Universidade de Aveiro
2013

Departamento de Electrónica, Telecomunicações e Informática

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Comunicações Cooperativas em Redes IEEE 802.11 Multi-Débito

Cooperative Communications in Multi-Rate IEEE 802.11 Networks

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Tese apresentada às Universidades de Minho, Aveiro e Porto para cumprimento dos requisitos necessários à obtenção do grau de Doutor no âmbito do doutoramento conjunto MAP-Tele, realizada sob a orientação científica do Doutor Rui Luis Andrade Aguiar, Professor Associado com Agregação do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro, e do Doutor João Paulo Barraca, assistente convidado do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro.

Apoio financeiro da FCT bolsa de doutoramento:
SFRH/BD/33444/2008

I would like to dedicate this thesis to my lovely wife, Neda, my dear daughter, Pantea, and my parents, Ramezanali and Zari.

o júri

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Acknowledgments

I owe gratitude to many people for their support and encouragement as I have been completing this PhD thesis.

First of all, I would like to thank my advisors, Prof. Rui Luís Andrade Aguiar and Dr. João Paulo Barraca, who have provided me with this wonderful opportunity to study at the University of Aveiro and I appreciate their help and guidance in this way. It has been a great pleasure working with them.

Thanks to the juries who kindly accepted to review my thesis!

Secondly, my gratefulness is extended to Scientific members of MAP-Tele program and specially Prof. Rui Valadas for his excellent coordination as a coordinator.

My appreciation goes also to FCT (Fundação para a Ciência e a Tecnologia) for financial supporting of this thesis.

I also extend my sincere thank to all my colleagues in ATNoG research group and IT.

palavras-chave Cooperação, protocolo MAC, IEEE 802.11, camada Cruz, Métrica.

resumo

Esta tese apresenta um estudo sobre alguns dos protocolos de cooperação MAC para redes sem fios utilizando o sistema IEEE 802.11 multi-débito. É proposto um novo modelo de arquitetura para a categorização e análise da cooperação em redes sem fios, tendo este modelo sido aplicado a protocolos cooperativos existentes para camada MAC.

É investigado como as características do meio físico, assim como os requisitos de níveis superiores podem ser aplicados ao processo de cooperação, com vista a melhorar as características de funcionamento da rede de comunicações. Para este propósito são exploradas as métricas mais relevantes para o processo de cooperação. São igualmente estudados os limites impostos pelos protocolos da camada MAC e as limitações práticas impostas por protocolos da família de normas que compõem o IEEE 802.11.

Neste trabalho foi criada uma métrica multicamada, que permite considerar os requisitos aplicacionais de performance e o tipo de tráfego, assim como a mobilidade dos dispositivos, no funcionamento dos mecanismos de cooperação. Como forma de validação, e para corretamente avaliar o impacto da métrica, um novo protocolo de cooperação foi desenvolvido e implementado. O seu funcionamento é descrito de forma analítica assim como validado através de a um ambiente de simulação.

Os resultados obtidos mostram que a utilização de uma métrica multicamada é uma técnica robusta, fornecendo melhorias consistentes no contexto de redes IEEE 802.11. São igualmente demonstradas várias outras características de funcionamento com impacto para as comunicações. Estes dados fornecem uma visão real e encorajadora para a realização de mais pesquisas para a melhoria da performance dos protocolos cooperativos, assim como a sua utilização num variado número de aplicações futuras. No final do documento são apresentados alguns desafios para a continuação da investigação deste tópico.

key words Cooperation, MAC protocol, IEEE 802.11, Cross layer, Metric.

abstract

This thesis presents a study on cooperative MAC protocols in Multi-rate IEEE 802.11 wireless networks. We proposed a novel architectural framework for cooperation algorithms in wireless network. This behavior model was considered for existing cooperative MAC protocols. A classification of these protocols was presented based on their cooperation objectives.

We investigate how physical layer specifications and higher layer requirements can be applied in cooperation MAC protocols to enhance the overall network performance. For this purpose, we exploit the appropriate metrics which are consistent to the cooperation objectives. Performance bounds provided by MAC protocols and practical limitations posed by IEEE 802.11 standards have been also studied.

A cross layer metric was achieved in cooperative MAC protocols to adapt cooperation performance to traffic service requirements and mobility scenario. In order to realize the impact of this metric, a new cooperative MAC protocol is designed and implemented. Analytical and simulation of this protocol was performed in different scenarios and environments.

The obtained results have shown a robust technique in providing consistent cross layer optimization in context of IEEE 802.11 networks. A number of findings was experienced which are illustrated at the end. These observations would enhance and encourage potential research in the area and optimize the performance of cooperative protocols for a number of interesting applications in future. A summary of future research challenges is presented at the end.

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LIST OF ACRONYMS

3GPP-LTE	Generation Partnership Project Long Term Evolution
ACK	Acknowledgment
AMC	Adaptive Modulation and Coding
AP	Access Point
ARQ	Automatic Repeat Request
CC	Coded Cooperation
CDMA	Code Division Multiple Access
CM	CoopMetric
CSMA/CA	Carrier sense multiple access with collision avoidance
DCF	Distributed Coordination Function
DR	Delay Ratio
DSTBC	Distributed Space Time Block Coding
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
GI	Guard Interval
HARQ	Hybrid Automatic Repeat Request
HTP	High Throughput PHY
MAC	Medium Access Control
MAI	Multiple Access Interference
MANET	Wireless Ad Hoc Networks
MAPE	Monitor, Analyze, Plan, Execute
CDMA	Code Division Multiple Access
CM	CoopMetric
CSMA/CA	Carrier sense multiple access with collision avoidance
DCF	Distributed Coordination Function
DR	Delay Ratio
DSTBC	Distributed Space Time Block Coding
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
GI	Guard Interval
HARQ	Hybrid Automatic Repeat Request
HTP	High Throughput PHY
MAC	Medium Access Control
MAI	Multiple Access Interference
MANET	Wireless Ad Hoc Networks
PLCP	Physical Layer Convergence Procedure

MAPE	Monitor, Analyze, Plan, Execute
MIMO	Multiple Input Multiple Output
MTU	Maximum Transmitted Unit
NAV	Network Allocation Vector
OSI	Open Systems Interconnection
OSTBC	Orthogonal Space Time Block Code
PER	Packet Error Rate
PHY	Physical layer
PLCP	Physical Layer Convergence Procedure
STC	Space Time Coding
TDMA	Time Division Multiple Access
VOD	Video On Demand
VOIP	Voice over IP
WCN	Wireless Cellular Networks
WLAN	Wireless Local Area Networks
WMN	Wireless Mesh Networks
WSN	Wireless Sensor Networks

CHAPTER 1 INTRODUCTION

Summary

Cooperative communication is becoming an alternative paradigm for next-generation wireless networks by offering efficient network resource management of bandwidth and energy. Cooperative techniques are envisioned to be used in a wide range of wireless networks. This work investigates in detail the cooperative MAC protocols in IEEE 802.11 networks. This chapter gives detail of motivation, objectives and original contributions. The thesis organization is presented at the end of the chapter.

1.1 Background and Motivation

The world has witnessed the fast evolution of wireless communications over the past few decades. A variety of wireless networks have been deployed, e.g., Wireless Cellular Networks (WCN), Wireless Local Area Networks (WLAN), Wireless Ad Hoc Networks (MANET), Wireless Sensor Networks (WSN), and Wireless Mesh Networks (WMN), etc. The rise of wireless networks is due to practical aspects, such as the low cost of deployment and mobility. However, wireless communications are facing increasing demands of high data rate and seamless connectivity, even in high mobile scenarios. Fulfilling this need at reasonable costs is a challenge for research and engineering. Several technologies are exploring approaches that maintain connectivity at high data rates but without investing in extra bandwidth or substantial changes in infrastructure. One of these approaches is *cooperative relaying communications*.

Cooperative relaying communications have recently emerged as a novel approach beyond the classical paradigms of point-to-point and point-to-multipoint. The key idea of cooperative communications is based on having users cooperating to transmit their messages, instead of operating independently and competing among each other for channel resources, as is done in conventional networks. Cooperative relaying achieves these benefits by allowing intermediate nodes (also called relays or helpers) to retransmit the source's messages towards the destination thereby splitting a single transmission into multiple transmissions. Compared to a direct transmission, the source node has to allocate less power to reach the next hop. This provides per node energy saving and allows one to precisely focus the signal power specially where it is needed, an issue of high relevance in scenario such as WSNs. In addition, intermediate paths provided by several relays in the network can increase overall network capacity [1].

Cooperative relaying communications are inspired by two fundamental concepts of wireless communications: relaying and multi-antenna communication. By overhearing different broadcasted signals, the destination can combine an original and the relayed signals transmitted respectively by source and relay nodes. Due to the spatial separation of the transmit antennas it is likely that both received signals were affected by statistically independent channels. In this case, combining these signals provides high spatial diversity gains that protect the overall transmission from rapid channel fluctuations (fading). While conventional research mainly consider the broadcast nature of wireless channel as the origin of interference and performance degradation, cooperative relaying communication exploits this inherent feature to develop promising solutions for existing challenges in wireless networks. Furthermore, cooperative communications provide a feasible solution to overcome the practical implementation problems of Multiple Input Multiple Output (MIMO) techniques [2] within relatively small devices, where the maximum distance between antennas is constrained by device size.

In wireless communications, overhearing other communications can provide different levels of information which can be beneficial for every layer of OSI model. For instance, cooperation at physical layer (PHY) exploits the overheard information to mitigate fading effects of wireless channels and improve the performance parameters of the physical layer in terms of outage probability, outage capacity, Bit Error Rate (BER) and Packet Error Rate (PER) [3]. In contrast, cooperation at higher layers (such as Medium Access Control (MAC) layer and network layer) takes advantage of overhearing information to enhance network performance by making use of extra network resources provided by relay nodes such as spectrum and power.

The concept of cooperative relaying goes beyond the conventional transmission techniques, and it can address a spectrum of features from information theory to collaborative use of resources and negotiating procedures, within and across the OSI layers. Cooperative techniques can also be deployed in different categories of centralized, distributed and heterogeneous wireless networks. There are some contributions in industry which demonstrate the potential vital role of cooperative communications in future standardization bodies. For instance, some cooperative relay techniques have been proposed in the IEEE 802.16j [4], and coordinated multicell space-frequency coding schemes were suggested in Third Generation Partnership Project Long Term Evolution (3GPP-LTE) [5].

Inspired by the attractive features and potential benefits of cooperative relay based communications, there have also been natural efforts to exploit the cooperative techniques in IEEE 802.11 standards [6][10]. During recent years, many authors have proposed various cooperative schemes for MAC protocols of IEEE 802.11 networks [16]-[30].

Every cooperative solution developed for the IEEE 802.11 MAC protocol has a different objective for the usage of cooperation techniques. These objectives address multiple issues, from capacity improvement to service differentiation and fairness. Classification of existing cooperative protocols and understanding their inherent shortcomings is a valuable guidance for designing efficient cooperative MAC protocols useful in the context of IEEE 802.11 standards. In particular, many analytical papers on cooperative MAC protocols focus on a cooperation process assuming ideal assumptions, regardless of higher layer requirements or overall constrains of IEEE 802.11 standards. Due to these idealistic assumptions, there is a large gap between design and theoretical analysis, and transforming these designs into real effective systems.

This gap between theoretical and practical research on cooperative MAC protocols is easily assessed when practical constraints are applied to the real scenario. Thus, it is expected that current theoretical performance results for cooperative MAC protocols are not upheld when practical constraints are imposed by real scenarios. So far, the conditions leading to situations when non-beneficial cooperation arises due to such practical constraints were not adequately studied in previous works. Furthermore, all cooperative MAC protocols in context of IEEE 802.11 focus on the cooperative objective and respective cooperative gain. Thus, there is no solid study to assess the achievable gains of performance.

1.2 Thesis Objective

It has become clear that cooperative communications appear as a new paradigm beyond the existing communication models. When cooperative techniques are employed in each wireless standard such as IEEE 802.11, a question we must ask gradually becomes apparent: what is the behaviour model of cooperation? and based on the solution space, several questions will be entailed consequently in the light of the outlined motivation: 1) Which performance metrics can be improved by the cooperation model?, 2) What is the impact of the higher layer requirements and overall constrains of standard on the expected performance gain?, and 3) How the cooperation model can be modified in order to achieve the performance gain consistent to practical scenarios?.The answer to these questions within the context of IEEE 802.11 provides a guideline which makes the framework of this thesis.

The main objective of this research work is developing a realistic approach to cooperative communications in IEEE 802.11 wireless networks. Such a study involves several phases: In the first place, an architectural reference model is presented to model the behaviour of cooperation in wireless networks. In the next phase, a classification of cooperative solutions is presented. This classification is based on cooperative objectives. Furthermore, the impacts of higher layers requirements and practical issues on expected performance gain provided by existing IEEE 802.11 cooperative MAC protocols are considered. The initial purpose of this phase is to explore how the issues beyond the MAC layer can limit the performance gain provided by cooperative MAC protocol. In the third phase, a metric is proposed to coordinate the requirements of the higher layer to performance gain provided by cooperation at lower layers. This metric provides a consistent cooperation in the whole of Open Systems Interconnection (OSI) model layer model.

1.3 Original Contributions

The work performed in this thesis has a set of contributions relevant to cooperation in 802.11 networks.

The primary contribution [32] of this thesis is developing a realistic approach to cooperative communications in wireless networks. In particular, there exist some dynamic aspects in wireless networks such as multi rate capabilities which directly affect cooperation. In order to model the cooperation in realistic environments, a framework is proposed to cope with the control and dynamic aspects of wireless technologies. In this framework, the behaviour concept of cooperation in wireless networks is represented by an architectural reference model. This reference model comprises all operation performed in each cooperative protocol and provides a similar method and common terminology to evaluate the cooperation in wireless networks.

A second contribution [35], published during the course of this thesis is to assess current cooperative MAC protocols, when their operations are mapped to our reference model. While previous works have designed every protocol separately, these protocols can then be classified based on their objectives and inherent limitations are identifiable. Toward the assessment of these current cooperative MAC protocols, appropriate performance metrics and mathematical analysis lead to performance bounds when the practical specifications of different IEEE 802.11 amendments are applied. In most of research works, cooperation is always beneficial when assuming the ideal conditions, but when applying practical constrains of 802.11 networks, it is possible to determine conditions leading to non-beneficial cooperation.

A third contribution [36] is a proposal to coordinate higher layer requirements and cooperation gains provided by lower layers, during the cooperation process. To achieve this cross layer purpose, a metric should be defined to take into account several aspects of wireless links and network features such as delay, reliability, mobility and stability. This novel metric is called CoopMetric and is applied to the well known cooperative MAC protocol (e.g. Cooperative MAC (CoopMAC) [15]). In order to compare the performance, a comparison of original and new version of CoopMAC is deployed in a network simulator. The simulation results demonstrate substantial improvements of new CoopMAC while mobility and different types of service traffic are considered.

The research work of this thesis was reported in several conference and journal papers.

1) A reference model is proposed in [32] for all cooperative algorithms used in relay-based cooperative wireless networks. Instead of link state information, which is considered as a key metric for radio performance aspects, we propose network state information for deciding when to cooperate, with the result of having effective solutions for application data. Network-centric metrics and user-centric metrics are discussed as two main aspects for beneficial cooperation. Access delay, movement, and delay ratio are considered as important metrics for cooperation algorithms, and their impact is analyzed in several scenarios. The simulation results, using 802.11b networks, demonstrate that these metrics strongly impact any cooperation strategy aiming to improve network performance. In the simplified analysis, guidelines are discussed in which conditions the cooperation will be effective when the rate adaptation is employed.

2) Cooperation in WLAN 802.11 standards is considered in [33] in terms of capacity gain and delay reduction. Delay ratio is introduced as the main metric for relay selection and the method for its calculation is described. Relay areas, as potential

locations of relay nodes for a given delay ratio, are calculated for different cooperation scenarios. The relay area corresponding a given delay ratio is an indication for the probability of occurrence of cooperation. The performance bounds of delay and capacity for cooperation scenarios are further analysed in the context of IEEE 802.11bg standards. These performance bounds demonstrate the potentials of cooperation in providing spectrum efficiency.

3) In [34], energy efficiency and capacity modelling are considered for cooperative cognitive networks. In this work, cooperative schemes to improve the performance of wireless cognitive networks are investigated. The idea of spectrum efficiency provided by cooperation is extended and it is further discussed how energy efficiency can be improved in cooperative scenarios with single relay nodes, for different wireless medium characteristics. Theses guidelines can be included in more advanced cognitive algorithms for cooperation decisions.

4) In [35], existing cooperative MAC protocols of IEEE 802.11 standards are reviewed and they are framed based on a proposed architectural model. A classification of the existing cooperative MAC protocols is further presented in three groups with respect to their operation and cooperative objectives: Minimum Transmission (Min-TX), Caching and Waiting for Failure (CWF) and Back-off Target Cooperation (BTC). By analysis of the system model and performance metrics for the Min-TX class of protocols, we evaluate the operation of Min-TX protocols and their performance gain. This evaluation indicates that cooperation techniques may provide a useful contribution to IEEE 802.11 communication challenges, but these are somewhat limited. For many communication scenarios, these protocols would only be useful for jumbo frames, packets larger than the 802.11 normal MTU. Only for direct data rates near the minimum values of the specific 802.11 amendment do clear advantages seem to exist. Also, it should be noticed that for random deployments of nodes, the probability of finding a node in a useful location is reasonably low for all stations except those with the same low direct data rate connections. Although the literature already presents many different cooperative protocols, with different performances, these weaknesses seem inherent to all protocols in the Min-TX class.

5) The concept of cooperative relaying strategies can be applied in autonomic management of mobile robotics [36]. In this work, the cooperative techniques appeared as the main techniques for the optimization of network resource utilization in autonomous networks. Due to the structure of mobile robotics, it is possible to control the location of relay nodes in such a cooperation scenario. This capability enables policy-based management schemes to determine the optimum location of each node of networks based on its power profile, application service and needed spectrum. It is further discussed in several scenarios how the replacement of relay nodes can enhance the performance of a mobile robotics network.

These contributions can lay down paths for cooperative schemes in other wireless technologies which have capabilities to exploit the cooperation.

1.4 Software Resources

Realizing the cooperative protocols in IEEE 802.11 standards needs an appropriate software resource. Any developed model in the context of IEEE 802.11 should be examined and verified through a network simulator. Most of the simulations were performed on OMNET++ [15].

OMNeT++ is a discrete event simulation environment. Its primary application purpose is the simulation of communication networks, but because of its flexible architecture, it is used in simulation of other distributed systems such as multi-processors and queuing networks. OMNeT++ provides modular architecture for models. The modules (components) are programmed in C++ and then by using a high level language called NED, the components are integrated into a larger components and models. OMNeT++ has extensive GUI support, can be embedded easily into applications. There are different simulation packages in OMNET++ which were developed for several communication systems and protocols. Mobility framework (MFw) is one of these work packages which supports IEEE 802.11 wireless networks, different mobility models, dynamic connection management and a wireless channel model. Therefore, MFw was used for implementation of proposed cooperative MAC protocols in simulation environment of OMNET ++ 4.0.

Besides the OMNET++, Matlab and MS-Excel were used for some mathematical analysis and data analysis.

1.5 Thesis Organization

Besides this introductory chapter, the remainder of this thesis is organized as follows:

Chapter 2 gives the background material of cooperative communications in wireless networks, especially for physical and MAC layers, and reviews the related works. Cooperation at the physical layer is often modelled as MIMO system, and MIMO performance metrics are applied for evaluation of different cooperative PHY protocols. The cooperative MAC layer comprises cooperation at multiple access issues and cooperation in standard MAC protocols. This chapter also presents how the conceptual difference of cooperation in the physical layer and higher layers of OSI model can affect the role of relay nodes.

Chapter 3 provides an overview of IEEE 802.11 standards. The physical layer specifications and frame formats are described in detail. Considering the frame format enables us to understand how the overhearing mechanism can obtain the useful information from exchanging packets between two stations. This chapter also presents the MAC protocols of IEEE 802.11 standards. The main characteristics of MAC protocol include Distributed Coordination Function (DCF), Carrier Sense Multiple Access with Collision Avoidance Mechanism (CSMA/CA). Different DCF access modes and frame formats in the MAC layer are also discussed. In this chapter, we classify the IEEE 802.11 cooperative MAC protocols based on their cooperative objectives. These categories are Minimum transmission (Min-TX), Caching and Waiting for Failure (CWF) and Back-off Target Cooperation (BTC). A generic architectural framework for cooperation called MAPE model is also presented in this chapter. The MAPE model covers all cooperation strategies, presenting a structured way to properly map the different cooperation phases. As a case study, we use MAPE model to present the operations of IEEE 802.11 cooperative MAC protocols. Accounting for the deployment features and mapping operation of the MAPE reference model, we present a comparison of all cooperative MAC protocols.

Chapter 4 presents the performance analysis of IEEE 802.11 cooperative MAC protocols. The system model and performance metric for Min-TX category are presented. Potential geographical area for locations of relay nodes for Min-TX and CWF category is analysed by theoretical and practical approximations. A theoretical analysis is developed to explore the performance bounds of throughput achieved by cooperative protocols of Min-TX category by accounting for amendments to the specifications of IEEE 802.11bgn . A lower bound of data packet size to guarantee the beneficial cooperation in Min-TX category is analysed and evaluated in term of Maximum Transmission Unit (MTU) imposed by IEEE 802.11. Furthermore, power performance and energy efficiency provided by cooperative schemes in IEEE 802.11 are also presented.

Chapter 5 details our development of the cooperative cross layer issues in IEEE 802.11 MAC protocols. Our proposed metric called CoopMetric is explained in detail for relay selection. This metric compromises several aspects of cooperation: Delay, reliability, mobility and stability provided by relay. A system model is presented for CoopMAC protocol enabled by CoopMetric. By implementation of this new version and original CoopMAC protocols in network simulator of OMNET++ and comparison of their performance, the role of CoopMetric is highlighted. The simulation results demonstrate how the CoopMetric can tune the lower layer operations to adapt to higher layer requirements. These adaptations are analysed for different types of traffic service which require various levels of bandwidth efficiency and reliability aspects.

Chapter 6 of this thesis concludes with a summarization of promising future research directions.

1.6 Concluding Remarks

This chapter presented an overall view of the thesis. The motivation and background for cooperative communications were discussed. The main motivation of cooperative communications is to maintain connectivity at high data rate but without investing in extra bandwidth or substantial changes in infrastructure. Although the initial contribution of cooperative communications is related to PHY layer aspects, cooperative techniques provide many solutions for other OSI layers such as MAC layer. The original contribution of the thesis and also the thesis organization were presented.

CHAPTER 2 COOPERATION CONCEPTS IN WIRELESS NETWORKS

Summary

The concept of cooperation can be addressed from different perspectives and it is important to determine the style of cooperation that should take place at each communication layer. Cooperation can offer different advantages and drawbacks, depending on how it is applied to each communication layer. Note that cross-layer approaches can provide different solutions for a cooperation scheme by combination of multiple layer approaches. The purpose of this chapter is to provide an overview of the structure of recent protocols and algorithms in cooperative wireless networks both at physical and MAC layers.

2.1 Introduction

The development of wireless communications has progressed tremendously due to its ability to provide mobile access and ubiquitous connectivity. However, there are key challenges that must be addressed in order to achieve reliable, high data rate, communication over the wireless channel. These are mainly related to channel aspects such as attenuation and multipath fading effects. Multipath fading is the random variation of channel quality in time, frequency and space which result in performance degradation of wireless communications. Therefore, effective solutions must address these different channel dimensions (time, frequency, and space) by providing diversity techniques and achieving different diversity gains. Diversity techniques increase the chances of a successful transmission by providing the receiver with several copies of the signal [37]. Many forms of diversity are possible depending on the characteristics of the underlying channel(s). Space diversity using multi-antenna systems is particularly interesting since it can complement other forms. MIMO techniques which are used in modern wireless transceivers have demonstrated promising possibilities to achieve spatial diversity gains. By exploring several links between source and destination and making use of advanced signal processing, MIMO systems are able to provide significant diversity gains for wireless channels due to the fact that fading occurs independently in each link. Nevertheless, practical limitations such as antennas dimension, battery size and power budgets in many users applications (e.g., sensor networks and cellular phones) are not easy to overcome and demand alternative approaches. One of these alternative approaches is cooperative diversity.

One view of looking to cooperative diversity paradigms lies in considering that these bring the advantages of MIMO systems to single antenna wireless devices by exploiting cooperation and antenna sharing. In this view, source nodes associate with other neighbour nodes, acting as relays (helpers) with the objective of providing extra transmission capacities to the given destination. As depicted in Figure 2.1, the destination (D) receives the combination of the original and relayed signals, respectively from source (S) and relay (R) nodes. The relayed signal can be reproduced by the relay node with amplification, compressing or decoding of the original data. In this case, by using relays as supportive antennas for forwarding or retransmitting the original transmission, cooperative communications can provide a virtual distributed antenna system to achieve diversity. Hence, the cooperative communication is sometimes known as Virtual MIMO (VMIMO) [38] in some of its realizations.

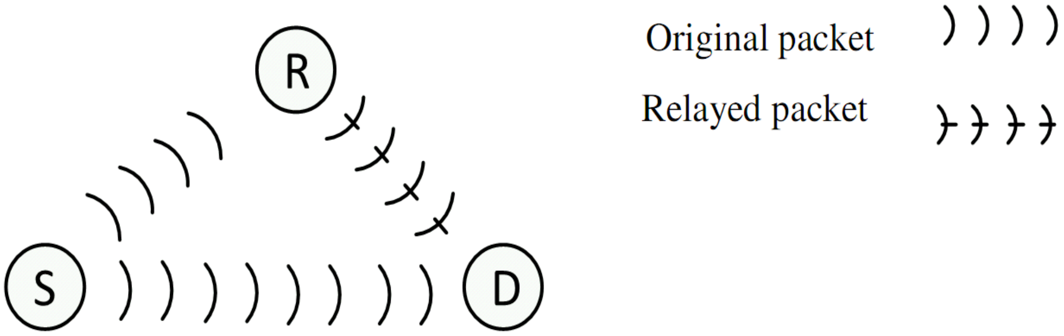


Figure 2.1 Cooperation at physical layer

Although the physical layer is the usual target of cooperative diversity techniques, cooperation is a versatile strategy which can be exploited by collaborative use of resources and by negotiating procedures within and across all OSI layers. Thereby, cooperative diversity differs from other cooperation techniques which improve successful communication opportunities, because it is limited to the physical layer. Cooperation gains can also be obtained by cross-layer design if other layers are involved.

The role of the relay node changes depending on the OSI layers which exploits the cooperation. The relay node operates as a virtual antenna when cooperation is applied at the Physical Layer. In contrast, when cooperation is applied in upper layers, the relay node mostly operates similarly to a repeater. Cooperative techniques in higher layers exploit useful characteristics of overhearing provided by conventional point-to-point wireless transmissions. This information enables nodes to decide if the cooperation is beneficial or not according to the cooperation objectives. For example, if overhearing information results in bandwidth efficiency of both S-R and R-D links compared to S-D link (Figure 2.2), a cooperative scheme in the upper layer can be triggered. In this case, appropriate signalling must be exchanged between source, relay and destination to control the cooperation action. Then the data packet is sent from source to relay first, and the same packet is (may be) forwarded from relay to the destination. This view of a relay node as a repeater does not support the combination of original and relayed signals at the destination node, the typical operation carried out by cooperative techniques at the physical layer. By using efficient methods of overhearing and analysis of information, cooperation in higher layers can provide more intelligent schemes without complex configuration requirements at the PHY layer.

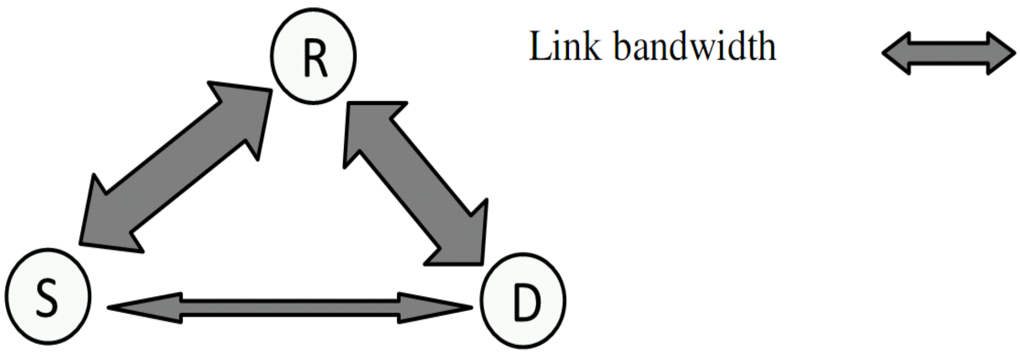


Figure 2.2 Relay node as a repeater for cooperation at upper layers. (Width of arrows illustrate practical link bandwidth)

In this chapter, we provide an overview of cooperative diversity and cooperative techniques, considering different aspects. Section 2.2 presents the concept of cooperation from the viewpoint of information theory. Cooperation techniques at the PHY layer and several cooperative protocols are discussed in section 2.3. Section 2.4 presents cooperation schemes at the MAC layer, considering multiplexing issues and MAC protocols. Section 2.5 concludes the chapter.

2.2 Information theory and Cooperation

The main idea behind cooperative diversity is to split resources allocated for direct and relaying transmissions, with the purpose of achieving important benefits in term of more successful transmissions. As an example, for a pre-assigned periodic symmetric Time Division Multiple Access (TDMA) scenario, as depicted in Figure 2.3 (a), there are two source nodes (S1 and S2) and two destination nodes (D1 and D2). In non-cooperation mode, each source node has also duration of T/2 to transmit its information (Figure 2.3(b)). In cooperation mode, there are two phases with duration of T/4: In phase I and III, each source node transmits its information to a given destination while the other source node overhears this information. In phase II, the overheard information will be relayed (Figure 2.3(c)). In this simple cooperative TDMA scheme, each source node wastes half of its transmission rate, since it allocates half of its transmission time to its own information and the other half to relaying information.

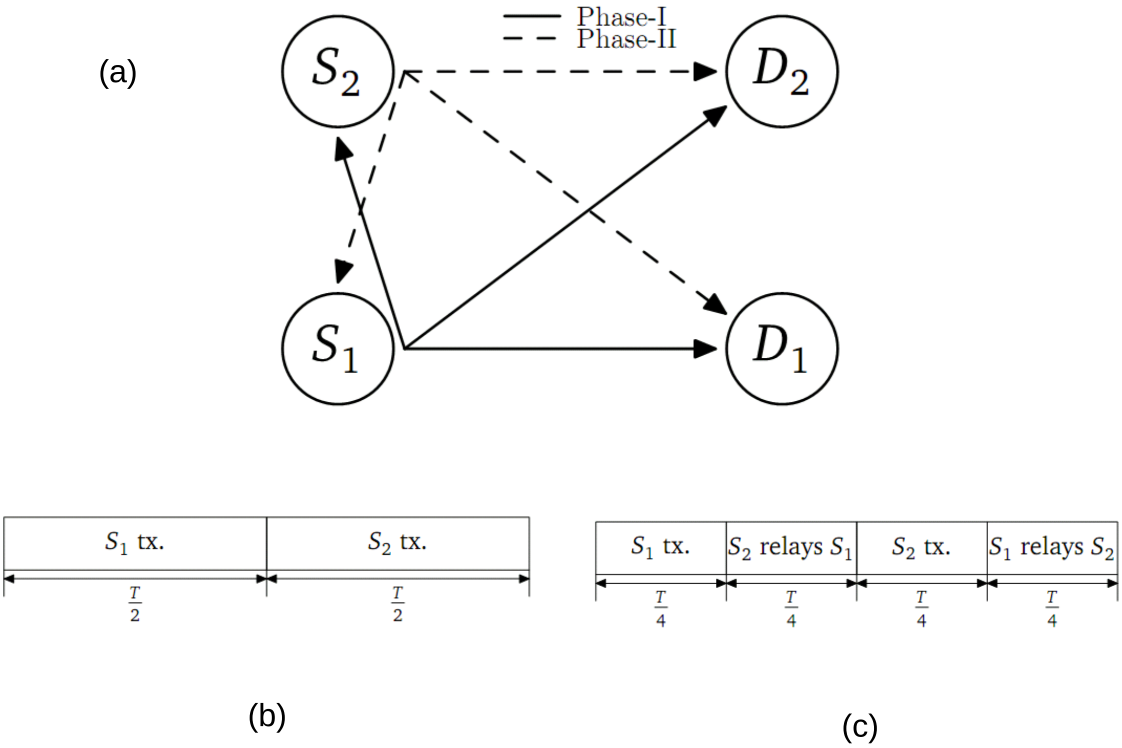


Figure 2.3 (a) Simple TDMA based cooperation: (b) TDMA in non-cooperation mode (c) TDMA in cooperation mode

The analysis of the above forwarding policy from the perspective of information theory as reported in [41] demonstrates the improvement of outage probability obtained by cooperative diversity. These achievements are provided due to independent realizations of the fading phenomena experienced by different nodes and independent success probabilities of different links. Moreover, the combination of the direct link and the relay link from a source to a destination leads to higher mutual information. This means that the destination can use information from both the direct transmission and the relayed transmission in order to decode the data. However, double transmission of the same information occurs at the cost of halving the transmission rate.

In order to improve this combination at destination, two classical relay protocols are considered by Laneman et al [42]: Decode-and-Forward (DF) and Amplify-and-Forward (AF). The main difference of these protocols refers to the operation of the relay node. In the cooperative AF protocol, the relay node amplifies the received signal and then forwards it. Therefore, the receiver accesses the information of two parallel noisy channels. In contrast, the relay node in a cooperative DF protocol decodes the received signal and then forwards it. Laneman et al considered some theoretical system models [41] applied for classical relay techniques, i.e. cooperative AF and cooperative DF protocols. Relay selection is made based on relay reception signal to noise ratio (SNR). If the SNR value is low, the relay stays silent, allowing the source to retransmit instead. Otherwise, the relay sends the amplified signal (for AF protocol) or decoded signal (for DF protocol). This technique is known as Selection Relaying. In another technique which is called Incremental Relaying, regular communication takes place and the relay overhears the transmitted signal, then if no acknowledgement (ACK) is received, the relay sends the stored signal to the destination. These proposals by Laneman improve the performance of the basic cooperative AF and DF protocols.

The study of cooperative diversity is inspired from classical MIMO. Thus, in most of the literature, MIMO-similar metrics, such as diversity and multiplexing gains, are taken into account for cooperative communications. From the point of view of information theory, there are multiple options to improve cooperative diversity transmission systems. By considering the basic mechanism in single relay approach, the first option can be to increase the number of relays [13]. In addition, the concept of orthogonality on source and relay nodes, using coding techniques borrowed from multi-antenna transmitter design and tuning the length of each phase of cooperation have posed several optimization issues related to cooperative diversity schemes [45][46][47]. Nevertheless, there are some existing challenges related to the theoretical aspects of cooperative diversity. These challenges can be classified into the generalization to network topologies and design of theoretical protocols that achieve (or improve approach to) the performance bounds computed by theoretical analysis.

2.3 Cooperation techniques at the PHY layer

There are several approaches to exploring cooperation at the physical layer which aim to achieve in practice the benefits predicted by information theory. Some techniques are based on adapting preexistent MIMO technologies and aim to achieve full diversity [41][43][44][47][49][50]. These techniques are usually developed starting from modeling cooperation as MIMO systems and consider the performance improvement obtained by diversity schemes in terms of power saving, coverage extension and reductions in error probability. They also investigate how to perform Adaptive Modulation and Coding (AMC) [39][40] boosting and consequently symbol rate boosting. By exploiting the benefits in a cooperative environment, it may be possible for an AMC system to shift to a faster modulation scheme leading to higher throughput performance. Moreover, this can reduce power consumption and average packet delivery delay.

Besides the techniques borrowed from MIMO and AMC systems, there exist other proposals that employ different types of coding schemes for exploring cooperation at the PHY layer, as we will discuss in following sections.

2.3.1 Coded Cooperation

In conventional communications, Forward Error Correction (FEC) codes are employed at the PHY layer for channel coding, in which each codeword begins with the original message bits followed by some redundancy. This redundancy allows the destination to detect a limited number of errors that may occur in the message, and even provides the correction for some types of errors without retransmission. Thus, this redundancy appended to the original message in FEC schemes provides additional information. Another type of additional information appended to the original message can also be obtained by cooperative diversity through the duplication of original message. This similarity between systematic FEC and cooperative diversity leads to their convergence into a powerful technique which is formally known as Coded Cooperation (CC).

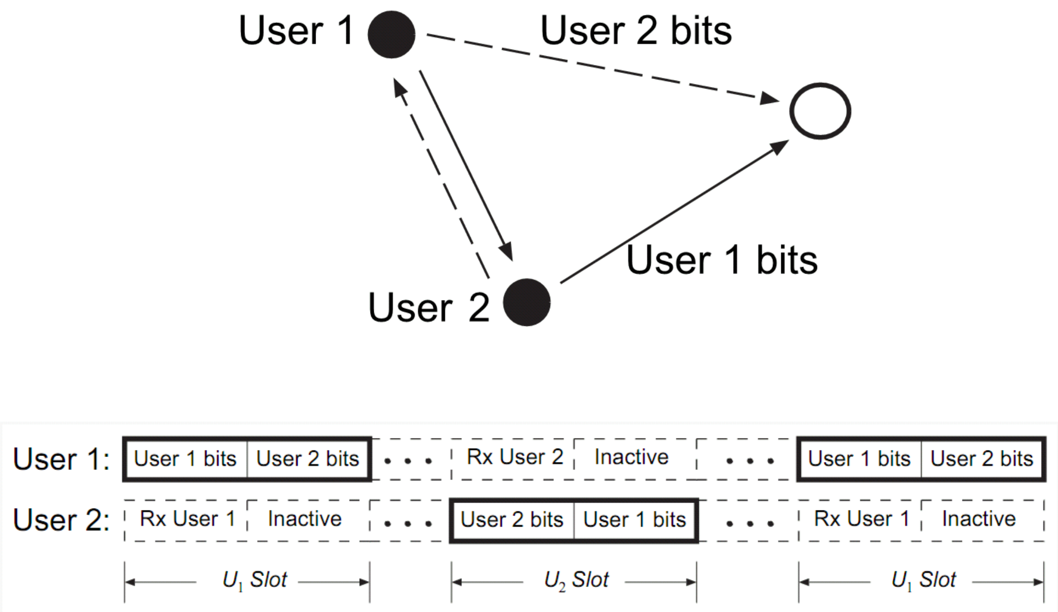


Figure 2.4 Coded cooperation implementation for a system using TDMA [52].

Hunter et al. [52] proposed a system model as indicated in Figure 2.4 in which CC is described for a TDMA cooperative system for two users with one destination. In this case, diversity is achieved by partitioning a user's codeword into two parts. Each user receives the first codeword partition from the partner, and upon successful decoding, transmits the second codeword partition. This technique results in that user's codeword being received at the destination through independent fading channels. The analysis shows the impressive gains in performance of this method. By applying more sophisticated and efficient coding schemes for the relaying decision, CC is able to avoid the retransmission of erroneous data leading to efficient resource utilization. Moreover, CC schemes are able to control the cooperation level by adjusting the amount of bits transmitted in each phase instead of using static portioning [51]. They can also enable the relay mode to operate efficiently in two modes of incremental relaying and selection relaying. As mentioned before, in incremental relaying, the relay only transmits if the packet at the destination is received with error, whereas, in selective relaying, the relay only transmits if it has correctly decoded the packet.

(a)

(b)

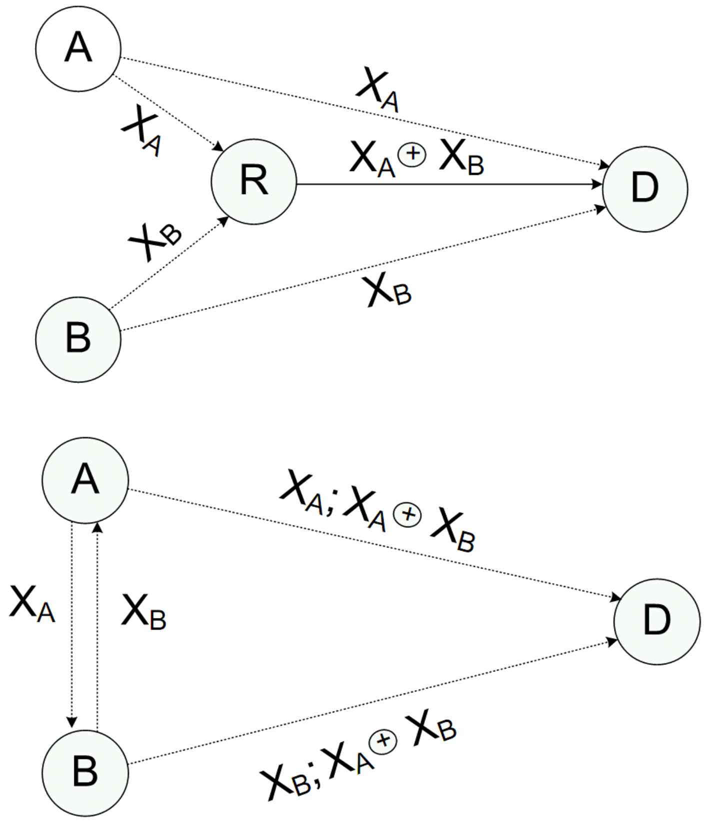


Figure 2.5 Cooperative communication with network coding

2.3.2 Cooperation Using Network Coding

Network coding was originally employed in wired networks in which additional information appended to the original message is obtained by linear combinations of the messages. This scheme explores the combination at bit level while channel coding operates at packet level. This combination can be also considered when cooperative diversity is employed. As a simple example, for two nodes of *A* and *B* shown in Figure 2.5 (a) with coded packets of X_A and X_B , relay node (R) can assist both terminals simultaneously by transmitting $X_A \oplus X_B$ where $\oplus$ is the XOR function to build a combined message. By using one relay node and allocation of at most three subsequent transmission slots, the information transmitted from both A and B can be retrieved correctly, even if the direct links of both nodes fail.

Network coding can be also applied in an alternative way as shown in Figure 2.5 (b). Here network coding is only carried out by each other's cooperative partner and the forwarded information is conducted in another time slot, which results in a potential gain. Cooperation through network coding outperforms other forms of diversity communication. According to the analysis performed in [54] with Binary Linear Combination, for a given slot error rate ρ, the probability of a successful packet transmission turns from $P_{succ} = (1-\rho)^2$ into $P_{succ} = (1+2\rho)(1-\rho)^2$. The improvement is obtained at the cost of one or two extra slots compared to the conventional direct transmission.

Building on the principle of PHY layer network coding, there are several proposals aiming to improve the performance of cooperative communications. The solutions presented in [55] and [56] provide Non-Binary Linear Combination with a focus on the composition of the relay messages with more combinations of original messages. The authors of these proposals demonstrate that binary combination is unable to reach the upper bound of improvement gain, thus they improve network performance by replacing non-binary combinations which increase the probability of successfully decoding relay messages. In other proposals using network coding, the authors focus on energy sharing [57] and minimization of interference effect [58][59] by simultaneous transmission. They show how the algebraic linear combination and classical complex approach of symbol constellations can enhance the cooperative communications when they are enabled by network coding schemes. Although network coding solutions bring some extra benefits for cooperation scenarios, the design of the MAC layer becomes quite complex.

2.3.3 Cooperation Techniques Exploring Space-Time Coding

Space Time Coding (STC) [60] has become known as a technique to improve the reliability of data transmission in wireless communication systems using multiple transmit antennas. STC schemes rely on transmitting simultaneous replicas of the same signal to the receiver in the hope that at least some of them may survive the physical path between transmission and reception in a good enough state to allow reliable decoding. Anghel et al [62] studied space-time coding for classical multi-antenna systems and showed how it can perform efficiently in a distributed VMIMO system. In [44] and [63], the authors employed Orthogonal Space Time Block Code (OSTBC) and they demonstrate the mutual benefit obtained by cooperative and local space diversities. However, there are some challenges for STC use in cooperative diversity. The main challenge refers to the number of available relays and their features in implementation of STC design techniques in cooperation systems. These features can be synchronization of relays, behaviour of the arriving and departing relays to the relays set and unfeasibility of OSTBCs exploitation in very large relay set. These challenges cannot be solved individually and there are trade-off issues between them. These trade-off issues are addressed by some designs presented in [61][64][65] in which different antenna selection and antenna combination methods are discussed to achieve STC techniques properties in cooperative diversity systems.

2.4 Cooperation Techniques Operating at MAC Layer

Over the last decade, the potential of cooperative relay based wireless communications has mostly attracted research activities in theoretical and practical aspects related to PHY layer. Some of the proposals aiming to provide beneficial performance improvements at PHY level were discussed in Section 2.3. Nevertheless, both telecommunications operators and end-users will reject a wireless network with manual configuration requirements at the PHY layer. Therefore, the MAC layer necessarily plays a crucial role in realizing wireless networks enabled by cooperative protocols, at least for automatically handling PHY layer cooperation aspects.

The concept of cooperation at MAC layer can be structured in two categories:

1) **Cooperation applied at access method level**: In this category, cooperation is explored in the physical layer and novel multiple access methods should be employed to properly coordinate the multiple users (sources, relays and destinations) and their access to the wireless medium.

2) **Cooperation applied at MAC protocol level**: In this class, cooperation is explored by near-to-standard MAC protocols while only conventional point-to-point communications exists from point of view of PHY layer. According to information obtained from PHY layer of neighbor nodes, these MAC protocols can determine potential beneficial cooperation. Therefore, instead of cooperation at

PHY layer (which often is decided hoping for improvements, or, in another words, as blind cooperation) the MAC protocol can perform more intelligent cooperation decisions. Moreover, capabilities provided by the PHY layer and requirements of upper layers can meet together in MAC layer by employing cross-layer design considerations. This improves network performance through the advanced usage of cooperative schemes in standard MAC protocols.

In this section, both of these categories will be discussed in detail.

2.4.1 Cooperation Applied at Access Method Level

In wireless communications, multiple access methods allow several nodes to connect to a common transmission medium and to transmit over it in order to share the capacity. In conventional wireless communications, there are three fundamental types of multiple access methods: TDMA, Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA). These methods are based on multiplexing schemes in time, frequency and spread spectrum respectively.

Since cooperative communications present a new paradigm with an extra entity of relay node which is added to source and destination nodes considered in conventional communications, multiple access techniques should coordinate source and relay node to access the wireless channel for transmission of a single packet. In order to transmit packets in two phases of cooperation from source to relay and relay to destination, orthogonal channels are needed. This orthogonality may be achieved in time by using modified TDMA, FDMA and CDMA. In TDMA and FDMA systems, source nodes transmit over orthogonal time or frequency channels and radio resources must be properly allocated to fully exploit the advantages of cooperation. In contrast, in CDMA systems, users transmit simultaneously over different code or spatial dimensions, but may experience Multiple Access Interference (MAI) due to practical difficulties in achieving orthogonality among the different dimensions. Therefore, in order to mitigate MAI, preceding techniques at the relays or multiuser detection schemes at the destination must be employed. Sendonaris et al. [37][66] investigate the cooperation problem in a network with two mobile users where they want to transmit their data to a base station. Nodes can cooperate with each other using CDMA, TDMA, or FDMA by combining the received message from the other node in their own signal. The results reveal that optimal strategy for combining the user signals is obtained in the case of CDMA. Furthermore, significant cooperation gain, in terms of higher data rate and more robustness to channel variations, is also achieved by this cooperation scheme. However, increasing number of users leads to high complexity, driving from optimal method, and makes it impractical for a larger network. Although a suboptimal solution is also provided by the authors, the implementation of this method still requires extra overhead in the receiver structure which may not be cost efficient in cheap wireless devices. Sadek et al. [67] proposed an approach for designing TDMA based protocols for relay-based wireless networks, and the results indicate a relevant increase in the maximum stable throughput by applying the solutions to pure TDMA. In this solution, potential relay nodes store packets sent to the Access Point in a queue, and if no reply is received they use the empty time slots in a TDMA allocation method to retransmit the failed transmitted packets.

One of the main challenges in multiple access strategies is relay selection algorithms to find the best relay to forward the overheard packet. This is in contrast to the PHY layer where individual signals are being retransmitted by the relay. This fact causes the cooperation in the MAC layer to be with less overhead compared to that in the PHY layer.

2.4.2 Cooperation Applied at MAC Protocol Level

In wireless communications, there are several issues such as addressing, assigning channels to different users, and avoiding collisions which need a control mechanism to be applied to multiple access methods. Therefore, new protocols which are known as Media Access Control (MAC) protocols operate based on a multiple access methods and control mechanism. While multiple access methods are classified based on channel resources (e.g. time, frequency and code), MAC protocols are concerned with the collision methods and packet delivery. Collision recovery and collision avoidance are two main categories in existing MAC protocols of wireless communications. ALOHA and Carrier sense multiple access with collision avoidance (CSMA/CA) protocols are well known examples residing in the respective mentioned categories.

Inspired by the attractive features and potential benefit of cooperative relay based communications [37][41][42][44][66], there have naturally been efforts to exploit the cooperative techniques in some standard MAC protocols. The main characteristic of these standard MAC protocols is that stations are able to overhear traffic from other stations. In a standard communication scenario this is a problem which imposes higher medium access variability as well as lower throughput. However, the same factors can be exploited in order to enhance network performance, if stations collaborate with each other by creating multiple signal paths from source to destination and forwarding overheard information.

When cooperation is applied in the MAC layer, the communication between source and destination is limited to signaling required for coordination of the cooperation while the data message is sent from source to relay and then is forwarded from relay to destination. It means that the relay operates similarly to a repeater or Store-and-Forward (SF) relaying protocol. In this case, the destination receives one copy of data packet through the relay. This is in contrast to physical layer relaying where the relay creates a distributed virtual antenna system for relaying the whole message and the destination receives the original and relayed packets respectively from direct and relay paths.

The MAC protocol is traditionally informed by the network layer about the next-hop to be used. Overhearing other node's traffic can be beneficial for those MAC protocols that are based on a shared communication medium with medium sensing functionalities. In cooperative MAC protocols the information overheard from neighbours, both from PHY and MAC layers, can help to choose intermediate relay neighbors with the aim of facilitating cooperation, while not requiring additional communication or processing at the network layer. ALOHA protocol and IEEE 802.11 MAC protocol are two categories which received special attention for cooperation.

The concept of cooperation is also addressed in some works related to ALOHA systems. Analyzing the stability of interacting queues in the ALOHA system were studied in [68] and [69]. The issue of stable throughput region and exploring bounds on the stable throughput region of ALOHA are the main concerns of works reported in [70][71][72][73]. Studies on the design and stability analysis of the cognitive collaborative multiple access protocol can be found in [74][75][76].

The IEEE 802.11[7][8][6][10] family of protocols arose as the dominant industrial standard for WLANs providing simple mechanisms for the establishment of both infrastructure or ad-hoc networks. Also, it can support multiple transmission data rates depending on observed wireless channel conditions, terminal capabilities, performance requirements, spectrum requirements, or administrative policies. Multiple transmission data rates allow the source node to adjust its data rates according to distance to the destination. The received SNR value at the destination has an inverse relation to its distance from the source node. Therefore, low distance can provide high SNR and modulation schemes with high symbol rate and thus data rate and inversely. This adaptation helps multiple data rates to increase the range of wireless communications. However, this feature leads to the so called performance anomaly problem [102]: if equal transmission opportunity is to be provided to all participant nodes in the same 802.11 network, the result is that nodes using a low data rate will take a longer time to complete transmission when they are allowed to transmit, thus degrading the performance of the remaining, higher rate nodes. For example, when using the IEEE 802.11g [7] protocol, transmitting a packet of fixed size at the minimum data rate (6Mbps) makes the shared communication channel busy for a period of time 9 times longer compared to a packet transmitted at the highest data rate (54Mbps). Developments of the most recent revisions to the standard, such as IEEE 802.11n [8], which boost the maximum data rate up to more than 300Mbps, further exacerbate the problem. So the ratio of low data-rate nodes to all nodes in the same collision domain affects channel efficiency and overall system performance. In other words, total system performance is constrained by nodes with low data rates. In addition, nodes at the edge of a multirate cell suffer from higher packet loss due to worse channel conditions and higher interference levels.

CoopMAC [17] and Relay-enabled Distributed Coordination Function (rDCF) [16] protocols are two relevant solutions which address the performance anomaly problem. The main idea behind these solutions is that one low data rate direct transmission link can be replaced by two faster transmission links, using a relay node, yielding higher performance. This mechanism is applied by overhearing other nodes' transmissions and by estimating their communication data rates. Based on overhearing information and in order to find the best relay node with high performance gain, a neighbour mapping model is employed. After the selection of relay node, a new set of modified control packets are exchanged to coordinate the packet transmission in two paths of source-relay and relay-destination. This cooperative technique can improve network capacity by reducing the transmission delay between the source and destination. The reduction of transmission delay appeared as a cooperative objective in several IEEE 802.11 cooperative MAC protocols [16]-[23]. Besides the reduction of transmission delay, there are other cooperative objectives such as service differentiation and fairness improvement which were further discussed in [30] and [29]. These solutions exploit the overhearing information exchange between users to address the aspects of higher layer issues by using cooperative algorithms.

Besides the well known MAC protocols which attract much attention for cooperative techniques, another class of cooperative MAC methods exploits the Automatic Repeat Request (ARQ) [77] for the purpose of cooperation. In standard ARQ, if the source node does not receive an acknowledgment before the timeout, it usually retransmits the packet until the source node receives an acknowledgment or exceeds a predefined number of retransmissions. In cooperative ARQ scheme, the relay node stores the packet originated by the source, and based on the Acknowledgment (ACK) from the destination the relay node decides to participate in cooperation. If the destination replies with a negative acknowledgement (NACK) to the original transmission, the relay node starts to cooperate by retransmitting the stored packet.

The concept of cooperative ARQ was tackled from a fundamental point of view, considering simplified network topologies, and considering ideal scheduling among the relays [79]-[84]. In [79], the performance gains using cooperative ARQ protocols were analyzed in terms of improved probability of error. The authors of [80][81] demonstrated how cooperation can enhance the outage probability and SNR gain. The effect of cooperation on saturation throughput performance was studied in [82] and the improvement through cooperation was concluded. A delay model for single source and single relay for cooperative ARQ protocols is presented in [83]. In [84], the authors propose a collaborative ARQ protocol that exploits diversity through collaboration in wireless networks. They demonstrate that the proposed cooperative ARQ protocol can achieve the same performance as an array of M antennas. Some other works focused on the relay selection algorithms for cooperative ARQ schemes wherein the best candidate relay node [85][86] and a set of the best candidates [87][88] are selected

Furthermore, the Hybrid Automatic Repeat Request (HARQ) method [78] can also be employed in the context of cooperation. Standard HARQ is a combination of high-rate FEC coding scheme and ARQ method. HARQ performs better than ordinary ARQ in poor signal conditions due to the use of coding schemes. Zhao and Valenti [89] proposed a cooperative HARQ method between the nodes in several clusters. In this method, each cluster has one pair of source and destination and several potential relay nodes. After the original transmission by the source is done, each relay has an opportunity for cooperation, provided that the original transmission to destination was failed and the relays store the original packet. The relay with less distance to the destination has high priority for cooperation. The numerical results and analysis confirm the performance improvement of HARQ over the non-cooperative HARQ method.

2.5 Concluding Remarks

In this chapter, cooperative communications were investigated from the view points of information theory, physical layer and MAC layer protocols. Cooperative diversity aims to reach the performance of MIMO systems at a lower cost with single-antenna nodes. Therefore, information theoretical models consider the MIMO system as an inception to compute the performance bounds achieved by cooperative diversity schemes in terms of MIMO system metrics. However, these models are far from being put into practice, and cooperation at PHY layer attracts further works to achieve the possible objectives predicted by information theory. The existing cooperative protocols in the physical layer were presented and it was discussed how different types of coding schemes can improve the performance of cooperative diversity. Cooperation in the MAC layer was analyzed in two categories of multiple access issues and standard MAC protocols. In the first category, multiple access issues are studied to fine tune the channel access for cooperative PHY layer protocols and the key objective of the second category is to exploit cooperation in standard MAC protocols such as DCF and ARQ protocols.

CHAPTER 3 COOPERATION IN IEEE 802.11 WIRELESS NETWORKS

Summary

There is great attention given to exploiting the cooperative techniques in different wireless technologies. IEEE 802.11standards have attracted major research works to provide solutions for the challenges faced. In order to apply efficient cooperative schemes and algorithms for a wireless technology, we need to consider its potentials and capacities as well as limitation, complexity and requirements needed to obtain the cooperative objectives. This chapter presents IEEE 802.11 specifications in PHY and MAC layers. It also presents three categories of cooperative MAC protocols in IEEE 802.11 standards and provides a brief description of the operation for each protocol. Finally, a comparison of protocols is presented to highlight their characteristics in terms of deployment issues and MAPE model phases.

3.1 Introduction

IEEE 802.11 standards[6]-[14] are known as the popular, cheap, and flexible technology to support infrastructure WLAN and many wireless ad hoc networks. This technology specifies both the MAC and the PHY layer protocols. The objective of the PHY layer is to use the suitable modulation schemes given the wireless channel conditions and provides the required bandwidth, whereas the MAC layer operates in a distributed manner on how to allocate the offered bandwidth in the shared medium between all stations.

The prominent element for the success of IEEE 802.11 is its MAC layer which can operate on top of several PHY layers and it provides robust and adaptive schemes, which can be tailored to varying conditions. The practical features of IEEE 802.11 MAC and cooperative schemes have led the research community to provide a diversified set of solutions for different challenges from rate adaptation techniques [90]-[99] concerned with the physical layer to service differentiation [29] at the application layer and even cross-layer approach.

In this chapter, we provide an overview of existing cooperative MAC protocols in IEEE 802.11 standards. In order to have a comprehensive study of cooperative MAC protocols, we present a new generic architectural reference model. This reference model enables us to model the cooperation behaviour of each protocol. It also provides a unified framework and terminology for comparison of protocols. In this chapter, the existing protocols are classified based on the potential objectives obtained by cooperative techniques. The architectural and practical aspects of these protocols are also addressed.

The remainder of this chapter is organized as follows: Section 3.2 reviews the Physical (PHY) layer and MAC layer of IEEE 802.11 standards. Section 3.3 provides different categories of cooperative MAC protocols proposed for IEEE 802.11 standards. This section is followed by the details of each category as well as existing protocols in each category. These protocols are also compared in concept of architectural model presented in Section 3.5 and also operational issues. Finally a summary of this chapter is presented in Section 3.5.

3.2 An overview of IEEE 802.11 standard

3.2.1 IEEE 802.11 Physical (PHY) Layer

The physical (PHY) layer provides functionalities to transmit and receive data packets properly over a shared wireless medium. The PHY layer operates as an interface between the MAC layer and the wireless medium. The main functions of the physical layer are: 1) carrier sense indication, 2) interaction and packet exchange with the MAC layer, and 3) transmission and reception of data packets by using signal carrier and spread spectrum. The IEEE 802.11 standard includes several physical layers:

The original IEEE 802.11standard was published in 1997. It defines three different PHYs: frequency hopping (FHSS) and a direct sequence spread spectrum (DSSS) in the unlicensed 2.4 GHz band, and infrared (IR) at 316–353 THz. It supported a basic data rate of 1 Mb/s with an optional 2 Mb/s mode.

The high-rate project 802.11b [6] was started in 1997 and was released in 1999. It boosts the data rates of the DSSS PHY to 11 Mb/s in the 2.4 GHz band. It is currently the most prevalent physical layer. The main challenge posed by 802.11b is the interference from the other devices in the free Industrial, Scientific and Medical band (ISM).

The IEEE 802.11a amendment was released in 1997. It operates in the 5 GHz band and it uses the orthogonal frequency-division multiplexing (OFDM) PHY that supports a data rate of up to 54 Mb/s data rate. The main issue with 802.11a is its short range. Furthermore, as 802.11a operates in the 5GHz band, communication with legacy 802.11 devices is not possible and this interoperability problem led to the formation of 802.11g.

The 802.11g standard [7] was released in 2003. Since it provides DSSS-compatible signalling in the 2.4 GHz band and operates on both DSSS and OFDM-based physical layers, it is able to support a maximum data rate of 54 Mb/s. Similar to 802.11b, it suffers from interference in the ISM band.

The IEEE 802.11n standard [8] was released in 2009. The main feature of this standard is multiple-input multiple-output (MIMO) capability. In order to obtain the spatial multiplexing, a flexible MIMO system allows for arrays of up to four antennas. The major innovation of this standard is the use of an optional 40 MHz bandwidth for the channel while the previous amendments support 20 MHz bandwidth. It operates in both the 2.4 and 5 GHz bands. Special features such as 20/40 MHz bandwidth, various antenna configurations and different modulation schemes provide data rates of up to 600 Mbps. Furthermore, IEEE 802.11n has some features which can be exploited by medium access enhancements. Proposed enhancements to 802.11n are under development as part of IEEE 802.11ac [9] amendment. In this amendment, wider RF bandwidth (up to 160 MHz), more MIMO spatial streams (up to 8), multi-user MIMO, and high-density modulation (up to 256 QAM) will be employed.

Comparisons of the PHY specifications for the most popular IEEE 802.11 standards (i.e.802.11a, 802.11b, 802.11g, and 802.11n) are illustrated in Table 3–1. Besides the PHY evolution in 802.11 in order to support the high data rates required for current and future application services, there are some other amendments which address different frameworks such as vehicular communication (802.11p [11]), mesh networking (802.11s[12]) and video transport stream (802.11aa[13]). More details of PHY layer architecture and frame format are presented in Appendix I.

Table 3–1 Characteristics of the various physical layers in the IEEE 802.11 standard

Characteristic	802.11a	802.11b	802.11g	802.11n
Frequency	5 GHz	2.4 GHz	2.4 GHz	2.4GHz/5 GHz
Rate (Mbps)	6, 9, 12, 18, 24, 36, 48, 54	1, 2, 5.5, 11	1, 2, 5.5, 6, 9, 11, 12, 18, 22, 24, 33, 36, 48, 54	6.5 to 600
Modulation	BPSK, QPSK, 16 QAM, 64 QAM (OFDM)	DBPSK, DQPSK, CCK (DSSS, IR and FH)	BPSK, DBPSK, QPSK, DQPSK, CCK, 16 QAM, 64 QAM (OFDM and DSSS)	BPSK, QPSK, 16 QAM, 64 QAM
Basic Rate	6 Mbps	1 or 2 Mbps	1,2, or 6 Mbps	

3.2.2 IEEE 802.11 Media Access Control (MAC) Layer

The IEEE 802.11 MAC protocol provides a reasonable reliable delivery mechanism for user data over a wireless shared medium, which is organized in channels. The key feature of the IEEE 802.11 standards is that even though its PHY layer has evolved over the different amendments, all the amendments are based on the same MAC layer, which operates on top of all the physical layers. Additional functionalities to the basic MAC were always added as optional functionalities, preserving backward compatibility [10][14].

The IEEE 802.11 MAC supports two access methods: Distributed Coordination Function (DCF) and Point Coordination Function (PCF). These methods are classified respectively as contention-based and polling based MAC protocols. The DCF method provides a contention-based service to access the shared medium while the PCF method is the optional access method in IEEE 802.11 and can provide infrastructure WLANs enhanced by Quality of Service mechanisms (QoS). Different access modes and MAC frame formats of IEEE 802.11 are explained in detail in Appendix I.

3.3 Classification of IEEE 802.11 cooperative MAC protocols

Several works have explored the cooperative communication concept in IEEE 802.11. Taking into consideration the different techniques and solutions proposed, it is natural that the underlying concepts and mechanisms share some similarities. Therefore, for a brief overview of the current state of the art, a categorization of the solutions is proposed, based on how these solutions exploit the wireless medium in order to provide enhanced performance. In this classification, three parts of the DCF transmission cycle will be improved by cooperation techniques: Back-off waiting, transmission of data packets, and acknowledgement of reception. The categories can be listed as following:

1) Minimum Transmission (Min-TX): The idea of this category is reducing transmission time while exchanging data frame by using two fast transmissions (by using relay) instead of a slow one. Although all protocols present similarities, some of them employ other known techniques such as traffic aggregation, network coding, throughput mapping and opportunistic relay selection always with the claim of enhancing the cooperation gain.
2) Caching and Waiting for Failure (CWF): The protocols of this category operate based on the overhearing and storing of the original packets by potential relay node(s) and when the ACK frame was not successful, the store packets will be retransmitted by relay node(s).
3) Back-off Target Cooperation (BTC): The key idea of this category is to modify the back-off window by cooperative techniques in order to achieve some performance improvements.

Table 3–2 summarizes the proposed classification of IEEE 802.11 cooperative MAC protocols, and for every category we present its key objective and special features. The protocols of each category and their special features will be described in the section following this one.

Table 3–2 Classification of 802.11 Cooperative MAC protocols, key objective and protocols

Category	Key objective	Special features
Minimum Transmission (Min-TX)	Replace two fast transmissions by using relay instead of one slow one (e.g. CoopMAC, rDCF, CoopMACA ,CODE ,EMR and ORP).	Aggregation (CoopMACA) Network coding (CODE) Priority mapping (EMR) Opportunistic Relay (ORP)
Caching and Waiting for Failure (CWF)	Neighbours which store the packet will forward it after they sense the lack of ACK (e.g. CMAC, CD-MAC, NCSW and PRCSMA).	PHY coding scheme (CMAC,CD-MAC) ARQ technique (NCSW, PRCSMA)
Back-off Target Cooperation (BTC)	To modify the back-off window and vary the priority for access the medium by a cooperative scheme (e.g. SD-MAC and C-MAC).	Service differentiation (SD-MAC) Collision resolution (C-MAC)

3.3.1 Minimum transmission (Min-TX)

The key objective of protocols in this category is to minimize the transmission delay of data packets. The main concept underlying solutions with this objective is that two transmissions at a faster data rate may result in a lower delay than a single transmission at a slower data rate. Protocols fitting this category are rDCF [15], CoopMAC [17], RAMA [18], and CCMAC [19]. Furthermore, some special techniques and features can improve the performance of the protocols in this category, such as frame aggregation in CoopMACA [20], network coding in CODE [21], priority mapping in EMR [22] and opportunistic method of relaying in ORP [23].

Since the design goal of this approach is to reduce the delay of transmitting data and to improve network performance, the Monitor phase of cooperation protocols considered in this category includes sensing several parameters such as data rate, RSSI and SNR. The Analyze, Plan and Execute phases vary according to the initiation of the cooperation and implementation method. In the following, we describe these phases for every protocol of this category.

Relay-enabled Distributed Coordination Function (rDCF)

The rDCF protocol [15] proposed the use of relay communications in the DCF mode of IEEE 802.11 for wireless ad hoc networks in order to improve the existing physical layer multirate capabilities. The main feature of this protocol is that a slower direct transmission is replaced by two faster hop transmissions. To do that, every node collects information from nearby neighbours by listening and monitoring ongoing transmissions. If the overhearing node finds that packets can be transmitted faster by acting as a relay between sender and receiver, it adds the identity of the sender and receiver into a database called *willing list*. The willing list is periodically advertised to all one-hop neighbours. After reception of other willing lists, nodes add the potential relay nodes into their *relay table*. When a node has a packet to send, it first searches the relay table. If it cannot find a compatible relay node, standard DCF is applied. Otherwise, to coordinate the cooperative communication, a new type of handshaking is performed between the sender, relay and receiver nodes by using modified RTS and CTS packets.

The mathematical analysis considered throughput gain and lower bound of node density. It was demonstrated that the throughput gain increases as packet length increases and when packet length is too small (less than 400 bytes), rDCF performs worse than DCF. It means that the control overhead of rDCF is more than DCF and there is a lower bound of packet length leading to useful cooperation. The lower bound of node density was further discussed in order to find at least one relay node when the distance between source and destination nodes is varied. In [15], rDCF protocol was compared to DCF known rate adaptation protocol, Receiving-Based Auto Rate (RBAR) [91]. In [90], it has already been shown that RBAR outperforms the standard DCF. According to simulations, the rDCF protocol outperforms the RBAR protocol in terms of throughput and delay as expected in mathematical analysis. The simulation also showed that unfairness does not exist under rDCF because the channel conditions between the sender and the relay node and between the relay node and the receiver are more stable than the direct link. As a result, the number of transmission failures due to channel errors can be significantly reduced by using relay. The impact of hidden relay nodes and mobility effects was further studied on the performance of rDCF. The simulation shows that the impact of hidden relay on the delay performance is almost negligible and throughput of rDCF is always greater than that of RBAR. In a mobility model drawn up by authors of rDCF protocol, the delay under rDCF is significantly less than that under RBAR. rDCF outperforms RBAR because it can have a higher transmission rate when the sender and the receiver are far away from each other. For the same reason, the total throughput under rDCF is much better than that under RBAR.

Cooperative MAC (CoopMAC)

The authors of the CoopMAC protocol [17] proposed two versions of a MAC protocol for WLANs and wireless ad hoc networks, the second version (CoopMAC II) being more compatible with the existing IEEE 802.11 standards. Similarly to the rDCF protocol, every node opportunistically and passively collects information about channel conditions from its neighbours. With this information, it can measure their signal to noise ratio (SNR) and estimate relative distances and the modulation scheme used. Although the node has access to this information, the modulation scheme is not present at the MAC layer. In the CoopMAC protocol, the MAC addresses of potential relay nodes, as well as the transmission rates to the Access Point (for infrastructure WLANs), are stored in a table called *CoopTable*. As shown in Figure 3.1, when a packet is ready to be sent, source node (S_s) searches the *CoopTable* for a potential relay node. If S_s succeeds in finding a relay node such as S_h which provides useful cooperation with performance improvement, then S_s sends a modified RTS packet including the MAC address of S_h in reserved field of MAC header (Figure 3.1). S_h responds with a new control packet called Helper To Send (HTS) to inform the source that it can operate as a relay node. Afterwards the destination (S_d) sends a CTS packet to complete the handshaking. The data packet is exchanged from source to relay and then forwarded from relay to destination. Figure 3.1 (c) shows the coordination of control and data packets and also the computation of NAV timer by hidden nodes (e.g. STA1 and STA2).

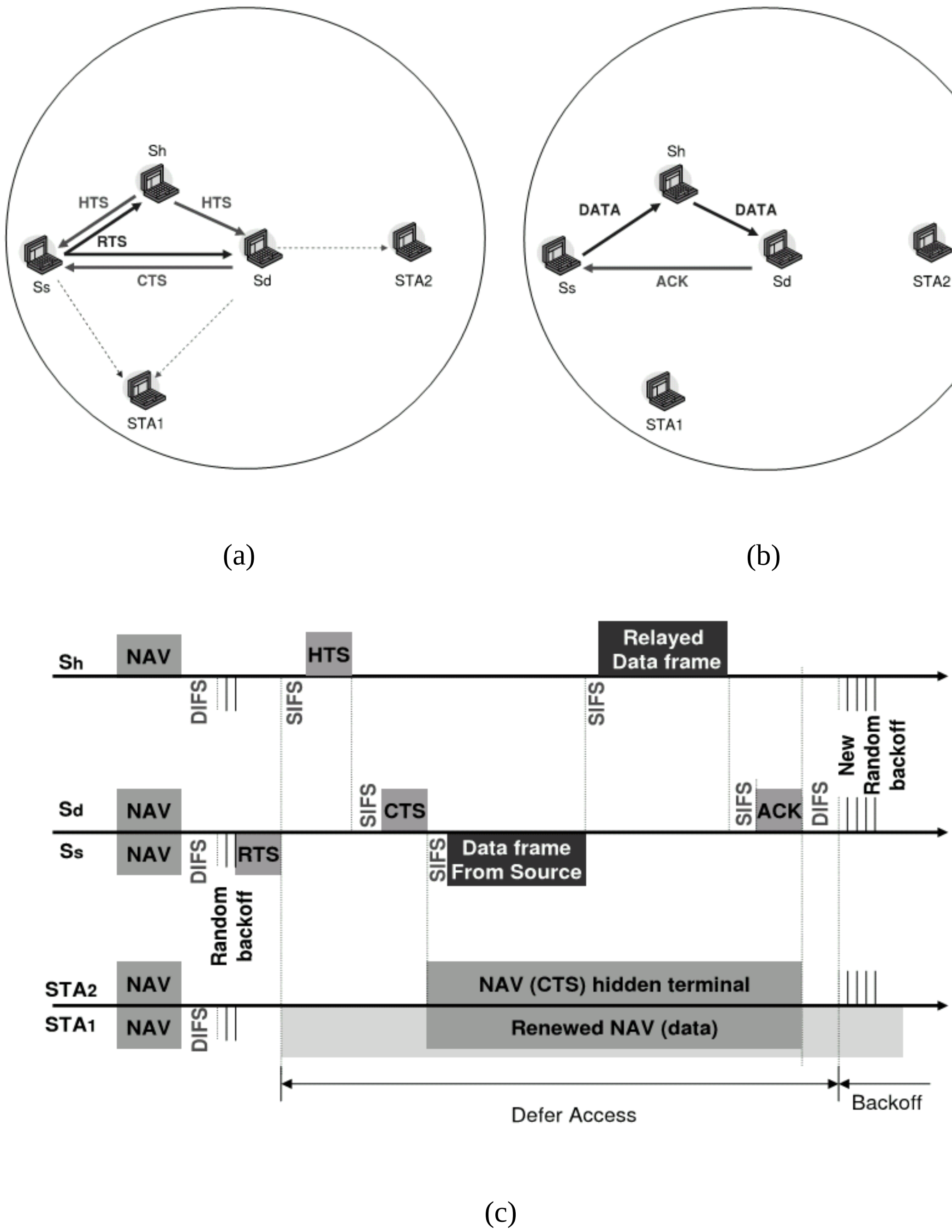


Figure 3.1 CoopMAC protocol [17](a) Control message flow, (b) Data message flow, (c) Defer access mechanism

In analysis of part of the CoopMAC protocol, the authors studied the mathematical model to obtain the saturated throughput of CoopMAC and also the computation of cooperative regions which are the potential area of relay nodes in IEEE 802.11b.

The simulation results obtained in [17] show that the CoopMAC protocol can provide better performance in terms of capacity gain, service delay, and energy efficiency when compared to legacy 802.11b MAC protocol. The throughput achieved by CoopMAC increases as the number of mobile nodes in the network increases since the probability of a low rate station finding a high-rate two-hop path increases. Results concerning the impact of node mobility in CoopMAC indicate that, for an indoor office mobility setting, performance improvements will be significant when compared with a legacy IEEE 802.11b network. Therefore, it is concluded that cooperative MAC almost isolates the impact of mobility on network performance compared to high impact of mobility on the link adaptation algorithm of legacy MAC protocol. The reduction in interference obtained with CoopMAC can further improve overall system performance due to a reduction of the total energy radiated by the network. Results concerning energy saving in CoopMAC indicate that, in a saturated network, a high data-rate node can get more bits per joule if it is participating in two-hop forwarding schemes.

In [17], implementation feasibility and alternative approaches to be pursued in order to reduce implementation constraints are further discussed.

Cooperative MAC protocol using packet Aggregation (CoopMACA)

The CoopMACA protocol [20] proposes a cooperative technique based on the Min-TX category and employs packet aggregation for cooperative MAC protocol in IEEE 802.11 WLAN. In the CoopMACA protocol, there are two types of relay selection processes: 1) relay selection by the source node, which is performed in a similar way to the CoopMAC [19] protocol and 2) distributed contention between candidate relay nodes. The main feature of CoopMACA is the distributed relay selection algorithm which takes into consideration the aggregation concept. Two factors determine the priority of the candidate relay nodes which contend for access to the channel: 1) Having the packet to be sent to the same destination node of ongoing transmission, and 2) providing throughput improvement for forwarding the packet from source to destination. In the CoopMACA protocol, the sensing parameters are obtained from overhearing RSSI of neighbour nodes and the PLCP sub-header of the IEEE 802.11 MAC frames. When the source node (N_S) has a packet to send, it will check its cooperative table. If (N_S) finds the appropriate relay node, it will announce this to the relay node by using a modified RTS (Figure 3.2). Otherwise, the distributed relay selection starts. After the potential relay nodes received the RTS, they will compete in three rounds. In the first round, those relay nodes which have packets to be sent to the same destination are selected (Classification Round). The winners of the second round are those relay nodes which can provide throughput improvement via forwarding the packets between corresponding source and destination nodes (Priority Round). The third round is the back-off contention round for access to the channel performed by the winners of the two primary rounds (Contention Round). After the final relay node is selected (N_H), similar to CoopMAC protocol, it will send out a packet Helper To Send (HTS) to signal the cooperation and then if the relay node has the original packet to send to same destination, the *aggregation* is applied for both its original packets and relayed packet.

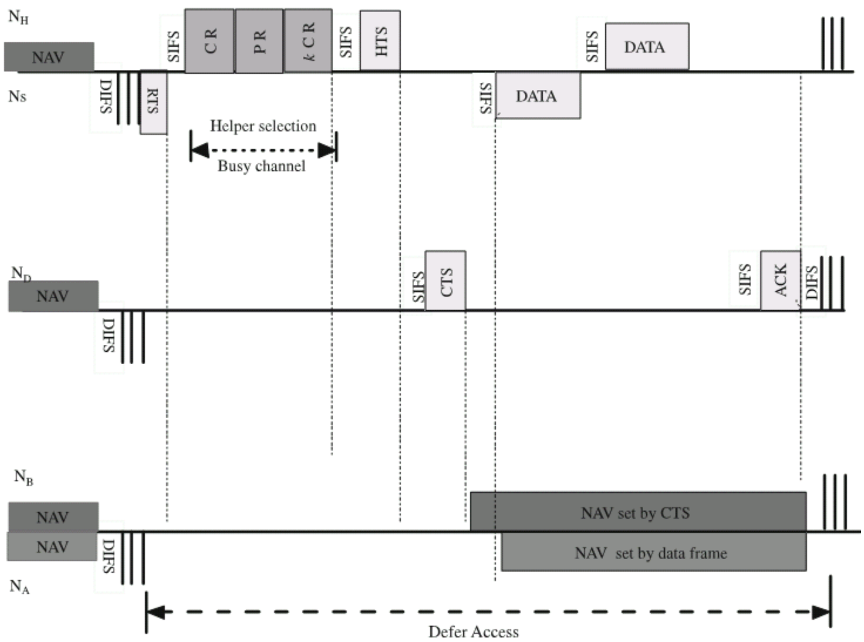


Figure 3.2 Time sequences of control and data packets in CoopMACA [20]

The mathematical analysis of the CoopMACA protocol derived an expression for the saturation throughput. To do that, the success probability of a packet transmission through the helper node and computation of cooperative regions were further analysed. The simulation results showed that CoopMACA outperforms the CoopMAC and DCF protocols in terms of saturation throughput, network throughput and collision probability. The innovative aspects of aggregation and three rounds of helper selection process in

CoopMACA provide a robust protocol compared to CoopMAC which can adapt to the changes in the network topology instantaneously especially in a general mobile scenario.

Coordinated Cooperative MAC (CCMAC)

The CCMAC protocol [19] considers the concurrent cooperative transmission for uplink from clients to AP. According to the channel condition and the helper's status of whether a data packet has been cached or not, the CCMAC supports three different transmission modes: basic, half and enhanced modes. In basic mode, the sender does not need a helper or there is no helper which can help, and normal DCF mode is applied. The operation of half mode and enhanced modes is based on successful transmission from relay to destination. The key idea of half mode is that if relay successfully receives a packet and if transmission from relay to destination is unsuccessful due to a bad channel, the relay does not drop the packet and store it. If this relay is selected again by the source node for retransmission when the previous failed packet, the relay will be informed by tag number written in the RTS. If this tag number is the same as the tag number of stored packet, the relay will send the HTS to indicate the cached packet (half mode). Otherwise, the enhanced mode activates, similar to CoopMAC operation. The half mode provides a shorter transmission duration than the other two modes, because the packet only needs to be transmitted once and through a fast link.

In theoretical analysis of CCMAC protocol, the WLAN was modelled as a stochastic environment and in order to solve the coordination of concurrent transmissions, a policy gradient algorithm was applied based on reinforcement learning. According to analysis and simulation of CCMAC in IEEE 802.11b, it was found that CCMAC can achieve considerable throughput performance improvement, without imposing significant network overheads. It was further discussed that CCMAC using IEEE 802.11b achieves good coordination between nodes in enhanced mode to provide up to 5 concurrent transmissions.

Relay Aided Media Access (RAMA)

The RAMA protocol [18] also employs relays to improve the rate adaptation mechanism of IEEE 802.11 DCF mode in wireless ad hoc networks. The main feature in the RAMA protocol is that the relay nodes introduce themselves to potential source nodes, advertising their capacity to participate in a cooperative relaying process. These advertisements are performed if the relay nodes find that they can reduce the transmission delay of ongoing communication between source and destination. The relay nodes produce an invitation frame and send it to source node in DCF mode. Upon reception of this frame, the source node will record it in a table named Relay List. Other relay candidates will cancel their invitation for corresponding source-destination after hearing the invitation from the winner relay node. The next time a source node wants to send data packets to the same destination, it will use the winner relay node (which was recorded from previous invitation). When the relay receives the relayed frame from the source, it will forward that immediately after SIFS. Since SIFS has the highest priority of inter frame spaces in DCF, this assures that the forwarding by the relay is free of contention. Results from analysis and simulation in [17] show that RAMA can significantly improve performance in terms of both throughput and delay specially when compared to known rate adaptation protocol, the RBAR protocol [91].

Efficient Multi-rate Relaying (EMR)

The EMR protocol [22] introduces a multi-rate relaying MAC protocol which is able to utilize the traditional shortest path routing algorithm and a fast forwarding scheme of packets to improve the throughput of a IEEE 802.11 multi-hop network. In EMR, the most prominent feature is the selection of the effective throughput with consideration of various combinations of the source, destination and relay. To do this, the available throughput can be mapped to a priority (a 4-bit value), where higher number means higher priority. In this protocol, modified RTS and CTS packets are exchanged at the basic rate. Potential relay nodes can estimate their distance from the source and destination based on the RSSI of the control packets. After one relay node is selected by the source node, the priority of the ongoing transmission is integrated into the control packets. Upon reception of the control packets, potential relays will calculate their own priority and compare it against the current priority announced in control packets. Those relays with higher priority may send out their relay request packet, which contains the relay address and priority path. The relay selection is then done by source when it selects the best relay and responds with a relay response packet which contains relay address and accepted priority value. This priority-based scheme implemented in EMR protocol enables IEEE 802.11 to improve throughput performance.

The throughput performance of the EMR scheme has been analytically modelled and it performs much better than the proposed multi-rate scheme of MTM.

Opportunistic Relay Protocol (ORP)

The Opportunistic Relay Protocol (ORP) [23] was proposed for infrastructure WLANs, when the relaying is performed for the uplink between a source node and the AP. The innovation of the ORP protocol is its opportunistic approach of using channel time reservations. In ORP, the source node reserves the channel optimistically with the hope that there is a potential relay node to complete the transmission of data faster than the direct transmission. The duration field of the data frame sent by the source to Access Point (AP) is set based on the maximum possible data rate (e.g., 11Mbps in 802.11b). From the PLCP header of this data frame every intermediate node can overhear the actual data rate and data frame length. These sensing parameters, as well as the channel reservation time, can help the intermediate node to decide if the data frame needs to be relayed or not. If the relaying is necessary and the intermediate node can forward the data frame to the AP within the time constraint implied by the duration value, the intermediate node contends for channel acquisition as a potential relay. After the AP receives a data frame from a potential relay, it will send out an ACK directly to the source. Otherwise, the source must retransmit the frame. To avoid collisions between multiple potential relay nodes, a shorter back-off timeout is used.

Cooperative Medium Access for Multi-rate Wireless Ad Hoc Networks (CODE)

The CODE protocol [21] exploits two techniques to improve the multi- rate capability of 802.11 for ad hoc networks: 1) Using multiple relay nodes to provide a more robust link, especially when there is mobility, and 2) Exploring network coding [31] to support bidirectional traffic and to further improve system throughput. These features enable simultaneous transmission of uncoded information by multiple nodes when the symmetric traffic flows are applied. The relay selection is based on sensing the signal strength of RTS or CTS packets and also by extracting the piggybacked transmission rate in the CTS packets, all performed by the source node. If the source node selects a single relay node, then the CODE protocol operation is similar to the rDCF protocol. Otherwise, the source node picks the two best relay nodes and determines their priority to access the channel via a Cooperative CTS (CCTS) based on channel quality registered in its cooperative table. The distinctive feature of CODE is its support of bidirectional traffic. When one or two relay nodes are available and the destination also has packets to send for the current source node, the mechanism of network coding will be triggered. In this case, the destination will request network coding, which requires that the relay node(s) should wait for the data packet from the destination before relaying packets from the source. Then, two packets (Source to Destination and Destination to Source) could be XORed into one packet and then broadcast (Figure 3.3). In CODE protocol a more control packet of NC (network coding) is designed for the relay nodes to reserve time duration if network coding is used. Simulation results [21] indicate that CODE outperforms rDCF [15] in terms of throughput gain.

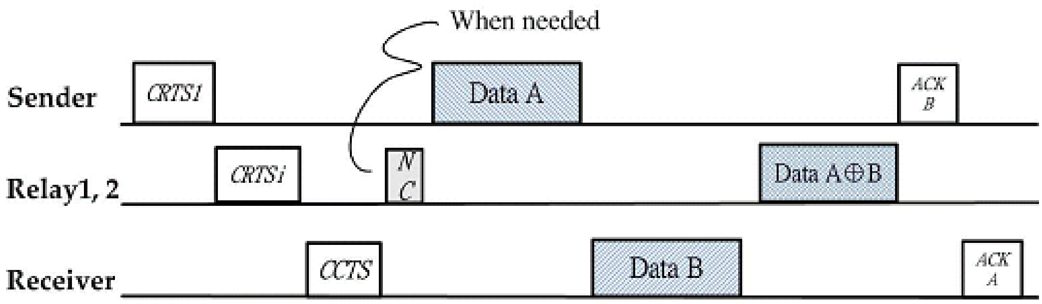


Figure 3.3 Control and data packets in CODE protocol [21]

3.3.2 Caching and Waiting for Failure (CWF)

The cooperative motivation of this category is to increase the reliability of wireless networks, leading to increased performance and transmission range. The main concept driving protocols of this CWF category is that the act of sensing failures, when transmitting packets, triggers cooperation. Applied to IEEE 802.11, when the transmission of a data packet fails, and the source node does not receive the ACK, neighbours (potential relays) which overheard the original packet and have stored it, can forward it again. The simplest protocol of this category is UTD MAC [24], while protocols enabled by coding schemes are presented in CMAC [25] and CD-MAC [26]; NCSW [27] and PRCSMA [28] employ ARQ-based cooperative MAC schemes.

University of Texas at Dallas MAC (UTD MAC)

The UTD MAC protocol [24] is a simple cooperative IEEE 802.11 MAC protocol for wireless ad hoc networks. The main idea behind UTD MAC is that the cooperation phase is initiated by packets failure to be received. For this, every potential relay node is overhearing mode, and store a copy of every data frame transmitted between a pair of source and destination. In the UTD MAC protocol, when the destination node does not acknowledge the received data frame, the relay nodes retransmit the stored packet. The final relay node is selected by the contention to access the channel after a new inter frame space period, called relay inter frame space (RIFS). If the destination node finally responds with a positive acknowledgment, the source node and corresponding relay nodes drop the stored packet. Otherwise, the data packet is retransmitted by the source node in a non-cooperation mode. The comparative results between UTD MAC and CoopMAC show that UTD MAC achieves average higher throughput and average lower delay especially for relay nodes placed close to the source and the destination. This happens because in UTD MAC relay nodes always participate in cooperation, as opposed to CoopMAC where relays are used only when a packet performance gain of less delay is clear[24].

(FEC) Cooperative Communication MAC (CMAC/FCMAC)

The CMAC protocol [25] exploits spatial diversity via user cooperation, in WLAN and wireless ad hoc networks. In the normal CMAC protocol, every node has two queues, one for its own data and another for its partner’s data. Overheard packets are stored in the partner queue of a potential relay. If after a certain interval, no acknowledgement message from the destination is received, the relay that received the data frame correctly from the source will transmit the frame. The CMAC protocol may utilize more than one partner and resolve potential collision between partners, thus a random back-off process should be performed by partners.

By using the FEC scheme, an improved version of CMAC protocol, called FCMAC was proposed. The distinctive feature of FCMAC is the usage of Forward Error Correction (FEC) and retransmission combining techniques to provide enhanced robustness in cooperative transmission. This gain can be obtained at the cost of additional overhead due to the partner queue and FEC for each packet.

Cooperative Diversity Medium Access Control (CD-MAC)

The Cooperative Diversity MAC (CD-MAC) protocol was proposed by Moh et al. in [26] for ad hoc networks. CD-MAC exploits coding schemes at the physical layer, thus requiring custom hardware, but not requiring any changes to the format of MAC frames. For cooperative diversity in the physical layer, there are two types of algorithms are used: 1) Repetition, in which the relays repeat the sender message individually on orthogonal channels, and 2) Space-time coding, in which all the relays transmit simultaneously on the same channel using orthogonal distributed space-time coding (DSTC).

Since DSTC was initially applied to transmit diversity in multi-antenna systems [101], cooperative diversity as a virtual multi-antenna model can also exploit Distributed Space Time Block Coding (DSTBC) to improve the performance of cooperative communications. When the first RTS packet fails, the source node sends a cooperative RTS (C-RTS) along to a Pre-selected relay using the DSTBC code. The relay is selected based on monitoring or overhearing the source’s neighbours with respect to link quality. The destination and its relay reply the C-RTS by using a cooperative CTS (C-CTS) packet. In a cooperative manner, channel reservation, data transmission and acknowledgment are performed. CD-MAC can achieve higher packet delivery ratios when compared to the legacy IEEE 802.11 DCF. However, this improvement is achieved at the cost of high transmission overheads and high complexity of the coding scheme.

Node Cooperative Stop and Wait (NCSW)

The NCSW protocol [27] exploits cooperative techniques to enhance the performance of Automatic Repeat Request (ARQ) schemes for wireless ad hoc networks. The Stop and Wait (SW) mechanism is selected as the core of ARQ scheme to provide a frame by frame acknowledgment mechanism and compatibility to IEEE 802.11. In the SW-ARQ protocol, if a transmitted frame cannot be decoded successfully by the receiver then the receiver node will send a not-acknowledgment (NAK) message to the sender node asking for a retransmission of the erroneous frame, and the sender node will respond to the NAK by retransmitting the frame. In this non-cooperative scheme, all the neighbour nodes are oblivious to the retransmissions between the sender and the receiver nodes. However in the

NCSW scheme, all the neighbour nodes monitor ongoing communications, and decode and store a copy of the last unacknowledged transmitted frame until the reception of a corresponding ACK. After the neighbour nodes receive a NAK from the destination node, they will cooperate with the sender in the retransmission process. The analytical and simulation results of the NCSW protocol demonstrate its improved performance in terms of throughput, average delay and delay jitter.

Persistent Relay Carrier Sensing Multiple Access (PRCSMA)

The PRCSMA protocol [28] can also be presented as a cooperative MAC protocol which allows distributed ARQ scheme in IEEE 802.11 wireless ad hoc networks. In the PRCSMA protocol, all nodes keep a copy of any ongoing transmission between given source and destination nodes. If the destination does not receive the packet successfully, the destination sends a Claim For Cooperation (CFC) message in the form of a RTS control packet to ask cooperation from the nearby neighbours. Those active relays which receive the CFC message and have the copy of the corresponding packet will be ready to forward their stored packet. As the destination node receives the stored packet, it will send the ACK message to inform the source node and potential relay nodes to discard the successful transmitted packet. In order to avoid collisions between active relays, a distributed back-off mechanism is applied at the beginning of the cooperation phase. The results demonstrate that the PRCSMA protocol outperforms the IEEE 802.11g when using the ARQ scheme [28].

3.3.3 Back-off Target Cooperation (BTC)

The protocols in this category employ cooperative techniques to determine which node has more priority to access the medium. The main objective of these protocols is to exploit cooperation for fairness improvement in IEEE 802.11 MAC protocol. Since the size of the back-off window determines the priority of every node to access the medium, priority-based cooperative protocols exploit cooperation concepts by dynamically adjusting back-off timers. This modification can be defined based on application service as in SD-MAC [29], or high priority of access to the medium for collided nodes in as C-MAC [30]. The main difference of this category and the two previous ones is the lack of a relay node: cooperation is a local action in neighbourhood nodes to improve medium access. However, in every protocol of this category we can still map the cooperation operation (in light of this, an argument can be constructed that the regular DCF back-off mechanism would also be a cooperative potential. However, this is not as an unusual view).

Cooperative Medium Access Protocol for Dense Wireless Networks (C-MAC)

The C-MAC protocol [30] is introduced for both infrastructure and ad hoc networks in the context of IEEE 802.11. Short term fairness and throughput degradation are the two main challenges of dense wireless networks addressed by this protocol. The C-MAC protocol relies on the principle that the collided nodes should have a higher priority than other nodes in terms of packet transmission. Toward this, first the non-collided nodes give permission to collided nodes to transmit their packets. Then the successful nodes select the larger back-off counter to allow non-collided nodes to transmit their packets.

In C-MAC, there are two types of back-off counter: 1) Back-off counter of collided nodes and 2) Back-off counter of non-collided nodes. Because there is a gap of 4 Slot Times (Slot Time duration is 20µsec) between DIFS (110µsec) and PIFS (30µsec), collided nodes choose their back-off counters from the range [0, 3]. Therefore, the collided nodes can choose at most 3 as a back-off counter, while in normal 802.11 DCF, the maximum counter value is 63 in the first retransmission. This new back-off procedure allows the collided nodes to transmit in the next contention period while others postpone their transmission until they detect two consecutive successful transmissions. The results of the C-MAC protocol show that it achieves short term fairness via collaboration of nodes while IEEE 802.11 is a long-term fair protocol. It also outperforms the IEEE 802.11 DCF in term of throughput performance even when the number of users increases [30].

Service Differentiation Medium Access Control (SD-MAC)

The SD-MAC protocol [29] proposed a new dynamic 802.11 MAC protocol which addresses service differentiation mechanisms for infrastructure and ad hoc networks. In IEEE 802.11e, service differentiation is applied based on different classes called Access Categories (ACs) [10]. The category with a higher AC number has more priority to access the medium. However IEEE 802.11e does not perform efficiently with high network loads. The SD-MAC protocol solves this problem by using a cooperative technique. The key strategy of SD-MAC is that every node changes its back-off counter window based on both its own packet's priority level and the level of the transmitted packet. To this end, each node will decrease its back-off counter exponentially with a lower priority (than its own) packet transmission and increase it linearly with a higher priority (than its own) packet transmission. For applications with diverse performance requirements, SD-MAC achieves better throughput and short term fairness for WLAN and wireless ad hoc networks when compared to static and dynamic MAC protocols.

3.4 Architectural reference model for Cooperation

Generally cooperation can be understood as a joint action for mutual benefit. This definition is valid in wireless networks and due to the broad diversity in possible interacting entities the concept of cooperation can be wider. Different cooperating entities within and across the OSI layers provide various cooperative techniques and algorithms. In order to present these cooperative techniques, we need to define an architectural model. The main feature of all systems using cooperation is that they are able to adjust their operation according to changes in their environment. In this case, cooperation concepts share some characteristics with concepts from Autonomic Systems [100], as both are based on feedback information. Therefore, an architectural reference model is proposed based on feedback information.

As depicted in Figure 3.4, cooperation consists of four phases: *Monitor*, *Analyze*, *Plan*, *Execute* (MAPE). In this reference framework, a cooperative protocol employs sensing methods to monitor the environment and to monitor neighbour nodes (Monitor). The observations acquired by the Monitor action will be further used to Analyze data according to key metrics. The values obtained are used to Plan the cooperation strategy including the using a relay channel or a direct channel, and if using the relay channel, which specific relay stations to use. The final phase is carried out by sending appropriate control packets for initiating the cooperative transmission and then data packets are exchanged (Execute). Then packets are exchanged accordingly.

There are several aspects which determine the operation of each phase in the MAPE model. These aspects include cooperation objectives, inter-layer or intra-layer schemes of OSI model and capabilities of each wireless technology. For instance, if the cooperation aims for minimizing delay, the parameters to be monitored, the analysis process and the decision methods differ from the case where cooperation is concerned with power issues. In addition, different environments such as WLAN, WSN and WMN have particular requirements, which can be mapped to the operation of all states in the MAPE model. Moreover, the requirements of cooperation in the MAC protocol of WMN are different from cooperative schemes in the network layer of WMN, as well as from cross- layer cooperative approaches. Therefore, the combination of various cooperation objectives, different wireless environments and inter-layer or intra-layer approaches can address a spectrum of features in system design of cooperative protocols while all of them are mapped in the MAPE model.

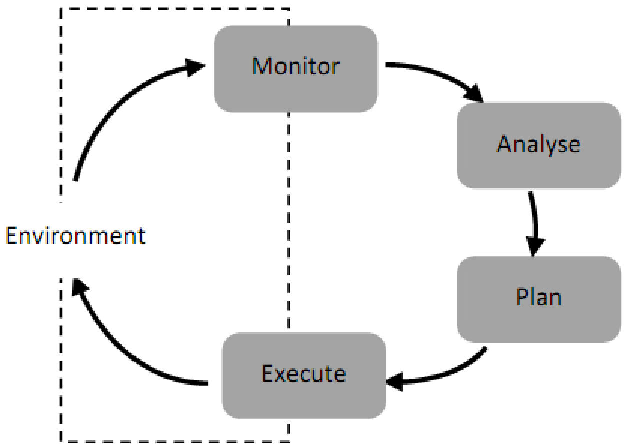


Figure 3.4 MAPE model

The MAPE model can cover most cooperation strategies, as long as they are properly mapped. Furthermore, it provides a standard terminology for studying any cooperative protocol and algorithm. Since the focus of this thesis will be on cooperative MAC protocols of IEEE 802.11, the aforementioned phases of MAPE model are described in the context of IEEE 802.11.

Monitor: In IEEE 802.11, each station not only transmits and receives data for its own applications but it can also monitor (overhear) the communication of the nearby neighbours. For instance, in normal operation of IEEE 802.11 in Distributed Coordination

Function (DCF) mode, by overhearing the ongoing DATA packet and control packets exchanged between two given nodes, the neighbours can compute the duration of time for which the shared channel is busy. This mechanism is performed by the help of the duration field in DATA packet and RTS-CTS control packets and by calculating the distributed Network Allocation Vector (NAV) timer which is explained in detail in Appendix I. Inspired by this monitor operation, information required for every cooperative MAC protocol can usually be obtained by monitoring data, control and management frames. The header of these frames has some information regarding the bit rate, packet failure and sometimes their reserved fields can be used for some extra information in accordance with the cooperative objective.

Depending on the cooperative objectives, the monitor phase uses different parameters. These parameters are used in the analysis phase and can be classified in the following categories:

— *Explicit parameters*: This category comprises parameters that are measured or achieved explicitly by overhearing the fields in the MAC header. These parameters can be used in the Analysis phase to compute required performance metrics. For instance, the bit rate of every data packet can be achieved by sensing the SIGNAL field in the Physical Layer Convergence Procedure (PLCP) header of that data frame. Another example of explicit sensing parameters can be obtained by overhearing the value of Received Signal Strength Indication (RSSI) (e.g. [15], CoopMAC [17] and CoopMACA [20]). Moreover, explicit parameters can be presented as a logical variable of YES or NO according to occurrence of some events. These events can be packet delivery failure [25][26][27][28] and the occurrence of collisions [30]. These logical variables mostly operate as trigger parameters for cooperation protocols.

— *Implicit parameters*: Some monitoring parameters can be obtained by applying some computations to explicit sensed parameters, and also user information itself. As an example, from the RSSI measurement of RTS and CTS control frames, between a pair of source and destination, each neighbour node can implicitly discover the potential bitrates and delay transmission between itself and source-destination pair. This monitoring method is used [15] [17] to estimate the transmission delay. User feedback can also be considered when users provide an indication about the Quality of Experience (QoE) they are having [29], or the willingness to cooperate.

— *Piggybacked parameters*: Some information used by cooperative MAC protocols is not achieved by explicitly and implicitly sensed information. Thus, in order to allow the whole network to know about this information, protocols make use of reserved fields in data and control packets. For example, the priority level of the relay nodes in [22] can be determined by mapping the priority to a binary number of n-bits in reserved fields of RTS or CTS frames.

Analyse: In order to achieve effective cooperation, two important questions should be answered: when to cooperate and with whom? Towards answering these questions, several aspects have to be taken into consideration in the Analyse phase. First, cooperation protocols should use the appropriate metrics based on the cooperative objective and the available monitor parameters, and then build a database to maintain the corresponding metric for each candidate relay node. The database can help the nodes to rank their neighbours according to the defined relay selection metric. Clearly, the relay selection metric should be mapped to the expected performance improvements provided by the intended candidate relay node. Selection of an appropriate metric depends on the OSI layers where cooperation takes place and also the capabilities of wireless technology.

Plan: The relay selection algorithms should be designed based on the information obtained by Analyse phase (e.g. metrics and relay node ranking), and other aspects of user and network. In case of the user, its willingness to participate in cooperation is the main concern. This willingness can be defined by internal parameters of each user which are relevant for its own behaviour in a cooperative scenario, most commonly related to energy and load. The energy source, if running from battery, and its remaining charge, are basic parameters that should be considered in every cooperative scheme. Nodes plugged into the grid have little energy constraints. When powered by a battery, if the remaining energy level is low, its cooperation with the other nodes in the network will lead to an inefficient use of the equipment, as it reduces network survivability (and potentially reduces overall capacity in the long term). Also, the transmission power selected by the candidate relay node will be a key factor in the total energy consumption of each node and overall network performance, together with sleep intervals. Thus, one node with low energy level has less opportunity to be selected as a relay even though its other metrics may suggest a potentially good performance increase. The effectiveness of each node to cooperate can also be evaluated by the input and output traffic. One node with too much input traffic cannot be a good candidate for the cooperation since its participation in the cooperation can reduce network performance, due to its inherent performance limitations in packet processing and medium access.

Besides the user internal parameters, application traffic services and cooperative scenarios can determine polices applied to the Plan phase. For instance, in a cooperative scenario which needs bandwidth improvement for handling the traffic service, the Plan phase is different from the scenario which is concerned with high reliability of traffic service. Moreover, the mobility should be taken into consideration in the Plan phase. In some cooperative scenarios, the mobility operates as a parameter which increases the complexity of cooperation algorithms. In contrast, the mobility can be operated in the direction of cooperative performance improvement especially for cooperation scenarios such as robotic networks which have the capability of commendable movement.

Execute: In order to complete the MAPE model the Execute phase should be defined. The main actions of Execute phase are *Initiation, Control* and *Notification*. After the relay(s) is selected based on related metric and Plan phase policy, it is very important to know which node initiates the cooperation. In some protocols, source node initiates the cooperation while there are many protocols in which cooperation initiates by relay node(s) or destination node. The Control action determines whether a centralized or distributed mechanism is employed for controlling the cooperation procedure and the Notification action defines the required signalling and modified control packets for exchanging between source, relay and destination nodes. In addition, the Execute phase of one cooperative protocol should address the legacy compatibility as well as the practical implementation aspects. Therefore, the design of Monitor, Analyze and Plan phases depends not only on the environment and cooperative objectives but it can also be affected by practical limitations imposed by the Execute phase.

3.4.1 Deployment Overview

In this section, we classified the cooperative MAC protocols in three categories according to their main operational concept: Minimum Transmission (Min-TX), Caching and Waiting for Failure (CWF) and Back-off Target Cooperation (BTC). The key objective of every category and cooperative operation of each protocol were also described.

Besides these key operational aspects of each protocol, according to the MAPE framework, other aspects should be also emphasized. In order to implement the cooperative MAC protocols in 802.11 networks, there are some limitations and properties imposed by operational aspects. Some of the protocols are designed only for ad hoc of infrastructure architectures, while others can operate in both of them. The compatibility of cooperative algorithms with the legacy of 802.11 MAC algorithm may (or may not) permit the protocol to operate in cooperation mode without fundamental changes in normal 802.11 modes. Furthermore, the additional control messages and inter frame time spaces required, as well as PHY modifications proposed by a cooperative protocol determine the complexity degree of that protocol.

Although these aspects are not easily quantified, Table 3–3 and Table 3–4 summarize some relative comparison of existing cooperative MAC protocols in terms of MAPE model phases and operational issues already discussed.

3.5 Concluding Remarks

In this chapter, the PHY and MAC specifications of IEEE 802.11 standards and their respective issues to cooperative schemes have been studied. Three objectives of cooperation were presented in cooperative MAC protocols: Minimum Transmission (Min-TX), Caching and Waiting for Failure (CWF) and Back-off Target Cooperation (BTC). In addition, multiple cooperation protocols in the context of IEEE 802.11 were presented with a brief description of operation. In order to have a generic architectural framework for cooperative protocols, the MAPE model was presented. This model covers all phases of cooperation strategies when the four actions of Monitor-Analysis-Plan-Execute are applied for completion of each cooperative scheme or protocol. As a case study, the MAPE model is explained in the context of IEEE 802.11 MAC protocol. Deployment issues and MAPE phases of the protocols are also provided in last section of this chapter.

Table 3–3 Cooperative MAC protocols and their operational issues

Protocols	Architecture	Compatibility	Complexity
rDCF	Ad Hoc	High	Moderate
CoopMAC	Infrastructure/Ad Hoc	Moderate	Low
CoopMACA	Infrastructure	Low	High
CCMAC	Infrastructure	Moderate	High
RAMA	Ad Hoc	Moderate	Low
EMR	Ad Hoc	Moderate	Moderate
ORP	Infrastructure	Low	Low
CODE	Ad hoc	High	High
UTD MAC	Ad Hoc	Moderate	Moderate
CMAC	Infrastructure/Ad Hoc	Low	Low
CD-MAC	Ad hoc	Low	High
NCSW	Ad Hoc	Low	High
PRCSMA	Ad Hoc	High	Low
C-MAC	Infrastructure/Ad Hoc	High	low
SD-MAC	Infrastructure/Ad Hoc	High	low

Table 3–4 Mapping of cooperative MAC protocols on MAPE model

Protocols	Monitor	Analyse/Plan		Execute		
		Relay	Relay Selection	Initiation	Control	Notification
rDCF	RSSI	Single	Maximum transmission rate	Source	Distributed	Modified RTS(s)
CoopMAC	RSSI, PLCP	Single	Maximum transmission rate	Source	Distributed	RTS/HTS
CoopMACA	RSSI, PLCP	Single	Maximum transmission rate	Source/Relay	Distributed	RTS-HTS
CCMAC	RSSI, PLCP	Single	Maximum transmission rate+ caching	Source/Relay	Distributed	RTS/HTS
RAMA	RSSI, PLCP	Single	Maximum transmission rate	Relay	Distributed	CFC
EMR	RSSI, PLCP	Single	Maximum transmission rate-priority based	Source and relay	Distributed	Relay-RQST/Relay-RES
ORP	Data rate	Single	Random	Source	Distributed	Relaying data transmission
CODE	RSSI(s), Data rate	Multiple	Maximum transmission rate	Receiver	Distributed	Cooperative- RTS (CRTS)
UTD MAC	Packet Failure	Single	Random	Source	Distributed	Invitation by relay
CMAC	Packet Failure	Single	Random	Relay	Central/ Distributed	N.A.
CD-MAC	RSSI	Single	Maximum transmission rate	Source	Distributed	CRTS / CCTS
NCSW	Packet Failure	Multiple	Random	Relay	Distributed	N.A.
PRCSMA	Packet Failure	Multiple	Random	Receiver	Distributed	CFC
C-MAC	Collision occurrence	Single	Random	Source	Distributed	N.A.
SD-MAC	Priority of traffic flow	Single	Service differentiation	Source	Distributed	N.A.

CHAPTER 4 COOPERATIVE PERFORMANCE METRICS FOR IEEE 802.11 MAC PROTOCOLS

Summary

The efficiency improvement of network resources in IEEE 802.11 wireless networks when using cooperative schemes is the main issue which should be tackled. This chapter considers several protocols of Min-TX category and evaluates their performance in terms of cooperation issues. A system model for Min-TX category and a metric for bandwidth improvement are also presented. The potential area of the relay node called the relay area is computed theoretically and practically for different data rates and transmission ranges of IEEE 802.11b/g/n. The performance bounds of bandwidth obtained by cooperative protocols are also discussed and presented for Min-TX category protocols when applied in IEEE 802.11b/g/n. The limitation imposed by high layer requirements is also considered for different amendments of IEEE 802.11.

4.1 Introduction

Cooperative communications have emerged as the promising approach in order to improve communication performance. The advantages of cooperative communications are appraised by considering the performance improvements. Moreover, analysis of achievable performance bounds indicates the potential of cooperative schemes in the context of the objectives for which they have been designed. As discussed in CHAPTER 2 , there are several works which analyse the performance bounds of cooperation techniques at the PHY layer. In most of these works, the performance bounds are obtained when the analysis is limited to ideal assumptions and theoretical aspects. However, these performance bounds are affected by some limitations when cooperation is applied in practical scenarios with specifications imposed by wireless technology standards.

In this chapter, the practical performance bounds of two cooperative objectives in IEEE 802.11 are considered: 1) spectrum efficiency and 2) energy efficiency. Min-TX category protocols have been selected as a case study of spectrum efficiency approach where the system model and some practical issues limiting the expected performance bounds are addressed. The performance bounds of energy efficiency approach are considered by taking into account several aspects such as wireless channel properties and transmission power.

The remainder of this chapter is organized as follows: in Section 4.2, a system model, performance metric and performance bounds of the Min-TX category are presented. This section also provides a mathematical analysis to find the minimum packet size leading to useful cooperation. Moreover, the theoretical and practical computations of geographical area for potential relay nodes are presented in context of IEEE 802.11bgn. In Section 4.3, a system model of cooperative schemes with objective of energy efficiency in IEEE 802.11 is presented. This section demonstrates the potential of cooperative schemes in overall energy saving when practical issues of IEEE 802.11 are taken into account. The analysis model is applied for IEEE 802.11bgn. Section 4.4 concludes this chapter.

4.2 Analysis of bandwidth improvements schemes

Bandwidth improvement is one of the cooperative objectives which can be achieved by Min-TX category. As discussed before, the condition of efficient cooperation in the Min-TX category is based on the low transmission delay of the cooperative path compared to the direct path. Transmission delay is the time a data packet takes to be transmitted over the medium. Different values of transmission delay are available due to the multi-rate capability of the PHY specification of the IEEE 802.11 standards. Therefore, a practical monitor method should be employed to obtain the data rates between neighbours as the potential relays and a given destination node. According to this monitor method, a performance metric can be defined. This metric is used to select the potential relay nodes in accordance with the cooperative objective of throughput improvement. It is also useful for ranking the relay nodes and determining the best relay node(s).

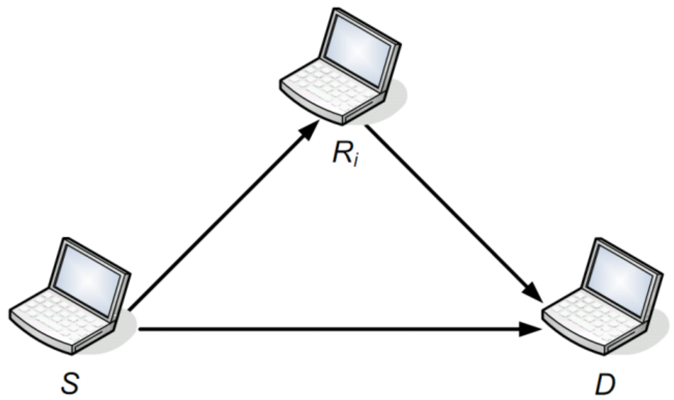


Figure 4.1 Example of cooperation with one relay node

4.2.1 System Model

All protocols in Min-TX category employ a common practical monitor method to define a metric for relay selection. Generally, this metric is related to the delay of direct and cooperative path. For simple scenario depicted in Figure 4.1, node R_i is a candidate relay between source (S) and destination (D). MAC header of IEEE 802.11 frame or in more detail, the PLCP sub-header, contains a field named SIGNAL, which denotes the bit rate of every data packet sent to the network (Annex I). Thus, R_i explicitly obtains the actual data rate between S and D from overhearing data frames exchanged between them. R_i can also estimate the potential data rate between itself and source-destination pair. Node R_i can measure the RSSI of RTS and CTS and ACK frames issued by nodes S and D, and compute the corresponding data rates of obtained RSSI(s). After obtaining the three data rates between these three nodes, a general metric of Delay Ratio (DR) can be defined. DR is the ratio between the transmission delay of relay path, and that of the direct path. If the relay node supports data rates of B_{SR_i} and B_{R_iD} to S and D, respectively, and the direct transmission data rate between S and D is B_{SD}, the delay ratio estimated by R_i can be expressed as:

$$DR_i = \frac{\left(B_{SR_i}\right)^{-1} + \left(B_{R_iD}\right)^{-1}}{(B_{SD})^{-1}} \tag{4.1}$$

The value of DR_i can be obtained by each of the relay source and destination nodes. Clearly, if the value of the calculated delay ratio is less than 1, the relay channel may provide better transmission characteristics than the direct channel, due to the resulting effective higher bandwidth and lower transmission delay for end-to-end communication. It is noted that source and destination nodes can obtain the same delay ratio estimation of using R_i as the relay when they do the same Monitor method and computation.

The average transmission delay between a pair of source and destination T_{SR_iD} can be then expressed as (4.2):

$$T_{SR_iD} = \sum_{i\,\in\,\mathbb{R}_{SD}} P_{R_i}.T_{C(R_i)} + \left(1 - \sum_{i\,\in\,\mathbb{R}_{SD}} P_{R_i}\right) T_{SD} \tag{4.2}$$

Where, the $T_{C(R_i)}$ and T_{SD} are the transmission delays of the cooperative path and the direct path respectively, and P_{R_i} is the probability of finding a relay node $R_i \in \mathbb{R}_{SD}$ with delay ratio of DR_i. The value of P_{R_i} can be estimated by considering relay areas. The relay area is the location of relay nodes and will be discussed in more detail later in this paper. $\mathbb{R}_{SD}$ is the set of relays R_i which satisfies the relay condition of the Min-TX category to guarantee a reduction in the transmission delay.

$$\mathbb{R}_{SD} = \{R_i | T_{C(R_i)} < T_{SD}\} \tag{4.3}$$

$T_{C(R_i)}$ and T_{SD} can be expressed as (4.4) and (4.5):

$$T_{C(R_i)}(L) = T_{C(R_i)/DATA}(L) + T_{C(R_i)/OH} + \tau_{RS} \tag{4.4}$$

$$T_{SD}(L) = T_{SD/DATA}(L) + T_{SD/OH} \tag{4.5}$$

where $T_{C(R_i)/DATA}(L)$ and $T_{SD/DATA}(L)$ are the transmission delay of a data packet with length of L bytes respectively using the relay and direct paths. The protocol overhears of these two modes are denoted by $T_{\mathrm{C}(R_i)/\mathrm{OH}}$ and $T_{SD/OH}$ respectively. τ_{RS} is the average time for relay selection, which varies between different relay selection algorithms.

By rewriting the delay ratio of equation (4.1) as a function of $T_{\mathrm{C}(R_i)/\mathrm{DATA}}(L)$ and $T_{SD}(L)$ in (4.6), and substituting (4.6) into (4.4), it yields (4.7).

$$DR_i = \frac{T_{C(R_i)/DATA}(L)}{T_{SD/DATA}(L)} \tag{4.6}$$

$$T_{C(R_i)}(L) = DR_i.T_{SD/DATA}(L) + T_{C(R_i)/OH} + \tau_{RS} \tag{4.7}$$

Since $T_{\mathrm{C}(R_i)/\mathrm{OH}}$ and τ_{RS} are often constant values in every cooperative MAC protocol, $T_{C(R_i)}$ mostly depends on DR_i, data packet size (L) and the direct data rate between source and destination. Thus, for a packet size L, direct data rate B_{SD}, and delay ratio DR_i equation (4.7) can be expressed as (4.8):

$$\begin{aligned} T_{C(R_i)}(L, B_{SD}, DR_i) &= DR_i.T_{SD/DATA}(L) + T_{C(R_i)/OH} + \tau_{RS} \\ &= DR_i.\frac{L}{B_{SD}} + T_{C(R_i)/OH} + \tau_{RS} \end{aligned} \tag{4.8}$$

From the perspective of the MAC layer, the throughput for direct transmission (η_{SD}) and cooperative transmission ($\eta_{C(R_i)}$) for the simple scenario of Figure 4.1 can be written respectively as (4.9) and (4.10).

$$\eta_{SD}(L, B_{SD}) = \frac{L}{T_{SD}(L, B_{SD}) + T_{col} + T_{idl}} \tag{4.9}$$

$$\eta_{C(R_i)}(L, B_{SD}, DR_i) = \frac{L}{T_{C(R_i)}(L, B_{SD}, DR_i) + T_{C(R_i)/col} + T_{C(R_i)/idl}} \tag{4.10}$$

where T_{idl} and T_{col} are the average idle time and the average time wasted on the channel due to collisions in direct transmission. $T_{C(R_i)/idl}$ and $T_{C(R_i)/col}$ denote the average idle time and collision time in the cooperative scenario. The average idle time is a function of the back-off timer and the collision time can be fixed or variable depending on the saturated and non-saturated scenarios [103].

Theoretical Performance bounds: In order to find the success level of cooperative schemes, the throughput performance bound of Min-TX protocols should be determined as a function of delay ratios. It can be concluded that for a fixed packet size (L) , fixed direct data rate (B_{SD}) between S and D and constant value of idle time and collision time, the throughput bounds ($\eta_{C(R_i)}^{min}$ and $\eta_{C(R_i)}^{max}$) can be obtained by minimum and maximum values of DR_i as expressed in (4.11) and (4.12).

$$\eta_{C(R_i)}^{min} = \frac{L}{T_{C(R_i)}(L, B_{SD}, DR_i^{max}) + T_{C(R_i)/col} + T_{C(R_i)/idl}} \tag{4.11}$$

$$\eta_{C(R_i)}^{max} = \frac{L}{T_{C(R_i)}\left(L, B_{SD}, DR_i^{min}\right) + T_{C(R_i)/col} + T_{C(R_i)/idl}} \tag{4.12}$$

4.2.1 Practical Issues and Performance Bounds

In theoretical analysis, we considered a system model with some assumptions. These assumptions are limited when the cooperation is applied to real scenarios. The limitations are imposed by design features of cooperative protocols and standard specifications of wireless technologies. Here, we consider these limitations in terms of beneficial data packet size for cooperation and geographical area for relay nodes.

4.2.1.1 Beneficial data packet size

The duration of packet transmission over the wireless medium is a function not only of the bit rate, but also of the packet length (L), which varies in different application services. In a cooperative scenario and for a specific cooperative MAC protocol, we can calculate the minimum packet length which can reduce the transmission time compared to the direct transmission. As indicated in (4.7), the maximum transmission delay, in cooperative cases, is obtained when the relay node provides the maximum delay ratio. Therefore, for the maximum delay ratio, we can express the inequality (4.13):

$$T_{C(R_i)}(L, B_{SD}, DR_i^{max}) < T_{SD}(L, B_{SD}) \quad (4.13)$$

By replacing $T_{C(R_i)}$ and T_{SD} into (4.13), we obtain (4.14) and then (4.15).

$$DR_i^{max}.T_{SD/DATA}(L, B_{SD}) + T_{C(R_i)/OH} + \tau_{RS} < T_{SD/DATA}(L, B_{SD}) + T_{SD/OH} \quad (4.14)$$

$$T_{SD/DATA}(L) > \frac{T_{C(R_i)/OH} + \tau_{RS} - T_{SD/OH}}{(1 - DR_i^{max})} \quad (4.15)$$

For a data packet with length of L and data rate of B_{SD}, $T_{SD}(L, B_{SD}) = L/B_{SD}$ and it yields (4.16):

$$L > \frac{B_{SD}(T_{C(R_i)/OH} + \tau_{RS} - T_{SD/OH})}{(1 - DR_i^{max})} \quad (4.16)$$

and the lower bound of packet length can be expressed as (4.17):

$$L_{min} = \frac{B_{SD}(T_{C(R_i)/OH} + \tau_{RS} - T_{SD/OH})}{(1 - DR_i^{max})} \quad (4.17)$$

This means that there is a minimum useful size of packet for cooperation to be useful. In Section 4.2.2, we will evaluate the lower bound of packet size for specific cooperative protocols of Min-TX category.

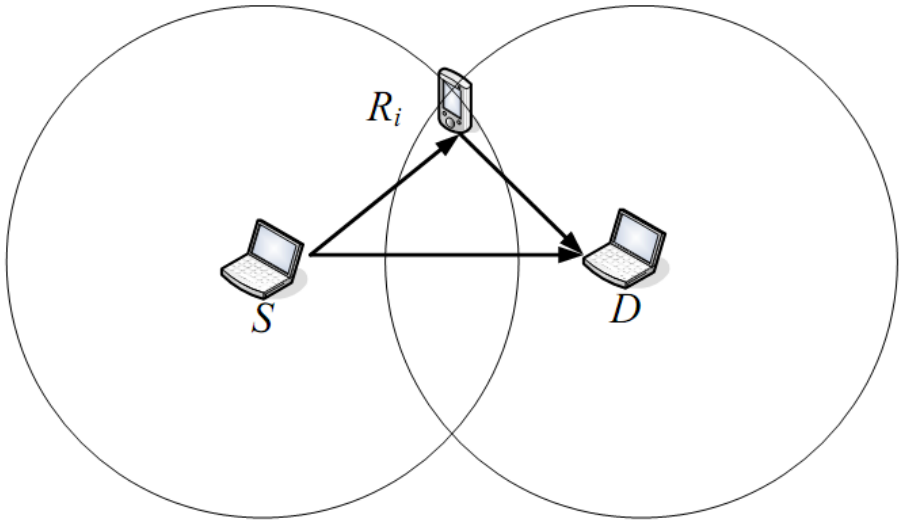


Figure 4.2 Relay area of Min-TX category

4.2.1.2 Relay area

The multi rate capability of IEEE 802.11 provides different data rates for different transmission ranges. According to the location of the relay node, it can sense various delay ratios and the cooperative throughput will change. According to the cooperation objective in Min-TX category and for a data packet with length L, we can write the equation (4.18):

$$T_{C(R_i)}(L) < T_{SD}\ (L) \tag{4.18}$$

Potential useful relay area is the location area of R_i when the inequality (4.18) will be satisfied. There are two methods for determining this relay area, based either on theoretical or practical analysis.

Theoretical approximation : In a theoretical analysis and for the scenario of Figure 4.1, we can consider the Shannon formula and a simple path loss wireless propagation model as expressed in (4.19) and (4.20), between two nodes (S,D).

$$B_{SD} = W_{SD}\ log(1 + \ SNR_{SD}) \tag{4.19}$$

$$P_r = K\frac{P_t}{d^n} \tag{4.20}$$

where B_{SD} is the achievable data rate, W_{SD} is the bandwidth; SNR_{SD} is the signal to noise ratio; P_r, P_t are received and transmitted power; d is the distance between the S and D; K is the constant; and n is path loss coefficient of the environment.

By applying the inequality (4.18) and substituting (4.19) and (4.20) into (4.18), we obtain the equation (4.21).

$$T_{C(R_i)/DATA}(L) + T_{C(R_i)/OH} + \tau_{RS} < T_{SD/DATA}(L) + T_{SD/OH} \tag{4.21}$$

If B_{SR_i} and B_{SD} are corresponding achievable data rates between *S*, *R_i* and *D* nodes, by substituting $T_{C(R_i)/DATA}(L)$ and $T_{SD/DATA}(L)$ as a function of data packet length (L) and corresponding data rates, we can have:

$$\frac{1}{B_{SR_i}} + \frac{1}{B_{R_iD}} + \frac{T_{C(R_i)/OH}}{L} < \frac{1}{B_{SD}} + \frac{T_{SD/OH}}{L} \tag{4.22}$$

For large packet sizes, we can assume $T_{C(R_i)/OH}/L \approx T_{SD/OH}/L \approx \tau_{RS}/L \approx 0$, and the inequality (4.22) can be approximated by (4.23).

$$\frac{1}{B_{SR_i}} + \frac{1}{B_{R_iD}} < \frac{1}{B_{SD}} \tag{4.23}$$

It should be noted that inequality (4.23) is compatible with the definition of the delay ratio (as expressed in (4.2) and demonstrates that if the delay ratio is less than one it satisfies the cooperative condition of Min-TX category.

If d_{SR_i}, d_{R_iD}, d_{SD} are devoted to the distances between *S*, R_i and *D*, by assuming $x = d_{SR_i}/d_{SD}$ and $y = d_{R_iD}/d_{SD}$, we can obtain the inequalities of (4.24).

$$\begin{cases} \dfrac{1}{W\ log(1+\ SNR/x^n)} + \dfrac{1}{W\ log(1+\ SNR/y^n)} < \dfrac{1}{W\ log(1+\ SNR)} \\ x + y > 1 \end{cases} \tag{4.24}$$

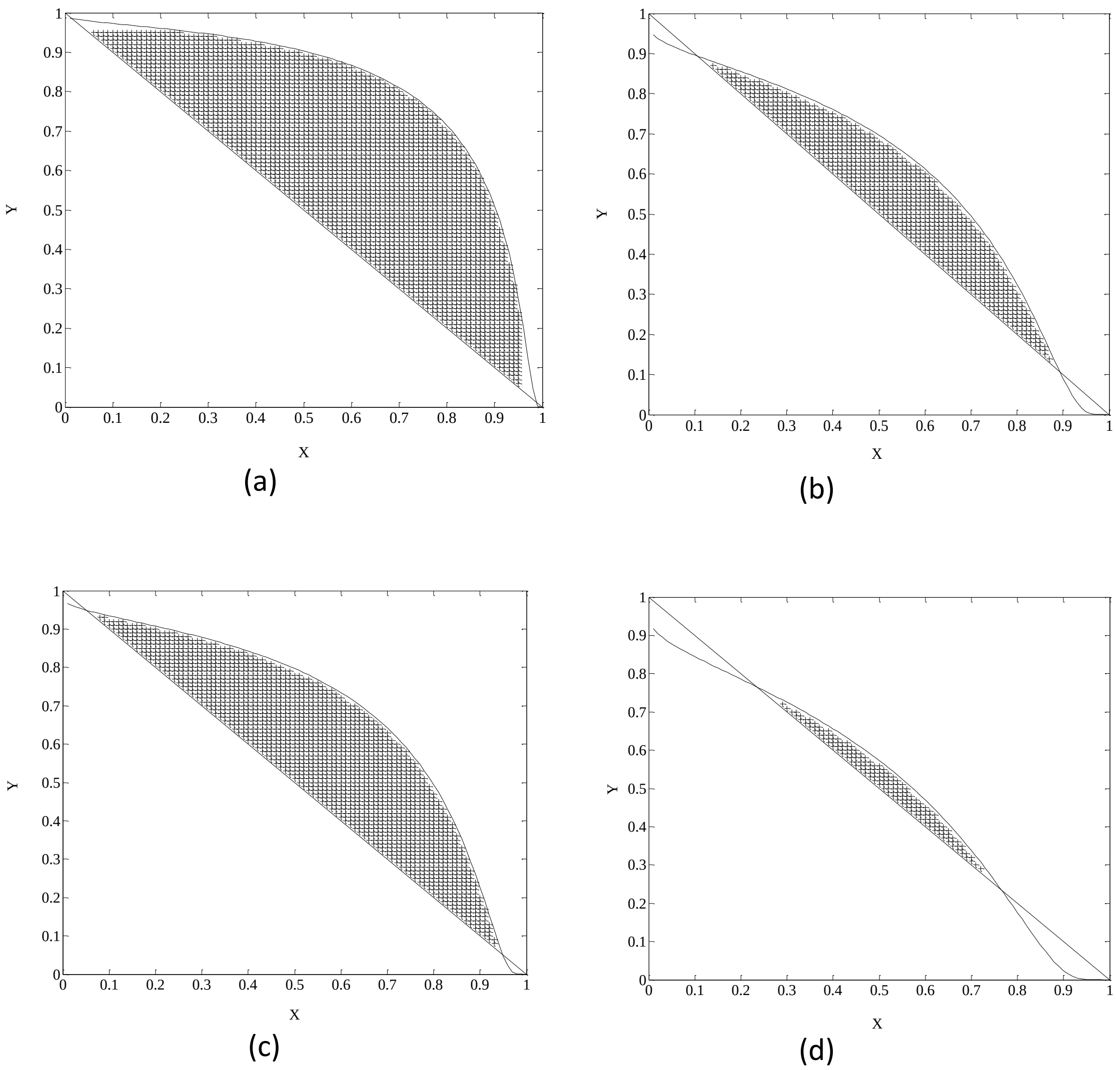


Figure 4.3 Relay area of path loss coefficient (n=4) and different SNR:(a) SNR=1, (b) SNR= 3, (c) SNR=6 and (d) SNR=10

In Figure 4.3, these inequalities with a path loss coefficient n= 4 (an usual value) and different *SNR´s* were solved. The shadow area is the useful relay area and theoretically shows the probability for the existence of a useful relay node for random position of R_i. The relay area depicted in Figure 4.3 indicates that as the SNR of direct transmission increases, the probability of finding relay nodes will decrease when the uniform node density is assumed. With the help of this analysis, the whole useful relay area for a pair of *S* and *D* was computed. However, the percentage of the relay areas corresponding to a specific delay ratio cannot be computed.

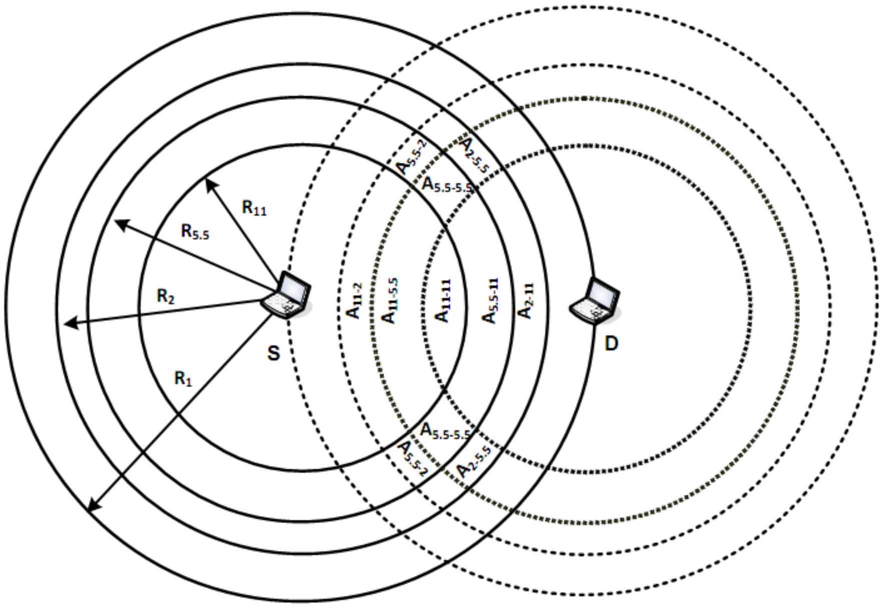
Geometrical approximation: By following a pragmatic approach which will be discussed in the remainder of this section, the relay area corresponding to a specific value of delay ratio can be computed. If the transmission ranges of every data rate are known, the relay area corresponding to its delay ratio will be determined. Figure 4.4 (a) shows different relay area of a direct transmission with data rate of 1Mbps between source (S) and destination (D). The transmission ranges corresponding to each data rate are represented with circles with radius of R_D, where D is the data rate supported in IEEE 802.11b. The corresponding delay ratios are indicated in Figure 4.4 (b). In order to calculate the relay area, we need to obtain the overlap area between two circles. The overlap area of two circles with radii of r_1 and r_2 and distance l between the centres can be written as (4.25).

$$S_{r1r2} = {r_1}^2 \, sin^{-1}(h/r_1) + {r_2}^2 \, sin^{-1}(h/r_2) - hl \tag{4.25}$$

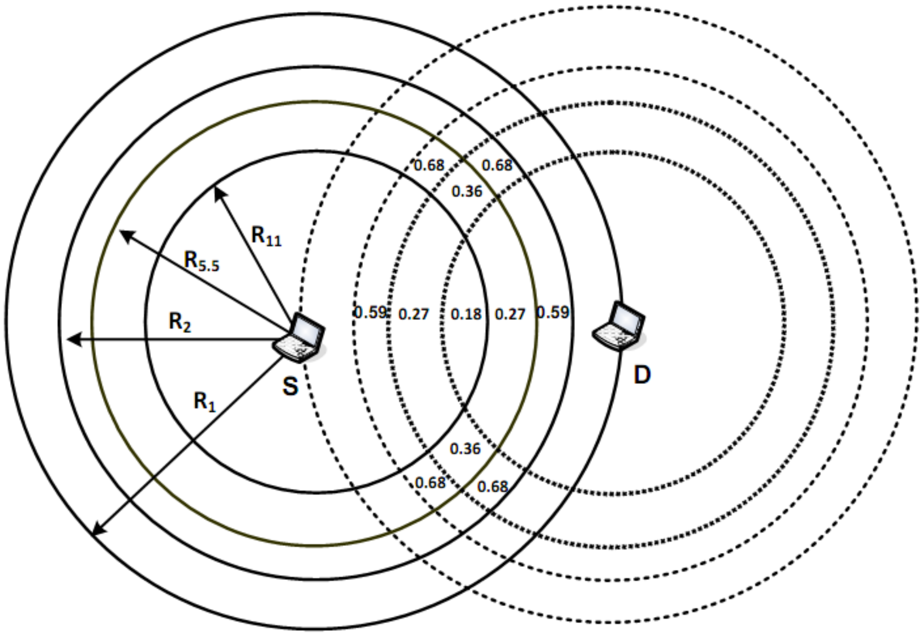
where, $\boldsymbol{h} = \frac{\sqrt{2{r_1}^2{r_2}^2+2({r_1}^2+{r_2}^2)l^2-({r_1}^4+{r_2}^4)-l^4}}{2l}$. The relay area of Figure 4.4 (a) can be computed as (4.26):

$$\begin{cases} A_{11-11} = S_{R_{11}-R_{11}} \\ A_{11-5.5} = A_{5.5-11} = S_{R_{11}-R_{5.5}} - S_{R_{11}-R_{11}} \\ A_{11-2} = A_{2-11} = S_{R_{11}-R_{2}} - S_{R_{11}-R_{5.5}} \\ A_{5.5-5.5} = \left(S_{R_{5.5}-R_{5.5}} - S_{R_{11}-R_{5.5}} - A_{11-5.5}\right)/2 \\ A_{5.5-2} = A_{2-5.5} = \left(S_{R_{5.5}-R_{2}} - S_{R_{5.5}-R_{5.5}} - A_{2-11}\right)/2 \end{cases} \tag{4.26}$$

By applying the recursive calculations in (4.26), the total area estimated in the previous theoretical analysis can be obtained by adding the area of the geometrical approximation for all possible delay ratios.



(a)



(b)

Figure 4.4 (a) Relay area of Min-TX category in IEEE 802.11b (b) Delay ratio corresponding to relay area

Table 4–1 Data rates and transmission ranges and corresponding Min-SNR of 802.11

802.11n	**Data rate (Mbps)**	7.2	14.4	21.7	28.9	43.3	57.8	65	72.2
	Typical Range (meter)	115	91	78	62	46	34	31	29
	Min-SNR (dB)	11	14	16	19	23	27	28	29
802.11g	**Data rate (Mbps)**	6	9	12	18	24	36	48	54
	Typical Range (meter)	122	107	96	85	75	61	42	31
	Min-SNR (dB)	8	9	11	13	16	20	24	25
802.11b	**Data rate (Mbps)**	1	2	5.5	11				
	Typical Range (meter)	180	150	130	100				
	Min-SNR (dB)	2	2.9	5.4	10				

Table 4–2 MAC layer parameters

Parameters	802.11b	802.11g	802.11n
Slot Time (μs)	20	9	9
SIFS (μs)	10	16	10
DIFS(μs)	50	34	28
RTS (μs)	352	46.7	38.89
CTS (μs)	304	38.7	32.23
HTS (μs)	304	38.7	32.23
ACK(μs)	304	38.7	32.23
PLCP (μs)	192	20	16.67
MAC header(bits)	272	272	272
Basic date rate (Mbps)	1	6	7.2
CWmin (SlotTime)	31	15	15
CWmax (SlotTime)	1023	1023	1023
Maximum Transmission Unit (MTU) (bytes)	2272	2272	7935

4.2.2 Discussion on Model

The geometrical model presented in Figure 4.4 provides a rate adaptation mechanism beyond the MAC layer operation. The existing rate adaptation schemes in MAC layer operate based on parameters such as SNR values and number of successful packets during the specific period of time. These parameters are dynamically changing due to channel variations and resulting in performance degradation. However, the proposed geometrical model operates based on the outcome of the channel variation impact by exploiting the diversity of two independent channels. The relay area corresponding to every delay ratio value is varied according to source-destination distance, and number of relay nodes in each relay area depends on the node density and its distribution in coverage area.

4.2.3 Evaluation of Min-TX protocols in IEEE 802.11bgn

In this section, some cooperative protocols of the Min-TX category are evaluated in terms of throughput. The relay area and the lower bound of useful packet size for every protocol are also presented. The simple scenario depicted in Figure 4.1 is applied for all Min-TX protocols in three amendments of 802.11b [6], 802.11g [7] and 802.11n [8]. In the case of 802.11n MAC layer, the study is limited to the legacy mode without special features such as aggregation, High Throughput PHY (HTP) and Block-ACK [8].

Table 4–1 indicates the data rates supported, corresponding minimum SNR and maximum transmission ranges of different amendments when BER=10^{-5} and bandwidth 20 MHz. For 802.11n, we assume one spatial data stream and short Guard Interval (GI) of 400 ns to transmit and receive the packet. Table 4–2 summarizes typical operational parameters of IEEE 802.11b/g/n.

4.2.3.1 Delay ratio and relay area

As discussed in Section 4.2.1 and according to the data rate and considering the approximated maximum transmission range of Table 4–1, the delay ratio of Min-TX category and corresponding useful relay area percentage (Table 4–3) are calculated. Table 4–3 presents the possible scenarios leading to delay ratio values less than one. For

802.11b, the relay area corresponding to every delay ratio value is presented in detail. For 802.11g and 802.11n, due to the many possibilities for delay ratios less than one, the delay ratio bounds and corresponding relay area are presented. Table 4–3 indicates that in 802.11g, which supports data rates from 6 Mbps to 54 Mbps, the cooperation of Min-TX category is beneficial for direct data rates between 6 Mbps to 24 Mbps. As the direct data rate increases, the probability of finding a useful relay node will decrease. Similarly, the delay ratio less than 1 is obtained for direct data rate in the range of 7.2 Mbps and 28.9 Mbps in 802.11n while 802.11n can support data rates from 7.2 Mbps to 72.2 Mbps in one spatial data stream. It is noted that for 802.11n with two, three and four spatial streams, we have the same delay ratio and relay area, while the data rates are multiplied respectively by two, three and four.

4.2.3.2 Throughput performance

In order to compute the throughput, which is possible to obtain by every cooperative protocol, the simple scenario depicted in Figure 4.1 is considered, and the different cooperative protocols of the Min-TX category applied. Therefore, their overhead, average idle time and average collision time should be computed. For simple scenario with three nodes, the average collision time is neglected, while the average idle time is calculated according to back-off time (T_B). T_B can be expressed as expressed in (4.27).

$$T_B = \frac{(CW_{min} - 1).(Slot\ time)}{2} \tag{4.27}$$

As shown in Table 4–4 and Table 4–5, the overhead and average idle time (T_{Idl}) of the protocols in different amendments for basic access and 4-way handshaking modes are computed respectively. T_{PLCP} is time duration of PLCP header; T_{DIFS} and T_{SIFS} are respectively DIFS and SIFS interval times; T_{ACK} is ACK frame duration time; T_B is average back-off time and T_{RS} is average relay selection time.

Table 4–3 Delay ratio and relay area of 802.11b, 802.11g and 802.11n

	S to D Data rate (Mbps)	S to Ri Data rate (Mbps)	Ri to D Data rate (Mbps)	Delay ratio	(Relay area/ Coverage area)%	
802.11b	1	11	11	0.18	1.2~4.5	19~22.3%
		11	5.5	0.27	7.2	
		5.5	5.5	0.36	1.8	
		2	11	0.59	6.4	
		2	5.5	0.68	2.4	
	2	11	11	0.36	4.5~7.3	11.2~14%
		11	5.5	0.54	4.9	
		5.5	5.5	0.72	1.8	
802.11g	6	24	36	min:0.42	13~16%	
		12	18	max:0.83		
	9	36	36	min:0.5	7.4~13%	
		18	24	max:0.88		
	12	36	54	min:0.55	3.3 ~4.6%	
		24	36	max:0.83		
	18	48	54	min:0.7	1.2~4.3%	
		36	48	max:0.88		
	24	54	54	min:0.89	2~3.6%	
		48	54	max:0.94		
802.11n	7.2	43.3	86.7	min:0.5	15.8~24.5%	
		28.9	43.3	max:0.83		
	14.4	57.8	144.4	min:0.7	8.6~12%	
		43.3	115.6	max:0.92		
	21.7	86.7	115.6, 130	0.87	0.1~1.5%	
	28.9	115.6	144.4	min:0.9	0.1~1.5%	
		115.6	130	max:0.94		

Table 4–4 Overhead and average idle time in basic access mode

Protocols	$T_{OH}+T_{Idl}$	802.11b (µs)	802.11g (µs)	802.11n (µs)
rDCF	$2T_{PLCP}+T_{DIFS}+3T_{SIFS}+2T_{ACK}+T_B$	1088	255.7	206.57
CoopMAC	$2T_{PLCP}+T_{DIFS}+3T_{SIFS}+2T_{ACK}+T_B$	1088	255.7	206.57
RAMA	$2T_{PLCP}+T_{DIFS}+4T_{SIFS}+2T_{ACK}+T_B$	1402	310.4	248.8
EMR	$2T_{PLCP}+2T_{DIFS}+2T_{SIFS}+2T_{ACK}+T_B$	1432	312.4	256.8
ORP	$2T_{PLCP}+T_{DIFS}+T_{SIFS}+T_{ACK}+T_{B1}+T_{B2}$	1218	373.7	336.57
CODE	$2T_{PLCP}+T_{DIFS}+4T_{SIFS}+2T_{ACK}+T_B$	1108	287.7	226.57
CoopMACA	$2T_{PLCP}+T_{DIFS}+4T_{SIFS}+2T_{ACK}+T_B+{}^{*}T_{RS}$ ${}^{*}T_{RS}=90+T_{SIFS}$	1208	393.7	326.57
CCMAC	$2T_{PLCP}+T_{DIFS}+3T_{SIFS}+2T_{ACK}+T_B$	1088	262.4	218.8
Normal-DCF	$T_{PLCP}+T_{DIFS}+T_{SIFS}+T_{ACK}+T_B$	856	171.7	149.9

Table 4–5 Overhead and average idle time in 4-way handshaking mode

Protocols	$T_{OH}+T_{Idl}$	802.11b (µs)	802.11g (µs)	802.11n (µs)
rDCF	$2T_{PLCP}+T_{DIFS}+5_{TSIFS}+T_{RTS}+2T_{CTS}+T_{ACK}+T_B$	2048	379.8	309.92
CoopMAC	$2T_{PLCP}+T_{DIFS}+5_{TSIFS}+T_{RTS}+2T_{CTS}+T_{ACK}+T_B$	2048	379.8	309.92
RAMA	$2T_{PLCP}+T_{DIFS}+6T_{SIFS}+T_{RTS}+T_{CTS}+2T_{ACK}+T_B$	2058	395.8	319.92
EMR	$2T_{PLCP}+3T_{DIFS}+4T_{SIFS}+T_{RTS}+T_{CTS}+2T_{ACK}+T_B$	2138	431.8	355.92
ORP	$2T_{PLCP}+T_{DIFS}+3T_{SIFS}+T_{RTS}+T_{CTS}+T_{ACK}+T_{B1}+T_{B2}$	1874	459.1	407.69
CODE	$2T_{PLCP}+T_{DIFS}+7T_{SIFS}+T_{RTS1}+T_{RTS2}+T_{RTS3}+T_{RCTS}+T_{ACK}+T_B$	2468	466.5	375.47
CoopMACA	$2T_{PLCP}+T_{DIFS}+6T_{SIFS}+T_{RTS}+2T_{CTS}+T_{ACK}+T_B+{}^{*}T_{RS}$ ${}^{*}T_{RS}=90+T_{SIFS}$	2158	501.8	419.92
CCMAC	$2T_{PLCP}+T_{DIFS}+5T_{SIFS}+T_{RTS}+2T_{CTS}+T_{ACK}+T_B$	2048	379.8	309.92
Normal-DCF	$T_{PLCP}+T_{DIFS}+3T_{SIFS}+T_{RTS}+T_{CTS}+T_{ACK}+T_B$	1532	289.1	241.02

As presented in equations (4.11) and (4.12), we can obtain the throughput performance bounds of every cooperative protocol according to delay ratio bounds. Figure 4.5 depicts the throughput bounds of these Min-TX protocols for the basic access mode of 802.11b, 802.11g and 802.11n when the data packet size changes from 500 to 3000 bytes. Two direct data rates with high probability (according to their relay area) of being useful for cooperation in each amendment are considered. This evaluation is also extended to 4-way handshaking mode: the results are depicted in Figure 4.6. Comparison of throughput bounds with the average DCF throughput (also presented in the same figures) in these two modes demonstrate the gain obtained for every direct data rate. It is concluded that throughput gain will improve for larger data packets, with rDCF/CoopMAC/CCMAC protocols presenting the higher bounds. The cooperative protocols cannot obtain throughput gains in the case of small data packet size since the extra overhead imposed by a cooperative scheme has a negative impact on the performance of Min-TX protocols which are based on delay reduction especially for small packet size. In some cases the lower bound or upper bound of throughput is less than the normal 802.11 DCF when the direct data rates varied. Therefore, for each protocol it is necessary to assess the lower bound of the data packet size which results in beneficial cooperation in term of throughput gain for each protocol.

Figure 4.7 shows the lower bound of data packets in two modes of basic access and 4-way handshaking and different amendments of 802.11b, 802.11g and 802.11n. The lower bound of data packet size is compared with the Maximum Transmitted Unit (MTU) (Table 4–2) in each amendment. These figures illustrate in each protocol which direct data rates cannot have any possibility for cooperation. Those protocols which have the lower bound of the data packet size higher than the corresponding MTU for a given direct data rate, cannot actually provide effective cooperation at that particular direct data rate.

The results indicate for direct data rates of 24 Mbps in 802.11g, that is no possible option for the cooperation in any of cooperative MAC protocols considered, and in 802.11n, ORP and CoopMACA also provide no effective cooperation when the direct data rate is 28.9 Mbps.

In practice, for 802.11g and 802.11n, it can be expected that a randomly positioned relay will be in a useful position only when the direct data rates are in the minimum possible.

Otherwise, the useful relay areas are very small and according to the computed minimum useful packet size, the situations with beneficial cooperation will be very special. Moreover, as the direct data rate increases the corresponding relay area will increase. This evaluation provides a practical view which demonstrates that the performance gain and high probability of cooperation are provided for low data rates of direct transmission with large packet size.

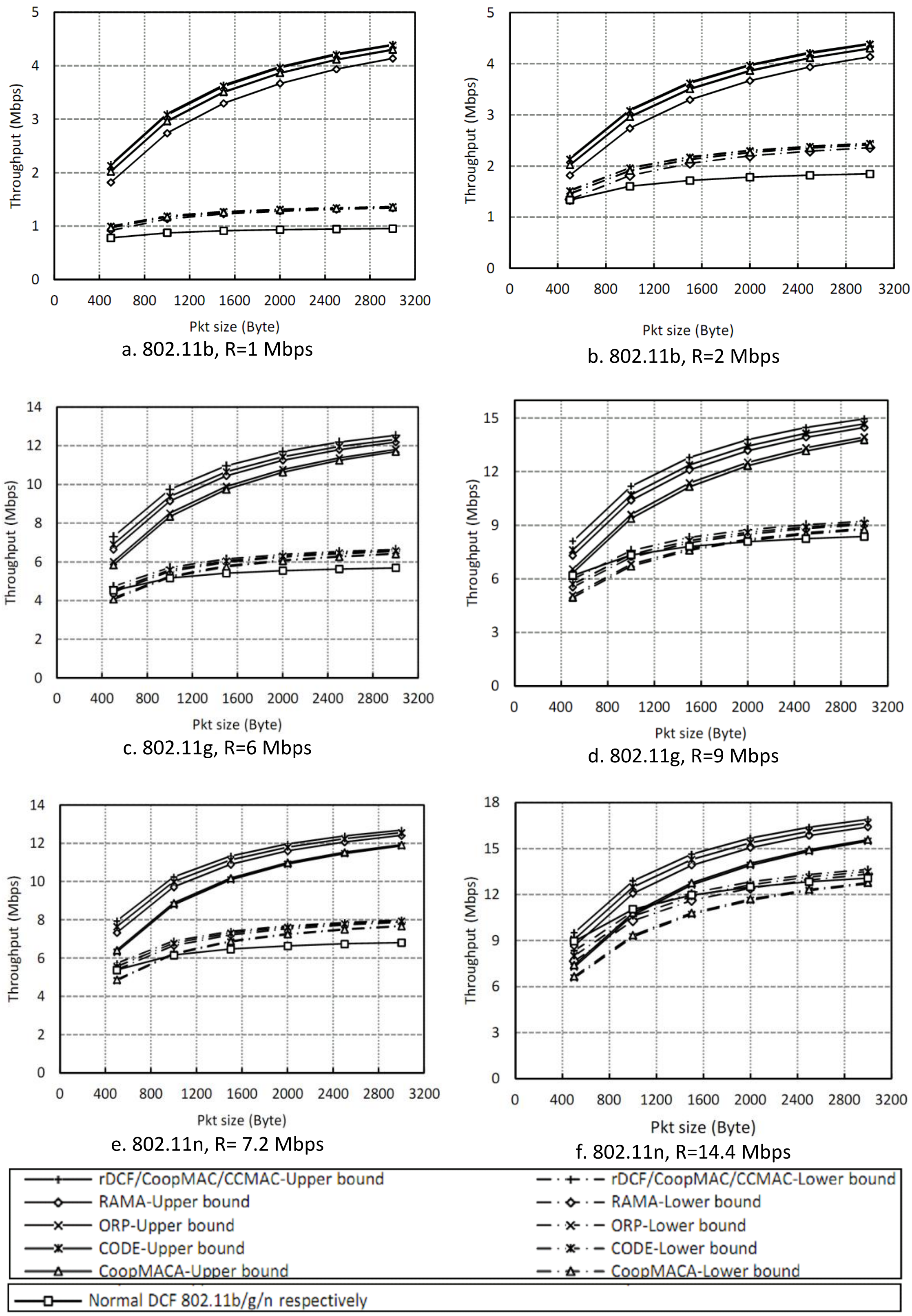


Figure 4.5 Throughput performance bounds of Min-TX protocols in basic access mode of DCF

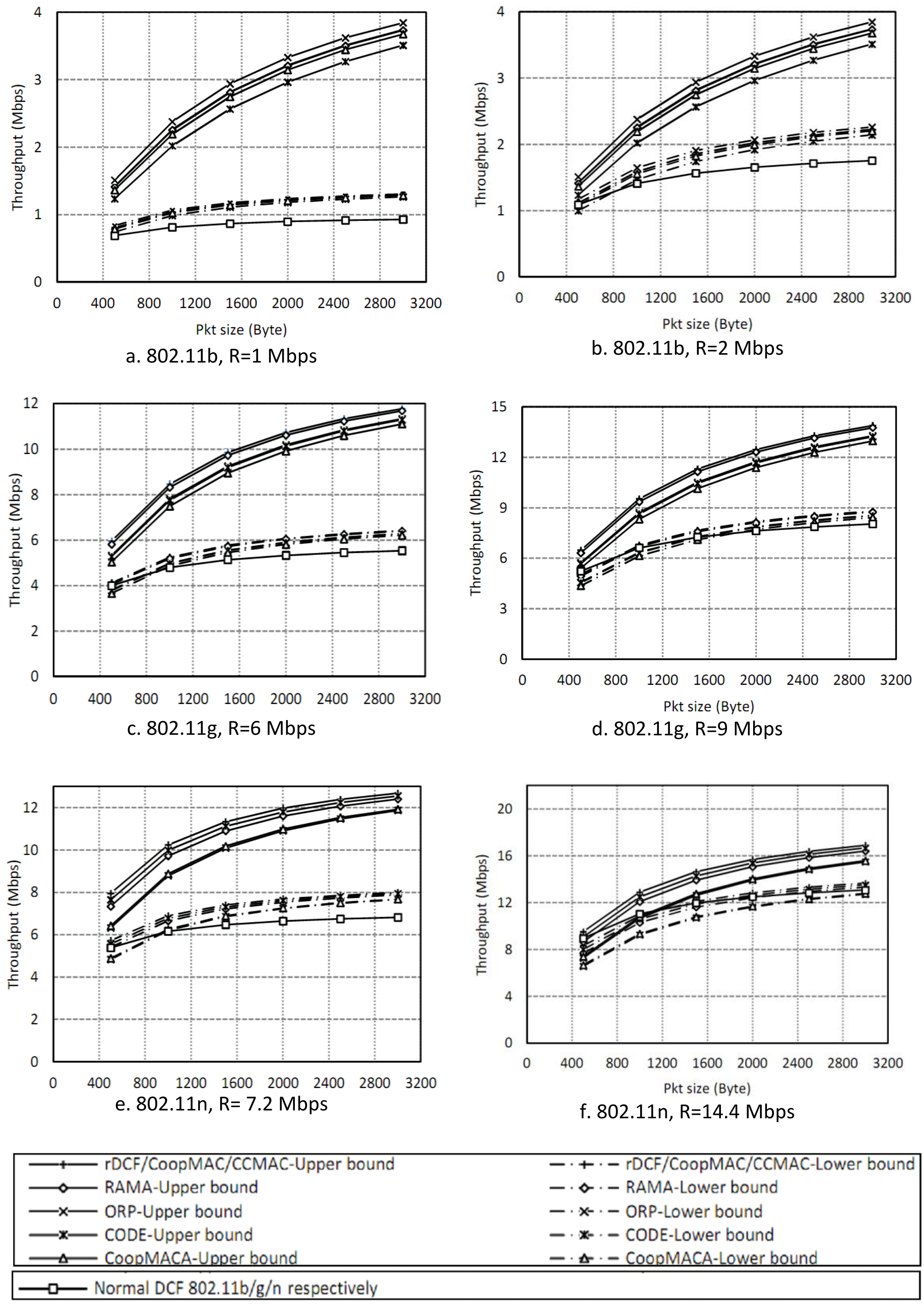


Figure 4.6 Throughput performance bounds of Min-TX protocols in 4-way handshaking mode of DCF

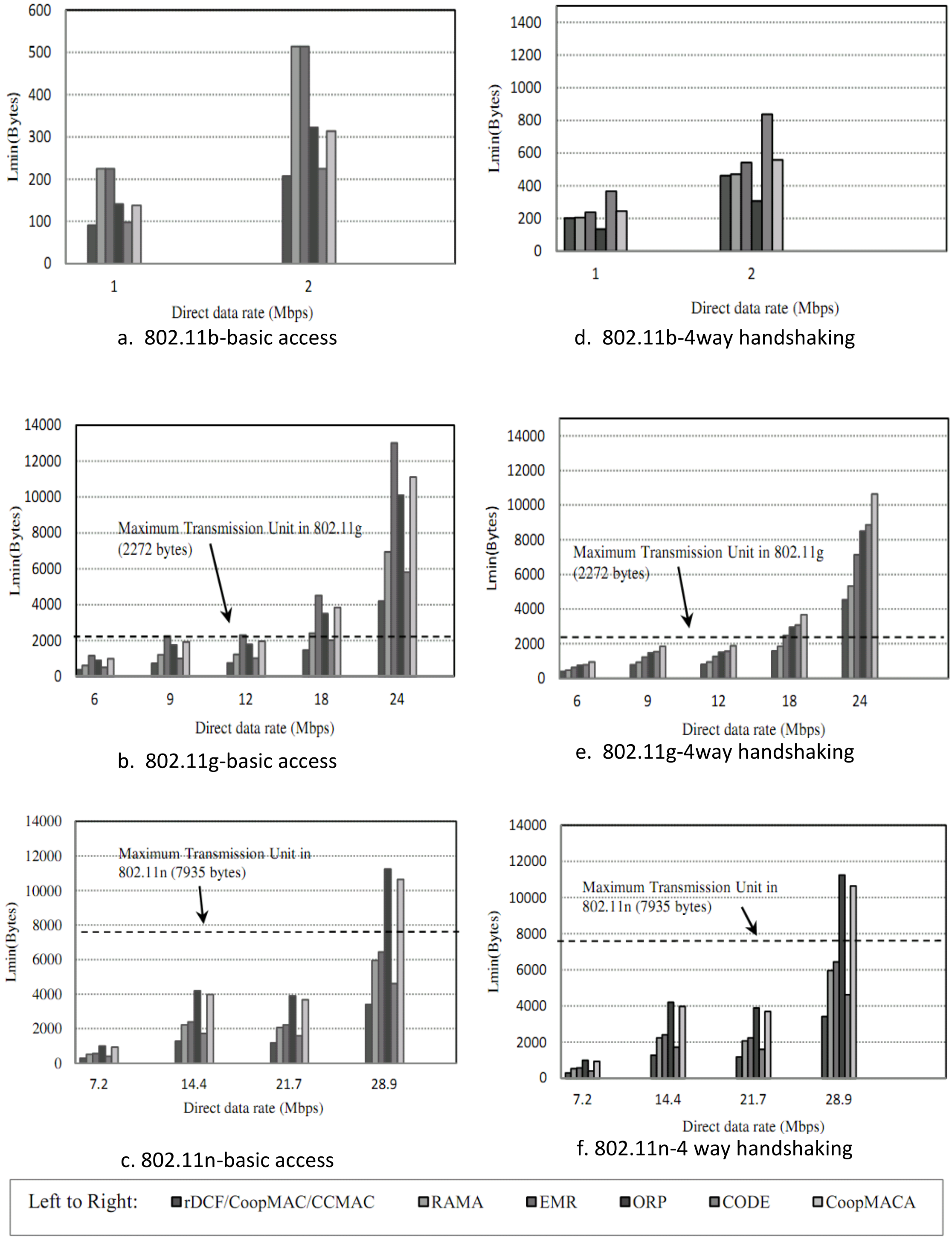


Figure 4.7 Lower bound of data packet size of Min-TX protocols in basic access mode (a, b, c) and 4-way handshaking mode (d, e, f)

4.3 Energy efficiency and cooperation

Energy efficiency is one of the objectives which can be obtained by cooperation. The main idea behind this type of cooperation is that splitting the distance between source and destination by relay nodes, we can consume less power for packet transmission, if the transmission delay is not concerned. In IEEE 802.11 networks, energy efficiency is affected by factors such as the transmit power, processing power required for forwarding packets by mobile nodes. In real scenarios, evaluating the required SNR to support multi-rate communications results in the mutual effects between spectrum efficiency and power efficiency. In this section, we present a system model and mathematical analysis to demonstrate the potential of IEEE 802.11 networks in providing energy efficiency.

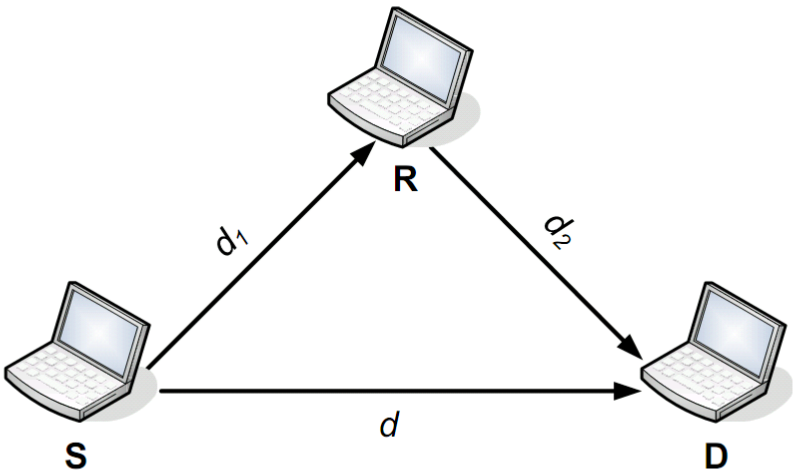


Figure 4.8 Example of cooperation with energy efficiency

4.3.1 System model

The multi rate nature of IEEE 802.11 standards provides different transmission delays based on received SNR. A higher SNR value results in a higher data rate with low Bit Error Rate (BER). The SNR value is a function of several parameters such as power transmitted, path loss, wireless environment and the distance between transmitter and receiver. Here, we consider a scenario that by reducing the transmitted power in source and relay two purposes are followed: 1) to overcome the path loss of source-relay and relay-destination channels and 2) to provide a twice data rate of direct transmission for S-R and

R-D links. The second purpose is the equivalent of unit delay ratio (DR=1). By this technique, we have a cooperation scenario with the same delay as direct one while the energy efficiency can be achievable. In direct transmission depicted in Figure 4.8, the SNR of received signal at destination with noise power of N_0 can be expressed as:

$$\mathrm{SNR_{SD}} = \frac{\mathrm{P_{tSD}}}{\mathrm{PL(d).N_0}} \tag{4.28}$$

Where P_{tSD} is the power radiated by the source in a direct transmission, $PL(d)$ is channel path loss between source and destination with distance of d and can be expressed as $P_L = K/d^n$ with constant of K and path loss coefficient of n. The SNR of received signals at relay and destination in cooperation scenario can be expressed as

$$\mathrm{SNR_{SR}} = \frac{\mathrm{P_{tSR}}}{\mathrm{PL(d).x^n.N_0}} \tag{4.29}$$

$$\mathrm{SNR_{RD}} = \frac{\mathrm{P_{tRD}}}{\mathrm{PL(d).y^n.N_0}} \tag{4.30}$$

Where P_{tSR} and P_{tRD} are transmitted power by source and relay and $x = d_1/d$ and $y = d_2/d$. By assuming a symmetric scenario ($x = y$) and applying Shannon's formula and considering unit delay ratio (i.e. $B_{SR} = B_{RD} = 2B_{SD}$), corresponding received SNR in three links can be expressed as (4.31) and (4.32).The SNR_{SR} value can be computed based on two expressions of (4.33). By substituting of SNR_{SR} and SNR_{SD} based on equations (4.28) and (4.29), we can obtain the relation of transmitted power of direct and cooperative transmissions as expressed in (4.35).

$$SNR_{SD} = 2^{\frac{B_{SD}}{\mathrm{W}}} - 1 \tag{4.31}$$

$$SNR_{SR} = SNR_{RD} = 2^{\frac{2B_{SD}}{\mathrm{W}}} - 1 \tag{4.32}$$

$$\begin{cases} SNR_{SR} = \dfrac{\mathrm{P_{tSR}}}{\mathrm{PL(d).x^n.N_0}} \\ SNR_{SR} = (2^{\frac{B_{SD}}{\mathrm{W}}} - 1)(2^{\frac{B_{SD}}{\mathrm{W}}} + 1) = SNR_{SD}(SNR_{SD} + 2) \end{cases} \tag{4.33}$$

$$P_{tSR} = x^n(\frac{P_{tSD}}{PL(d).N_0} + 2) \tag{4.34}$$

Here, we define a metric of Power Gain (PG) for this scenario as expressed in (4.35). In order to achieve power efficiency, the condition of $PG > 1$ should be satisfied. This condition results in the lower bound of P_{tSD} for direct transmission as expressed in (4.36). The value of PG is a function of SNR_{SD} and can be expressed as equation (4.35).

$$PG = \frac{P_{tSD}}{(P_{tSR} + P_{tRD})} \xrightarrow[(P_{tSR}=P_{tRD})]{} PG = \frac{P_{tSD}}{2x^n(\frac{P_{tSD}}{PL(d).N_0} + 2)} \tag{4.35}$$

$$PG > 1 \Rightarrow P_{tSD} > \frac{2}{\frac{1}{2x^n} - \frac{1}{PL(d).N_0}} \tag{4.36}$$

This theoretical analysis provides the power gain and conditions leading to power efficiency by cooperative schemes. However, in a practical scenario the minimum SNR corresponding to each data rate is determined by vendors (Table 4-1). Therefore, it is necessary to modify the PG formula based on the required minimum SNR. Equations (4.37) and (4.38) provide this modification in absolute form and logarithmic form versus dB. Lets suppose $(SNR_{SD})_{dB} - (SNR_{SR})_{dB} = \beta$, Therefore, PG_{dB} can be expressed as (4.39) Equation (4.39) can determine the range of path loss coefficient (n) as computed in (4.40). This condition indicates the relation between the location of relay node (x) , the required SNR (β) and wireless environment (n) when energy efficiency is achievable.

$$PG = \frac{(SNR_{SD}.PL(d).N_0)}{2x^n(SNR_{SR}.PL(d).N_0)} = \frac{SNR_{SD}}{2x^n SNR_{SR}} \tag{4.37}$$

$$PG_{dB} = (SNR_{SD})_{dB} - (SNR_{SR})_{dB} - 10\log 2x^n \tag{4.38}$$

$$PG_{dB} = \beta - 3 - 10n\log x \tag{4.39}$$

$$PG_{dB} > 0 \rightarrow n > \frac{3 - \beta}{10\log x} \tag{4.40}$$

Table 4–6 Data rate set and power gain in 802.11/b/g/n

	Data rate (Mbps)	Min(SNR) (dB)	Data rate set (Delay ratio≈1)			PG(dB)	
			$R_{S\to D}$	$R_{S\to R}$	β	n= 4	n=6
802.11n	7.2	11	-	-	-	-	-
	14.4	14	7.2	14.4	3	6	12
	21.7	16	-	-	-	-	-
	28.9	19	14.4	28.9	5	4	10
	43.3	23	21.7	43.3	7	2	8
	57.8	27	28.9	57.8	8	1	7
802.11g	6	8	-	-	-	-	-
	9	9	-	-	-	-	-
	12	11	6	12	3	6	12
	18	13	9	18	4	5	11
	24	16	12	24	5	4	10
	36	20	18	36	7	2	8
	48	24	24	48	8	1	7
802.11b	1	2	-	-	-	-	-
	2	2.9	1	2	0.9	8.1	14.1
	5.5	5.4	2	5.5	2.5	6.5	12.5
	11	10	5.5	11	4.6	4.4	10.4

4.3.2 Evaluation of energy efficiency in IEEE 802.11

To evaluate the energy efficiency achieved by a cooperative scheme, an indoor environment with obstructed communication paths (i.e. a normal building with walls and furniture). The path loss coefficient of this environment varies between 4 and 6 [104]. Table 4–6 indicates the data set rates which provide the delay ratio close to 1, the value of β and the power gain (PG) as discussed in Section 4.3.1. Figure 4.9 presents the power gain obtained for minimum and maximum value of path loss coefficient for data rates supported in 802.11b/g/n. In cooperative scenarios, if communicating with a lower data rate, we can achieve higher energy efficiency, when compared to the higher data rate. The energy efficiency of 802.11b in a cooperative scenario outperforms 802.11g/n when the main purpose of cooperation is energy saving with no improvement over throughput. This has to do with the communication range provided by the lowest data rate of both protocols. In the case of 802.11b, this range is much higher, thus leading to a more energy efficiency communication.

4.4 Concluding Remarks

In this chapter, a system model and performance metrics for the Min-TX class of protocols were presented. Due to the importance of transmission delay, a performance metric, delay ratio, was proposed to evaluate the operation of Min-TX protocols and their performance gain. An analysis was developed for effective relay area along theoretical and geometrical aspects. This allowed the evaluation of Min-TX protocols and the calculus of throughput performance bound for 802.11b, 802.11g and 802.11n in the two modes supported by the DCF method. Furthermore, the useful relay area corresponding to every data rate and lower bound of data packet size of each protocol were also computed.

This chapter also addresses performance bounds, and not average value since these would depend on multiple factors (such as application). Nevertheless, the bounds estimated in this paper suffice to indicate that cooperation techniques may provide a useful contribution to 802.11 communication challenges, but these are somewhat limited. The multiple protocols analyzed show some common weakness. For many communication scenarios, these protocols would only be useful for jumbo frames, packets larger than the 802.11 normal MTU. Only for direct data rates near the minimum values of the specific 802.11

amendment do clear advantages seems to exist. However, note that this usually corresponds to bad coverage areas prone to disconnections in most deployments, and as such wireless network designers try to avoid them at the planning stage. Also, it should be noticed that for random deployments of nodes, the probability of finding a node in a useful location is reasonably low for all stations except those with the same low direct data rate connections. Although the literature already presents many different cooperative protocols, with different performances, this weakness seems inherent to all protocols in the Min-TX class. As such, the selection of a specific cooperative protocol has to be carefully made, and should include aspects which are scenario dependent, such as application usage and implementation complexity.

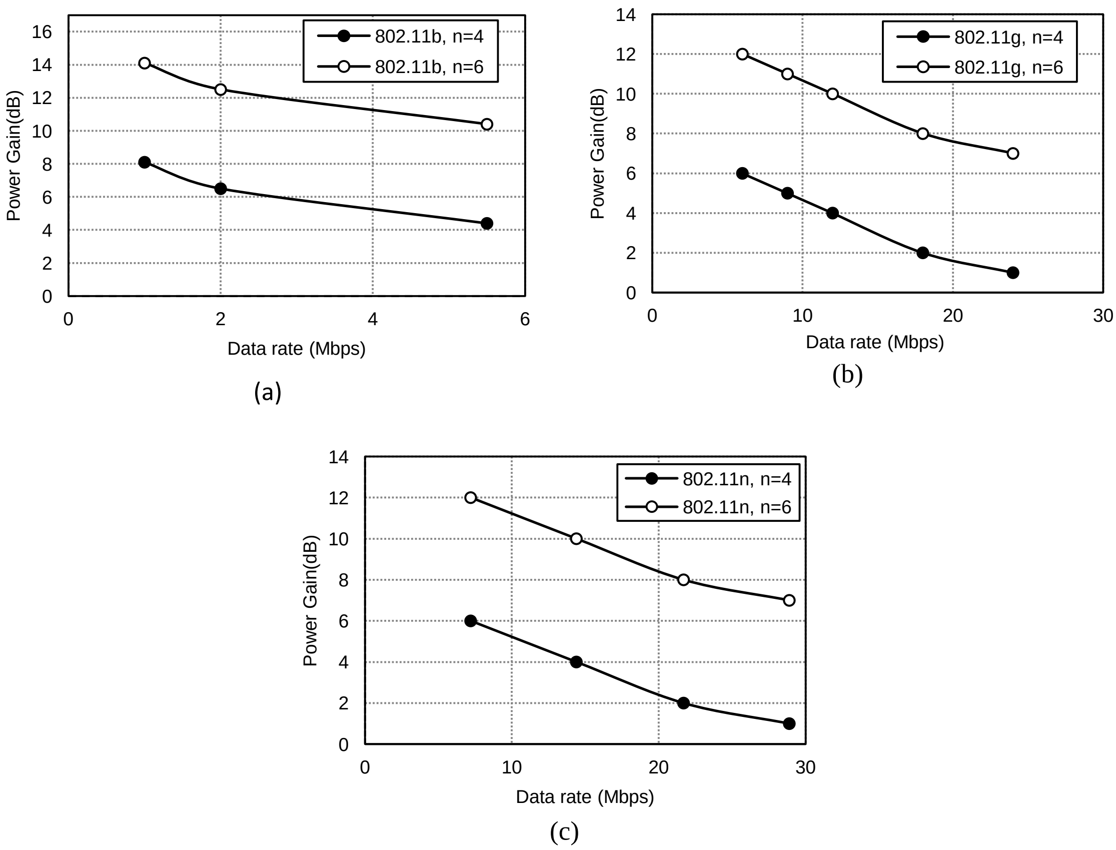


Figure 4.9 Power gain versus data rate and path loss coefficient (n) in (a) 802.11b, (b) 802.11g and (c) 802.11n

CHAPTER 5 CROSS LAYER METRICS IN IEEE 802.11 COOPERATIVE MAC PROTOCOLS

Summary

There has been great concern over cooperation algorithms and protocols in lower layers especially physical and MAC layers. However, the characteristics of application service types and overall aspects of wireless network such as mobility impose novel situations on cooperation design algorithms. Definitions of new metrics for analysing the sensing information and applying it to relay selection are the main objective of this chapter. This chapter introduces a new metric for cross layer design approaches when reliability, stability and mobility of the relay nodes are the main components of the metric.

5.1 Introduction

In the MAPE framework explained in Section 3.3, Analysis and Plan are two important phases which make use of information obtained during the Monitor phase and determine whether the cooperation is beneficial or not. When the cooperation is applied in the MAC layer, cross layer issues are one of the main aspects in designing an appropriate protocol. Cross layer issues include application service requirements from higher layer, mobility aspects of the nodes on the whole networks and reliability of selected cooperative links. With the aim of providing enhanced performance, the idea of cross layer issues is extended to design a cooperative metric. In the rest of this chapter, cooperation and cross layer issues are discussed in Section5.2. A new metric called CoopMetric (CM) is proposed for cross layer cooperation in Section 5.3. In Section 5.3, a system model based on CM is analysed and it is discussed how the CM improves the relay selection algorithm. The evaluation of CoopMAC protocol enabled by CM metric for different types of traffic service is presented and discussed in Section 5.5. Section 5.6 concludes this chapter.

5.2 Cooperation and cross layer issues

As discussed in the MAPE framework, the goals of the cooperation process can adjust the operation of each phase. For instance, if the cooperation purpose is to increase the bandwidth efficiency, the Monitor, Analysis and Plan phases operate in the direction of reducing transmission delay by using the selected relay node(s). In this case, by using the appropriate sensing methods, the Monitor phase discovers the relays which reduce the transmission delay while the Analysis and Plan phases exploit the criteria and metrics to determine which relay node(s) can provide more efficiency in term of bandwidth. Then the Execute phase starts to apply the cooperation to selected relay node(s). The cooperative protocols of the Min-TX category follow this cooperation purpose.

Nonetheless, there are some aspects which have not been taken into consideration. Application service properties and their mutual effects on MAC and physical layer parameters can also be important in cooperative scenarios. As an example, in a direct transmission scenario, if the bandwidth provided at the physical layer is more than the data rate generated at the application service layer, there is no need to improve the bandwidth efficiency by using cooperative schemes. Therefore, the goal of bandwidth efficiency provided by cooperation is useful for applications with high data rate generated compared to bandwidth provided by the direct path at lower layers.

Moreover, some applications may benefit more from reliability and stability (Voice over IP (VOIP)) rather than bandwidth efficiency. As an example, for a real time UDP traffic, jitter reduction and low packet loss have a high order of importance. In addition, mobility can impact remarkably on relay links and subsequently on cooperation performance, although VOIP applications usually do not require much bandwidth. Therefore, respective mobility aspects should be taken into consideration for relay selection algorithms. In the next section, a metric for relay selection algorithms is presented in which all the above mentioned aspects including bandwidth, reliability, stability and mobility aspects are taken into consideration.

5.3 CoopMetric for relay selection

In order to find the appropriate set of relay nodes providing the required throughput improvement and reliability, a metric called CoopMetric is proposed. This metric has two main components corresponding to delay reduction and reliability of the cooperative path: Delay Ratio (DR) and Reliability (RE). In this section, we explain how to obtain these components and then we discuss their compositions in CoopMetric. Delay Ratio was described in detail in Section4.2.

Reliability: Besides the transmission delay which is indicated by delay ratio, a parameter is needed to relate the reliability of cooperative path including source-relay and relay-destination links. By using a practical sensing method, the total number of transmitted packets (N_T) and number of acknowledgment packets (N_{ACK}) can be overheard. Then, the corresponding reliability of source-relay (RE_{SRi}) and relay-destination (RE_{RiD}) can be given as (5.1).

$$RE_{SRi} = \frac{N_{ACK-SRi}}{N_{T-SRi}} \text{ , } RE_{RiD} = \frac{N_{ACK-RiD}}{N_{T-RiD}} \tag{5.1}$$

The reliability of cooperative path of S-R_i-D is the product of RE_{SRi} and RE_{RiD} can be expressed as (5.2):

$$RE_i = RE_{SRi} \, . RE_{RiD} \tag{5.2}$$

CoopMetric: In order to select the best relay node, the source node needs to evaluate the delay ratio and reliability values of all neighbours in a table called RelayTable. The RelayTable contains instantaneous value of DR_i and RE_i for a specific period of time called observation window ($W_{obs.}$). In order to calculate the average of delay ratio and reliability, the source node calculates the exponential moving average (EMA) of DR_i and RE_i as expressed in (5.3) and (5.4).

$$(\mathrm{DR_i})_{\,t} = \alpha(\mathrm{DR_{i-obs.}})_{\,t} + (1-\alpha)(\mathrm{DR_i})_{\,t-1} \tag{5.3}$$

$$(\mathrm{RE_i})_{\,t} = \beta(\mathrm{RE_{i-obs.}})_{\,t} + (1-\beta)(\mathrm{RE_i})_{\,t-1} \tag{5.4}$$

where $(\mathrm{DR_{i-obs.}})_{\,t}$ and $(\mathrm{RE_{i-obs.}})_{\,t}$ are the observed values at time t, $(\mathrm{DR_i})_{\,t-1}$ and $(\mathrm{RE_i})_{\,t-1}$ are EMA values obtained by the previous sample, and α and β are the constant values. The EMA values provide the decision based on the overall variation trend of delay ratio and reliability values. When source node has a data packet to send, it should determine which relay node has less variation of delay ratio and reliability. Low variation of delay ratio may indicate lower mobility of the relay node in respect to the source and destination locations. Similarly, a relay node with low variation of reliability presents a cooperative path with more stable links and constant value of packet loss. Therefore, $\sigma_{\mathrm{DR_i}}$ and $\sigma_{\mathrm{RE_i}}$ are selected as standard deviation of delay ratio and reliability for a relay node R_i for samples registered during t and t- $W_{obs.}$. Clearly $(1-\sigma_{\mathrm{DR_i}})$ and $(1-\sigma_{\mathrm{RE_i}})$ refer to the stability of relay node respectively in delay ratio and reliability.

According to the above discussion, it is concluded that the CoopMetric is directly proportional to reliability (RE) and inversely proportional to delay ratio (DR). CoopMetric is also directly proportional to the stability of a relay node including reliability and delay ratio values. All these relations are expressed as (5.5) to (5.7).

$$CM_i \propto \frac{1}{DR_i} \Rightarrow CM_i = \frac{K_{DR}}{DR_i} \tag{5.5}$$

$$CM_i \propto RE_i \Rightarrow CM_i = K_{RE}.RE_i \tag{5.6}$$

$$CM_i \propto \left(1 - \sigma_{DR_i}\right).\left(1 - \sigma_{RE_i}\right) \Rightarrow CM_i = K_{ST}\left(1 - \sigma_{DR_i}\right).\left(1 - \sigma_{RE_i}\right) \tag{5.7}$$

We can finalize the CM as expressed in (5.8):

$$CM_i = K_{DR}K_{RE}K_{ST}\left(1 - \sigma_{DR_i}\right).\left(1 - \sigma_{RE_i}\right)\frac{RE_i}{DR_i} \tag{5.8}$$

and since the coefficient ($K_{DR}K_{RE}K_{ST}$) is a constant value and it only presents a scale of CoopMetric, it can be eliminated and the CoopMetric summarized as (5.9):

$$CM_i = \frac{RE_i}{DR_i}\left(1 - \sigma_{DR_i}\right).\left(1 - \sigma_{RE_i}\right) \tag{5.9}$$

Table 5–1 RelayTable and CoopMetric

Relay	**Time**	$(DR_{i-obs.})_t$	$(DR_i)_t$	$(RE_{i-obs.})_t$	$(RE_i)_t$	$(\sigma_{DR_i})_{(t,t-W_{obs.})}$	$(\sigma_{RE_i})_{(t,t-W_{obs.})}$	CM_i
R_1	t							CM_1
	t-1							
	...							
	$t\text{-}W_{obs.}$							
R_2	t							CM_2
	t-1							
	...							
	$t\text{-}W_{obs.}$							
...	t							….
	t-1							
	...							
	$t\text{-}W_{obs.}$							
R_N	t							CM_N
	t-1							
	...							
	$t\text{-}W_{obs.}$							

Table 5–1 depicts the RelayTable created by the source node in which CoopMetric at time *t* is computed based on the EMA values and standard deviation values of delay ratio and reliability in duration of (t , t- W_{obs}).

5.4 System model

Similar to the system model discussed in Section 4.2.1, a new system model can be presented based on CoopMetric. The primary condition of the cooperation is lower transmission delay of cooperation scenario compared to direct transmission. Equations (5.10) to (5.12) present the system model and lower bound of CM.

$$T_{C(R_i)}(L, B_{SD}, CM_i) < T_{SD}(L, B_{SD}) \tag{5.10}$$

$$\frac{1}{CM_i} . T_{SD/DATA}(L, B_{SD}) + T_{C(R_i)/OH} + \tau_{RS} < T_{SD/DATA}(L, B_{SD}) + T_{SD/OH} \tag{5.11}$$

$$CM_i > \left(1 + \frac{B_{SD}(T_{SD/OH} - T_{C(R_i)/OH} - \tau_{RS})}{\mathrm{L}}\right)^{-1} \tag{5.12}$$

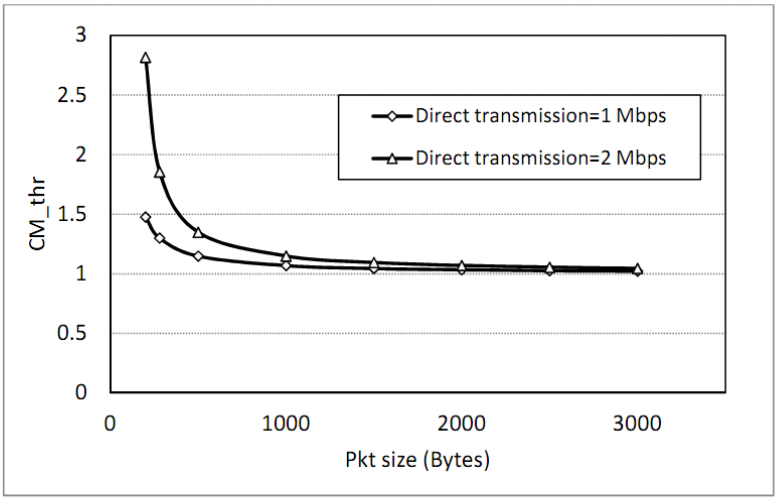


Figure 5.1 Threshold of CooMetric versus the packet size for different direct data rates in IEEE 802.11b

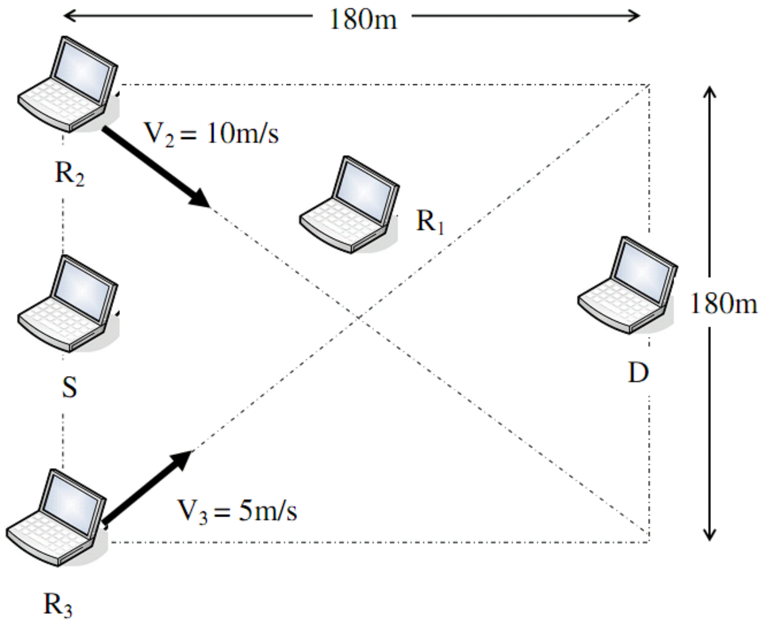
Figure 5.1depicts the CM_{thr} for different packet sizes and direct transmission of 1Mbps and 2 Mbps in IEEE 802.11b. As can be seen in Figure 5.1, the probability of cooperation for larger packets is higher than for smaller packets. Because, with higher packet size, the value of CM_{thr} is remarkably reduced and the possibilities for cooperation will be increased.

5.5 Evaluation and results

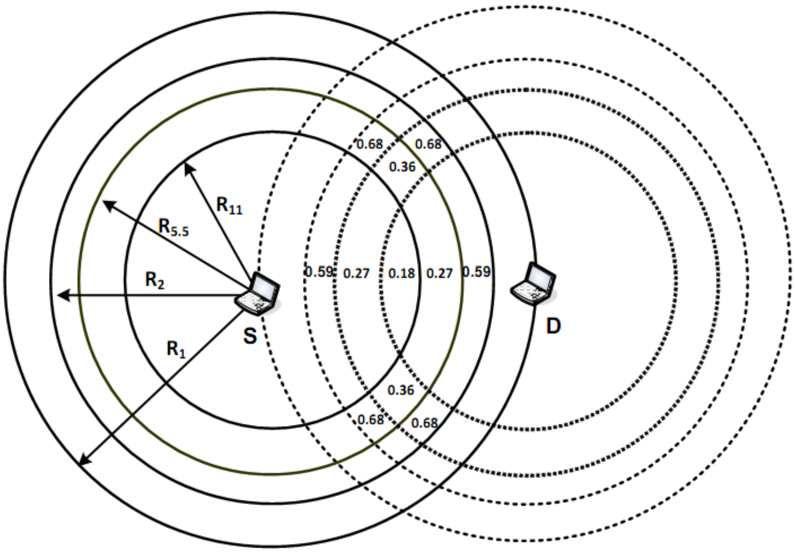
In this section, CoopMetric is employed as a metric for relay selection in CoopMAC protocol. Two versions of CoopMAC protocol are implemented in OMNET++ based on delay ratio and CoopMetric. A simulation scenario is set up to evaluate the performance provided by these metrics.

5.5.1 Simulation scenario

In this section, CoopMetric is employed by CoopMAC protocol for relay selection metric. An implementation of CoopMAC protocol is presented in OMNET++ when delay ratio and CoopMetric are considered as two relay selection metrics. Figure 5.2 depicts a cooperation scenario, where one static node (R1), and two mobile nodes (R2 and R3) with speed of 10 m/s and 5 m/s respectively can be the potential relay nodes for a pair of source (S) and destination (D) nodes. Node R1 is placed in a relay area which provides the delay ratio of 0.36 while R2 and R3 could sense different delay ratios as depicted in Figure 5.2.b. Since R2 and R3 have different speeds, they would not sense similar variation rate. We select VOIP as a UDP traffic type and Video on Demand (VOD) as a TCP traffic type for application services with the characteristics presented in Table 5–2, Table 5–3 and Table 5–4 present simulation parameters.



(a)



(b)

Figure 5.2 (a)cooperation scenario with three relay nodes ,(b) Delay ratio profile

Table 5–2 VOIP traffic characteristics

Codec	Voice Payload Size (ms)	Voice Payload Size (Bytes)	Data packet rate (kbps)	RTP header+IP+UDP (bytes)
G.711	20 (default)	160	16	40
	30	240	64	40
G.729	20 (default)	20	8	40
	30	30	8	40
G.723	30 (default)	24 /20	6.4/5.28	40

Table 5–3 TCP traffic- Video on demand (VOD) characteristics

Video on demand		
Video Payload Size (Bytes)	**Data packet rate (Mbps)**	**Header(IP+UDP) (Bytes)**
500-2250	4	28

Table 5–4 Simulation parametrs

parameters	values
IEEE standard	802.11b
Data rates (Mbps)	1,2,5.5,11
Simulation time (Sec.)	60
Delay ratio	[0.18,0.27,0.36,0.59,0.68]

5.5.2 UDP traffic-VOIP

In UDP traffic services, parameters such as jitter and packet loss are the two main concerns in performance evaluations. Figure 5.3 and Figure 5.4 present jitter values and packet loss in the cooperation scenario of Figure 5.2, where the direct transmission is 1 Mbps and 2 Mbps. As depicted in Figure 5.3, the average jitter value of CoopMAC protocol using CM is reduced compared to metric DR and normal 802.11b. In addition, the variation range of jitter value when using CM is lower than the situation using DR and also 802.11b. For packet loss, the performance of CoopMAC is improved when using CM as a selection metric.

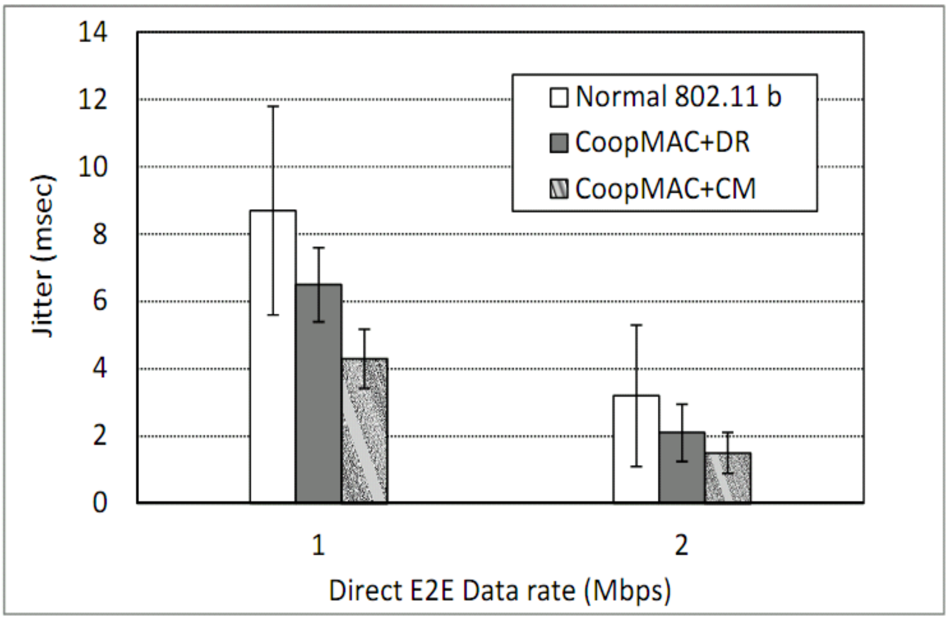


Figure 5.3 Jitter value of UDP VOIP when using CM and DR as metric compared to 802.11b

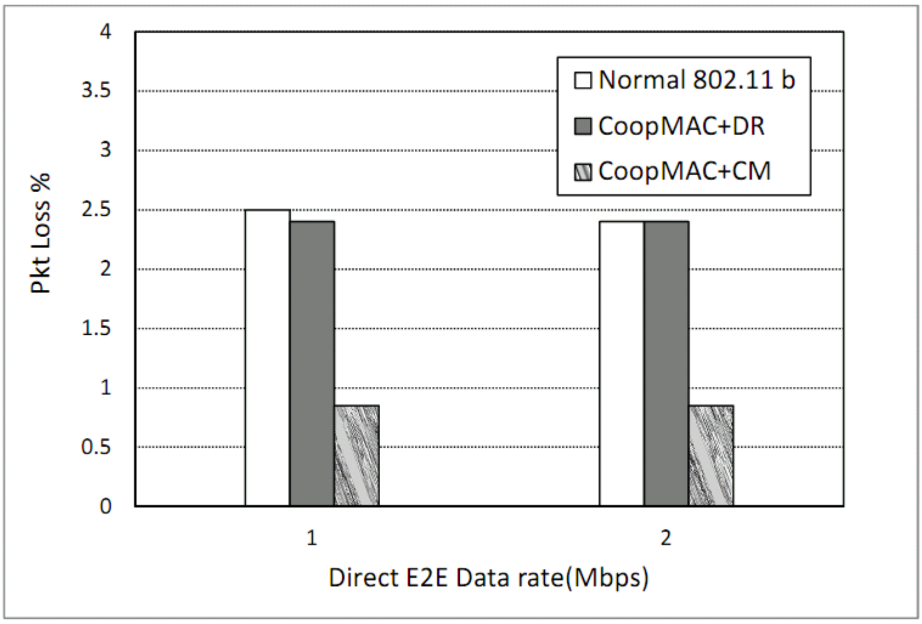
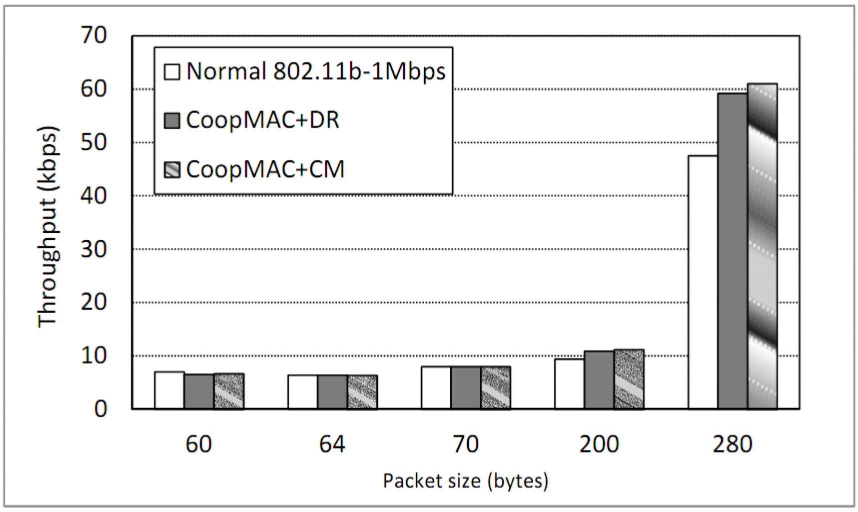
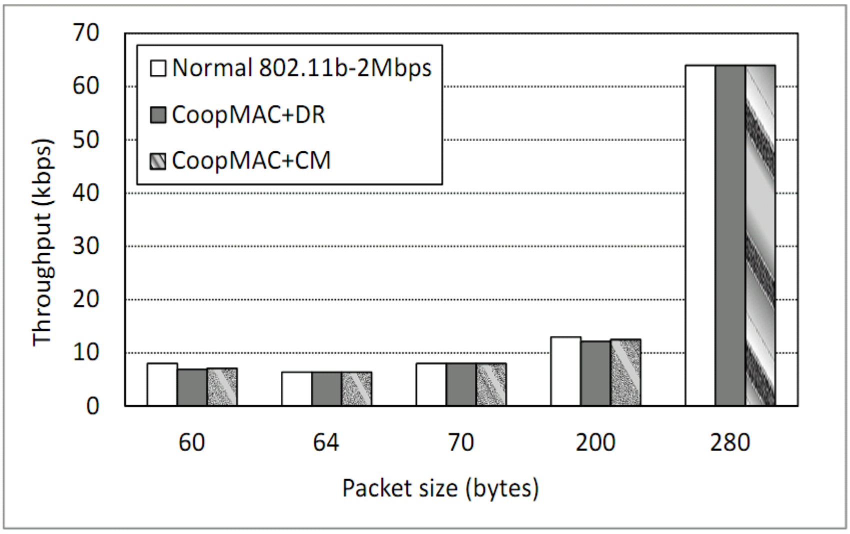


Figure 5.4 Packet loss percentage of UDP VOIP when using CM and DR as metric compared to 802.11b

Figure 5.5 presents throughput of VOIP traffic when the direct transmission is 1Mbps and 2Mbps. Since there is much difference between application service rate and existing bandwidth provided by the physical layer, it is not expected to have remarkable improvement in throughput when using cooperation regardless of relay selection metric applied.

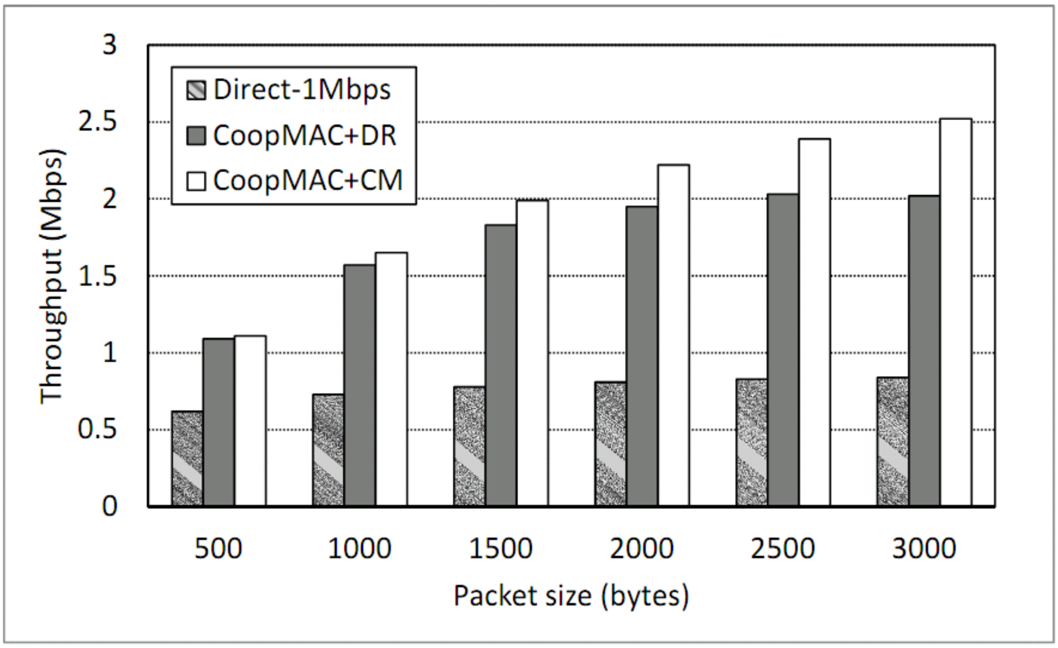


(a)

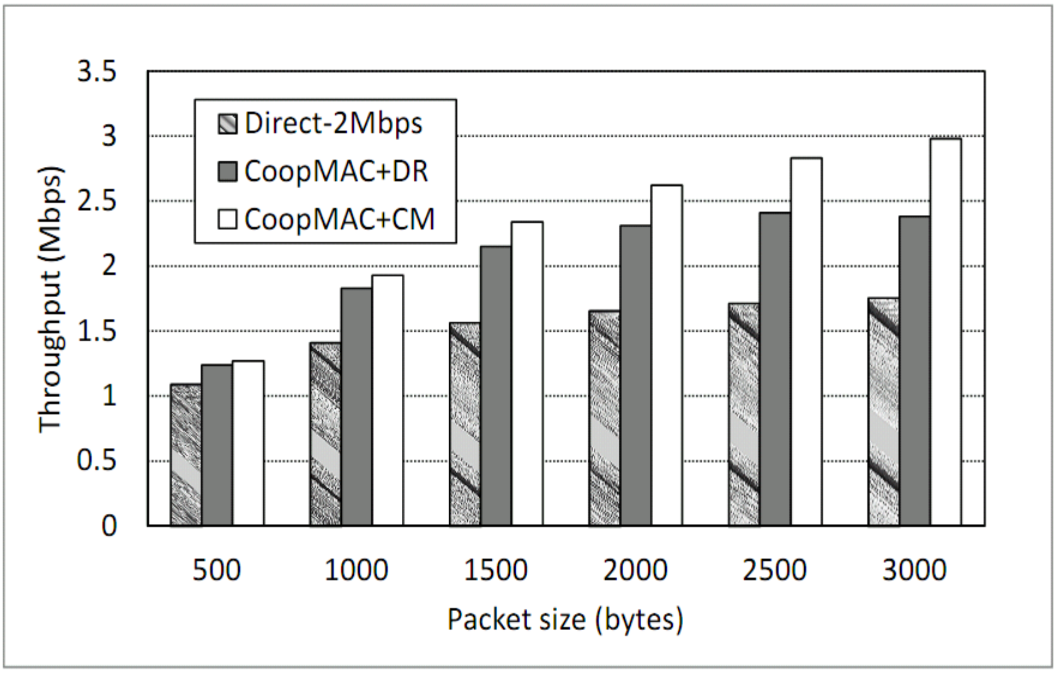


(b)

Figure 5.5 Throughput of CoopMAC for VOIP when using CM and DR as metric compared to 802.11 for direct transmission (a) 1Mbps and (b) 2Mbps



(a)



(b)

Figure 5.6 Throughput of CoopMAC for VOD when using CM and DR as metric compared to 802.11 for direct transmission (a. 1Mbps and b. 2Mbps

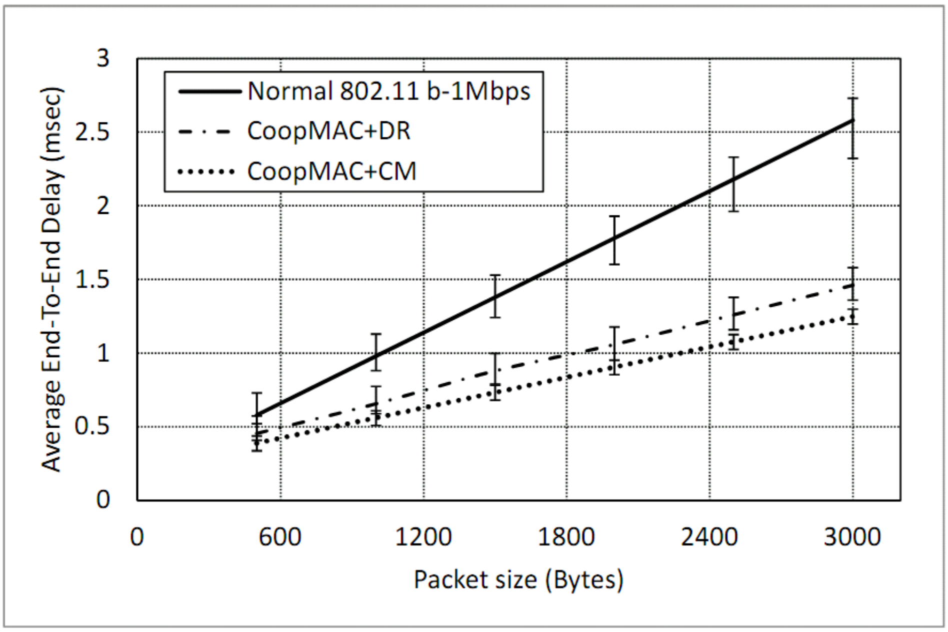
5.5.3 TCP traffic-Video On Demand

Using TCP, throughput and end-to-end delay are the two most important performance parameters. In this section, the traffic service type is Video On Demand (VOD) with characteristics of Table 5–3 and the performance metric of CoopMAC protocol with metrics of CM and DR is considered and compared to normal 802.11b. Figure 5.6 (a) presents the throughput of CoopMAC when direct transmission is 1Mbps. This figure demonstrates the improvement of using CM especially when the packet size is increased. The stability of relay links are improved by using CM, while using DR selects the relay links without the consideration of stability. Figure 5.6 (b) depicts the results of CoopMAC with 2Mbps as a direct transmission.

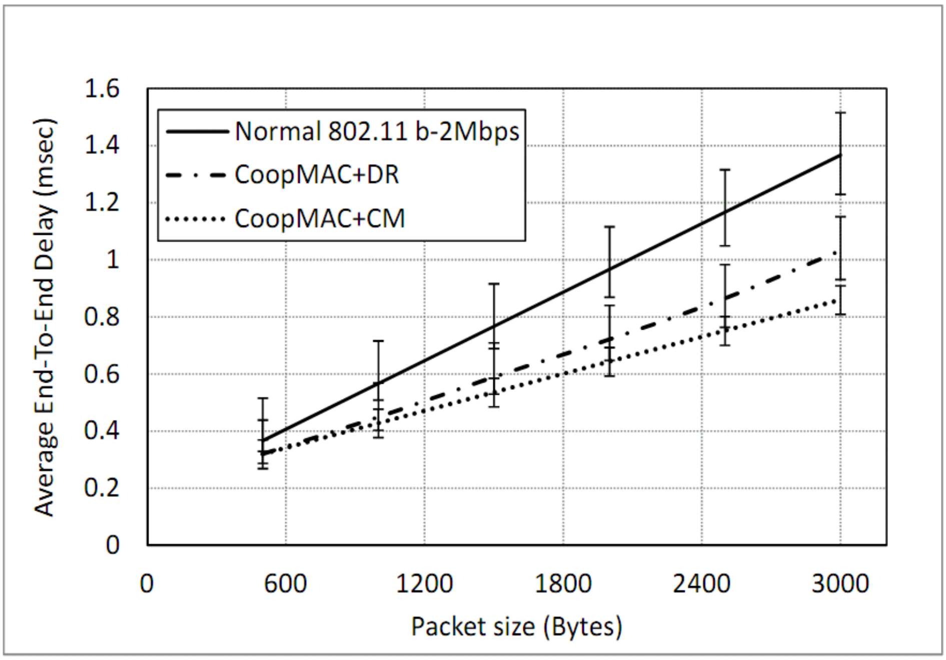
Figure 5.7 presents End-to-End delay performance of IEEE 802.11b when using CoopMAC with CM, DR and normal 802.11b when direct transmission is 1 Mbps and 2Mbps. As can be seen, variation of delay when CoopMAC using CM is very low due to the provision of stable relay links compared to CoopMAC using DR and also normal 802.11b.

5.6 Concluding remarks

In this chapter, cross layer issues are discussed for cooperation when higher layer requirements are well suited to lower layer specification monitored by sensing parameters and performance metrics. The concerning parameters in UDP traffics (e.g. jitter and packet loss) and TCP traffics (e.g. delay and throughput) are considered as the main components in CoopMetric. CoopMetric exploits the geometric model of delay ratio and relay area as a tool to provide instantaneous throughput improvement. It also used ACK frames monitoring to determine the relative link reliability. The stability of relay nodes is measured by considering the variations of reliability and delay ratio. Therefore, CoopMetric presents a robust criteria comprising cross layer aspects and mobility aspects of IEEE 802.11 networks in order to provide optimum performance in cooperative communications



(a)



(b)

Figure 5.7 End-to-End delay of CoopMAC for VOD when using CM and DR as metric compared to 802.11 for direct transmission a. 1Mbps and b. 2Mbps

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CHAPTER 6 CONCLUSIONS AND FUTURE WORKS

Summary

This final chapter presents the most important conclusions on theoretical and practical aspects of cooperative IEEE 802.11 MAC protocols. Some guidelines for future research works are also recommended.

6.1 Summary of the works and Contributions

Throughout the different chapters we presented several aspects of practical issues in cooperative relay protocols using IEEE 802.11 standards. We started with cooperation concepts in wireless networks to address different theoretical techniques providing the performance improvement in physical and MAC layers. It was concluded that cooperation at physical layer is inspired from the MIMO systems with relay node as a virtual element in a distributed antenna system. In contrast, cooperation in MAC layer and higher layers is based on the new function of the relay node as a repeater to forward the original packet from source to destination nodes. The cooperation performance at physical layer can be improved by using the powerful coding schemes in source-relay and relay-destination links while the overhearing mechanism provides useful information of many aspects in MAC layer leading to optimized cooperative resource allocation algorithms.

The next step was to classify the existing cooperative MAC protocols of IEEE 802.11 based on the parts of the DCF transmission cycle which are exploited by cooperation techniques. According to the analytical and simulation results performed by number of contributions in cooperative MAC protocols, the Min-TX and CWF protocols result in spectrum efficiency while BTC protocol improves fairness. The study and classification of existing protocols enabled us to propose an architectural framework for cooperation model in wireless networks. This model draws the consequence of different phases during each cooperation algorithm and protocol. This model also provides a guideline to compare different cooperative protocols according to their operation during the cooperation. The comparison of Min-TX category led to define a common metric to model their operation analytically.

Delay ratio was the common metric and a system model of Min-TX protocols was proposed based on this metric. The performance bounds of Min-TX protocols were computed as a function of delay ratio and a geometric model was also modelled to determine the area corresponding to each delay ratio values. Moreover, by considering the range of delay ratio values and overhead of cooperative MAC protocols, it was concluded that packet size can be critical in some cases of cooperation scenario. High value of delay ratio and extra overhead of cooperative MAC protocols result in the transmission delay more than non-cooperation mode. Therefore, a lower bound of packet size was defined as a threshold for beneficial cooperation. In practice and according to IEEE 802.11 standards, there is limitation for data packet size which is known as MTU. The analytical results indicated that the lower bound of packet size is more than MTU in some cooperation cases. Thus, those cooperation cases cannot be implemented in real scenarios and the expected cooperation gains were not obtained, even in number of scenarios specially for IEEE 802.11g/n, the upper bounds of cooperation performance were not able to reach to non-cooperation performance.

The evaluation of Min-TX protocols demonstrated that delay ratio is a good metric for cooperation objective of spectrum efficiency and its purpose is to reduce the packet transmission delay. Therefore, the spectrum efficiency of Min-TX is beneficial for those traffic services requiring bandwidth more than bandwidth provided by direct transmission. However, there are some traffic services with low bit rate and delay ratio metric cannot provide extra performance for them. This is motivated by the need for some improvements. Moreover, the reliability of cooperation links and stability of relay nodes specially in mobile scenarios cannot be obtained by delay ratio. These shortcoming motivated other contributions based on cross layer approach and mobility aspects. The CoopMetric was constructed based on two main components of delay ratio and reliability of channels. The stability of relay nodes was defined as the variation of these two components. The stability of relay nodes affects the protocol performance specially in mobile scenarios. The simulation results of CoopMAC protocol using CoopMetric demonstrated the fine coordination of traffic service requirements, mobility aspects and extra resources provided by overhearing of PHY layer characteristics.

6.2 Main Challenges and Future Works

The existing cooperative MAC protocols addressed a number of significant issues such as throughput and fairness. However many other key issues have not been covered by these protocols. Some of these issues are listed below and require further investigation.

Security: Overhearing packets to obtain the necessary sensing parameters can increase the risk of security attacks and vulnerability in cooperative MAC protocols rises. Cooperative security schemes can increase the reliability of networks as well as the performance gain due to cooperation, but this is an area not yet properly developed.

Power control: The issue of power control in cooperative MAC protocols can be analyzed based on two aspects. 1) The relay node consumes more energy due to relaying transmission and 2) replacing a long distance transmission with two small distance transmissions can decrease the interference and improve energy efficiency. These two aspects can pose an optimization problem with energy constrains from PHY layer up to MAC and higher layers, in terms of the decision to cooperate or not, opening a new research direction.

Incentives and fair relay selection: the incentives and motivation of nodes to participate in cooperation and introduce themselves as relay nodes can improve the relay selection algorithms to choose the optimum relay node. Moreover, current relay selections which are mostly based on available rates, may result in the use of one relay node for a long time. This would reduce the energy efficiency of the protocols for specific mobile nodes. Thus, in the design of efficient and fair relay selection algorithms, potential relay nodes should be selected based on incentives, energy consumption and network throughput together. Once again this is an area full of open challenges.

Annex I IEEE 802.11 specifications

This annex summarizes 802.11 features which are relevant to understand the cooperation techniques described

I-1 Architecture of PHY

The architecture of PHY in 802.11 standards is depicted in Figure I.1. It consists of two sub-layers: Physical Layer Convergence Procedure (PLCP) and Physical Medium Dependant (PMD). The frame exchange between Physical and MAC layers is coordinated by PLCP and PMD is responsible for the frame transmission and reception on the wireless medium. Communications between the PLCP and MAC layer is performed through a Service Access Point (SAP) called PHY SAP, and the PLCP communicates with the PMD through the PMD SAP.

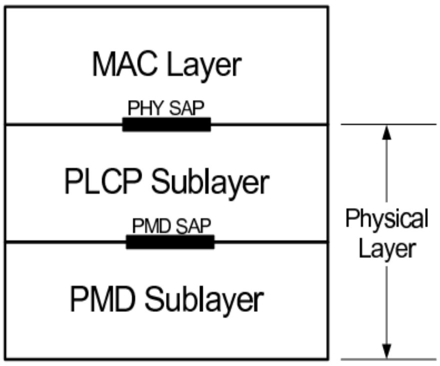


Figure I.1 Architecture of PHY in 802.11 standards

I-1-1 PHY Frame Format

In order to be more familiar with 802.11 PHYs, the PHY frame format of IEEE 802.11b is explained here. There is a similar frame format in different PHYs with slight changes. The transmitted frame on the wireless channel, shown inFigure I.2, is PLCP Protocol Data Unit (PPDU) consisting of PLCP preamble, PLCP header, and PSDU fields which are explained in detail as follows.

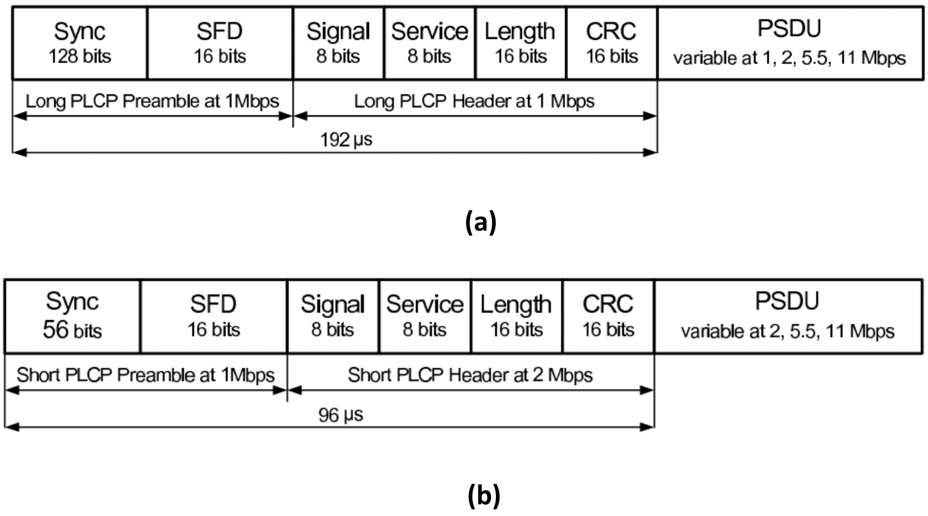


Figure I.2 IEEE 802.11b PHY frame format (a) Long Preamble and (b) Short preamble

PLCP Preamble: There are two types of PPDU frames in the IEEE 802.11b that differ only in the length of the preamble. The long preamble is a 144-bit field including a 128-bit Sync field that enables the synchronization between receiver and transmitter and a 16-bit Start of Frame Delimiter (SFD) field which defines the beginning of a frame. In contrast, the short preamble is a 72-bit field consisting of a 56-bit Sync field and 16-bit SFD field. The short preamble improves the performance efficiency. By using the Differential Binary Phase Shift Keying (DBPSK) modulation technique, data rate of both short and long PLCP preambles is 1 Mb/s.

PLCP Header: This is a 48-bit field and is sent at 1 Mb/s and 2Mb/s respectively under long PLCP preamble and short PLCP preamble. It consists of four fields: Signal (8-bit), Service (8-bit), Length (16-bit), and CRC (16-bit).

- **Signal**: This field identifies the data rate of the 802.11 frame, with its binary value equal to the data rate divided by 100Kbps. It describes the type of modulation used by transmitter and informs the receiver to employ corresponding demodulation for the received signal. Data rates supported by the IEEE 802.11b [5] are 1, 2, 5.5, and 11 Mb/s and Table I–1illustrates the corresponding Signal field value.
- **Service:** This field is always set to 00000000, and the 802.11 standard reserves it for future use.

- **Length:** This field is an unsigned twooctet integer specifying the number of microseconds that it takes to transmit the MPDU. Given the data-rate, the length of the MPDU can be determined at the receiver.
- **CRC**: This is two octets in length, and is used for error detection of the physical layer header. The MAC Layer also performs error detection functions on the PPDU contents.

PSDU: Physical Layer Service Data Unit (PSDU) is actually the MPDU sent by the MAC layer. It has a variable length, and is transmitted at the data rate indicated in the Signal field. Table 6.2 summarizes the corresponding modulation required for every data rate of PSDU supported by 802.11b.

Table I–1 Digital Modulation and data rate of IEEE 802.11b

Data rate (Mb/s)	Modulation
1	DBPSK
2	DQPSK
5.5	CCK / PBCC
11	CCK / PBCC

I-2 Distributed Coordination Function

DCF is the main medium access scheme of the IEEE 802.11 standards, and supports both infrastructure and ad hoc modes. DCF operates based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol and it operates according to two modes: basic access and 4-way handshaking.

I-2-1 Carrier Sense Multiple Access with Collision Avoidance Mechanism

In CSMA based protocols, the node senses the medium by measuring the signal level at the carrier frequency to check whether it is idle or not. If the medium is idle, the source node waits a minimum predefined duration called Distributed Inter-frame Space (DIFS). Along DIFS period, if the medium stays idle, the source node starts transmission to the receiving node. Otherwise, it defers its transmission after a random back-off delay. The back-off time counter is decremented in terms of time slots when the medium is sensed free. The counter is stopped once a transmission is detected on the medium. The source node will transmit its packet when its back-off counter becomes zero.

There are two ways to carry out the carrier sense in CSMA procedure: virtual carrier sense and physical carrier sense functions. The physical carrier sense, provided by the IEEE 802.11 PHY layer, is a logical function implemented called Clear Channel Assignment (CCA). The CCA function uses a single fixed power carrier sense method to measure the level of Received Signal Strength Intensity (RSSI). If the measured RSSI is less than the threshold value, the channel is assumed to be idle, otherwise, the medium is busy and not ready for transmission.

The virtual carrier sense is provided by a timer in IEEE 802.11 MAC layer called Network Allocation Vector (NAV). The NAV is maintained by all stations to determine the time which the medium is reserved by other stations. There is a duration field in each frame that indicates the required time period for exchange of the following frame. The NAV timer decrements when the station’s CCA function indicates a busy medium. The NAV is set after receiving a frame and it decrements when the station’s CCA function indicates a busy medium. When the NAV timer of each station reaches zero, they start sensing the medium with packets waiting to be transmitted. If the medium is idle, stations can send their data packet after a time interval named Distributed Inter Frame Spacing (DIFS). Otherwise they generate a random back-off counter.

I-2-2 Inter-frame Space

The Inter-frame Space (IFS) plays a key role in coordinating access to the transmission medium. There are four different inter-frame spaces to access the wireless medium at different priority levels. These are Short Inter-frame Space (SIFS), Point Coordination Function Inter-frame Space (PIFS), Distributed Coordination Function Inter-frame Space (DIFS), and the Extended Inter-frame Space (EIFS). Some of them are illustrated in Figure I.3.

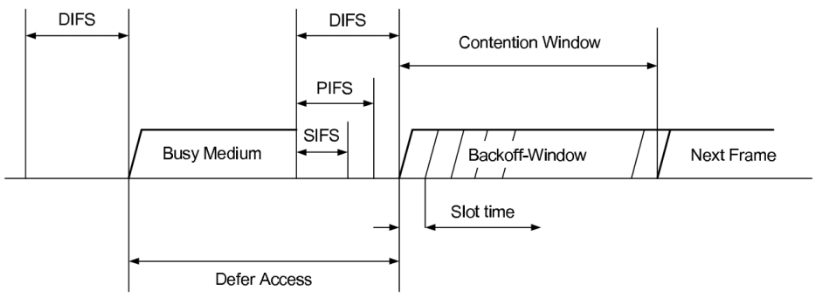


Figure I.3 Inter-frame Space in DCF mode

SIFS is the shortest IFS interval time and but it is longer than propagation delay and processing the time at PHY and MAC layers. The SIFS is employed as time interval between the control packets and data packet in every DCF transmission cycle. The SIFS value for the 802.11b is 20 µs, and for the 802.11a, 802.11g, and 802.11n is 16 µs.

The PIFS is the next shortest IFS interval time. It is employed PCF mode to gain priority access to the wireless channel at the beginning of the Contention Free Period (CFP).

The DIFS is used by the nodes to sense the idle state of the medium before sending a new transmission. When the back-off counter of a node reaches zero and the medium is sensed as idle for duration of the DIFS, the node immediately access to the medium for packet transmission. DIFS is equal to SIFS plus two slot times.

The EIFS is used by a node in the DCF mode when the received frame is incorrect. A node applies the EIFS instead of the DIFS interval when the imperfect channel conditions or collision lead to the reception of an erroneous frame. EIFS is the longest IFS which allocates the higher priority to the transmit nodes encounter to failure for packet transmission.

Table 6.2 summarizes the slot time and IFS values of different IEEE 802.11a/b/g/n. In the case of EIFS, TACK is the duration of the ACK frame at the basic data-rate.

Table I–2 IFS values in IEEE 802.11b/g/n

Parameter	Value
SIFS	aSIFSTime = 20 μs (802.11b) and 16 μs (802.11a/g/n)
PIFS	aSIFSTime + aSlotTime
DIFS	aSIFSTime+ 2 × aSlotTime
EIFS	aSIFSTime+ ACKTxTime + DIFS

I-2-3 Random Back-off Algorithm

In DCF mode, collision occurs when two or more stations transmit at the same slot time. To avoid the collision, a procedure called back-off is performed before starting transmission. If the channel is sensed as busy, a station defers the transmission until the channel state becomes idle. According to the previous packet transmission being successful (or failed), a node waits for DIFS (or EIFS) idle period and then selects a random back-off periods in terms of slot time, and defers the transmission for that number of slot times. The random back-off counter is selected from a uniform distribution over the interval [0, CW-1], where CW is the Contention Window. The procedure of doubling the CW is called the Binary Exponential Back-off (BEB) algorithm. The counter is decremented by one and transmission is started when the back-off counter reaches zero. If the current transmission is failed due to some reason, the CW is doubled. As shown in Figure I.4, the minimum and maximum value of CW can be 31 and 1023 respectively.

When the CCA function indicates the channel is busy, the back-off counter is stopped until the medium becomes idle for a DIFS or EIFS once more again. The node then continues decrementing without selecting a new back-off value. When the counter reaches zero, the intended node takes a higher priority to access the channel in the following transmission. The back-off algorithm reduces the collision probability when multiple nodes are trying to access the channel at the same slot time.

I-2-1 DCF Access Modes

There are two access modes in DCF scheme: basic access mode and RTS/CTS mode which are referred to two-way handshaking and four-way handshaking respectively.

I-2-2 Basic Access mode

In the basic access mode, a node having a packet to transmit should sense the medium to be idle for a DIFS time interval when the last frame is received correctly, or an EIFS time interval when the last frame fails due to collision or imperfect channel conditions. Then, the node generates a random back-off interval according to the BEB algorithm. When the back-off timer reaches zero, the node transmits its data packet. If the destination receives the data packet correctly, it then sends an ACK frame immediately following a SIFS period. Otherwise, the medium must be free for the amount of the EIFS. If the transmitting node receives no ACK frame within a predefined ACK-timeout, it sets its Retry Count to one more for every unsuccessful transmission. Then it applies rescheduling data frame retransmission according to BEB algorithms. After every successful transmission, the CW and Retry Count are reset to CWmin and zero respectively. Figure I.5 illustrates the frame exchange sequence of the basic access mode.

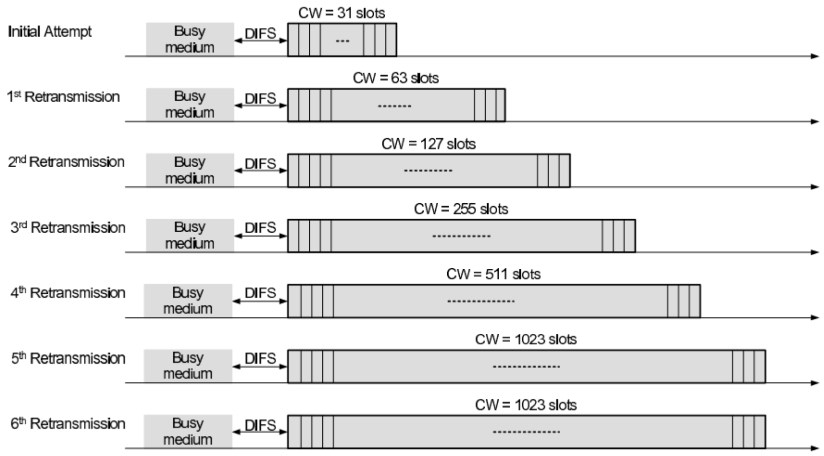


Figure I.4 Minimum and maximum value of Contention Window

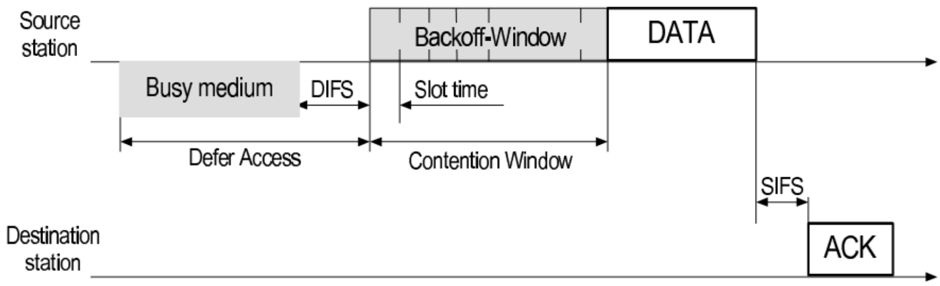


Figure I.5 CSMA-Basic Access

The mechanism of the basic access mode is not efficient due to two special problems: the hidden node and exposed node. The hidden node is a node which is located outside of the carrier sensing the range of the source but is inside the carrier sensing the range of the destination. This makes that hidden node unaware of the source's transmission and may cause a collision at the receiver. In the inverse situation, the exposed node appears. The exposed node is a node located inside the carrier sensing range while outside the destination´s range. Since the exposed node senses the medium busy, it cannot transmit its data packet thus leading to low performance. For a scenario depicted in Figure I.6, when node A is sending its packet to node B, node C is the hidden node since it unaware of transmission originated by node A. In the same configuration, if node B is sending a packet to node A, node C is the exposed node because it senses the medium busy and cannot transmit the packet to the intended destination (e.g. node D). The hidden node occurs in both infrastructure and ad hoc configurations while the exposed node happens in infrastructure configuration. In the infrastructure configuration each node cannot send directly to its destination and it first sends to the AP and the AP then sends to the destination. The hidden node and exposed node problems cause performance degradation in the IEEE 802.11 networks with basic access mode.

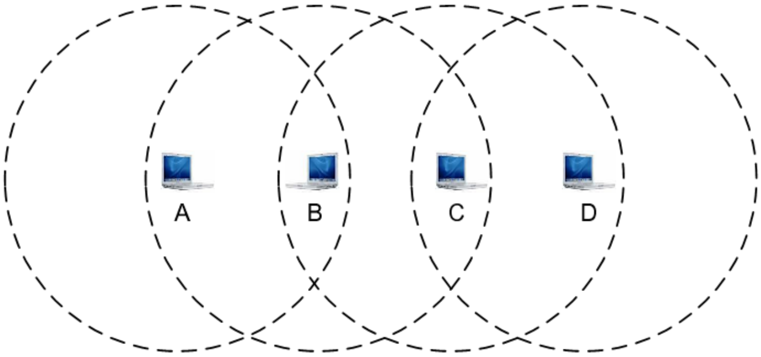


Figure I.6 The problems of hidden node and exposed node

I-2-3 RTS/CTS access mode

To reduce the performance degradation caused by hidden node and exposed node problems, another access mode called Request-To-Send/Clear-To-Send (RTS/CTS) mechanism is employed by IEEE 802.11 standards. This access mode is also called four-way handshaking. When source node has a packet to send, it sends out a RTS packet to the destination and waits for CTS packet from the destination. The timeout for waiting the CTS is CTStimeout. If the CTS packet is received within CTStimeout, the source node sends its data packet to the destination and sets a new timeout for ACK the packet called ACKtimeout. If the source node receives the ACK packet during the ACKtimeout, it starts a new transmission cycle.

If the destination successfully receives the RTS packet, the destination transmits a CTS packet back to the source after a SIFS interval is elapsed. It also sets a DATAtimout for receiving the data packet. If the destination receives a data packet within the DATAtimout, then the source node sends an ACK packet back to the source following a SIFS interval, Otherwise, it concludes that the transmission is terminated and it starts a new transmission cycle if it has an empty transmission buffer.

Table I-3 presents timeout values when using the RTS/CTS mode.

Table I–3 Timeout of control and data packet types

Parameter	Value
$CTS_{timeout}$	T_{CTS} +2 T_{SIFS}
$ACK_{timeout}$	T_{data} + T_{ACK} + 2 T_{SIFS}
$DATA_{timeout}$	T_{data} + 2 T_{SIFS}

In order to perform the virtual carrier sensing process, the neighbouring nodes of both source and destination set their NAV after receiving the RTS, CTS, Data, and ACK packets. Every packet includes a duration field that indicates the required time for completing the following frame exchange. The duration field values are presented in Table I.4. The ACK packet has a duration field which is set to zero as the end of the transmission.

Table I–4 Duration of control and data packet types

Parameter	Value
$RTS_{duration}$	T_{CTS} + T_{data} + T_{ACK} + 3 T_{SIFS}
$CTS_{duration}$	T_{data} + T_{ACK} + 2 T_{SIFS}
$DATA_{duration}$	T_{ACK} + T_{SIFS}

I-2-4 Frames Format

Since the MAC layer of IEEE 802.11 standards works on top of a wireless PHY layer, it should provide special features to respond the challenges posed by a wireless data link. The frame format of the MAC layer provides these features as well as other requirements for coordination of the operating communications of higher layers. There is a generic format for 802.11 MAC frames whichincludes three main parts: MAC header, variable length frame body and frame check sequence. (See Figure I.7)

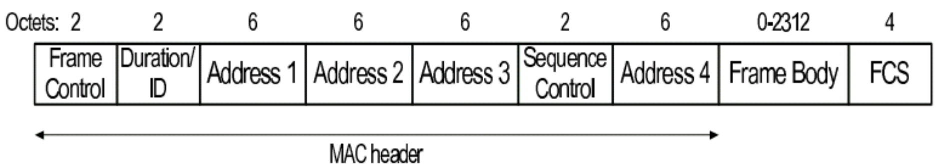


Figure I.7 Generic 802.11 MAC frame

Every 802.11MAC frame starts with a two-byte Frame Control field. As depicted in Figure I.8, the Frame Control field comprises the following subfields:

- **Protocol Version**: Two bits in length it indicates which version of the 802.11 MAC is contained in the rest of the frame. The value of the protocol version is always set to zero for the current standards.

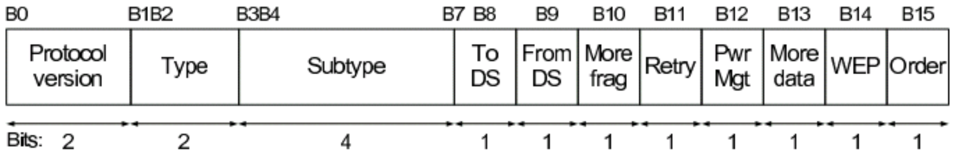


Figure I.8Format Frame Control

Table I–5 type field value

$b_2\,b_3$	Frame type
00	Management frame
01	Control frame
10	Data frame
11	Reserved

- **Type and subtype:** The type field identifies the category of the frame which can be management, control, or data. The subtype field indicates which is the associated packet in that category. Table I–5 and Table I–6 indicate the function of these fields.

Table I–6 Subtype field value

Type ($b_2\,b_3$)	Subtype ($b_4\,b_5\,b_6\,b_7$)	Frame function
01	10111	RTS
	1100	CTS
	1101	ACK
10	0000	DATA

- **To DS:** a single bit Field and set to 1 for any frame destined to the destination; otherwise, it is set to 0 in all other frames.

- **From DS:** a single bit Field and set to 1 in any data frame leaving the DS; otherwise it is set to 0 in all other frames. Table 2.6 illustrates different combinations of both To DS and From DS fields.

- **More Fragment:** a single bit Field which if set to 1, means that another fragment of the current data frame follows in a subsequent frame; otherwise it is set to 0 in all other frames.
- **Retry:** a single bit Field which set to 1, indicates that the current data frame is a retransmission of the earlier frame; otherwise it is set to 0 in all other frames.
- **Power Management:** a single bit Field, when the node is in the power-save mode, will be set to 1. Otherwise, it is set to 0 to indicate the active mode of the intended node. It is also set to 0 in frames transmitted by the AP.
- **More Data:** a single bit Field set to 1 if the AP has at least one additional data frame for a station in that is power-save mode; otherwise it is set to 0 in the all other frames.
- **Wired Equivalent Privacy (WEP):** a single bit Field set to 1 if the Frame Body field of a data frame has been processed by the WEP algorithm (encrypted); otherwise it is set to 0 in all other frames.
- **Order:** a single bit Field set to 1 to tell the receiving node that the data frames must be processed in order. The Order field is set to 0 in all other frames.

• **Duration/ID:** 16 bits in length and used to set the NAV. The value represents the number of microseconds that the medium is expected to remain busy during the transmission currently in progress. All nodes monitor the headers of all received frames and update their NAV accordingly.

• **Address Fields:** There are four addresses used in a 802.11 MAC frame. Every address field is 48 bits in length and can be the Destination Address (DA), Receiver Address (RA), Source Address (SA), Transmitter Address (TA), and Basic Service Set Identifier (BSSID). The DA is the MAC address of the ultimate receiving node that will hand the frame to the upper layers. The RA is the MAC address of a node that should process the frame. The SA is the MAC address of the original source of the frame. The TA is the MAC address of a station that transmitted the frame onto the medium. According to the value of To DS and From DS fields, the content of address fields has different meaning (Table I.7).

Table I–7 Address field contents

To DS	From DS	Address 1	Address 2	Address 3	Address 4
0	0	DA	SA	BSSID	N/A
0	1	DA	BSSID	SA	N/A
1	0	BSSID	SA	DA	N/A
1	1	RA	TA	DA	SA

- **Sequence Control:** 16-bit Field is used for both defragmentation and discarding duplicate frames. It consists of two subfields which are the Fragment Number (the leftmost four bits) and Sequence Number (the next 12 bits). The Fragment Number indicates the number of each fragment of a data frame. It is set to zero and incremented by one for each succeeding transmission. The Sequence Number identifies the sequence number of a data frame. Each data frame is assigned a sequence number starting at zero and incrementing by one per data frame. The sequence number is not changed for all fragments if fragmentation occurs and also for all retransmissions.
- **Frame Body:** It has a variable length payload and contains the information to be sent.
- **Frame Check Sequence (FCS):** 32 bits in length and is used for checking the validity of the MAC frame information. The FCS contains a Cyclic Redundancy Code (CRC). In sending node, the CRC calculates a checksum of all fields of the MAC frame. The receiving node also calculates the CRC of the received frame and compares it with the attached CRC. If the two CRCs are the same, the receiver verifies that the frame has been received correctly; otherwise the frame has been computed and is discussed.

Annex II Analysis of CWF protocols

This annex presents an analytical model for CWF protocols. A new metric is defined based on the overhearing of information. The relay area is also calculated theoretically and practically based on the geometric model and metric.

II-1 System model

The main idea behind the CWF category protocols is to improve reliability and provide delay reduction by caching the overheard message and waiting for its failure. In order to define a system model for this category, we consider again the scenario of Figure 4.1 when the operation of R_i is overhearing, caching and waiting for failure. If failure occurs, R_i will retransmit the overheard packet. The average transmission delay between *S* and *D* for this category can be expressed as (II.1):

$$\overline{T_{SD}} = P_{succ}.T_{Dir} + (1 - P_s)\left(T_{Dir} + \sum_{i \in \mathbb{R}_{S\to D}} P_{R_i} T_{Ret_{R_i}}\right) \qquad \text{(II.1)}$$
$$= T_{Dir} + (1 - P_s)\sum_{i \in \mathbb{R}_{S\to D}} P_{R_i} T_{Ret_{R_i}}$$

where T_{Dir} and $T_{Ret_{R_i}}$ are the transmission delay of direct path and retransmission path as expressed respectively in (II.2) and (II.3), P_s is the probability of successful transmission through the direct path and P_{R_i} is probability of existence a relay node Ri ε $\mathbb{R}_{SD}$ (II.4).

$$T_{Dir} = T_D(L) + T_D(OH) \qquad \text{(II.2)}$$

$$T_{Ret\_R_i} = T_{Ret_{R_i}}(L) + T_{Ret_{R_i}}(OH) + \overline{T_{RS}} \qquad \text{(II.3)}$$

$$\mathbb{R}_{SD} = \{R_i | BER(SNR_{SR_i}) < \gamma_{th}\} \qquad \text{(II.4)}$$

where γ_{th} is the bit error rate threshold for a successful packet at the MAC layer. To consider the cooperative gain provided by CWF category, we can define the performance metric as (II.5):

$$\mathrm{DR_i} = \frac{\mathrm{T_{Ret\_R_i}(Data)}}{\mathrm{T_{Dir}(Data)}} = \frac{\mathrm{j^{-1}}}{\mathrm{k^{-1}}} = \frac{\mathrm{k}}{\mathrm{j}} \tag{II.5}$$

where, *j* is data rate between relay and destination nodes and *k* is data rate between source and destination. By substituting (II.5) into (II.3)) and applying for the data packet length (L) and data rate R, we can obtain (II.6):

$$\begin{aligned} \mathrm{T_{Ret_{R_i}}(L,R,DR_i)} &= \mathrm{DR_i.T_D(L)} + \mathrm{T_{Ret_{R_i}}(OH)} + \overline{\mathrm{T_{RS}}} \\ &= \mathrm{DR_i.}\frac{\mathrm{L}}{\mathrm{R}} + \mathrm{T_{Ret_{R_i}}(OH)} + \overline{\mathrm{T_{RS}}} \end{aligned} \tag{II.6}$$

We can also define the throughput of CWF category as expressed in (II.7):

$$\eta_{\mathrm{Coop_{R_i}}}(\mathrm{L,DR_i}) = \frac{\mathrm{L}}{\mathrm{T_{Dir}(L,R)} + \mathrm{T_{Ret_{R_i}}(L,R,DR_i)} + \mathrm{T_{c-coop}} + \mathrm{T_{i-coop}}} \tag{II.7}$$

where T_{c-coop} and T_{i-coop} are the average collision time and average idle time. As indicated in (II.7), the performance bounds of throughput are obtained by delay ratio bounds.

II-2 Relay area

To find the possible location of the relay node (R_i), we can consider again two theoretical and practical methods. In theoretical analysis, we apply the condition of cooperation as given by (II.8):

$$\begin{cases} \mathrm{BER(SNR_{SD})} > \gamma_{\mathrm{th}} \\ \mathrm{BER(SNR_{SR_i})} < \gamma_{\mathrm{th}} \\ \mathrm{BER(SNR_{R_iD})} < \gamma_{\mathrm{th}} \\ 1 \le \mathrm{x} + \mathrm{y} \le 2 \end{cases} \tag{II.8}$$

By substituting $x = \frac{d_{SR_i}}{d_{SD}}$ and $y = \frac{d_{R_iD}}{d_{SD}}$ and applying the path loss equation, we can obtain the inequalities of (II.9). We can also consider the equivalent inequality of (II.9) and the inequality which yields to new one.

$$\begin{cases} \mathrm{BER}(\mathrm{SNR_{SD}}) > \gamma_{\mathrm{th}} \\ \mathrm{BER}(\mathrm{SNR_{SD}}/\mathrm{x^n}) < \gamma_{\mathrm{th}} \\ \mathrm{BER}(\mathrm{SNR_{SD}}/\mathrm{y^n}) < \gamma_{\mathrm{th}} \\ \mathrm{x} + \mathrm{y} \geq 1 \end{cases} \Rightarrow \begin{cases} \mathrm{SNR_{SD}} < \mathrm{SNR_{th}} \\ \mathrm{SNR_{SD}}/\mathrm{x^n} > \mathrm{SNR_{th}} \\ \mathrm{SNR_{SD}}/\mathrm{y^n} > \mathrm{SNR_{th}} \\ \mathrm{x} + \mathrm{y} \geq 1 \end{cases} \quad \text{(II.9)}$$

Obviously, because of variable x and y and in order to have the second and third inequality consistent to the first one, we obtain the inequality (II.10). Since for all wireless environments the value of n is more than unit (n>1), we can express the inequality in simple form.

$$\begin{cases} \mathrm{SNR_{SD}} < \mathrm{SNR_{th}} \\ \mathrm{x^n} \leq 1 \\ \mathrm{y^n} \leq 1 \\ \mathrm{x} + \mathrm{y} \geq 1 \end{cases} \Rightarrow \begin{cases} \mathrm{SNR_{SD}} < \mathrm{SNR_{th}} \\ 1 \leq \mathrm{x} + \mathrm{y} \leq 2 \end{cases} \quad \text{(II.10)}$$

As shown in Figure II.1, The shadow area is the relay area of CWF category.

Although theoretical analysis can provide the relay area for different values of SNR_{SD} and path loss coefficient (n), it cannot provide the delay ratio corresponding to the relay area. Therefore, we can consider the practical analysis for multi-rate scenario as indicated in Figure II.2 (a), when the transmission range of each data rate is available. The corresponding delay ratio supported can be indicated in Figure II.2 (b).

According to the overlap area of two circles, we can calculate the relay area of Figure II.1 as expressed in (II.11).

$$\begin{cases} \mathrm{A_{1-11}} = \mathrm{S_{R_1-R_{11}}} \\ \mathrm{A_{1-5.5}} = \mathrm{S_{R_1-R_{5.5}}} - \mathrm{S_{R_1-R_{11}}} \\ \mathrm{A_{1-2}} = \mathrm{S_{R_1-R_2}} - \mathrm{S_{R_1-R_{5.5}}} \end{cases} \quad \text{(II.11)}$$

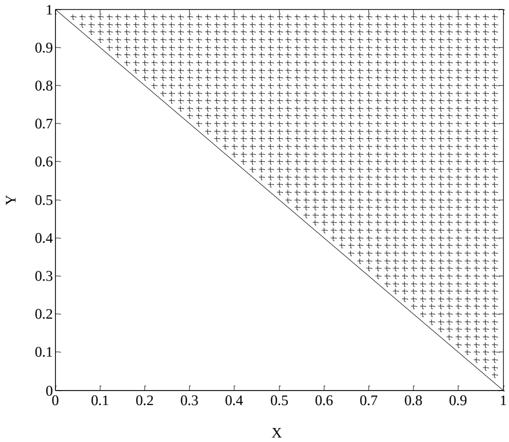
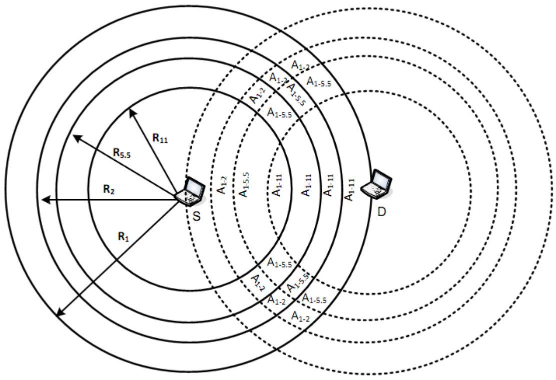
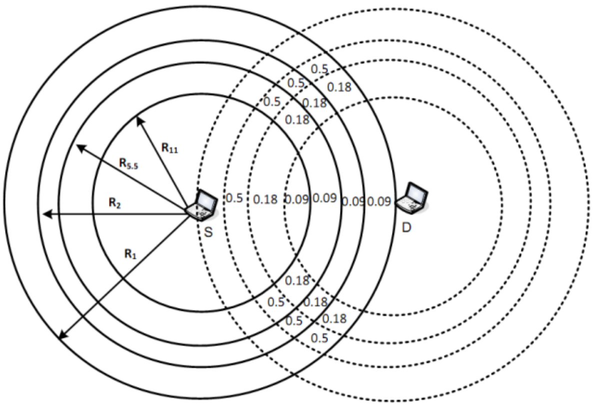


Figure II.1 Relay area of CWF category



(a)



(b)

Figure II.2 (a) Relay area of CWF category in IEEE 802.11b (b) Delay ratio corresponding to relay area

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