at destination, which allows destination to wait for relays to qualify. The destination does not maintain any table or global map as in case of prior art, but only select a relay among qualified relays. Below are the analyses of RelaySpot protocol in scenarios when all nodes are static.

6.2.1 Overall Network Performance

The performance of RelaySpot (with relay selection and scheduling only) is evaluated by analyzing its impact on the overall network capacity. This is done by measuring the overall network throughput and latency when all 25 nodes transmit to the AP. The motivation is to understand if RelaySpot can increase the capacity of a WLAN by increasing the overall throughput and decreasing the overall latency. The goal is to verify if RelaySpot can perform a good trade-off between the number of helped transmissions and the number of degraded transmissions, resulted from the action of the relay.

In this set of simulations the network load is uniformly distributed among all the 25 nodes. Figure 6.9 compares the average network throughput achieved by RelaySpot and IEEE 802.11 under a series of different traffic load when frame size is 500 bytes, 1K bytes and 2K bytes. Simulation results show that RelaySpot can achieve higher throughput even with high load, mainly because the scheduler at destination allows the selection of the best candidate among the qualified relays: So it is more likely to get a pair of channels (source-relay; relay-destination) with good throughput than the direct link. RelaySpot achieves a throughput gain of 58%, 46% and 45% in relation to 802.11 for frames with payload size of 2K, 1K and 0.5K bytes respectively, under network load of 11K frames per second.

In what concerns the overall network latency, Figure 6.9 shows that RelaySpot achieves a gain of 110%, 154% and 195% in relation to a direct transmission for frames with payload size of 2K, 1K and 0.5K bytes respectively, under a network load of 11K frames per second. The main reason for this result is the fact that in RelaySpot the selected relay does not contend. Furthermore, since RelaySpot allows low data-rate

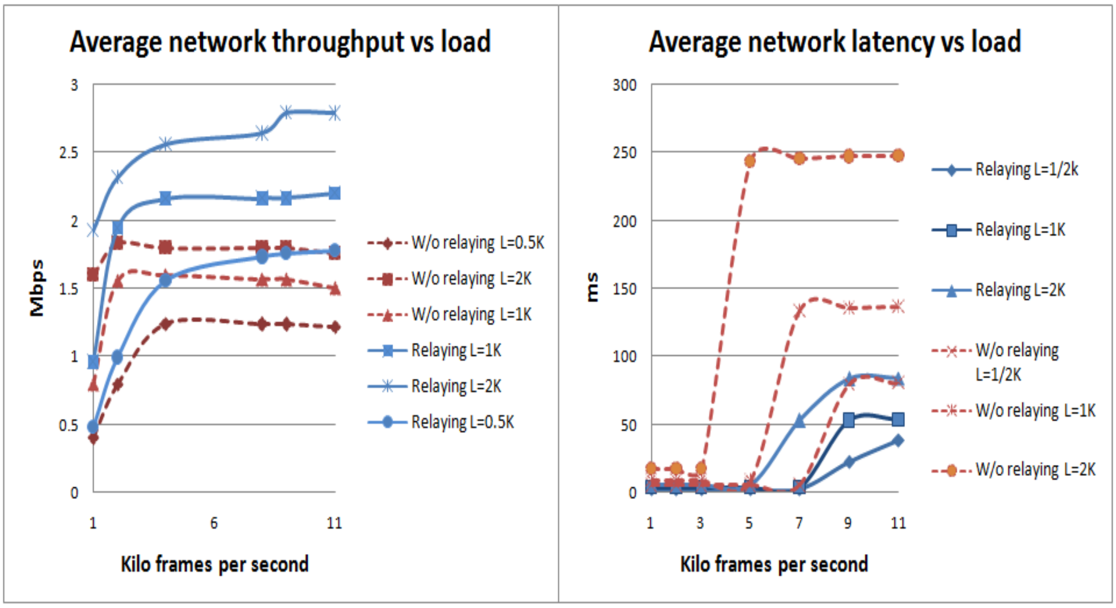


Figure 6.9: Throughput and latency analysis (relay selection & scheduling).

nodes to release the wireless medium faster, other nodes can access the medium more frequently, leading to less delay in transmitting all the load in the network.

As it is well known, the frame size has a great impact on the performance of any MAC protocol. Figure 6.9 observes this effect for both RelaySpot and 802.11 protocols: The performance gets better as the frame size grows, since more bits are transmitted in each transmission opportunity. Since RelaySpot leads to a reduction of frame retransmissions, the potential bad impact of handling large frames is diminished.

6.2.2 Effect of Reception Window

As the size of reception window plays an important role in the selection of the most suitable relay, Figure 6.10 shows the effect that different reception window sizes have on throughput and latency. In this set of simulations the scenario is the same as defined in previous subsection (6.2.1), using frames with a payload size of 1K bytes. Figure 6.10 shows that RelaySpot has worse performance than 802.11 in term of throughput and latency when the size of reception window is too small (i.e., 404 us). The reason is that a significant number of qualification messages fail to arrive to the destination limiting the selection options of the destination. As mentioned earlier, the qualification message has a size of 112 bit, and is transmitted at the basic bit-rate of 1 Mbps, which means that the transmission of the qualification message takes 304 us. Choosing a reception window of 404 us, allows the destination to receive only one qualification message leading the destination with only one choice of relay to select upon. Such relay is with high probability, a node closer to the source, since such nodes overhear a good copy of the frame first. Moreover, in case of collision of qualification messages there is no chance for the destination to select a relay, leading to low throughput and high latency. With the reception window equal to 604 us, the gain in throughput over direct link improves, but the latency is still worse than 802.11. This is because the reception

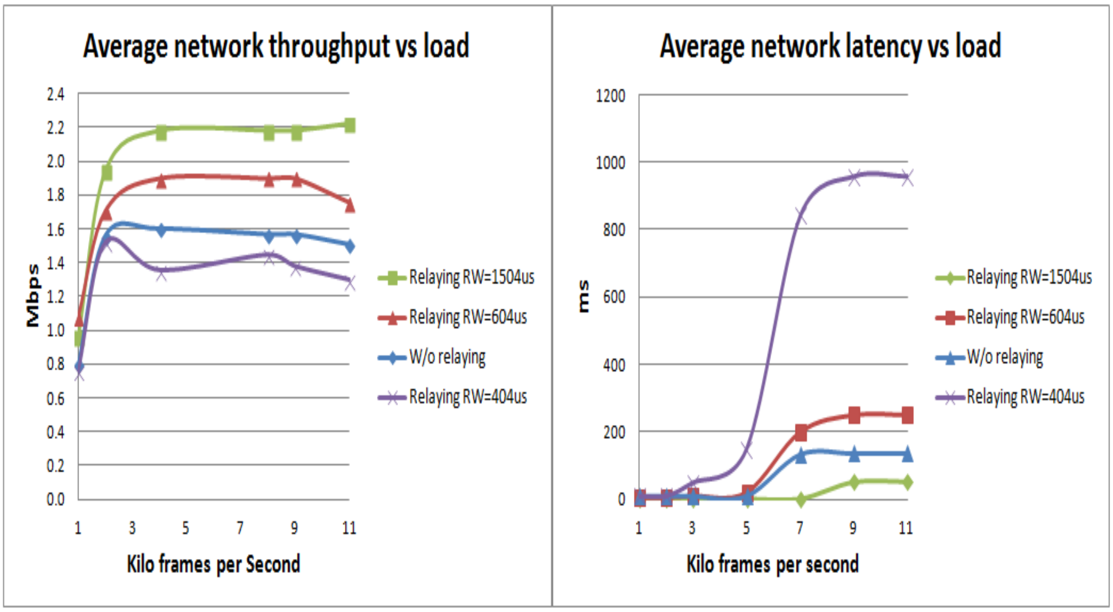


Figure 6.10: Impact of reception window.

window is still not big enough to allow multiple qualification messages to reach the destination, namely of relays closer to the destination, when the load in the network is high (few chances for transmitting QM by potential relays).

Figure 6.10 shows that the latency decreases with a big reception window, which may be the opposite of expected when thinking that a big reception window delay the response of the destination. Although the reception window introduces a delay in the response of the destination, this only occurs at time of relay selection and not during the data relaying. Therefore, it is better to have large reception window in order to allow the destination to select a good relay among qualified relays.

6.2.3 Impact of Interference

Figure 6.11 shows that in the presence of interference, RelaySpot has better performance than IEEE 802.11, as RelaySpot allows higher number of transmission opportunities, avoids selecting overloaded nodes as relays, and select relays with low blockage probabilities. In this set of simulations, I consider a scenario where one source is placed at a distance from AP to observe poor data-rate, and interference is added by randomly placing transmission pairs (each with 5 Mbps in average) among the available 25 nodes using frames with payload of 1K bytes. Results show that with the introduction of interference the gain in throughput and latency drops linearly as the probability for the source to get the channel decreases. However, RelaySpot achieves high throughput (147% higher in average in relation to 802.11), due to its capability to select the relays with better transmission success rate towards the destination. Since those relays are within the cooperation area, the condition supported by Equation 4.1 (i.e., CF $>$ *Rsd)* ensures that the rates of source-relay and relay-destination links are better choice than the direct link.

In term of latency the gain is of 148% in average in relation to 802.11, since RelaySpot is able to select relays with low load of concurrent neighbor flows, leading to a

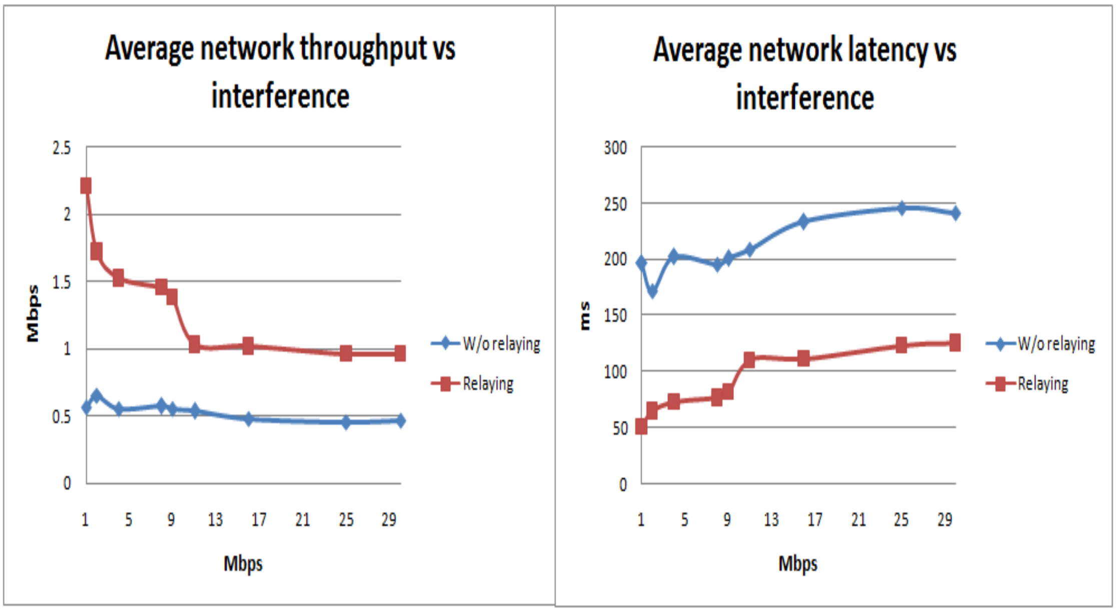


Figure 6.11: Analysis of impact of interference (relay selection & scheduling).

higher number of successful transmission opportunities for the relay, as the relay faces low blockage (less direct and indirect transmissions) which lower the latency.

Figure 6.11 shows that the gain in both throughput and latency stabilize at an interference level of 25 Mbps, which is better than RelaySpot without scheduler [40], where the gain only stabilize at an interference level of 60 Mbps. The reason is that the relay selection mechanism is able to select relays with less blockage probability, while the scheduler at the destination is able to choose a relay with better rate, among the qualified relays, ensuring a good performance with high interference.

6.2.4 Conclusions

This section analyzed the relay selection and scheduling components of proposed RelaySpot protocol, to improve the performance of wireless networks. The main focus was to see if scheduler at destination can improve the performance further. In this set of experiments, a relay is chosen for a cooperative transmission opportunistically, without any broadcast overhead. Through overhearing RTS/CTS control frames exchanged by the source and destination nodes, relays can acquire related rate information used to calculate their cooperation factor used to determine if they are eligible to become a potential relay. Eligible relays are then able to self-elected themselves as qualified relays by computing their selection factor based on local information such as interference level. The proposed protocol can effectively choose a suitable relay among all qualified relays, increasing the performance gain in relation to 802.11, even in the presence of interference.

In this experiment I considered cooperative transmissions using one relay. However, there may be several situations when the selected relay may fail, or a better relay is available later on. Therefore, next section includes the relay switching functionality. Relay switching will try to react to relay failures and poor relay selections, by allowing transmissions to take advantage of more than one relay.

6.3 Relay Selection, Scheduling and Switching

In this section, I evaluate the performance of RelaySpot framework including all three basic components which are relay selection, scheduling and switching, and compare it with the IEEE 802.11 standard, as well as two versions of RelaySpot: one that is not aware of mobility and another that does not use relay switching. The reason for not comparing with other cooperative MAC protocols is that RelaySpot is a framework which provides both reactive and proactive relaying, and is also combination of opportunistic and cooperative behavior, while the other proposals belong to different categories.

As discussed before, the majority of the existing literature is focused on the single relay domain (with the exception of CODE [73]). This is mainly due to the complexity involved in relay selection, defining maximum number of relays, multiple relay coordination and handling of additional overheads. Though from physical layers perspective, researchers have found that multiple relays results in higher gains in terms throughput and outage probability. However, these results do not include overheads in coordination of multiple relays. Relay switching provides usage of multiple relays different in time. As said in Section 6.2.4, switching is performed when the current relay is poor or fails. Therefore, this section aims to analyze the advantages of switching as compare to RelaySpot in previous section which is without switching. Below are the analyses of RelaySpot protocol in scenarios when all nodes are mobile.

6.3.1 Network Capacity Analysis

In this section I analyze the performance of RelaySpot based on its impact on the overall transmission capacity of a wireless local network. This is done by measuring the overall network throughput and latency when all 25 mobile nodes transmit to the AP, while moving with random pause time between 10 to 100 seconds. The goal is to understand if RelaySpot can increase the transmission capacity of the network by increasing the overall throughput and decreasing the overall latency in the presence of nodes with different levels of mobility.

In this set of simulations the network load is uniformly distributed among all 25 nodes. Figure 6.12 compares the average network throughput achieved by RelaySpot (which is aware of mobility by means of factor M in equation 4.3 as well as interference and history), by a version of RelaySpot without mobility-awareness and by the 802.11 standard, all under a series of different traffic load (frame size equal to 1K bytes). Simulation results show that RelaySpot can achieve higher throughput than the 802.11 standard and the mobility unaware RelaySpot even with high load, mainly because it is able to select stable relays (with low mobility), which are more likely to help for longer time. RelaySpot achieves an average throughput gain of 42% in relation to 802.11. RelaySpot without mobility-awareness can still achieve an average throughput gain of 17.6% in relation to 802.11, due to the scheduler at the destination, which is able to select a relay with a pair of channels (source-relay; relay-destination) with better throughput than the direct link.

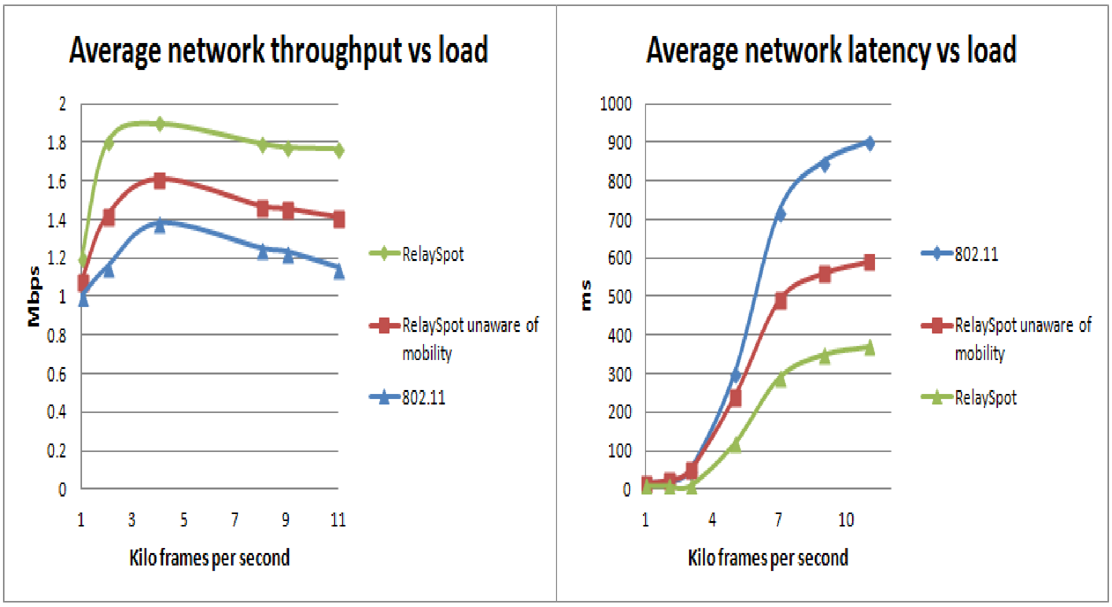


Figure 6.12: Analysis of network capacity.

In what concerns the overall network latency, Figure 6.12 shows that RelaySpot achieves an average gain of 152% in relation to a direct 802.11 transmission, while the mobility unaware RelaySpot achieves an average gain of 17.8% in relation to the direct transmission. The main reason for the gain that RelaySpot has in relation to 802.11 is the fact that with RelaySpot the selected relay does not contend, thus reducing the delay. What differentiates RelaySpot from its mobility unaware version, is the fact that by selecting relays with high pause time RelaySpot reduces the overall communication delay, by avoiding re-selection of relays during the communication session. Furthermore, since RelaySpot allows low data-rate nodes to release the wireless medium faster, other nodes can access the medium more frequently, leading to less overall network latency, even in scenarios with high mobility.

As it is well known, the network load has a great impact on the performance of any MAC protocol. Figure 6.12 observes this effect for both RelaySpot and 802.11 protocols: the performance gets better as the load increases, since more bits are transmitted at each transmission opportunity. However, when the network is overloaded (4 kilo frames per second) then the margin gain is reduced mainly due to collisions. Since RelaySpot operation leads to a reduction of frame retransmissions, the potential bad impact of retransmissions in a heavy loaded network is diminished.

In comparison to static scenarios (Figure 6.9), it is clear that with RelaySpot the overall network capacity does not decrease significantly in the presence of mobility. Even the mobility unaware RelaySpot has gains over 802.11. The reason is that the overhead of relay failure due to mobility is smaller than the benefit achieved from helping poor communication sessions.

6.3.2 Impact of Relay Switching

The aim of this experiment is to analyze how much can relay switching contribute to a good network capacity, by rectifying the impact of relay failures. In this set

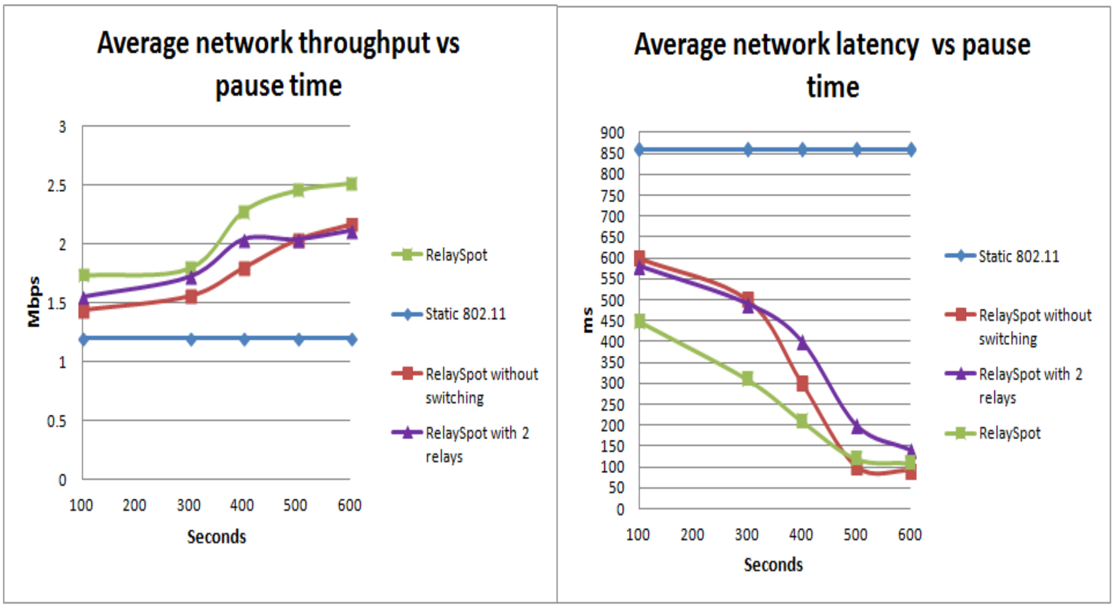


Figure 6.13: Analysis of impact of switching.

of simulations, I consider a scenario with one AP and 25 mobile sources, each one generating a traffic load of 10K bytes per second. Several simulations are run with different levels of mobility, from simulations where all nodes have 100 seconds of pause time to simulations where nodes pause time is of 600 seconds (static nodes, since the pause time equals the simulation time).

Figure 6.13 shows the benefits of RelaySpot over 802.11 and highlights the benefits of relay switching. The advantage of switching between relays during the lifetime of a communication session is analyzed by comparing RelaySpot with two benchmark versions of itself: a version without relay switching; a version where switching is done between two relays only (if one fails the other relay forwards the data).

Results illustrated in Figure 6.13 clearly show that RelaySpot has always a better performance than 802.11. This performance gain is still clear even when RelaySpot switches between two predefined relays only, or when RelaySpot does not switch at all.

In what concerns the analysis of relay switching, my first finding shows that the performance of RelaySpot increases with its capability to switch between any qualified relay: relay switching gives RelaySpot an average throughput gain of 20% in relation to the RelaySpot version that does not use switching at all. Moreover, it is also clear that the flexibility of being able to switch between any qualified relay brings additional performance to RelaySpot: Figure 6.13 shows that RelaySpot has an average throughput 13.5% higher than the RelaySpot version that uses only two predefined relays in the switching process.

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

In static scenarios, switching traffic between just two relays does not bring any major gain (c.f. Figure 6.13). The reason is that the usage of two relays brings some extra overhead that does not compensate the small throughput gain that comes from switching a communication session between two relays that may be under similar interference conditions with high probability. Such probability is lower when we increase the number of relays involved in the switching process, as happens with RelaySpot (which is evident from the results illustrated in Figure 6.13). Moreover, when compared with RelaySpot, the probability of non optimal relay selection is higher when we consider only two relays.

The problem of using only a small number of predefined relays to switch upon (two relays in this experiment) is also evident in terms of latency, as shown in Figure 6.13. The overall latency of the RelaySpot version with two relays is higher than the version not using switching for pause times higher than 300 seconds. These experiments show that for the majority of the scenarios, switching among two relays does not bring any advantage, due to the high probability of having the two relays under the same interference conditions.

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

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

6.3.3 Conclusions

Usage of multiple relays as well as mobility is not well addressed in cooperative relaying. It is well known that mobility can degrade the performance of relaying network, mainly due to relay failures. Experimental results show that RelaySpot brings an overall average throughput and latency gains of 42% and 152%, respectively, in relation to 802.11, and of 17.6% and 17.8% in relation to a version of RelaySpot that is unaware of node mobility.

Multiple relays or relay switching tries to rectify such degradations. In [81, 80], authors have proposed a multi-relay MAC protocol with directional antennas. The main idea is to use directional antennas to allow parallel transmissions. In this protocol two relays are selected and the parallel transmission takes place from the first relay to the destination and from the source to the second relay. Compared to traditional omnidirectional antennas, the use of directional antennas can give rise to hidden terminal problems due to different antenna gains [15, 72]. In another recent work presented in [10], this prevailing assumption of omni-directional antennas is loosened by assuming multiple beam antennas which, unlike the omni-directional antennas, can use the multiple beams to communicate with multiple nodes simultaneously. The idea behind this notion of multiple beam antennas is to enable parallel transmissions. These works show significant improvement in the system throughput by increasing spatial reuse, reducing collisions and avoiding co-channel interference. However, this assumption of directional or multiple beam antennas leads to compatibility issues as the existing IEEE 802.11 MAC protocol and devices have no support for directional antenna or multiple beam antennas. In future, MAC protocols would require major modifications and hardware support to enable these features.

Therefore, it is necessary to devise some clever mechanism that can overcome the coordination overhead and transmission time overhead while using multiple relays. Relay switching is one of the solution to overcome relay failures with minimum overhead, while taking advantage of multiple relay usage. With relay switching we can achieve higher throughput and lower latency.

Advantages of Relay Switching

In case of multiple relays, transmission and coordination overheads are associated with number of selected relays. More relays lead to more overheads and if not utilized efficiently may result in no gains. To achieve maximum gain it is important to minimize the overheads. Another problem with multiple relays is that, with the coverage expansion due to the relays, the possibility of hidden and exposed terminals increases. We also do not know how many relays to select, as beyond certain number of relays there will be no gain. The work presented in [12], defined a limit to the number of relays to be 5 beyond which there is no significant gain. Increasing the number of relays is thus directly linked to the complexity and delay faced by the whole system.

In case of relay switching, only one relay is selected at a time while other relays can cooperate at time when needed. Moreover, the choice of relays to react is not limited to only specific predefined set of relays. Switching can decrease the overall contention by avoiding relay re-selection and replacing relays by the better opportunistic node.

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

Chapter 7

Conclusions and Future Research Issues

Radio technology has advanced rapidly to enable transmissions over larger distances with better quality, less power, smaller and cheaper devices, thereby enabling public and private radio communications, television and wireless networking [21]. There are a number of issues that can cause poor performance in a wireless system. The effects of such issues can be combated with cooperative communications.

While cooperative communications have a rich theoretical history in the literature, efforts to actually implement cooperative systems have been much more limited. Cooperative communication refers to the sharing of resources and the realization of distributed protocols among multiple nodes in a network. It is a very active research area with promising developments. With the development of diverse kinds of applications of wireless communications, the demand for higher data-rate is increasing, pushing the achieved data-rates towards the saturation limit of channel capacity [17, 70]. With the purpose of offering effective and efficient interaction between the physical and higher protocol layers, research on cooperative communication has been exploring the MAC layer. Recently, the exploitation of link-layer diversity (cooperative relaying) in wireless networks has attracted considerable research attention. Cooperative techniques utilize the broadcast nature of wireless signals: the source node sends data for a particular destination, and such data can be “overheard” at neighboring nodes; these neighboring nodes, called relays, process the data they overhear and transmit it towards the destination; the destination receives the data from the relay or set of relays (on behalf of the source) enabling higher transmission rate, or combines the signals coming from the source and the relays enabling robustness against channel variations. Such spatial diversity arising from cooperation is not exploited in current cellular, wireless LAN, or ad-hoc systems. Cooperative diversity relies on two principles:

- Due to the broadcast nature of wireless medium, most transmissions can be heard by multiple nodes in the network with no additional transmission power and bandwidth.

- Different nodes have independent channel fading statistics to a given destination node and the destination can listen, store, and then combine signals from different nodes.

Hence, cooperative relaying is different from traditional multi-hop or infrastructure methods. Therefore, for cooperation to be implemented at the link layer, link layer needs to be changed in order to allow indirect transmission between source and destination.

Cooperative communications can find their niche in diverse applications, from increasing capacity or extending coverage in cellular networks to enhancing transmission reliability and network throughput in WLANs; from offering more stable links in volatile and dynamic propagation conditions in vehicular communications [68, 23], to saving energy and extending network lifetime in wireless networks.

7.1 Conclusions

This thesis focused on cooperative relaying network, which is one of the opportunities to improve performance of wireless communication. I considered dual-hop cooperative relaying in different scenarios and studied relaying strategies.

This thesis presented arguments in favor of a new type of cooperative relaying scheme based upon local decisions, leading to a simpler and more stable solution. I described an 802.11 backward compatible cooperative relaying framework, called RelaySpot [37, 41], which aims to ensure accurate and fast relay selection, posing minimum overhead and reducing the dependency upon CSI estimations, which is essential to increase system performance in scenarios with mobile nodes. The basic characteristic of any RelaySpot-based solution is the capability to perform local relaying decisions at potential relay nodes (can be more than one), based on a combination of opportunistic relay selection and cooperative relay scheduling and switching. Intermediate nodes take the opportunity to relay in the presence of local favorable conditions (e.g., no concurrent traffic). Relay switching is used to compensate unsuccessful relay transmissions and poor selections.

During the development of proposed framework, I started by analyzing relay selection approaches [31]. I devised taxonomy for relay selection and classified the existing approaches. The findings lead to conclusion that relays should be selected opportunistically based on local information. I analyzed that relay selection as well as cooperative transmission introduces some extra overhead and interference, therefore, relay should be selected in a fair way, so that it not only increase the performance of one source-destination pair, rather it should also increase the overall network capacity. I analyzed existing relaying MAC protocols and classified them. With the pros and cons of both kinds of classes, I proposed an hybrid relaying framework. From the analysis of prior art it is concluded that it is hard to find the best relay based on probabilistic measurements, so I devised a cooperative scheduler that allow the destination to select one or more answered relays. ORP [19] is similar to RelaySpot in the sense that both does not rely on CSI for relay selection and the relay is opportunistically selected. However, with ORP the source does not know the rate of the source-relay and relay-destination channels. With RelaySpot the destination is aware of the relay diversity as well as the rates of the used links. With ORP the relays back-off every time when they forwards the data frame. While with RelaySpot the selected relay does not contend. This way RelaySpot is similar to broadcast-based proposals, such as (CoopMAC or rDCF), where the selected relay does not contend. But RelaySpot does not maintain CSI tables, periodic broadcast and extra control overhead. RelaySpot behavior was previously compared with broadcast-based proposals, highlighting the operational advantages [28, 41].

Since the wireless networks are very unstable, therefore, the relaying conditions may change with time. Especially in dynamic networks, there is high probability of relays to fail, this way cooperation may not be useful. To overcome with such situations, I also proposed a relay switching functionality. This way we are able to use multiple relays i.e., switch between relays whenever needed. The performance of RelaySpot is analyzed over OMNet++ simulator with MiXiM framework.

During implementation of proposed framework, as an initial work, RelaySpot analysis was carried out in a scenario without interference. This served as a reference point for further investigation. The referenced scenario gave 151% gain in throughput and significant gain in latency with respect to 802.11 standards with poor direct link of 1 Mbps [41].

As a next step I focused on relay selection parameters, I devised a novel relay selection mechanism based on interference, mobility and history factors. The first set of experiments was based on interference. Results from relay selection in presence of indirect interference showed the average throughput and latency gain of 23% and 16% respectively, with respect to distance-based relay selection, while in the presence of direct interference, results showed the average throughput and latency gain of 17.5% and 9.3% respectively, with respect to distance-based relay selection [36].

The second set of experiments on relay selection parameters took into consideration history and interference where relay selection was history/interference-aware. The experimental findings also showed that relay selection (with interference together with history factor) has better performance than distance-based relaying systems with 48.8% throughput gain in the presence of indirect interference, and 39% latency gain in the presence of direct interference at a load of 30 Mbps (c.f Figure 6.7). In the presence of combined interference, the performance gain of RelaySpot is still evident: 150% in throughput (at load of 30 Mbps) and 10% in latency (at load of 60 Mbps) [40].

The analysis of relay selection together with scheduler showed that scheduler at destination can further improve the performance of cooperative relaying system even in presence of interference [34]. During this experiment, RelaySpot achieved an overall average throughput and latency gain of 46% and 154% respectively, in relation to 802.11, with payload size of 1K bytes, under network load of 11K frames per second.

As next experiment I analyzed impact of relay switching. The analysis showed that in very dynamic scenarios, RelaySpot brings an overall average throughput and latency gains of 20% and 21%, respectively; with respect to a version of RelaySpot that does not perform relay switching. In what concern the mobility factor, experimental results showed that RelaySpot brings an overall average throughput and latency gains of 17.6% and 17.8% with respect to a version of RelaySpot that is unaware of node mobility [35].

It means, RelaySpot has the capability to improve the utilization of spatial diversity by selecting, scheduling and switching relays in real time to offer best cooperation opportunities. Overall, this thesis has highlighted the gains associated with relay based MAC protocols and their role in WLANs. On the other hand, the work in this thesis also raises a number of open issues which require further investigation. These are shown in the next section.

7.2 Future Research Issues

In the context of the proposed framework to the problem of cooperation the following research issues require further work:

- Though RelaySpot has been analyzed using two metrics, throughput and delay. As a next step I aim to analyze RelaySpot with energy expenses. And, perform optimization if required to achieve a better level of energy gain vs throughput.
- As impact of interference is different in relation to throughput and latency. Hence, I aim to analyze RelaySpot using various traffic types.
- There is need to address various optimization issues such as size of reception window and network density. I aim to analyze RelaySpot under various network densities and to investigate its impact in larger network.
- The performance of RelaySpot has not been compared with prior art due to its hybrid nature. Therefore, I aim to implement RelaySpot under same mode (e.g., proactive), same metrics and same network conditions as considered by a prior art (e.g., ORP) in order to analyze against it.
- As discussed in Section 4.1, RelaySpot second version will include chain relaying and partial frame combining features. This will integrate networking and physical layers into RelaySpot, as explained below:

7.2.1 Multi-hop Cooperative Relaying

Multi-hop networks such as ad-hoc networks have been active research topics in both academia and industry for many years. The application of cooperative communications needs to be extended to multi-hop scenarios. However, a lot of challenges will be confronted in a cooperative multi-hop network. Questions like how to explore cooperative diversity from the routing layer, or how to combine routing with the underlying cooperative systems, need to be answered.

Although significant efforts have been made on the study of cooperative systems, there has been very little work on cooperative routing. Some of the relevant studies focus on the theoretical analysis on routing and cooperative diversity [24, 9]. With regard to the implementation of a cooperative routing protocol, the theoretical optimal route is too complicated and therefore unsuitable for the current status of ad-hoc and sensor networks [42].

An alternative way to extend cooperative communications to the routing layer (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 [84] is an important research topic.

One of the solution proposed by RelaySpot is chain relaying, with the usage of chain relaying the relaying will be triggered over relay-destination link. This leading to serial relaying, i.e., multi-hop relaying. Such relaying can be beneficial only if the relay is

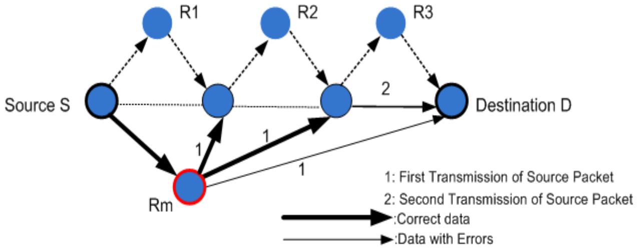


Figure 7.1: Multi-hop cooperative network.

aware of next hop. Hence, the relay can forward the frame to next hop. This way complexity of hop-by-hop relaying can be mitigated. In chain relaying, the destination node may receive more than two independent signals of the same frame (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.

Figure 7.1 shows that by devising a cooperative MAC where a relay to assist several transmissions in a multi-hop scenario (Rm) can reduce the number of relays (R1, R2 and may be R3) and consequently the number of transmissions. As Rm has the knowledge of the following hops from routing information. Consequently, with Cooperative MAC, a simpler alternative to layer-3 routing is possible, where wireless networks do not need complicated distributed routing algorithms, as in ad-hoc networks.

7.2.2 Partial Frame Combining

The focus of the thesis was on MAC layer perspective of relaying. However, cross layer solutions should greatly benefit cooperative networks. To yield the gain, the cross layer approach should integrate the physical layer and MAC layer. This can result in reduced overheads.

One of the solution proposed by RelaySpot is the partial frame combining, where the selected relays will operate in parallel if required. The destination on the other hand will try to construct an error free frame by combining different copies of received frame received from different relays. Research is needed to investigate how relays will coordinate and how the frames will be combined. Many combining techniques could be employed at the receiver, such as Maximal Ratio Combining (MRC), Equal Gain Combining (EGC), Fixed Ratio Combining (FRC) [79] etc. With Physical layer assisting MAC, we can remove lot of complexity level. The aim is to make RelaySpot system much simpler and scalable.

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