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DHT-based Cluster Routing Protocol (DCRP): A Scalable Path Selection and Forwarding Protocol for IEEE 802.11s Mesh Networks

A thesis presented

by

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Abstract

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DHT-based Cluster Routing Protocol (DCRP): A Scalable Path Selection and Forwarding Protocol for IEEE 802.11s Mesh Networks

Wireless Mesh Network (WMN) is a generic term that refers to a communication network composed of wireless nodes in a multi-hop topology, in which each node acts as a “router”, forwarding packets on behalf of other nodes. WMNs are becoming attractive by their dynamic self-organization, self-configuration and self-healing properties. These properties enable, among other, fast deployment, low installation cost, and reliable communication. Because of this, their application spans a wide range of domains such as office, campus/public access, residential, public safety, military, and industrial. Recent research works suggest WMN as a widely accepted replacement for Mobile Ad hoc Network (MANET). In a broader perspective, WMN technology has become a new paradigm for wireless communication.

This thesis focuses on a particular type of WMN: the IEEE 802.11s Wireless Mesh Networks. The IEEE 802.11s standard specifies a WMN technology based on the IEEE 802.11 standard. Its inheritance from previous IEEE 802.11 standards makes it an attractive solution for ubiquitous WMNs but is also a burden as the IEEE 802.11 standard mechanisms were not designed for multi-hop communication. Among the limitations caused by this heritage, we focus on the low scalability of IEEE 802.11s WMNs. A complete redesign of the core mechanisms of the standard, specially those related with MAC and PHY layers, is not foreseeable due to the high level of penetration of IEEE 802.11 devices. Therefore, in this thesis we studied the most relevant scalability and instability issues of the IEEE 802.11s standard and proposed a scalable path selection and message forwarding mechanism that efficiently works on large IEEE 802.11s networks.

As a main contribution to the related research field, this thesis presents the DHT-based Cluster Routing Protocol (DCRP). DCRP targets the IEEE 802.11s shortcomings regarding the scalability by exploiting both Distributed Hash Tables and hierarchical routing by using Clustering, which have proved to be efficient effective in scaling wireless (e.g. MANETs) and wired (e.g. P2P) networking systems. DCRP was implemented and assessed through simulation for different scalability parameters and performance metrics. Simulations results demonstrated that DCRP uses the wireless resources in a more efficient way, overcoming the standard path selection and forwarding scheme and allowing the deployment of larger IEEE 802.11s communication scenarios.

Keywords: *Wireless Mesh Network, IEEE 802.11s, Scalability, Distributed Hash Table, Clustering*

Resumo

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DHT-based Cluster Routing Protocol (DCRP): Um Protocolo de Seleção de Caminhos e Repasse Escalável para Redes Emalhadas IEEE 802.11s

Redes Emalhadas Sem Fio, em inglês *Wireless Mesh Networks* (WMNs), é um termo genérico que se refere a uma rede de comunicação composta de nodos sem fio organizados em uma topologia de múltiplos-saltos, na qual cada nodo atua como "roteador", repassando pacotes/quadros em favor de outros nodos. WMNs têm se tornado atrativas por conta de suas propriedades dinâmicas de auto-organização, auto-configuração e auto-recuperação. Estas propriedades permitem uma montagem rápida, baixo custo de instalação, comunicação confiável, entre outras. Por isso, sua aplicação abrange um vasto domínio, tais como: pequenas redes em escritórios, redes de acesso público, redes residenciais, redes de segurança pública, redes militares e industriais. Investigações recentes sugerem WMN como uma substituta para Redes Móveis Ad-hoc, em inglês *Mobile Ad-hoc Networks* (MANETs), amplamente aceita. Numa perspectiva mais alargada, a tecnologia WMN vem se estabelecendo como um novo paradigma em comunicações sem fio.

Esta tese tem como foco um tipo particular de WMN: Redes Emalhadas Sem Fio IEEE 802.11s. O padrão IEEE 802.11s especifica uma tecnologia de rede emalhada sem fio baseada no padrão IEEE 802.11. Esta herança torna esta tecnologia uma solução atrativa para WMNs ubíquas, mas é também um fardo, uma vez que os mecanismos descritos no padrão IEEE 802.11 não foram desenvolvidos para comunicação multi-salto. Entre as limitações causadas por esta herança, focamos na baixa escalabilidade das IEEE 802.11s WMNs. Um completo redesenho dos principais mecanismos do padrão, especialmente aqueles relacionados às camadas MAC e PHY, não é prevista devido ao alto nível de penetração dos dispositivos IEEE 802.11. Portanto, nesta tese, foram estudados os principais problemas relacionados à escalabilidade e instabilidade do padrão IEEE 802.11s e proposto um mecanismo para seleção de caminho e repasse de mensagens que funciona eficientemente em grande (em número de nodos) redes IEEE 802.11s.

Como principal contribuição para o campo de pesquisa relacionado, esta tese apresenta o *DHT-based Cluster Routing Protocol* (DCRP). DCRP tem como alvo as deficiências do padrão IEEE 802.11s, no que diz respeito à escalabilidade, explorando ambos os conceitos de Tabelas Hash Distribuídas, em inglês *Distributed Hash Tables* (DHT), e roteamento hierárquico utilizando Agregação, em inglês *Clustering*. Ambos os conceitos têm comprovada eficiência em aumentar a escalabilidade em ambientes sem fio, MANETs por exemplo, e cabeados, a exemplo dos sistemas P2P. DCRP foi implementado e avaliado através de simulação para diferentes parâmetros de escalabilidade e métricas de desempenho. Resultados das simulações demonstraram que o DCRP faz um uso mais eficiente dos recursos sem fio, superando o esquema de seleção de caminhos e encaminhamento de mensagens padrão em cenários com grande quantidade de nodos.

Palavras-chave: *Redes em Malha Sem-fios, IEEE 802.11s, Escalabilidade, Tabelas Hash Distribuídas, Agregação*

"With regard to commitment, effort, dedication,
there is no middle ground.
Or you do something well or not at all."

Ayrton Senna

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I would like to dedicate this doctoral dissertation to my beloved family. Their unconditional love, support and patience have made this possible.

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Acknowledgments

*"God gave you a gift of 86,400 seconds today.
Have you used one of them to say thank you?"*

William Arthur Ward

This document is a result of many years of work, full of a diversity of experiences, many doubts, dedication, and persistence above all. The research carried out for this thesis was only achieved through the efforts and contributions of many individuals and organizations.

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Lastly, if someone feel left out, please remember that chances are pretty good I do remember you, do appreciate your assistance, and do wish you the best, even though you have been either implicitly or explicitly mentioned above. In resume, I offer my regards and blessings to all of those who supported me in any form to reach this dream.

Thank you all!

Silvio Costa Sampaio

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Abbreviations and Acronyms

A-MPDU	aggregate MPDU
A-MSDU	aggregate multiple MAC service data unit
A-PPDU	aggregate PHY protocol data unit
AARF	Adaptive ARF
AC	Access Category
ACK	Acknowledge
ADP	Association Discovery Procedure
AIFS	Arbitration Inter-Frame Space
AIFSN	Arbitration Inter-Frame Space Number
AIL	Average Interfering Load
ALM	Airtime Link Metric
AMRR	Adaptive Multi Rate Retry
AODV	Ad-hoc On-demand Distance Vector
AODV-MR	Multi-Radio Ad-hoc On-Demand Distance Vector
AODV-ST	Ad-hoc On-Demand Distance Vector Spanning Tree
AP	Access Point
APE	Ad hoc Protocol Evaluation
ARF	Auto Rate Fallback
ARP	Address Resolution Protocol
B.A.T.M.A.N.	Better Approach To Mobile Ad-hoc Networking
BCA	Beacon Collision Avoidance
bMS	Border mesh STA
BSS	Basic Service Set
CAN	Content Addressable Network
CATT	Contention-Aware Transmission Time

CBRP	Cluster Based Routing Protocol
CBT	Channel Busy Time
CCA	Clear Channel Assessment
CDMA	Code Division Multiple Access
CFP	Contention-Free Period
CG	Cluster Gateway
CH	Cluster Head
CID	Cluster Identifier
CM	Cluster Member
COAR	Coding Aware Opportunistic Routing
CORE	Coding-aware Opportunistic Routing mEchanism
CP	Contention Period
CRM	Coding-aware Routing Metric
CSC	Channel Switching Cost
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to Send
CW	Contention Window
CWB	Contention Window based
DA	Destination Address
DART	Dynamic Address RouTing
DASS	Dynamic Aggregation Selection and Scheduling
DCAR	Distributed Coding-Aware Unicast Routing Protocol
DCF	Distributed Coordination Function
DCRP	DHT-based Cluster Routing Protocol
DHCP	Dynamic Host Configuration Protocol
DHCPv6	Dynamic Host Configuration Protocol version 6
DHT	Distributed Hash Table
DIFS	Distributed-coordinated Inter-Frame Space
DNS	Domain Name Service

DOLSR	Directional OLSR
DPT	Directional Path Table
DS	Distribution System
DSDV	Destination-Sequenced Distance Vector
DSR	Dynamic Source Routing
DTIM	Delivery Traffic Indication Message
EDCA	Enhanced Distributed Channel Access
EED	Average End-to-End Delay
ENT	Effective Number of Transmissions
ERA	Effective Rate Adaptation
ESS	Extended Service Set
ETT	Expected Transmission Time
ETX	Expected Transmission Count
ExOR	Extremely Opportunistic Routing
FBR	Field-Based Routing
FER	Frame Error Rate
FIFO	First-In First-Out
FSR	Fisheye State Routing
GA	Genetic Algorithm
GAB	Global Association Base
GANN	Gateway Announcement
GHWMP	Geographical Hybrid Wireless Mesh Protocol
GPS	Global Positioning System
HC	Highest Connectivity Cluster
HCCA	HCF Controlled Channel Access
HCF	Hybrid Coordination Function
HSLS	Hazy-Sighted Link State Routing Protocol
HWMP	Hybrid Wireless Mesh Protocol
HWMP-RE	HWMP-Reliability Enhancement

iAWARE	Interference Aware routing
ID	Identifier
IE	Information Element
IEEE	Institute of Electrical and Electronics Engineers
iETT	Improved Expected Transmission Time
IFS	Inter-frame Spacing
ILA	Interference-Load Aware
iMS	Internal mesh STA
Inter-DHT	inter-cluster DHT
Inter-kMP	inter-cluster key mesh STA
inter-RT	inter-cluster RT
Intra-DHT	intra-cluster DHT
Intra-kMP	intra-cluster key mesh STA
intra-RT	intra-cluster RT
INX	Interferer Neighbors Count
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
IR	Interference Ratio
IRU	Interference-aware Resource Usage
kMS	Key mesh STA
LAB	Local Association Base
LABA	LAB Advertisement
LAETT	Load Aware ETT
LID	Lowest-ID
LQSR	Link Quality Source Routing
LS	Link State
LSP	Link State Packet
MAC	Medium Access Control layer
MADPastry	Mobile Ad-Hoc Pastry

MadWifi	Multiband Atheros Driver for WiFi
MAF	MCCA Access Fraction
MANET	Mobile Ad Hoc Network
MAP	AP collocated with a mesh gate
MBSS	Mesh Basic Service Set
MCBRP	Mesh Cluster Based Routing Protocol
MCCA	MCF Coordinated Channel Access
MCCAOP	MCCA Opportunity
MCF	Mesh Coordination Function
MCL	Mesh Connectivity Layer
MCR	Multi-Channel Routing
MD	Minimum Delay
MD5	Message-digest algorithm version 5
MDA	Mesh Deterministic Access
MDART	Multi-path Dynamic Address RouTing
MDMR	multiple destination multiple receiver
MDSR	multiple destination single receiver
Mesh DA	Mesh Destination Address
mesh Portal	mesh Portal
Mesh SA	Mesh Source Address
mesh STA	mesh Station
Mesh TTL	Mesh Time To Live
mETX	Modified Expected Number of Transmissions
MHWMP	Modified HWMP
MIC	Metric of Interference and Channel-switching
MIFS	Mesh Inter-Frame Space
MIMC	Multi-Interfaces and Multi-Channels
MIND	Metric for INterference and channel Diversity
MIT	Massachusetts Institute of Technology

MMRP	Mobile Mesh Routing Protocol
MORE	MAC independent Opportunistic Routing & Encoding
MPDU	MAC protocol data unit
MPM	Mesh Peering Management
MPMP-C	MPMP with Conditional Confirmation
MPMP-U	MPMP with Unconditional Confirmation
MPR	Multi-Point Relay
MR-LQSR	Multi-Radio Link Quality Source Routing
MRP	Mesh Routing Protocol
MRP-B	Mesh Routing Protocol Beacon mode
MRP-H	Hybrid Mesh Routing Protocol
MRP-OD	Mesh Routing Protocol On Demand
MTI	Metric of Traffic Interference
NAV	Network Allocation Vector
NRO	Normalized Routing Overhead or Routing Load
ns-2	Network Simulator 2
ns-3	Network Simulator 3
NT	Neighbor Table
OGM	OriGinator Message
OLSR	Optimized Link State Routing Protocol
OPT	Omnidirectional Path Table
OTR	Optimized Tree-Based Routing
P-cache	proxy cache
P2P	Peer-to-Peer
PC	Point Coordinator
PCBR	Path Cost-Based Routing
PCF	Point Coordination Function
PDR	Packet Delivery Ratio
PER	Packet Error Rate

PERR	Path Error
PHY	Physical layer
PIFS	Point-coordinated Inter-Frame Space
pMS	Proxy mesh STA
PREP	Path Reply
PREQ	Path Request
PSDU	PHY service data unit
PSPSA	Path Selection Protocol for Smart Antennas
PXU	Proxy Update
PXUC	Proxy Update Confirmation
Q-HWMP	QoS-aware HWMP
QoS	Quality of Service
RA	Receiver Address
RA-OLSR	Radio-Aware Optimized Link State Routing Protocol
RADV	Route Advertisement
RANN	Root Announcement
RARE	Resource Aware Routing for mEsh
RC	Remaining Capacity
RDIS	Route Discovery
RDR	Root Driven Routing
RF	Radio Frequency
RM-AODV	Radio Metric Ad-hoc On-demand Distance Vector
ROMER	Resilient Opportunistic MEsh Routing
RREP	Route Reply
RREQ	Route Request
RSSI	Received Signal Strength Indication
RT	routing table
RTS	Request to Send
RTT	per-hop Round Trip Time

SA	Source Address
SC	Switching Cost
SDMR	single destination multiple receiver
SDSR	single destination single receiver
SHA-1	Secure Hash Algorithm version 1
SIFS	Short Inter-Frame Space
SimYES	Simple yet Effective Scheme
SINR	Signal to Interference Noise Ratio
SNR	Signal Noise Ratio
SNR	signal to noise ratio
SREP	STA Reply
SREQ	STA Request
SSR	Scalable Source Routing protocol
ST	Aggregate Throughput or System Throughput
STA	Legacy Station
STBC	Simple Space Time Block Codes
TA	Transmitter Address
TBR	Tree-Based Routing
TBTT	Target Beacon Transmission Time
TC	Topology Control
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TG	Task Group
TSF	Timing Synchronization Function
TTL	Time-to-Live
TU	Time Unit
TXOP	Transmission Opportunity
UAV	Unmanned Aerial Vehicle
VANET	Vehicular Ad Hoc Network

VRR	Virtual Ring Routing
WCETT	Weighted Cumulative Expected Transmission Time
WCETT-LB	Weighted Cumulative ETT-Load Balancing
WDS	Wireless Distribution System
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Network
WVM	Wireless Virtual Mesh

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CHAPTER 1

Overview

"Say all you have to say in the fewest possible words,
or your reader will be sure to skip them;
and in the plainest possible words
or he will certainly misunderstand them."

John Ruskin

The research work presented in this document intends to be a contribution to the advance of the state-of-the-art of IEEE 802.11-based mesh networks. In this chapter, first the research context, scope, and motivation for this work are presented. Following, the research problem is stated and the key contributions of this research work are outlined. Finally, the document structure is presented.

1.1 Research Context and Scope

Since its introduction, wireless communication has been a revolution for communication and networking technologies with the great advantages that it provides in comparison to its wired counterparts [1]. Over the past few years, the IEEE 802.11 family of standards has become a dominant solution for wireless communication due to its performance, low cost and fast deployment characteristics [2, 3]. With the rapid growth of both Internet and wireless communications, there is an increasing demand for wireless broadband access and higher data rates. Evidence of this is the increasing market share of wireless devices and the increasing penetration of these devices at homes, a school, in the office, and “everywhere else” incorporated into modern phones.

However, as Abdel Hamid et al. [1] emphasized, such advantages comes at the price of some drawbacks and limitations, among them:

- Interference between wireless devices due to the broadcast nature of wireless communication, that can result in lower reliability of data transmission;
- Lower bandwidth and data rates compared to wired communication which results in higher delay/jitter and longer connection setup;

- Highly dynamic network conditions due to interference, loss of signal power with distance, and freedom of mobility;
- Fading due to obstacles and the "multipath effect";
- Frequency reuse due to limitation of bandwidth and spectrum, usually causing more interference.

Moreover, new challenges arise due to the fact that usually increasing the data rate means that the communication range should be decreased [3].

In this context, *Wireless Mesh Network* (WMN) concept appears as a potential "next step" in the evolution of wireless networks, and also a promising solution for wireless environments demands, due to its characteristics (e.g. performance, low cost and fast deployment [2, 3]) and fields of application [4]. In Akyildiz et al. [5] a number of application scenarios for WMNs is presented, going from simple communication environments, such as broadband home networking, community and neighborhood networks, enterprise networking, building automation; to more complex environments as industrial networks, disaster recovery networks, public safety and many others.

A WMN is essentially formed by a set of wireless nodes, generally known as *mesh Stations* (mesh STAs), that work together to create a backhaul for communication between mesh clients. In a WMN each mesh STA may operates not only as a host (non-mesh station) but also as a router (mesh STA), forwarding packets on behalf of other nodes that may not be within direct wireless transmission range of their destination or do not have mesh capabilities. It is gaining significant attention due to its specific characteristics. WMNs are decentralized, easy to deploy and characterized by dynamic self-organization, self-configuration and self-healing [2]. They can be used in several application domains, like broadband home networks, community and neighboring networking, enterprise networking, metropolitan area networks, transportation systems, building automation, health, medical and security surveillance systems [5].

In a WMN the installation costs may be significantly reduced when compared to traditional WLANs, as they require less cabling connections. Unlike traditional WLANs, where there is the need for both a data cable and a power line for each *Access Point* (AP), a WMN AP requires only to be connected to a power line. This feature may be very attractive for setting-up industrial plants, where it is quite easy to extend power lines, but it is usually difficult to re-cable the plant installation in order to get a direct cable connection from the AP to the nearest data communication switch.

Besides the cabling cost reduction, the use of WMNs may be also very effective to reach the required reliability level for the wireless communication infrastructure. Such reliability improvement is a direct consequence of the WMN multi-hop capabilities, where mesh devices are capable to relay frames among them, creating multiple paths to deliver data through the mesh network. It provides a high robustness level against link failures, as the self-healing property will automatically sense the path failure and reroute the traffic.

In the literature, it is possible to recognize multiple classifications for Wireless Mesh Networks. Most of them are related to the resources of the network devices [6]. Resources are the wireless medium (e.g. amount of channels) and hardware capabilities (e.g. amount of radios). Protocols designed for WMN need to consider these resources. Figure 1.1 shows a

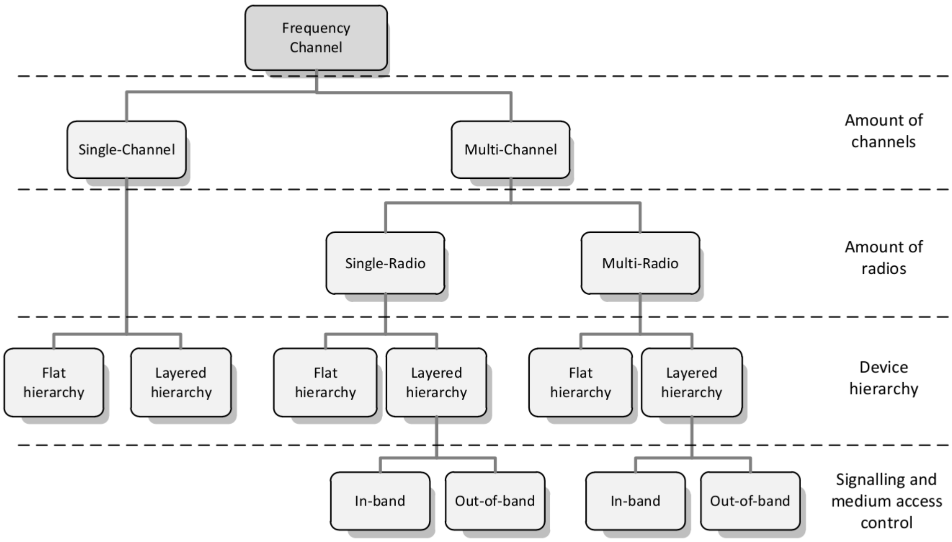


Figure 1.1: Resources related classification of Wireless Mesh Networks. Redrawn from [6].

classification of WMN proposed by Hiertz et al. [6]. WMN taxonomies are discussed in Section 2.2.2.

Following the classification introduced in [6] (see Figure 1.1), in a WMN, wireless devices can operate with or without a hierarchical structure. In a flat hierarchical WMN, any device in the network is able not only to send and receive frames, but also to forward frames in behalf of other devices. Layered hierarchical WMN are formed by two types of nodes: mesh nodes and non-mesh nodes. Mesh nodes are full mesh capable nodes which means they can use the mesh structure to relay frames. Non-mesh nodes do not have such relaying capabilities. Typically, non-mesh nodes are associated with mesh nodes to use the mesh network. Thus mesh nodes play the role of an access point for non-mesh nodes.

Although traditional deployments of IEEE 802.11-based WMN rely on single-channel communication, 802.11 WMNs can be used for multi-channel communication as well, taking advantage of multiple non-overlapping channels. However, the absence of a common and shared channel among all mesh nodes brings new challenges for the mesh management. That is the main reason why traditional IEEE 802.11-based WMN are developed for single-channel communication. Additionally, new routing mechanisms must be applied in order to enable routing among the multiple channels. In fact, a IEEE 802.11s mesh network can be deployed as any of the combinations illustrated in Figure 1.1, i.e. from a traditional single-channel with flat hierarchy (without non-mesh point) to a multi-channel multi-radio with layered hierarchy.

Regarding to the use of the frequency channel, wireless mesh networks may operate in-band or out-of-band. Using in-band signaling, the control information is exchanged on the same channel as the data transmission. In order to minimize the control overhead, the out-of-band approach is clearly more attractive.

Based on the classification illustrated in Figure 1.1, all the development of this thesis and its outcomes were designed targeting single-channel and layered hierarchical mesh network scenarios, which represents most of the current deployments.

There are several ongoing standardization bodies working to extend wireless communication specifications for mesh networking [7], which highlights its importance. For this task, several IEEE *Task Groups* (TGs) have been created to specify all the requirements and standards to establish a mesh network in a wireless environment according to their specific standards. This thesis focuses on a particular type of WMN: the IEEE 802.11s Wireless Mesh Networks. The IEEE 802.11s standard specifies a WMN technology based on the IEEE 802.11 WLAN. The IEEE 802.11s standard is a result of one of these TGs and aims to create a framework that will enable wireless mesh networking for standard IEEE 802.11 devices. The goal of the IEEE 802.11s TG was to describe the mechanisms to enable mesh networking for WLANs for Wi-Fi (802.11) devices. The major challenge for the TG was to specify the *Medium Access Control layer* (MAC) and *Physical layer* (PHY) requirements but keeping the compatibility with other 802.11 standard. For example, the PHY aims to be compatible with existing IEEE 802.11a/b/g/n PHY operating in the unlicensed frequency spectrum. A brief technical background on the IEEE 802.11s is presented in the next chapter (see Section 2.1).

1.1.1 Scalability of IEEE 802.11s mesh networks

Scalability is one of the major deciding factors for any new networking technology to be accepted, deployed and to evolve continuously [8]. Scalability is a well-known issue in multi-hop networking. The network scalability could be defined in many different ways. From the network point of view, in a basic definition, it means that when the size of the network increases the performance degrades significantly. Regarding the protocol, a wide accepted high-level definition is scalability is the ability of a protocol to perform efficiently as one or more network parameters grow to be large in value. In this dissertation, both definitions of scalability are used interchangeably henceforth. Typical network parameter that have an impact on the network scalability are number of nodes, concurrent connections, frequency of transmissions, node density, and node mobility. Protocol scalability is also very sensitive to the message control overhead.

There are many factors that affects the scalability in WMNs. Srivathsan et al. [8] listed a set of reasons for poor network scalability in WMNs:

1. Co-channel interference;
2. Routing protocol overhead;
3. Half-duplex nature of radio antennas;
4. Difficulties in handling multiple frequency radio systems;
5. Deployment architecture;
6. Medium access control;
7. Topology (denseness of nodes, degree of nodes);
8. Communication pattern (locality and number of hops).

To our knowledge there is still scarce conducted research regarding the scalability of the IEEE 802.11s networks. One reason for this can be fact that IEEE 802.11s networks are viewed as medium sized networks, in which the scalability is not regarded as a problem. Moreover, is notable the increasing interest in developing large mesh networks based on IEEE 802.16 networks, also known as *Worldwide Interoperability for Microwave Access* (WiMAX), due to its long range covering and high bandwidth.

Typical deployments of IEEE 802.11 WLANs consist of a series of wired APs that rely on a wired infrastructure to extend its connectivity. As result, the size (number of nodes) of the network is largely restricted by the wired infrastructure. Conversely, in a IEEE 802.11s Mesh Network, APs can be interconnected to other APs in a multi-hop fashion in order to establish the *Extended Service Set* (ESS). Thus, the IEEE 802.11s approach allows the setup of large sized networks (i.e. with a larger number of nodes). However, as the network size increases, the mesh network may face severe scalability problems. As a result, the available throughput will decay as the network gets bigger, and the end-to-end delay becomes too large. One of the major reasons for this behavior is the increase of the number of hops in the multi-hop network. Due to the multi-hop nature of WMNs, they tend to experience high restrictions on network capacity. Gupta and Kumar [9] derived the per-node throughput capacity for static ad-hoc networks (such as IEEE 802.11s WMNs) and proved that when the node density increases, it reduces the throughput.

Although the capacity problem is heavily influenced by the unsuitability of standard IEEE 802.11 MAC schemes, usually based on the *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA), which was not design for multi-hop environments, when crossing multiples hops, the way that nodes forwards the message is also important. Thus, the efficiency of the path selection and message forwarding play an important role to increasing the scalability by optimizing the number of hops for a communication path. The solution proposed in this thesis was envisioned under this perspective.

1.1.2 Application Scenarios

The compatibility with the set of IEEE 802.11 PHY specifications, enables the IEEE 802.11s devices to use a variety of signalling coding, data rates, and frequency spectrum. Thus, IEEE 802.11s mesh networks can be deployed in a number of distinct configurations, which allows it to cover a wide range of application scenarios. Although scientifically promising, research and deployments of large IEEE 802.11s mesh networks is still scarce. Even so, a few examples of large deployment can be envisioned (with some current research on it), among them:

1. **Citywide Mesh Networks**. Citywide mesh networks are becoming attractive for metropolitan areas of all sizes and thereby reshaping the traditional roles of municipal access networks [10]. These networks aims to provide connection service to a large number of both stationary and mobile users. IEEE 802.11 mesh networks are potentially attractive for this type of application [11, 12] due to its low cost of installation and its full compatibility with community client devices already in place.

2. **Public Safety Networks**. Public safety networks are receiving more attention and priority in many countries as they have to deal with ever increasing cases of terrorism threats. These networks are usually deployed in large areas to cover the most sensible

city locations. Mesh networks have become a very attractive technology for public safety networks. Its self-healing capability combined with the mesh topology's inherent redundancy, provides wireless mesh networks with a high level of robustness and fault tolerance [13]. In typical deployments, stationary or mobile (e.g. those mounted in security forces vehicles) IP cameras are connected to the mesh nodes to transmit real time video over the mesh network to the base station video monitors. Studies about the use of IEEE 802.11s mesh networks to provide wide wireless video surveillance can be found in [14, 15]. In fact, given that WMNs are essentially IP networks, they can provide all the set of applications and services available on the Internet, including voice and video. The wide range of services supported by WMNs is one of the key advantages over traditional public safety communication systems [13].

3. **Emergency Response Networks**. Communication, sharing information among organizations and across many people, is a major priority in any disaster planning initiative. Communication disruptions may occur in the event of a disaster, as a result of damage to the infrastructure caused by the disaster, as well as excessive demands. Tragic events such as "9/11" and "Hurricane Katrina" in the United States clearly demonstrated the inadequacies and limitations of current first-responder communications technology [13]. Regarding this specific application, an interesting study is presented in [16]. In this study, the authors investigated if traditional access points, already available in developed cities with high population density, can be used to create a mesh network to support first response communication. The main finding of this work was that the mesh topology is indeed more robust than a random deployment and robust enough to cope with the removal of up to 20% of the most critical nodes. This is an interesting property for this application scenario.

4. **Military Networks**. According to Srivathsan et al. [8], WMNs were originally developed to give soldiers reliable broadband communications anywhere in the battlefield. Today, military applications still dominate the research needs in wireless networking [17]. Modern warfare is becoming more and more "network-centric", improving the effectiveness at both the tactical point of view and in the achievement of broader strategic goals. In this scenario, information superiority has become critical for both war fighters and commanders. The required information, from diverse sources, includes real-time video, data and voice, terrestrial forces and sensors "inteligence", satellites information, *Unmanned Aerial Vehicle* (UAV) control information, and a wide variety of centralized and distributed information assets. The vast majority of these information must be delivered wirelessly, due to limited connection to infrastructured networks in the field. Even though the IEEE 802.11s standard does not address any real-time communication requirement, it still arouses interest from researchers for military use [18], including UAV applications [19–21].

5. **Smart Grid Multiuse Networks**. Smart grid refers to a way of operating the power system using communications, power electronics, and storage technologies to balance production and consumption at all levels [22]. A deployed large-scale commercial Smart Grid may have tens of millions of nodes. The emerging Smart Grid will attempt to integrate WMN into power grids [23]. Recently, some researchers [24–27] have conducted some studies along this line, using IEEE 802.11s mesh networks.

6. **Vehicular Networks**. *Vehicular Ad Hoc Network* (VANET) has emerged as a new technology to integrate the capabilities of new generation wireless networks to vehicles [28]. The natural next generation of Vehicular Networks tends to take advantage of mesh properties. In this sense, initial studies about the use of IEEE 802.11s mesh networks to provide vehicular communication can be found in [29–31].

7. **Mobile Enterprise Networks**. This application scenario requires a private and secure high capacity wireless network. In most cases, many different type of data (e.g. normal internet traffic, video surveillance data, real-time video and machine communication data) must be delivered across the mesh backhaul, many wireless hops away. This is one of the most demanding application scenarios for large mesh networks, as they present - besides high scalability - very strong real-time, security, and *Quality of Service* (QoS) requirements.

8. **Small Towns and Rural Area Networks**. The ability to provide high performance with a large number of hops (node-to-node) connections is a key advantage of WMNs in small towns and rural areas. Such networks allow to connect low-populated areas in a large multi-hop network. Examples of exploratory research on using IEEE 802.11s in this application scenario can be found in [32–34].

The architecture of WMNs is mainly determined by the target application scenario. Some of those scenarios exhibit more demanding requirements, such as time constrained communication, and high mobility support. In this thesis, we consider large-scale WMNs that serve as wireless access networks over large geographic areas, such as Citywide Mesh Networks, Public Safety Networks, and Emergency Response Networks scenarios, in which such requirements are not a main concerning or can be neglected. In principle, the problem of low scalability affects all the above scenarios and hence the solution proposed in this thesis can be applied to any of those scenarios presented above. Although, of course, all these scenarios can be benefited by a scalability improvement provided by the proposed solution, it is arguably not a best fit solution to fulfil those demanding scenarios.

An interesting large network scenario is devised by Aggelou [35], in which:

> “..several thousands of tiny devices [e.g., nanoelectromechanical systems (NEMS)] being deployed on public transport means (metro, buses, taxis) capable of performing a wide spectrum of functionalities, including the detection of their location, road, and weather conditions, and so on. As vehicles pass each other, they exchange information summaries. These summaries eventually diffuse across different sections of the metropolis. Drivers can plan alternate routes, estimate trip times, send queries, locate and call the nearest available cab driver, and be warned of dangerous driving conditions. This mesh of wireless devices eventually forms a massively populated network, commonly named a wireless mesh network.”

The Aggelou’s scenario implies in a very integrated, large-scale, heterogeneous and sophisticated network. In this sense, it is possible to imagine a wireless mesh network architecture from his description.

1.1.3 Motivation

Wireless mesh networking is a relatively new technology that follows recent advances in ad-hoc networking research. The majority of previous research on WMN has been carried out using routing protocols or mere adaptations from ad-hoc networks, which is proved to not scale very well on wireless mesh settings [36]. In fact, IEEE 802.11 ad-hoc mode was not designed having multi-hop communication in mind. The novelty of the IEEE 802.11s standard and the lack of solutions to deal with multi-hop communication using IEEE 802.11 devices are the main motivation of the presented research work.

Nevertheless, in a broader perspective, other motivations were identified. From a commercial point of view, the IEEE 802.11s standard is experiencing the same growth track that IEEE 802.11n standard experienced. When it was still a draft standard, several vendors has been developing their own solutions. Outdoor mesh vendors included BelAir Networks[1], Firetide[2] and Tropos Networks[3], eventually followed by Motorola[4], Nortel[5], and finally Cisco[6] complete this list. Some of them have already “IEEE 802.11s-like” products on the market. Many of these vendors are also active members of the IEEE 802.11s Working Group. Obviously, mesh vendors will likely prefer to have proprietary solutions with enhanced features beyond what 802.11s will provide. However, a standard mesh architecture for ubiquitous devices as such as IEEE 802.11 devices, might lead to an increase in the demand for new mesh products and solutions which are more flexible and more cost effective than the current wired APs.

From a research point of view, new challenges arise because the IEEE 802.11s specification must comply with the PHY and MAC implementations of existent 802.11a/b/g/n devices. It must be highlighted that there is a trade-off between the compatibility with legacy IEEE 802.11 devices provided by any IEEE 802.11s mesh solution and its performance. If in one hand, the IEEE 802.11s standard brings flexibility and low cost of installation due to its compatibility with all the set of IEEE 802.11 standards, on the other hand, the use of unlicensed frequency bands (which are subject to uncontrolled interference from a range of sources) poses extra challenges to ensure reliable communication.

1.2 Research Problem

In this thesis the following research problems are tackled.

How to build scalable IEEE 802.11s wireless mesh networks? When building large scale networks, scalability to the number of nodes is a major concern. In theory, in a scalable network, the size does not affect the throughput and the loss. In practice, it is expected that the performance does not drop as far as the network size increases. Moreover, the solution must also be able to scale other parameters such as traffic load, number of concurrent connections,

[1] www.belairnetworks.com/
[2] www.firetide.com/
[3] www.tropos.com/
[4] www.motorola.com/
[5] www.nortel.com/
[6] www.cisco.com/

packet size, and delay. It is well known that the standard IEEE 802.11s path selection and forwarding mechanism presents limited scalability [37]. Therefore, it is necessary to devise a scalable scheme for path selection and forwarding. The major problems regarding IEEE 802.11s scalability are surveyed in Chapter 2.

How to manage non-mesh station information in an efficient and robust way? One of the most interesting features in wireless mesh networks is to provide wireless connection in an autonomous way. Self-organization and self-configuration are the most appealing properties of this type of network. However, these properties also imply in an expected increasing of connected nodes, where most of them are legacy IEEE 802.11 (most known as WiFi) stations without mesh capabilities. Although the IEEE 802.11s standard was developed to support legacy stations, its current mechanisms for keeping information about these legacy station heavily relies on message flooding. Large-scale wireless mesh networks demands more efficient and robust mechanisms than flooding (even controlled one).

It must be noted that many other challenging research questions arise from this idea of a scalable IEEE 802.11s wireless mesh network, such as mobility, location and traffic balancing of network gateways, as well as the possibility for improvements of traditional network services. However they are out of the scope of this thesis.

1.3 Thesis Statement

As aforementioned, the path selection and message forwarding scheme defined in the IEEE 802.11s standard - the *Hybrid Wireless Mesh Protocol* (HWMP) - relies on traditional IEEE 802.11 medium access mechanisms and protocols. Thus, the network scalability is partially bounded by the inherited ad-hoc approaches, which neither perform well or take any advantage from the multi-hop architecture of these networks.

Seeking to provide answers to the research questions presented above, in this dissertation we support the following thesis: **It is possible to improve the scalability of IEEE 802.11s mesh networks by integrating both Clustering and *Distributed Hash Table* (DHT) concepts, providing a hierarchical (due to the use of clustering) and efficient key-based lookup (due to the use of DHT) in a way to efficiently handle the multi-hop characteristics of these type of WMN**. The proposed approach does not follow the traditional adaptations from ad hoc and *Mobile Ad Hoc Network* (MANET) routing, done by the majority of previous research works on WMN. To support this thesis, we designed, implemented and assessed through simulations, a scalable path selection and message forwarding scheme called *DHT-based Cluster Routing Protocol* (DCRP).

1.4 Contributions

The main contribution of our work is the design, implementation, and assessment of a novel and scalable path selection and message forwarding scheme for IEEE 802.11s networks. The *DHT-based Cluster Routing Protocol* (DCRP) [38–40] exploits the traffic contention from hierarchical clustering routing with the key-based lookup provided by DHTs to increase the network scalability. The proposed clustering method takes into account specific details from the standard, such as the peering scheme. Moreover, this work provides an identification of the main scalability issues of current IEEE 802.11s standard path selection and forwarding mechanisms.

1.5 The Document Outline

The remainder of this dissertation is organized as follows.

Chapter 2 Provides an overview on the IEEE 802.11s standard, and discusses related work to our. Most of the content of this chapter was published in [41–44].

Chapter 3 DHT-based Cluster Routing Protocol (DCRP), a scalable DHT-based clustering path selection and forwarding protocol is introduced in this chapter, where its major components are detailed . A description of the proposed DCRP approach was published in [38–40].

Chapter 4 Presents performance assessment of DCRP, following by the discussion of the simulation results. Detailed evaluations and comparisons between DCRP and the standard IEEE 802.11s mechanism are presented in this chapter. Also, the results are discussed. Most of results and findings reported in this chapter were submitted for publication in [38].

Chapter 5 Finally, this chapter concludes this document and provides an outlook on future research directions.

A list of publications and other outcomes of this thesis is presented in Appendix A.

CHAPTER 2

Background and Relevant Work

*"If you can't explain it simply,
you don't understand it well enough."*

Albert Einstein

In this chapter, the background and review the related work is surveyed. The goal is to point out the many contributions of previous researchers and to place the contributions of this work in the proper context. This chapter is organized around both the general and specific themes of our research: Wireless Mesh Networks and IEEE 802.11s Mesh Networks. It starts by providing the reader with background information about the IEEE 802.11s standard, followed by a review of the related work.

2.1 An Overview of the IEEE 802.11s Standardization

In this section, a brief overview on the most relevant mechanisms of the IEEE 802.11s standard is given. An extensive review on the standard mechanisms and principles are out of scope for this thesis. Therefore, the interested reader may wish to read the chapter 13 of the standard [45] for further background on the mechanisms discussed in this thesis. Complementary information can be found in [5, 46–53].

The IEEE 802.11s standard specifies a wireless mesh network technology based on the IEEE 802.11 WLAN. The objective is to extend the coverage of traditional WLANs and to allow the support of a larger diversity of wireless technologies. In a traditional IEEE 802.11-based WLAN, an Extended Service Set (ESS) is constituted by a set of *Basic Service Set* (BSS), usually interconnected via a wired IEEE 802.3 (Ethernet) network, which leads to poor scalability and also increases the installation costs. In a IEEE 802.11s mesh network, the BSSs can be interconnected both via wired or wireless connections. In a 802.11 ESS, each node within a BSS can communicate only with its neighbors in ad-hoc mode, or through the access points (APs) [54]. Thus, there is no routing inside the ESS. Conversely, in a 802.11s mesh network, every node can work a relaying node, creating the mesh.

The IEEE 802.11s standardization process can be summarized in the following major steps. The IEEE 802.11s Task Group was created in July 2004, and the first draft was published in March 2006. The draft document was approved at the end of 2011, and then integrated to the IEEE 802.11 standard in 2012. In addition to generic IEEE 802.11 mechanisms, the IEEE 802.11s [45] also addresses improvements at the MAC layer, and security issues.

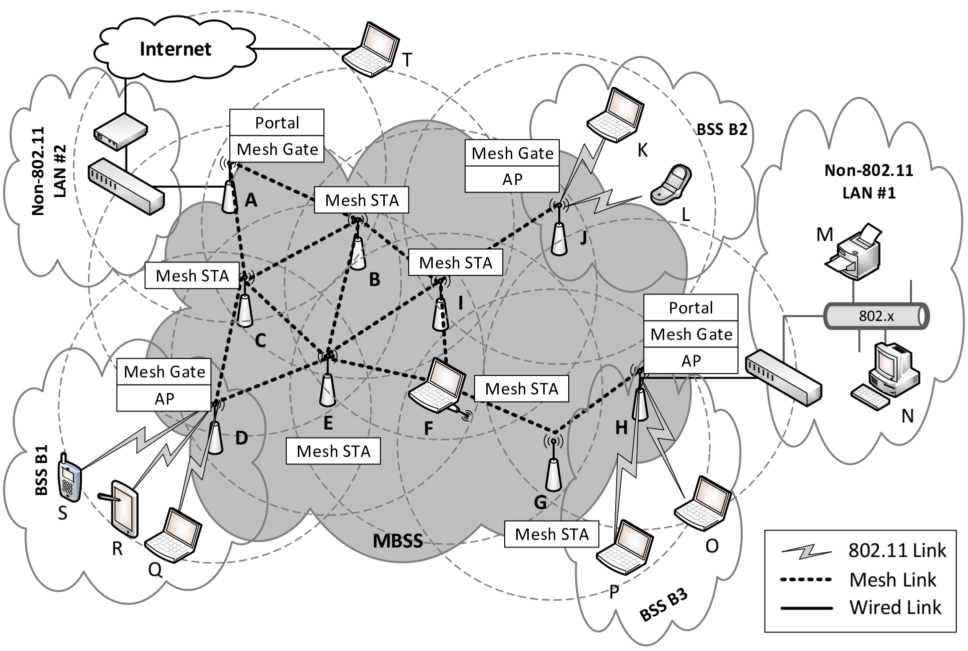


Figure 2.1: IEEE 802.11s network elements described in the standard [45].

Although IEEE 802-11-based wireless LAN supports an ad-hoc mode in which stations can communicate directly with other stations in their range, usually IEEE 802.11 WLANs use an infrastructure mode. In this mode, stations are organized in Basic Service Sets (BSS), each of which has a special station known as the Access Point (AP), and all communication to and from any station in a BSS goes always through its AP. Several BSSs may be interconnected by a so-called *Distribution System* (DS) into an Extended Service Set (ESS), which from the point of view of the stations in the component BSS appears to be a single BSS. That is, any station in one BSS can communicate with another station in another BSS and can move from one BSS to another in a transparent way. The standard specifies a DS only abstractly in terms of the services it must provide. Most often an IEEE 802.3 (Ethernet) network is used as a DS.

The IEEE 802.11s standard specifies the *Mesh Basic Service Set* (MBSS) which is composed by a set of nodes with a mesh station (STA) capability, i.e. nodes with the ability to forward frames on behalf of other nodes. The new standard introduces new terms to denote the functionality that nodes in an 802.11s mesh network may provide. To facilitate the reading of the remaining of the paper we put together a description of these functions in the next paragraphs. Figure 2.1 illustrates the relationship between all different types of nodes (based on its functionalities) in a mesh network, as described below. Note that one mesh STA may offer any combination of the functions of an AP, a portal, and a mesh gate [45] (e.g. node *H*).

(i) **Access Point (AP).** The IEEE 802.11-2012 standard defines the element AP as a station that provides wireless access to distributed services of a DS for associated stations. So, the AP is a central point to connect a set of client stations, creating a BSS. In the IEEE 802.11s standard, the AP functionality can be collocated with any mesh STA. In Figure 2.1, the nodes *D*, *H*, and *J* are AP collocated with mesh gate.

(ii) **Mesh STA.** A mesh STA is an IEEE 802.11s device (i.e. any device that implements the IEEE 802.11s standard stack) that participates in the mesh forwarding process and that can forward frames on behalf of other mesh STAs in an ad-hoc way. In fact, a mesh STA can be an end user wireless device, such as a laptop or a smart phone with an IEEE 802.11s interface, as well an Access Point (AP). In Figure 2.1, nodes *H* to *J* are mesh STAs and form the MBSS.

(iii) **Mesh gate.** In essence, a MBSS does not exist independently, instead it is used as backhaul network to interconnect other DS. Therefore, a mesh gate is a logical point that allows external (non-mesh STAs, i.e. stations outside the MBSS) to communicate through the MBSS. Thus, two different entities (mesh STA and mesh gate) co-exist in the device, i.e. *any mesh gate is also a mesh STA*. The way how an entity is collocated with a mesh STA is out of the scope of the standard and is open for implementations. It keeps the MBSS hidden from external STAs that associate to the AP or behind the portal, but at the same time allowing them to communicate with other external devices through the MBSS. Thereby mesh gates allow extending the mesh network coverage. In Figure 2.1, node *D* and *J* act as AP collocated with mesh gate to *BSS A* and *BSS B*, respectively. Node *A* acts as gate to the a non-802-11 LAN. Finally, the node *H* acts as both AP collocated with a mesh gate, and portal collocated with a mesh gate for the *BSS C* and a non-802-11 LAN, respectively.

(iv) **Mesh portal.** A mesh portal is a logical point simply acting as a bridge between 802.11 and non-IEEE 802.11 networks (usually wired Ethernet networks). The Annex P of the IEEE 802.11s standard document alerts to the differences between the integration service provided by a portal and the service provided by an IEEE 802.1 bridge, such as the IEEE 802.1D bridge. First, a portal provides the minimum connectivity between the networks, whereas a 802.1D bridge would create non-compliant implementations. Firstly, a portal has only one “port” (when compared to the IEEE 802.1D) which is used to access the DS, being unnecessary to update mapping tables inside a portal each time a STA changes its association status. In other words, the details of distributing frames inside the MBSS is a task of the mesh gate only. Finally, although some deployments (e.g. *open80211s* project) use to attach a 802.11D bridge to the mesh STA, this is not an architectural requirement of the standard. Mesh portals also allow extending the mesh network coverage. In Figure 2.1, the nodes *A* and *H* are portals to non-802-11 LANs.

All the aforementioned IEEE 802.11s’ elements create a multi-hop wireless relaying infrastructure, where all nodes cooperatively work to forward data from an originator node to a target node in a multi-hop fashion. However, it is also well known that multi-hop communication has severe impact over the throughput capacity, degrading the throughput quickly as the number of hops increase [9]. In an IEEE 802.11s Mesh Network, the relaying is performed at the data link layer (layer 2) and to this procedure is given the name of path selection.

The following subsections cover the most important characteristics of the 802.11s standard, which extends the 802.11 standard in order to form a mesh network.

2.1.1 Assembling the Mesh

The characteristics of dynamic self-organization, self-configuration and self-healing of the WMNs, described in Section 1.1, depend on the ability of the network nodes to autonomously establish links to their neighbors in order to create or repair the mesh.

Following the specifications in [45], when the parameter *dot11MeshActivated* is true, the STA must start a procedure to become a mesh STA of a MBSS[1] already established, or to create a new one. So, first, the STA shall perform either active or passive scanning to discover operating MBSS to which it can join. On passive scanning, the node shall passively scan for any beacon frames transmitted by other STAs. Conversely, on active scanning, the STA must transmit Probe Request frames over the medium and wait for the Probe Responses frames.

The frames exchanged during the scanning procedure must carry a mesh profile that is used by the STA to configure itself according to the MBSS configurations. A mesh profile is a set of parameters that specifies the attributes of a MBSS, and includes: a Mesh ID, a path selection protocol ID, a path selection metric ID, a congestion control mode ID, a synchronization protocol ID, an authentication protocol ID, and a mesh peering protocol ID. In a mesh BSS, all STAs use the same mesh profile. Based on the result of the scanning, the STA may join to a MBSS or create a new one. A STA that becomes a member of a BSS may establish a mesh peering with one or more of its neighbors that are also member in the same BSS.

Any neighbor mesh STA that has been discovered during the scan, shall be considered as a candidate peer mesh STA, as long as few conditions are met, such as belonging to the intended MBSS. A candidate peer mesh STA becomes a peer mesh STA only after the Mesh Peering Management protocol has been successfully completed, and a mesh peering is established between the two mesh STAs. Although the IEEE 802.11s standard suggest a peering management protocol, the framework is able to work with other protocols for this purpose.

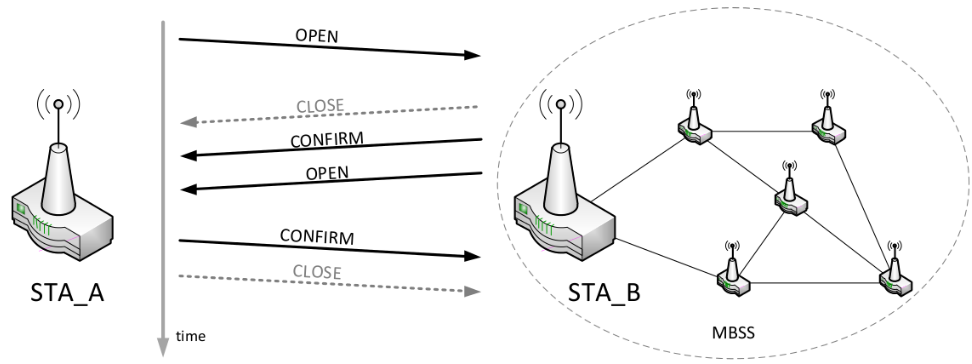


Figure 2.2: Peering establishment message exchange.

The proposed *Mesh Peering Management* (MPM) framework supports all functions to establish, manage, and tear down mesh peers. The MPM uses three special types of frames: Mesh Peering Open frames, Mesh Peering Confirm frames, and Mesh Peering Close frames.

The Figure 2.2 shows the message exchange for the establishment of a mesh peering instance between two mesh STAs. Following the same nomenclature adopted in Figure 2.2, the peering procedure starts when STA_A sends a Mesh Peering Open frame to the STA_B requesting that a mesh peering instance be established between them both. The request

[1]A Mesh Basic Service Set (MBSS) is a basic service set that forms a self-contained network of mesh points. A MBSS contains zero or more mesh Portals.

includes a mesh profile proposal for the mesh peering instance. Upon received the Mesh Peering Open frame from STA_A, STA_B processes the received profile and then, if it agrees with the proposed profile, it sends both a Mesh Peering Confirm frame and a Mesh Peering Open frame to STA_A in response to the Mesh Peering Open frame. The STA_A, upon receiving these frames from STA_B and also agreeing with its parameters, in order to establish the peering, sends a Mesh Peering Confirm frame to STA_B. In case any of the STAs disagrees with the proposed profile, or if there is a failure due to any other reason[2], the mesh STA tears down the mesh peering by sending a Mesh Peering Close frame.

Although specifying a specific peering management protocol, the IEEE 802.11s standard framework [45] allows the use of other protocols for this purpose.

2.1.2 The Frame Format

Data frames transmitted from one mesh STA to another use the IEEE 802.11-1999 [55] four addresses format as a basis, extended with the IEEE 802.11e [56] QoS header field and a new Mesh Control field (see Figure 2.4). Moreover, it extends a set of IEEE 802.11 management frames (e.g. beacon, probe, and data frames) and also introduces a new set of frames and *Information Elements* (IEs), as shown in Figure 2.3. Detailed information about the structure of frames and IEs can be found in the Chapter 8 of the standard document [45].

With respect to 802.11s frames, they can be of two types: either a Mesh Data frame, or a Multi-hop Action frame. A Mesh Data is a four or six MAC addresses frame that is used for transporting data between mesh points within the mesh, whereas a Multi-hop Action refers to a four MAC addresses frame used for specifying extended management actions. The Mesh Control field is prepended to the frame Body for both Mesh Data frames and Multi-hop Action frames transmitted by a mesh STA. The Mesh Control Present bit (Bit 8) of the QoS Control field (which is an IEEE 802.11e QoS header) is used to indicate whether the Mesh Control field is present. The Mesh Control field length is variable (6, 12, or 18 octets) and depends on the values in the Mesh Address Extension field, as shown in Figure 2.4. The Address Extension Mode subfield (present in the Mesh Flags field of the Mesh Control) basically indicates which extended addresses (if any) are present in the Mesh Address Extension field.

The *Mesh Time To Live* (Mesh TTL) field contains an unsigned integer corresponding to the remaining number of times that the frame can be forward in the mesh. The Mesh Sequence Number field contains an unsigned integer counter and is used by a mesh STA to detect duplicate mesh frames.

The issue that should be highlighted is that a six-addresses frame allows to support communication involving non-mesh STAs (IEEE 802.11 devices attached to a AP collocated with a mesh gate or IEEE 802.x devices behind a mesh Portal) over the mesh as follows: two addresses are required to address the *Transmitter Address* (TA) and *Receiver Address* (RA) on the link layer, two other addresses are required to address the *Mesh Source Address* (Mesh SA) and the *Mesh Destination Address* (Mesh DA) on the mesh, and finally two more addresses have to be used to address the *Source Address* (SA) and the *Destination Address* (DA) (end points of the communication). In the case of a six-addresses scheme, the Mesh DA and Mesh SA will be the addresses of the AP collocated with a mesh gate or mesh Portal

[2]The reasons for closing a mesh peering are outside the scope of the specification.

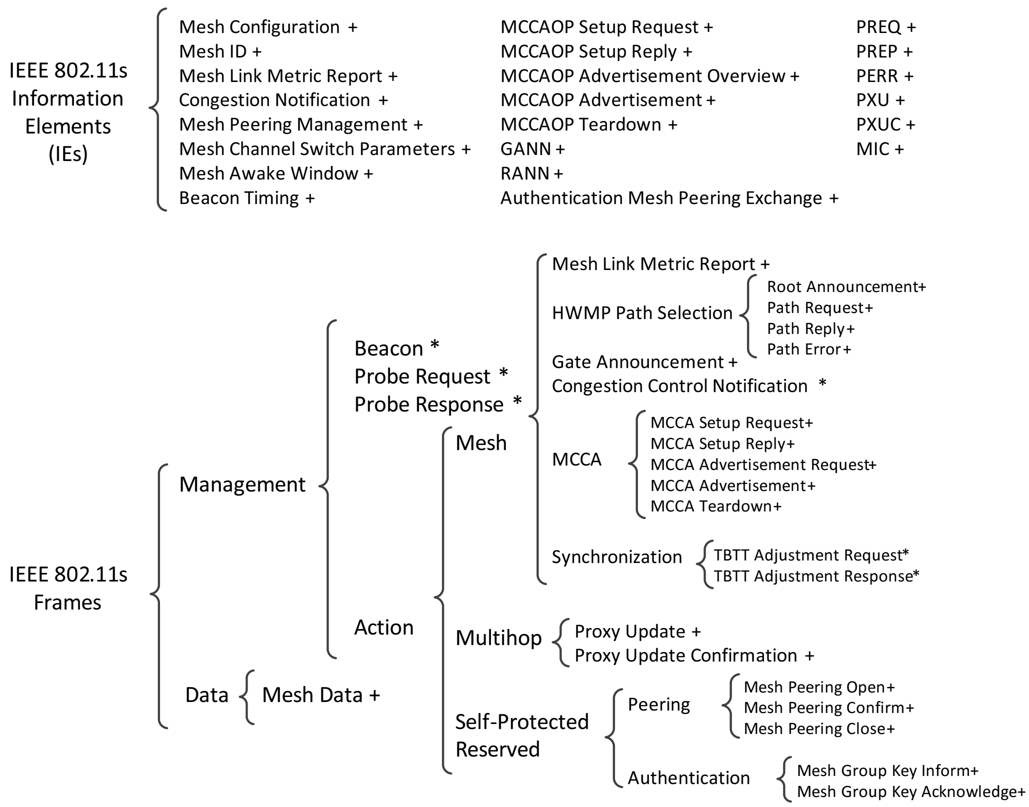


Figure 2.3: Frames/Information Elements (IE) introduced (+) or extended (*) by the IEEE 802.11s standard.

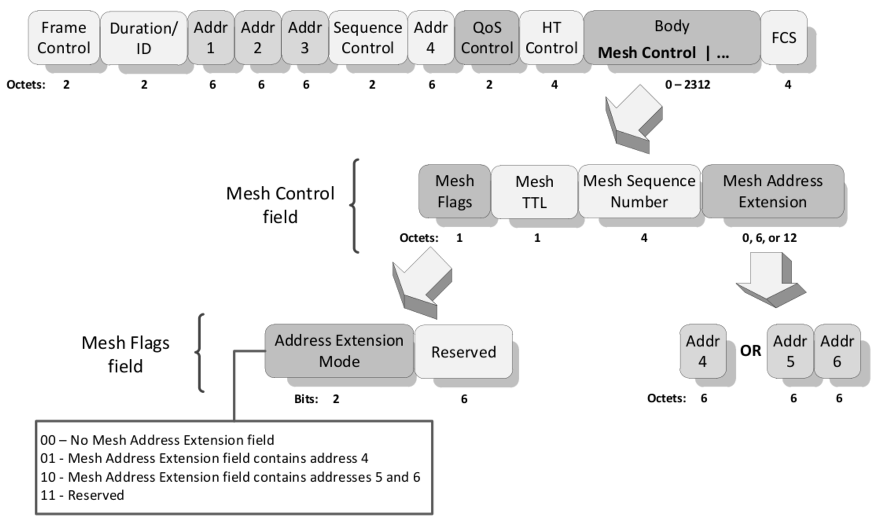


Figure 2.4: IEEE802.11s frame format.

related to the respective non-mesh STA. Figure 2.5 illustrates a six-addresses communication over a IEEE 802.11s mesh architecture. Details on how to address IEEE 802.11s mesh frames in forwarding processing are described in the standard [45].

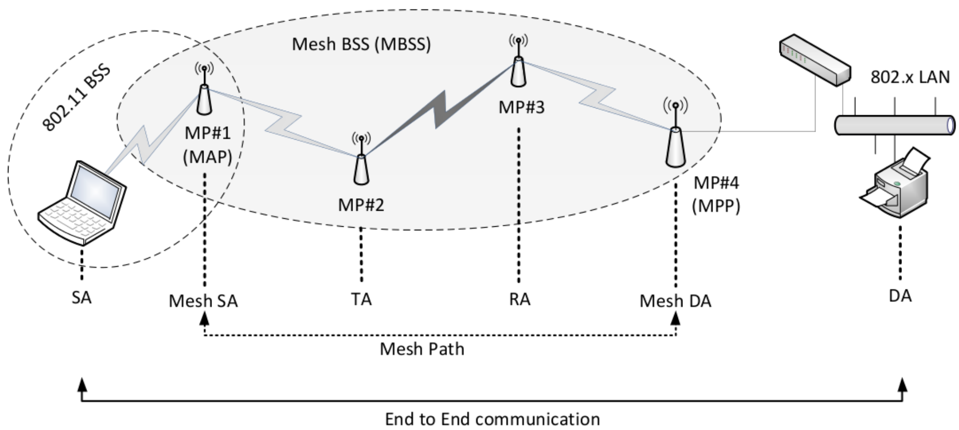


Figure 2.5: Example of IEEE802.11s addressing.

2.1.3 Radio-Aware Airtime Metric

The IEEE 802.11s defines the *Airtime Link Metric* (ALM) as the default link metric, but it also allows the use of other alternate link metrics. This metric reflects the amount of channel resources consumed by transmitting the frame over a particular link [45]. The ALM is used as an estimation of the cost of using a peer link within the mesh to forward a frame.

Formally, the airtime cost for each peer link is given as:

$$c_a = \left[O + \frac{B_t}{r} \right] \frac{1}{1 - e_f} \tag{2.1}$$

where O and B_t are constants related to the physical layer. In fact, the channel access overhead O can be decoupled into the channel access overhead O_{ca} plus the protocol overhead O_p (see Table 2.1). The argument r represents the data rate in Mb/s, while e_f represents the frame error rate for the test frame with size B_t. The ALM takes into account every information transmitted over the channel, as frame headers, trailing sequences, access protocol frames, etc. The estimation of e_f corresponds to transmissions of test frames (B_t) at the current transmit bit rate (r). The standard does not specify any specific procedure to estimate the frame error rate, leaving it as an implementation choice.

Table 2.1: Examples of ALM cost constants values.

PHY standard	O_{ca}	O_p	B_t
802.11a	75 μs	110 μs	8192 bits
802.11b/g	335 μs	364 μs	8192 bits

The ALM is encoded as an unsigned integer in units of 0.01 *Time Unit* (TU). The ALM is defined in a way to be used for any path selection protocol, as part of an extensible path selection framework. During path discovery, each node in the path contributes to the metric calculation by taking advantage of the management frames used to exchange route information [52].

The ALM metric is well adapted to single-radio single-channel mesh networks due to its simple design [57].

2.1.4 Path Selection

Path selection is the expression used in the 802.11s standard for what is usually known as routing, i.e. the process of finding the best route/path to a node. Formally, it is defined as a selection of multi-hop paths between mesh STAs (in the sense of Mesh Point) at the link layer [45]. This process usually requires that MPs exchange messages to build a snapshot of the network topology. Forwarding is the process of passing a packet/frame from an input interface to the appropriate output interface. This task is performed by the routers using only its local information - usually obtained through the routing process. Thus the goal of path selection is to discover a valid route for forwarding.

On the Internet, both functions are usually performed at the network layer and the IP packet is not changed along the way. In contrast, on 802.11s mesh networks the routing is performed at the data-link layer and along the way some fields of the frame may need to be changed, usually when they enter or leave the mesh network.

Until draft version 1.06 of the IEEE 802.11s, every mesh STA should support two path selection protocols: the Hybrid Wireless Mesh Protocol (HWMP) [48] as the default routing protocol and the *Radio-Aware Optimized Link State Routing Protocol* (RA-OLSR) [49] as an optional one. Since draft version 1.07, the RA-OLSR has been removed from the IEEE 802.11s specification. HWMP can work in both reactive and proactive modes. In reactive routing, the route discovery is performed on-demand. In proactive routing, performed only on mesh Portals, a distance vector tree is used to avoid unnecessary routing path discovery and recovery messages. The RA-OLSR protocol is a proactive, link-state wireless mesh path selection protocol based on the *Optimized Link State Routing Protocol* (OLSR) [58]. It also includes extensions like the *Fisheye State Routing* (FSR) protocol [59], and uses radio-aware metrics.

Both HWMP and RA-OLSR have several shortcomings, namely in what concerns the scalability of the network. In HWMP, the proactive mode is centralized and constrained by the root node. Even when two MPs near to each other need to communicate, the proactive routing protocol routes the frames through the root node, which results in poor performance. At the same time, the reactive (on-demand) mode will initiate a path discovery process to search for an optimized path before sending the frames, resulting in an excessive number of broadcasted messages. The problem with RA-OLSR is the overhead of control messages, even when the Fisheye protocol is used.

The Airtime Link Metric (see Section 2.1.3) is the default metric in the 802.11s standard and shall be used with both RA-OLSR and HWMP. Ghannay et al. [60, 61] presents a comparison of hop count and radio aware path selection protocols in IEEE 802.11s mesh networks. In a first simulation scenario, the authors compared the OLSR and the FSR applied to the OLSR (FOLSR) with its radio-aware version, the RA-OLSR. In a second simulation scenario, they compared the *Ad-hoc On-demand Distance Vector* (AODV) with its radio-aware version, the *Radio Metric Ad-hoc On-demand Distance Vector* (RM-AODV). For both simulation scenarios, the results suggested that the radio-aware metric outperforms the hop count metric.

Although the standard assures compatibility between devices of different vendors by dictating mandatory mechanisms (such as HWMP and ALM), it also includes an extensible framework for path selection [52] that allows vendors to implement their own path selection protocol and metric to meet special needs [63] (see Figure 2.6).

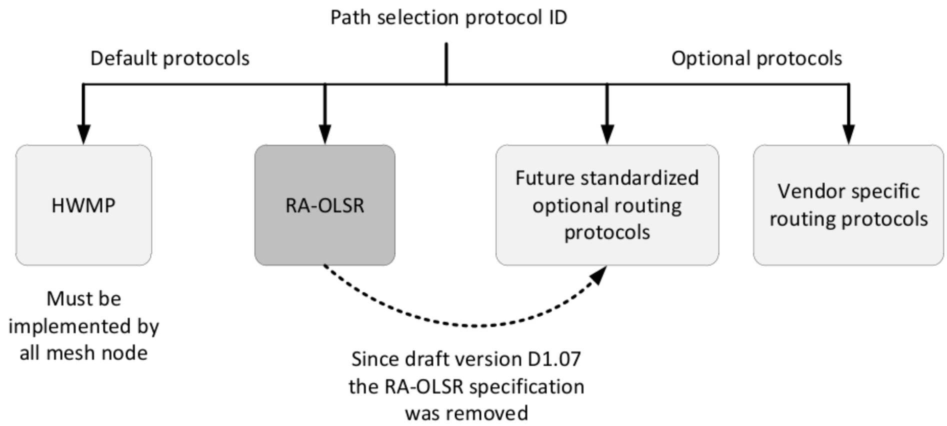


Figure 2.6: Extensibility of IEEE 802.11s path selection protocols. Based on Bahr et al. [62].

2.1.4.1 Hybrid Wireless Mesh Protocol (HWMP)

The Hybrid Wireless Mesh Protocol (HWMP) is the default mesh path selection protocol defined for the 802.11s standard; it must be implemented by all 802.11s-enabled stations (mesh STAs). HWMP uses a set of protocol primitives derived from AODV with proactive topology tree extensions to perform routing related functions, and adapted for using MAC addresses and the Airtime Link Metric. The flexibility that arises from the combination of reactive and proactive elements enables HWMP to work in a wide variety of mesh network scenarios, hence the RA-OLSR has been removed from the standard.

The HWMP operation is based on the exchange of frames containing HWMP elements. These elements are the *Path Request* (PREQ), *Path Reply* (PREP), *Path Error* (PERR), and *Root Announcement* (RANN). Briefly, PREQ is sent either in broadcast or unicast modes and has the purpose to ask the destination MPs to generate/build a reverse route to the originator of the PREQ. The reverse route is used to establish the path. PREP is always sent in unicast mode and is used to communicate the reverse route. PERR is always sent in broadcast mode and alerts receiving mesh STAs that the originator no longer supports certain routes. RANN is always sent in broadcast mode and informs mesh STAs about presence and distance of the root mesh STA. The proper use for each HWMP element, in both reactive and proactive modes, is discussed below.

The reactive (or on-demand) mode is always available to the MPs. In proactive tree building mode a mesh STA must be configured as root mesh STA through PREQ or RANN message exchanges. These mechanisms to configure the root mesh STA are presented below. The reactive and proactive modes are not exclusive. They can be used concurrently in a 802.11s mesh network, essentially because the proactive mode is an extension of the reactive mode. This concurrent usage allows a mesh STA to start communicating instantly using the proactive mode, while the reactive mode finds the best path between the mesh STA and the destination. In this case, the mesh STA will initially send frames through the root mesh STA until a direct path to destination is available, thus reducing the communication starting delay.

Reactive Mode. In HWMP reactive mode, the route discovery process is initiated only when a mesh STA needs to find a path to a destination mesh STA. In that case, the source mesh STA broadcasts a PREQ on the mesh network with the address of the destination mesh STA in the list of targets. Upon receiving a PREQ, a mesh STA creates or updates its path information to the source mesh STA and propagates the PREQ to its peer MPs if and only if the new sequence number is greater than the currently stored, or the new sequence number has the same value but the new metric value is better than the currently stored. This is because each mesh STA may receive multiple copies of the same PREQ. If the mesh STA is in the list of targets for the PREQ, it sends an unicast PREP back to the source mesh STA. Intermediate MPs create a path to the destination mesh STA on receiving a PREP, and also forward the PREP towards the source mesh STA. When the source mesh STA receives the PREP, it creates a path to the destination mesh STA. In the case the destination mesh STA receives a new PREQ with a better metric, it updates the path to the source mesh STA and sends a new PREP to the source mesh STA using the new path.

Proactive Mode. As stated above, when using HWMP in proactive mode there is a root mesh STA to which all routing traffic is sent. Two mechanisms can be used to pro-actively create the paths to the root mesh STA. The first mechanism uses a proactive PREQ element in order to create paths between all MPs and the root mesh STA. First, the root mesh STA send a proactive PREQ element in broadcast containing the path metric and a sequence number. Actually, the proactive PREQ is sent periodically by the root mesh STA. Upon receiving a proactive PREQ, a mesh STA creates or updates its forwarding information (creates a path) to the root MP, updates the metric and hop count of the PREQ element, and then broadcasts the updated PREQ. It also sends an unicast PREP back to the root mesh STA. As each mesh STA may receive multiple copies of a proactive PREQ, a MP updates its current path to the root if and only if the new sequence number is greater than the currently stored, or the new sequence number has the same value but the new metric value is better than the currently stored. The second mechanism uses a RANN element to disseminate information to reach the root mesh STA. In this mechanism, the root mesh STA periodically propagates RANN elements to all other MPs in the mesh network. Upon receiving a RANN element, each mesh STA in order to create or update a path to the root mesh STA, sends an unicast PREQ to the root mesh STA through the same mesh STA from which it received the RANN. The root mesh STA sends a PREP in response to each PREQ received from a mesh STA. The unicast PREQ is used to create the reverse path from the root mesh STA to the source MP, while the PREP is used to create the forward path from the mesh STA to the root mesh STA. This way, the tree path is constructed and updated.

2.1.5 The Mesh Coordination Function (MCF)

As an amendment to the *Wireless Local Area Networks* (WLANs) MAC and PHY specifications, the 802.11s standard adopts the 802.11 MAC sublayer architecture which includes the Distributed Coordination Function (DCF), *Point Coordination Function* (PCF), the *Hybrid Coordination Function* (HCF), and introduces an additional coordination function, called *Mesh Coordination Function* (MCF). The Figure 2.7 shows how these coordination functions coexist in the current 802.11 (including the 802.11s) MAC sublayer, where the DCF is used as basis for all other coordination functions, including the MCF. As most of the MAC concepts and definitions are often used or cited in this thesis, and to better understand the enhancements incorporated in the MCF, a brief description of each coordination function is given below.

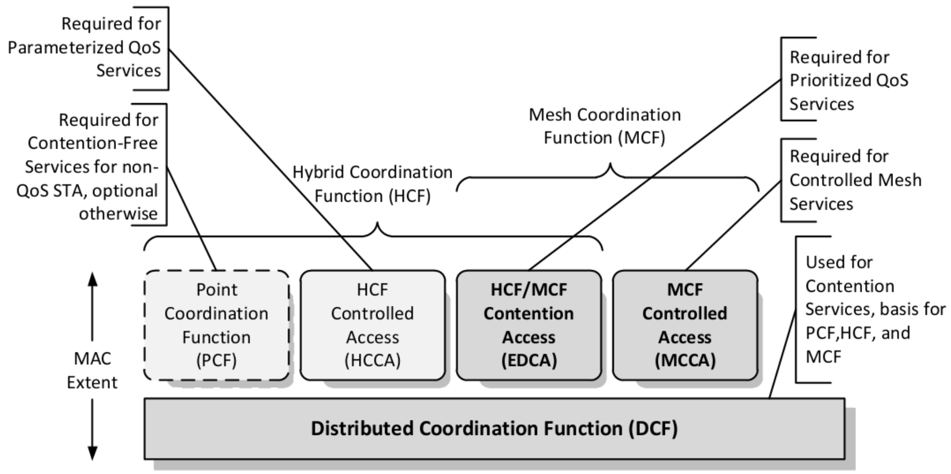


Figure 2.7: MAC architecture. Redrawn from [45].

The IEEE 802.11s standard introduces a new coordination function called *Mesh Coordination Function* (MCF). MCF includes both a contention-based channel access and contention-free channel access mechanism. MCF adopts *Enhanced Distributed Channel Access* (EDCA) as its contention-based mechanism, exactly how it is used in HCF, as aforementioned. The contention-free mechanism, called *MCF Coordinated Channel Access* (MCCA) aims to optimize the frame exchange in the MBSS. This mechanism is optional and may be implemented only by a subset of the MPs. As a consequence, MCCA-enabled MPs must be able to inter-operate with non-MCCA MPs [52]. The MCF is usable only in a *Mesh Basic Service Set* (MBSS) and every mesh STA shall implement this coordination function, having the MCF/EDCA as basic access method.

The MCF/EDCA provides the same functionalities as the *Hybrid Coordination Function* (HCF)/EDCA (IEEE 802.11e) and were already summarized. A detailed description of HCF/EDCA operation can be found in [56].

Hiertz et al. [6, 50, 64] introduces the fundamental operation of the MCF*/MCCA*, formerly called *Mesh Deterministic Access* (MDA)[3]. Although many previous works regarding the MCF/MCCA have been developed before the name change, for uniformity reasons, henceforward the nomenclature MCF* and MCCA* is adopted for the coordination function and access method, respectively, rather than the old indistinct designation MDA. A core concept explored in MCF is the use of *Transmission Opportunity* (TXOP). Under MCF, there are two types of TXOPs: EDCA TXOPs and MCCA TXOPs. The former is obtained by a mesh STA winning an instance of EDCA contention. The latter is obtained by a mesh STA gaining control of the wireless medium during a *MCCA Opportunity* (MCCAOP). The

[3] In version D3.0 of the standard draft, the IEEE TG changed the name from Mesh Deterministic Access (MDA) to a more adequate name, as there was nothing of deterministic in the proposed approach. Then it was decided to separate the coordination function which was renamed to MCF (Mesh Coordination Function), and the reservation access method which was named MCF Coordinated Channel Access (MCCA).

MCCAOP is a time interval scheduled in advance by means of a MCCAOP Reservation procedure.

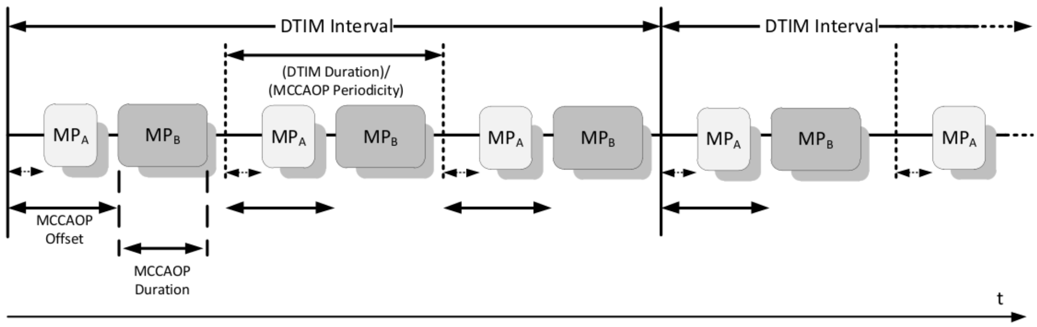


Figure 2.8: Example of MCCAOP reservation with periodicity equal to 3.

In MCF/MCCA, all nodes are synchronized at fixed time boundaries, which are called *Delivery Traffic Indication Message* (DTIM) intervals. This synchronization is achieved through beaconing exchange. Therefore, the DTIM interval represents the number of time units (TUs) between consecutive *Target Beacon Transmission Times* (TBTTs), used for synchronization, containing a DTIM.

A MCCA reservation defines a regular schedule of MCCAOPs in the DTIM interval. The Figure 2.8 shows the scheme for a MCCAOP reservation with periodicity equal to 3. The base time period is the Mesh DTIM interval, which is enforced by means of the mesh beaconing and synchronization procedure. Synchronization plays a critical role in the beaconing functionality of MPs [10]. In order to stay synchronized, MPs collect beacon timing information from their neighbors and set their *Timing Synchronization Function* (TSF) accordingly [65]. The MCCAOP Periodicity specifies the number of MCCAOPs to be scheduled in a DTIM interval or, in other words, the number of subintervals periods into which the mesh DTIM is splited. Therefore, each subinterval will have a duration of DTIM Duration/MCCAOP Periodicity. The MCCA Offset specifies the position of the MCCAOP relative to the beginning of each subinterval. The MCCAOP Duration specifies the duration time of a MCCAOP.

According to Hiertz et al. [66], in presence of non-MCCA nodes such as legacy stations or non-MCCA MPs, the performance of the MCF/MCCA may be seriously affected, as the MCCA owner may have to contend for the wireless medium without any priority over non-MCCA nodes. This means that access to the medium is not guaranteed to the MCCA owner at the beginning of the MCCAOP. Therefore, this can lead to a delay in accessing the medium such that the remaining MCCAOP time is insufficient to transmit the frames.

$$MIFS = SIFS + SlotTime \tag{2.2}$$

Islam et al. [67] proposed a new IFS time to be used by the MCCAOP* owner node to contend for a EDCA TXOP, called *Mesh Inter-Frame Space* (MIFS). The MIFS value is defined as one *Short Inter-Frame Space* (SIFS) time plus one SlotTime, as shown in Equation 2.2. Although the MIFS value is equal to *Point-coordinated Inter-Frame Space* (PIFS), used by an

AP in contention free period (i.e. *HCF Controlled Channel Access* (HCCA)), as there is no centralized node in the mesh and is also unlikely to have neighbor HCCA nodes, the MCCA* owner will have priority to access the channel over any other non-MCCA* station.

2.2 Relevant Work in Wireless Mesh Networks

In the past few years, a myriad of routing protocols have bee proposed to make use of these new metrics or proposing new approaches to improve the routing performance in WMNs. In fact, much research work has been conducted in these directions. This section presents an overview of relevant work in WMN found in the literature, focusing on the main topics of this thesis. Part of the contents of this section will be later used to compare the novel mechanisms proposed in this thesis with these previous works whenever appropriate.

2.2.1 Routing Metrics

Although in this thesis only the standard IEEE 802.11s' metric - the ALM (see Section 2.1.3) - is applied, the study of the routing metrics presented below was intended to better understand the requirements of a "good metric", which allow to disclose the ALM advantages and drawbacks.

Hop count is the traditional routing metric used in most of the common routing protocols designed for multi-hop wireless networks. However, due to the specificities of WMNs, the minimum hop-count metric may lead to poor performance making it unsuitable for such networks [68–70].

In general terms, a "good routing metric" must accurately capture the quality[4] of the network links and allows to compute the best quality paths.

So far there is no standard routing metric to be used in WMNs. In fact, it is likely that no single metric will be suitable for all WMN settings. The use of different routing metrics on WMNs is necessary to cope with these different settings. For example, a multi-channel and multi-radio setup will require a special routing metric, different from that used in a traditional WMNs where the nodes use only one wireless card and communicate on the same channel. Therefore, a multiplicity of routing metrics have been proposed for WMNs.

Many link and node characteristics can be taken into account to provide a good metric for the link/node/path quality. Besides basic measures such as delay, path length, transmission rate, and loss rate, few more important characteristics includes: the asymmetry of the links and the interference (both concepts are explained below). Another important characteristic is its measuring method, i.e. the method used to gather all information necessary to its calculation.

Regarding the measuring method, a routing metric can be classified as active (if it uses probe frames to measure the metric) or passive (otherwise). Although active probing can provide much more updated and useful information, it suffers from an associated overhead.

[4]The quality is usually determined by performance parameters of the links or nodes such as delay, bandwidth or loss ratio. In some cases, it will also consider the interference of the neighborhood, the load of the link, or a mix of these measures. The quality value is usually given as a function that takes these measures into account on its computation.

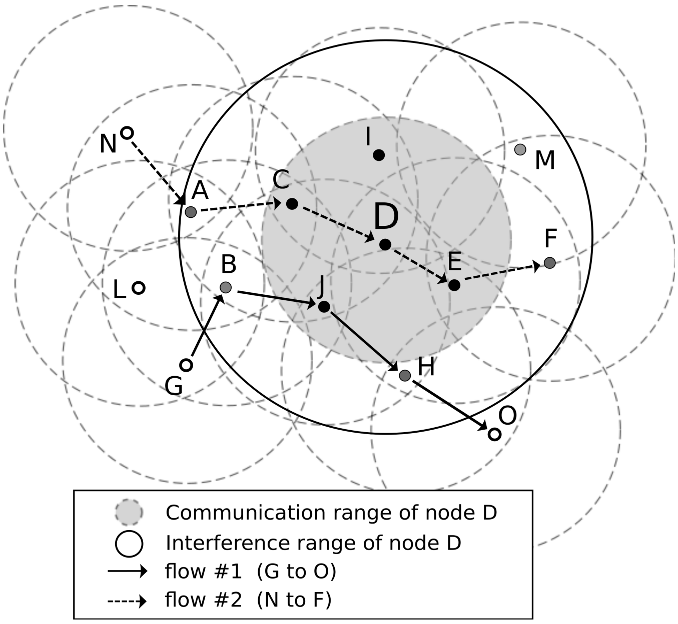


Figure 2.9: Example of interference in a WMN.

When passive measuring is used, all information is gathered by just observing the traffic coming in and going out of a node. No active measurements are required. A good routing metric must also present a special property: the isotonicity (explained below).

Kotz et al. [71] observed that wireless links often exhibit quite different propagation conditions in one direction than in the other. Frames may be successfully sent from one node to another but not in the opposite direction. This phenomenon is known as link asymmetry and may affect the accuracy of some routing metrics.

The impact of interference on the capacity of wireless networks has been broadly studied by researchers [9, 72, 73]. The interference includes the inter-flow interference and intra-flow interference. In wireless routing, the intra-flow interference is the interference caused by intermediate nodes sharing the same flow path. As consecutive packets in a single flow can be spread over the entire route, they may interfere with one another; this intra-flow interference limits the achievable throughput in multi-hop wireless networks [74]. Inter-flow interference refers to the interference caused by neighboring nodes of distinct flow paths but competing for the same busy channel. For example, in the Figure 2.9, adjacent nodes are within the transmission range of each other, and the interference range is much higher than the communication range. In the figure, the node D has in its communication range the set of nodes $C_D = \{C, E, I, J\}$, while its interference range includes the set of nodes $I_D = \{A, B, C, E, F, H, I, J, M\}$. It means that a communication from $node\ D$ will affect all these nodes. This way, even in distinct flows, a communication from $node\ D$ may interfere on the $flow\ \#1$. This type of interference is called *inter-flow interference*. Likewise, a communication from $node\ D$ will interfere with the nodes of its own flow sharing the same channel. This type of interference is called *intra-flow interference*.

The isotonicity property of a routing metric ensures that the order of weights of two paths or links is preserved if they are appended or prefixed by a common third path or link. Formally, if two paths a and b have a weight relation in which $w(a) \geq w(b)$, and both relations $w(a \oplus c) \geq$

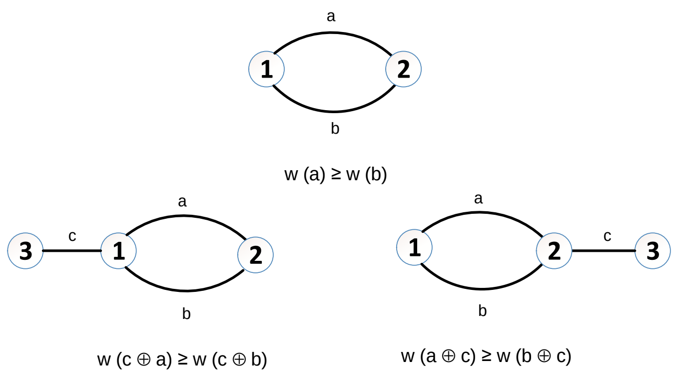


Figure 2.10: Example of the isotonicity property for a routing metric.

$w\,(b \oplus c)$ and $w\,(c \oplus a) \geq w\,(c \oplus b)$ are preserved, after the appending and prefixing of a link c, respectively, for all set of links (a,b,c), then the routing metric is isotonic, as shown in Figure 2.10. Isotonicity is a necessary condition for a routing metric in order to allow the routing protocol to apply well-known algorithms to find minimal weight paths, such as Bellman-Ford or Dijkstra's algorithm. A non-isotonic metric will force the routing protocol to apply complex algorithms to find the best quality paths.

In order to classify the routing metrics proposed for WMNs, Borges et al. [68] introduces a sub-taxonomy that takes into account their measures. According to this sub-taxonomy, routing metrics are grouped in four distinct groups: Basic, Interference, Traffic Load, and Hybrid. Basic routing metrics uses simple measures that are directly related to the traditional performance parameters, such as transmission rate, delay, path length, and loss ratio. Interference-aware routing metrics uses measures taken from the physical and logical models to compute the interference. The main measures used by Load-aware routing metrics are the available bandwidth and the average queue length. These measurements allow to estimate both traffic load and transmission rate, respectively. Finally, Hybrid routing metrics combines different type of measures aforementioned. The most common is to combine interference and traffic load together. This sub-taxonomy is applied in this thesis hereinafter.

Basic metrics. Among the basic routing metrics, the *Expected Transmission Count* (ETX) [75] and *Expected Transmission Time* (ETT) [76] are the most studied metrics and have been broadly extended in order to capture new measures from the links giving rise to a new family of metrics. As discussed below, many other metrics includes ETT or ETX-related components in their calculation.

The Expected Transmission Count (ETX), introduced by De Couto et al. [75], aims to find paths with the fewest expected number of transmissions (including retransmissions) required to deliver a packet from its source to its destination. The metric predicts the number of retransmissions required using per-link measurements of packet loss ratios in both directions of each wireless link.

Although experimental results in [75] show that ETX outperforms the traditional hop-count metric under static conditions, it may perform poorly under high channel variations. The main reason is that the mean loss ratio used by the ETX does not adapt fast enough to the variations on the channel under bursty loss conditions. To overcome this shortcoming, Koksal and Balakrishnan [77] introduced two modified versions of ETX: the *Modified Expected Number of Transmissions* (mETX) and the *Effective Number of Transmissions* (ENT). Both mETX and ENT aim to capture the time-varying characteristics of the channel by estimating the losses by means of the bit error probability rather than the packet error probability. The ENT has also a configurable parameter that allows the higher layer protocols (e.g. the *Transmission Control Protocol* (TCP)) to bound the packet loss rate. However, as discussed by Borges et al. [68], these metrics are impracticable in real world because, in most real implementations, the packets received with errors at the MAC are discarded, without any notification to the upper layers.

Draves et al. [76] introduces the Expected Transmission Time (ETT) of a link as a "bandwidth-adjusted ETX". In other words, the ETT extends the ETX metric by taking into account the bandwidth of the link. The ETT of a link is given by its ETX (number of expected transmissions) multiplied by the estimated time necessary to transmit a packet successfully over the link.

As the ETX is used to compute the ETT, it takes into account the asymmetry of the links. However, a number of drawbacks from the ETX still remain in the ETT, including: it does not completely capture the intra-flow and inter-flow interferences, it does not consider traffic load explicitly, hence it cannot avoid routing traffic through overloaded nodes or links. As the ETT, the ETX is isotonic. Similar probing mechanisms are also used in other delay-based routing metrics such as *per-hop Round Trip Time* (RTT) [78], *Minimum Delay* (MD) [79], and *Improved Expected Transmission Time* (iETT) [80].

Interference-aware metrics. Although basic routing metrics allow measuring the performance of the links, they do not take into consideration a significant characteristic of wireless channels - the interference. It directly affects the throughput and delay. In order to refine the performance measures, interference-aware routing metric protocols have been proposed.

The *Weighted Cumulative Expected Transmission Time* (WCETT) metric proposed by Draves et al. [76] is an extension of the ETT metric. As an improvement to the ETT metric, WCETT captures the intra-flow interference since it essentially gives low weights to paths that have more diverse channel assignments on their links and hence lower intra-flow interference. However, because its second term, the WCETT is not isotonic. Finally, WCETT still does not explicitly consider the effect of inter-flow interference. As a result, a routing protocol using WCETT may establish routes via nodes that are intermediate nodes of many flows and hence with a high inter-flow interference.

The *Multi-Channel Routing* (MCR) metric, proposed by Kyasanur and Vaidya [81], combines the measured link ETT and *Switching Costs* (SCs) into a single path cost, using the technique introduced for the WCETT metric. MCR incorporates the majority of the properties of WCETT, among its major limitations are its inefficiency to capture the inter-flow interference and being non-isotonic. An improvement of the WCETT is the use of passive monitoring.

The *Metric of Interference and Channel-switching* (MIC) is introduced by Yang et al. [82]. This metric is designed to support load balanced routing and also consider the inter-flow interference. The MIC is an improvement of the WCETT by considering inter-flow interference. MIC is a non-isotonic metric if it is used directly over a real network. However, in [83], the authors presented the Load and Interference Balanced Algorithm, which aims to create a virtual network from a real network and decompose MIC into isotonic link weights.

Subramanian et al. [84] introduces a routing metric for multi-radio WMNs which takes into account both inter-flow and intra-flow interference: the *Interference Aware routing* (iAWARE). The iAWARE captures the effect of link loss ratio variability, differences in transmission rate, as well as intra-flow and inter-flow interferences.

Interferer Neighbors Count (INX), proposed by Langar et al. [85], is more precise in capturing the inter-flow interference than the MIC metric, as it takes into account more than only the quantity of interfering nodes. In INX, instead of simply counting the number of interferer links, the bit rate of each interferer link is considered. This allows to distinguish between high throughput and low throughput interferer links.

Traffic Load-aware metrics. Being mesh networks often used for Internet access, both traffic routing and Internet gateway selection may play a crucial role on the overall network performance. Thus, traditional metrics can lead to a poor performance as they do not consider the load on the links. This way, an Internet gateway or a central node can easily become a bottleneck due to the high load. So, to provide load balancing and improve the overall performance of WMNs, previous studies suggested to use a load-aware metric able to depict the load over the links. Issues related to Load-aware routing in mesh networks are discussed by Ancillotti et al. [86].

Aiache et al. [87] proposed the *Load Aware ETT* (LAETT) as a traffic-load metric for WMNs. The LAETT metric extends the ETT so that it can estimate the traffic load of the link. LAETT captures both traffic load and link quality (by considering the ETX of the link in its computation). Another aspect of LAETT is that this metric allows to calculate the marginal cost of adding a new flow on the link. One drawback of LAETT is that it uses the current bandwidth to estimate the traffic load of the link. Although the current bandwidth can be obtained from the wireless card, it is subject to high variations because of interference on the shared channel. In other words, LAETT metric can suffer from inaccuracy on a real WMN.

Ma and Denko [88] introduced the *Weighted Cumulative ETT-Load Balancing* (WCETT-LB) metric which adds load-balancing to the WCETT metric. The load-balancing component in WCETT includes two components: the congestion level and the traffic concentration level at each node in a particular path. The first is estimated by the relation between the average queue length at a node in the path and its rate.

Hybrid metrics. Although most of the above discussed routing metrics address the interference and the traffic load separately, these characteristics are clearly interrelated. After all, the interference at a node will affect the traffic load as well as more traffic load tends to increase the interference at the node. As a result of this observation, hybrid routing metrics have emerged to combine both interference-aware and load-aware approaches. Hybrid routing metrics appears as a new trend with regard to cross-layer routing metrics.

Kowalik et al. [89] introduced a new routing metric which is used in its proposed *Resource Aware Routing for mEsh* (RARE). This metric employs passive monitoring for measuring the link characteristics. This approach avoids the network load caused by active monitoring employed in many of the metrics previously discussed. RARE link cost computation takes into account the bandwidth, signal strength, and contention measurements.

The *Contention-Aware Transmission Time* (CATT), introduced by Genetzakis and Siris [90], is an isotonic routing metric that accounts for both intra-flow and inter-flow interference as well as the traffic load in an uniform way, by making a sum of the delays of interfering neighbor links that are 1 and 2 hops away.

Manikantan Shila and Anjali [91] proposed a new interference and load-aware routing metric called *Interference-Load Aware* (ILA). ILA is composed of two components: *Metric of Traffic Interference* (MTI) and Channel Switching Cost (CSC). The two components of ILA allows to capture the effects of intra-flow and inter-flow interference, difference in transmission rates, packet loss ratio and congested areas. As MIC metric [83], ILA includes a component to capture the intra-flow interference of each link forming the path. This metric also includes a component to capture the interference.

With the *Contention Window based* (CWB) metric, Nguyen et al. [92] aims to capture the effects of both channel utilization level and congestion level of a link. The CWB routing metric consists of two parts, one part is based on the channel utilization, and the other part is based on the average Contention Window of links.

The *Metric for INterference and channel Diversity* (MIND) introduced by Borges et al. [93] includes two components, one was designed to capture both the inter-flow interference and traffic load, and the other was designed to capture the intra-flow interference. MIND is an isotonic interference-aware routing metric that considers the inter-flow interference in a more realistic way, intra-flow interference based on the local information, and traffic load estimation through passive monitoring.

Table 2.2: Comparison of routing metrics.

Metric	Interference		Traffic Load	Isotonic	Monitoring method		Asymmetric link
	inter	intra			active	passive	
ETX	○	○	○	●	●	○	●
ETT	○	○	○	●	●	○	●
WCETT	○	●	○	○	●	○	●
MCR	○	●	○	○	○	●	●
MIC	●	●	○	●	○	●	●
iAWARE	●	●	○	○	○	●	●
INX	●	○	○	●	○	●	●
LAETT	○	○	●	●	○	●	●
WCETT-LB	○	●	●	○	○	●	●
RARE	●	○	●	●	○	●	○
CATT	●	●	●	●	○	●	●
ILA	●	●	●	●	○	●	●
CWB	●	○	●	●	○	●	○
MIND	●	●	●	●	○	●	○

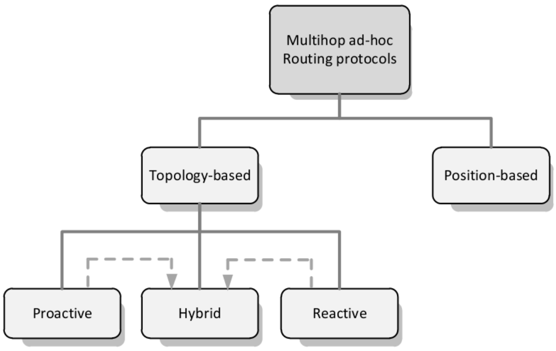
After reviewing some of the most relevant routing metrics that have been proposed for WMNs, it becomes clear that there is no *one size fits all* solution for routing in Wireless Mesh networking, in what concerns routing metrics. It becomes also clear that a good routing metric for WMNs tends to capture all the cited characteristics of the links. However, it still needs to be flexible enough in order to allow giving a higher weight to some criteria in favour of other, or even ignore some criteria for the sake of efficiency. This flexibility will allow the routing metric to be applied to more diverse application scenarios. A comparison of the routing metrics discussed above is shown in Table 2.2. More detailed comparisons of routing metrics suitable to WMN can be found in [47, 68–70, 94].

2.2.2 WMN Taxonomies Based on the Routing Scheme

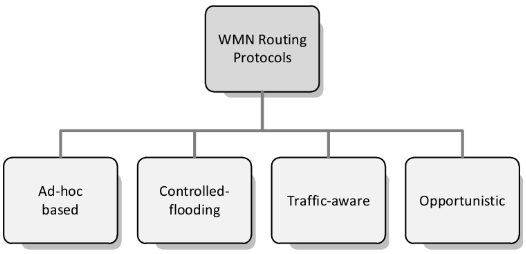
There have been a few works in the related literature [1, 47, 94, 95] that have proposed a taxonomy for routing protocols in WMNs. Bahr et al. [62] presented a broadly used taxonomy, designed for ad-hoc routing protocol, in which the routing protocols are classified based on the information used to select paths and the strategy used to calculate the route. Following this criteria, the routing protocols can be classified into topology-based and position-based (see Figure 2.11(a)). Topology-based routing protocols depend on the information about the links in the network (network topology) to determine the paths. The topology-based class can be further divided into proactive, reactive and hybrid. In the proactive approach the routing protocol computes all the paths before they are requested and any change in the topology is periodically updated. In contrast to the proactive, the reactive approach computes the path only when it is required. This on-demand approach reduces the overhead caused by periodical updates but introduces a high latency for the routing discovery. The hybrid approach tries to combine both approaches in a way that the proactive approach can be used for near nodes or often used paths, while reactive can be used for the other cases. Many routing protocols proposed for WMNs still use similar strategies to compute routes [96]. Position-based routing protocols rely on the availability of additional information about the physical location of the nodes. Typically, the nodes determine their own position by using the *Global Positioning System* (GPS) or some other type of positioning technique or device. This taxonomy is generic, does not make any reference to any WMN characteristics and applies also to ad-hoc routing protocols.

Campista et al. [94] proposed a taxonomy for WMN routing protocols (see Figure 2.11(b)) based on route discovery and maintenance procedures. According to this taxonomy, the routing protocols are classified in four groups: ad-hoc-based, controlled-flooding, traffic-aware, and opportunistic. However, given the fact that it covers protocols initially designed for ad-hoc networks, the criteria used for classification are still generic and do not capture essential characteristics of a WMN. The taxonomy proposed in [94] is also used in [96].

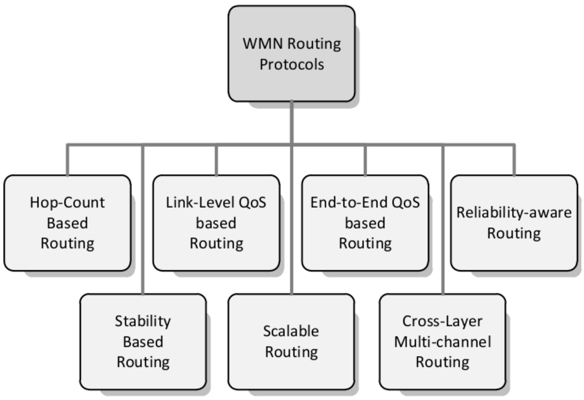
In seeking to be more specific in their classification, Akyildiz and Wang [47] presented a taxonomy of routing protocols for WMNs (see Figure 2.11(c)) based on their performance optimization objectives. According to this classification, a routing protocol can be of one of six classes: Hop-count based routing, Link-Level QoS Routing, End-to-End QoS Routing, Reliability-Aware Routing, Stability-Aware Routing or Scalable Routing. Hop-count based routing protocols rely on the simplicity of minimizing the number of hops. In link-level QoS routing protocols, the performance is optimized by measuring the quality of the links in a hop-by-hop approach. The goal of this type of routing protocol is to choose high throughput links, usually considering medium access contention delays, interference, and retransmission count as metrics of quality. End-to-end QoS routing protocols tries to guarantee the



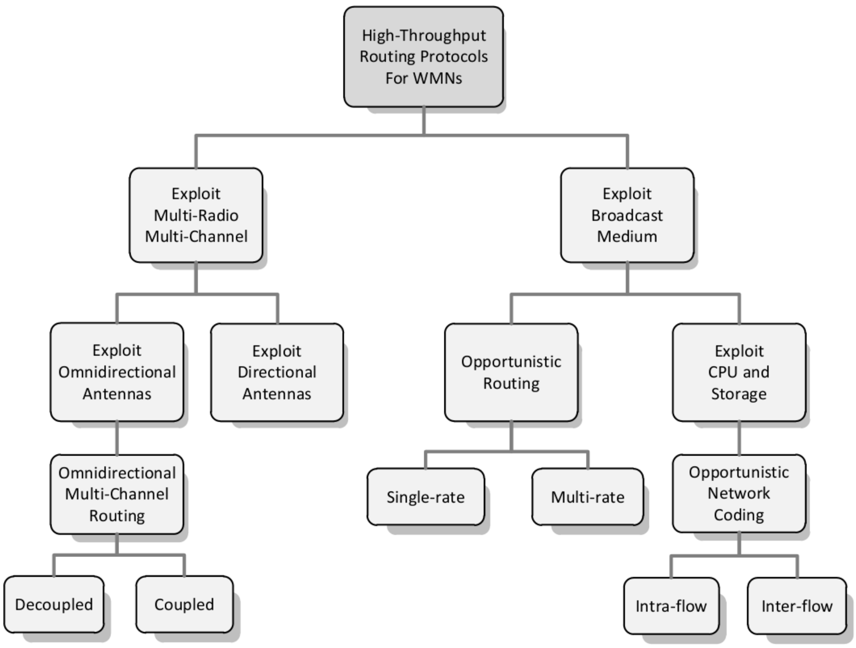
(a) Bahr et al. [62] (2006).



(b) Campista et al. [94] (2008).



(c) Akyildiz and Wang [47] (2009).



(d) Martínez and Bafalluy [95] (2010).

Figure 2.11: Taxonomies of Routing Protocols for WMNs proposed in the literature.

Table 2.3: Specific Properties & Choices. Source: Martínez and Bafalluy [95].

Properties	**Choices**
Wireless-aware	Multi-radio multi-channel, opportunistic
Bandwidth aggregation	Network coding, overlay, opportunistic, multi-radio multi-channel, multi-rate
Scalability	Overlay, geographic
Path stretch	Overlay, multi-rate
Distributed	Overlay, geographic
Overhead	Overlay, geographic
Reliability	Opportunistic, network coding, multi-rate
Load balancing	Opportunistic, multi-radio multi-channel

end-to-end QoS in order to improve the performance and usually includes delay, and packet loss as metrics of link's quality. In some specific scenarios, reliability is the most desirable characteristic of the network. For these cases, reliability-aware routing usually improves the reliability by providing multipath routing. Designed for scenarios where the stability of the routes is the most important, stability-aware routing protocols take advantage of the fact that mesh STAs are usually stationary and some of them may also be connected to the wired infrastructure to improve the stability of the routes. Scalable routing protocols aim to increase the network scalability. Among diverse approaches to do it, hierarchical routing and geographic routing are the most explored choices. Although the authors consider WMNs, this classification is very focused on ad-hoc routing protocols that have been proposed to be used in WMNs and hence do not take into account specific characteristics of the WMNs.

Another attempt to classify routing protocols for WMNs is given by Martínez and Bafalluy [95]. First, the proposed classification (see Figure 2.11(d)) is based on a list of desirable properties (shown in Table 2.3) that a routing protocol should ideally incorporate in its design to maximize throughput. Second, the authors devise several choices or strategies that can be integrated as part of the routing scheme to achieve each property. Although this taxonomy is more suitable to classify the WMN routing protocols, it suffers from its excessive specificity. Moreover, this classification neglects ad-hoc based routing protocols and position-based routing protocols as well.

Proposing a new Taxonomy. Considering that there is no common consensus about the taxonomy to be adopted and that also the aforementioned taxonomies suffer either of excessive generality or specificity, this thesis proposes a new taxonomy for WMN routing protocols as shown in Figure 2.12.

In this proposed taxonomy, the way how the information is exchanged between network nodes is used as first classifier and hence a WMN routing protocol can be initially classified as unicast or anycast. Unicast protocols can be further classified according to the resources of the network used to improve the routing. Thus, based on the use of the channel spectrum, these protocols can be classified as Single-Channel or Multi-Channel. The latter can be further classified into Single-Radio or Multi-Radio depending on the number of radios used. Regarding anycast routing protocols, these can be grouped in three main categories: Opportunistic Routing, Opportunistic and Network Coding, or Field and Gradient-based Routing.

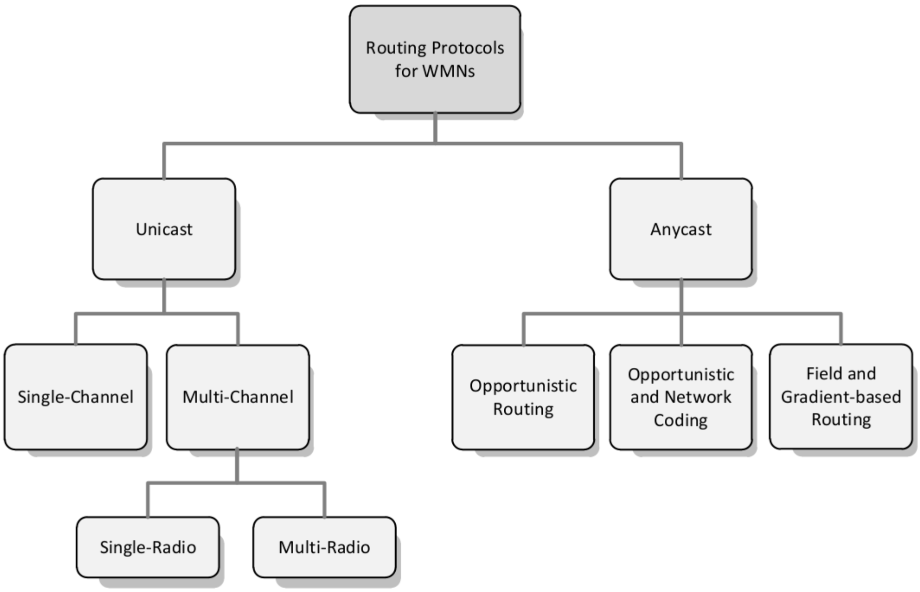


Figure 2.12: Proposed taxonomy for WMN Routing Protocols.

The proposed taxonomy in Figure 2.12 is further used (see Section 2.2.3) to classify routing protocols used in WMNs.

2.2.3 Routing Protocols

This section provides a brief overview of representative routing protocols that exploit relevant WMNs features. It must be noted that: first, an exhaustive listing of available routing protocols for ad-hoc networks and adaptations to wireless mesh networks is far beyond the state-of-art of this thesis; and second, this section aims to survey the general WMN protocols. The HWMP-like proposals, are separately presented in Section 2.2.4, where the performance and scalability issues of the standard HWMP are also discussed.

The heart of Wireless Mesh Networks is the routing protocol [97]. The performance and robustness of a WMN will greatly depend on its routing protocol [98]. In the past few years, routing has been a very active research area in the context of ad-hoc wireless networks, and hence many proposals have appeared in the literature (see AODV [99], DSR [100], DSDV [101], FSR [59], OLSR [58], ZRP [102] for a few samples; a non-exhaustive listing including almost 50 ad-hoc routing protocols can be found in [103]). Some of them are adaptations from routing within the context of wired networks, while others aim to cover the new requirements imposed by these networks.

One important decision on the design of a new routing scheme in WMN is its location. In the literature, three main approaches stand out according to the network layer where they are implemented: layer 3 (L3), layer 2 (L2), and layer 2.5 (L2.5). The L3 approach is the most traditional one and comes from the classical internet routing. Here the mesh functionalities are implemented at the IP layer. Therefore, many protocols for MANETs can be easily modified to work as a WMN protocol. Most of the solutions presented above apply the L3 routing. The main idea behind the L2 approach is to enhance the MAC layer's capabilities to offer mesh functions. The IEEE 802.11s standard follows this approach. To avoid misunderstanding, in L2, the routing is usually divided into: frame forwarding (the nodes forward frames in behalf of other nodes), and path selection (i.e. finding the best path at layer-2). The L2 approach has the advantage of being able to route right after the mesh connectivity. The L2.5 is a cross-layer approach that relies on an additional software layer (like a middleware) to allow the communication between layer-2 and layer-3. One of the advantages of the L2.5 approach is to be able to gather IP information (e.g. QoS parameters), and MAC information (e.g. Frame Error Ratio, or FER) in order to compute the routing metric. Another advantage is that, as a middleware, L2 deployments are not hardware dependent. The L2.5 is the approach followed by Microsoft with its Mesh Connectivity Layer (MCL) module to create mesh networks.

WMNs and ad-hoc networks have strong similarities. Thus, routing protocols developed for ad-hoc networks can usually be applied to WMNs [47]. In fact, ad-hoc networks can be considered as a particular case of WMNs in which all nodes are clients, Conversely, WMNs can be considered a particular case of ad-hoc network in which each node must not only capture and disseminate its own data, but also serve as a forwarder for other nodes. According to Mahmud et al. [104], WMNs aim to diversify the capabilities of ad-hoc networks. WMN introduces a hierarchy in the network architecture in which a set of mesh routers cooperatively forms a backhaul while others provides communication services through the mesh to both mesh and non-mesh clients, unlike the flat architecture of ad hoc networks. According to Waharte et al. [105], WMNs exhibit unique characteristics that differentiate them from other wireless and wired technologies, making it necessary to revisit routing protocols (those that have been adopted from other technologies) and question their real adaptability to WMNs. The authors also highlighted some of the main differences, namely: network topology, traffic pattern, inter-path interference, link capacity and channel diversity.

The most relevant routing protocols for WMN presented below are organized by the taxonomy proposed in Section 2.2.2 (see Figure 2.12).

A. Unicast. Unicast is communication from a single sender to a single destination identified by an unique address. Unicast is the dominant form of message delivery on current network technologies, including WMNs.

A.1 Single-Channel. Even though multiple non-overlapping channels are available in the IEEE 802.11 2.4GHz and 5GHz spectrum, most IEEE 802.11-based WMNs deployments today make use of only a single channel. As a result, a diversity of routing protocols that have been proposed to these networks does not takes advantage of the channel diversity and hence rarely achieve high throughput [106]. Most of these routing protocols are enhanced versions of ad-hoc routing protocols.

Fisheye State Routing (FSR) [59] algorithm for ad-hoc networks introduces the notion of multi-level scope (or controlled flooding scope) to reduce routing update overhead in large networks. In FSR, a node stores the *Link State* (LS) for every destination in the network. It periodically broadcasts the Link State update of a destination to its neighbors with a frequency that depends on the hop distance to that destination, i.e. the scope. State updates corresponding to far away destinations are propagated with lower frequency than those for close by destinations. From state updates, nodes construct the topology map of the entire network and compute efficient routes. The route on which the packet travels becomes progressively more accurate as the packet approaches its destination. FSR resembles link state routing in that it propagates LS updates. However, the updates are propagated as aggregates, periodically (with period dependent on distance) instead of being flooded individually from each source. FSR leads to major reduction in link overhead caused by routing table updates. It enhances scalability of large, mobile ad-hoc networks.

Johnson and Maltz [100] proposed the *Dynamic Source Routing* (DSR) as an on-demand routing protocol based on concept of source routing. In source routing algorithm, each data packet contains complete routing information to reach its destination. Nodes are required to maintain route caches that contain source routes of which the node is aware. There are two major phases in DSR; the route discovery and route maintenance. For route discovery, the source node broadcasts a route request message which contains the address of the destination, along with source nodes' address and an unique identification number. Every node which receives this packet checks if it has route information to destination. If not, it appends its own address to route record of the packet and forwards the packet to its neighbors. A route reply is generated if the route request reaches either the destination itself or an intermediate node which has route information to the destination. DSR uses a route cache to maintain route information to the destination. Route maintenance is done through the use of route error packets and acknowledgments. The main disadvantage of DSR is that it has high overhead as each data packet must contain complete route information.

The Ad-hoc On-demand Distance Vector (AODV) [99] is a reactive on-demand routing protocol which builds on both DSR and *Destination-Sequenced Distance Vector* (DSDV) [101] routing protocols. AODV is an improvement on DSDV as it minimizes the number of required broadcasts by creating routes on demand. It is also an improvement on DSR as a node only needs to maintain routing information about the source and destination as well as next hop, thereby largely cutting back the overhead. The process of route discovery is similar to DSR. *Route Request* (RREQ) packets are broadcasted for route discovery while *Route Reply* (RREP) packets are used when active routes towards destination are found. HELLO messages are broadcasted periodically from each node to its neighbors, informing them about their existence.

The Optimized Links State Routing (OLSR) [58] protocol have been largely used for Mobile Ad Hoc Networks (MANETs) but can also be used in WMNs. The key mechanism behind the OLSR is an optimized flooding mechanism based on *Multi-Point Relay* (MPR), used to diffuse topology information. OLSR uses Hello and *Topology Control* (TC) messages to discover and then disseminate link state information. The nodes use this topological information to pro-actively compute the routes to the known destinations in the network. MPR flooding optimizes flooding by minimizing the redundant retransmissions of TC messages as the set of MPRs relays is a small set of neighbors through which a sender can reach all two hop neighbors. As a drawback, the original OLSR does not sense link quality, i.e. it simply assumes that a link is functional if a number of hello packets have been received recently.

The Radio-Aware Optimized Links State Routing (RA-OLSR) [49] is a proactive, link-state wireless mesh path selection protocol based on the OLSR [58] protocol. It also includes extensions like the mechanism to control the flooding used in the FSR [59] protocol, and the use of radio-aware metrics for forwarding path computation. The RA-OLSR protocols also include an Association Discovery and Maintenance protocol to support non-mesh STAs both internal (associated with APs collocated with mesh gates) and external (connected through mesh Portals). The base mechanism of this protocol is the following: mesh points diffuse the whole set of mesh clients associated to themselves. It works in a proactive fashion, similar in spirit to the topology information exchange of OLSR: in both cases the information messages must be refreshed within a guaranteed interval. However, in addition, in case of topology/association change, this mechanism allows faster updates. As mentioned in Section 2.1.4, the Hybrid Wireless Mesh Protocol (HWMP) [48] is the hybrid (both reactive and pro-active) routing protocol proposed as standard path selection protocol in the current version of the IEEE 802.11s standard, and the RA-OLSR [49] protocol is a pro-active routing protocol formerly proposed as optional standard path selection protocol.

The *Mobile Mesh Routing Protocol* (MMRP) [107] is a mobile ad-hoc routing protocol which is based upon the link state protocol. Nodes periodically broadcast an UDP datagram, called *Link State Packet* (LSP) over each interface which is participating in the protocol. Upon reception of a LSP, the node relays it until it has reached a certain time-to-live and then it is discarded. As a result, each node gains information about the entire topology in a certain radius around him (like in fish-eye routing).

SrcRR [108] is a reactive ad-hoc networking protocol developed at the *Massachusetts Institute of Technology* (MIT) for the Roofnet [109] project. The ScrRR protocol is based on the DSR protocol [100], but uses the ETX as routing metric. Briefly, in the SrcRR, route discovery is done by flooding. When a source node ($node_{src}$) needs to find a route to a destination node ($node_{dst}$), it broadcasts a query message, asking for a route to $node_{dst}$. Upon reception of a query message, each intermediate node $node_{int}$ forwards the query message, appending its own identifier (ID) to a source route in the packet. Each time $node_{dst}$ hears a query message for itself, it sends a reply back to $node_{src}$ through the source route accumulated in the query. The $node_{src}$ (every node that receives the query or reply as well) adds all the links mentioned in the message to a local link-state database, which will be later used by the Dijkstra's algorithm to find the best route. After that, when $node_{src}$ needs to send data to $node_{dst}$, it just includes that route (i.e. the sequence of node identifiers) in each packet as a "source route". The Roofnet implementation of SrcRR is a complete Linux distribution that implements ad-hoc and AP mode simultaneously using a single radio card.

The major goal of the *Mesh Routing Protocol* (MRP), proposed by Jun and Sichitiu [110], is to improve the routing to and from the gateway rather than between ordinary nodes. This protocol takes advantage of the fact than in most WMN deployments the major traffic flow is to and from the Internet through a gateway. Therefore, MRP's routing scheme is based on a tree in which each node is attached to a single local gateway node which is attached to a Super Gateway. The Super Gateway is the root of the tree and provides Internet access to the mesh network. The authors have proposed three versions of MRP. The first version is the *Mesh Routing Protocol On Demand* (MRP-OD). In this version, when a node joins the network, it will broadcast locally a *Route Discovery* (RDIS) message asking to the closest gateway or neighboring node for a route to the gateway. In contrast to well-known on-demand MANET protocols (e.g. AODV and DSR), RDIS messages are received by only one-hop neighbors and thus are not flooded to the entire network. In response to a RDIS message, the node may receive a *Route Advertisement* (RADV) message. Once the joining node has received all the RADV messages, it can select the best route and start to send data. If a node loses its connection to the gateway, it will send a route error (RERR) message to all of its children nodes in the tree. The second version is called *Mesh Routing Protocol Beacon mode*

(MRP-B) and it is a modified version of the MRP-OD. In MRP-B, any node that wishes to join the network, listens for beacon packets and collects beacon packets rather than to sending route discovery messages. In substitution to the RDIS/RADV scheme, a node periodically sends beacon advertising its available routes and metrics in order to setup a route. This beaconing approach also allows a node to detect invalid routes without the need of receive a RERR message, just by monitoring the beacons sent from its parent node. The third version, the *Hybrid Mesh Routing Protocol* (MRP-H), is a combination of both MRP-OD and MPR-B. In MPR-H, a joining node broadcasts RDIS messages and waits for RADV messages for a time interval *min(MRP-OD::RandomDelay, MRP-B::BeaconPeriod)*. In case of timeout, the node will extract route information from the next beacon. To detect invalid routes, the MPR-H uses both RERR message and beacon monitoring.

Ikeda et al. [111] proposed the *Better Approach To Mobile Ad-hoc Networking* (B.A.T.M.A.N.) protocol as a link state routing protocol for multi-hop ad-hoc mesh networks. However, in contrast to most link state protocols (e.g. OLSR protocol), in B.A.T.M.A.N., there is no topology message dissemination. In substitution, every node must execute three main procedures: (a) advertises itself by using *OriGinator Message* (OGM); (b) selects the best one-hop neighbor for every known destination in the network following a ranking based on the number of received OGM messages; (c) re-broadcasts the OGMs received from one-hop neighbors. Therefore, in B.A.T.M.A.N., OGM messages are used for: link sensing, neighbor discovery, and flooding. B.A.T.M.A.N., by using OGM messages, determines only the next hop in the right direction, instead of determining the whole path. This process is repeated in a hop-by-hop fashion until the data reaches its destination. B.A.T.M.A.N. is currently under development by the Freifunk Community [112] and aims to replace OLSR.

The *Hazy-Sighted Link State Routing Protocol* (HSLS) [113] is a scalable, non-hierarchical, and link-state routing protocol that uses both proactive and reactive link-state routing to minimize network updates. The HSLS limits the scope of topology information dissemination in time and space, so nodes which are located far away receive topology information less frequently than those that are closer to a node. According to the authors, HSLS is designed to scale well to networks containing more than one thousand nodes. The most popular implementation of HSLS is the CUWiN [114] testbed.

The *Dynamic Address RouTing* (DART) proposed by Eriksson et al. [115] is a proactive distance vector routing protocol based on the dynamic addressing paradigm. According to such an approach, network addresses are assigned to nodes on the base of the node position inside the network topology. By means of dynamic addressing, DART is able to implement hierarchical routing in a feasible way, reducing considerably the routing state information maintained by each node. Since the whole routing process is based on the transient network addresses, they have to be efficiently distributed across the network. The mapping between node identities and network addresses is provided by a Distributed Hash Table (DHT). The *Multi-path Dynamic Address RouTing* (MDART), proposed by Caleffi and Paura [116], extends the DART protocol to discover multiple routes between the source and the destination. The main difference between DART and M-DART lies in the number of routes stored in the routing table: the former stores only one route for each sibling, while the latter stores all the available routes toward each sibling.

A.2 Multi-Channel. As aforementioned, the IEEE 802.11 standards provide non-overlapping frequency channels that could be used simultaneously within a neighborhood (e.g. the IEEE 802.11b/802.11g standards and the IEEE 802.11a standard provide 3 and 12 non-overlapping frequency channels, respectively). Ability to utilize multiple channels within the same network substantially increases the effective bandwidth available to wireless network nodes [117]. In seeking further bandwidth, a number of multi-channel routing protocols have been proposed. A full multi-channel WMN requires topology discovery, traffic profiling, channel assignment, and routing. Nevertheless, as the focus of this thesis is on the routing, other aspects, including the channel assignment, are neglected.

A.2.1 Single-Radio. Despite being the most common type of implementation of WMNs, a single-radio architecture limits the network node to operate in one single channel at a time. Moreover, cross-channel communication in single-radio WMNs also requires channel-switching capability within each node, which also implies complex synchronization among the nodes. It is likely that these issues were the main cause why only few researchers have proposed multi-channel single-radio routing protocols.

Zhu and Kuo [118] proposed the *Path Cost-Based Routing* (PCBR) as a cross-layer routing scheme for multi-channel multi-hop WMNs based on the path cost. The path cost δ is a path metric composed by the end-to-end delay ETD_{MSDU}, the available bandwidth B_{path}, and the *Packet Error Rate* (PER_{path}), as shown in Equation 2.3. C_1, C_2 and C_3 are weight factors. In PCBR, mesh clients are grouped into clusters. Each mesh client periodically reports its link states to the cluster head, which will be used to compute the ETD_{MSDU}, the B_{path} and the PER_{path}. The cluster head discovers all the alternative routes and calculates their associated path cost. The path with the minimum path cost will be selected as the active path.

$$\delta = C_1 \cdot ETD_{MSDU} \; + \; C_2 \cdot \frac{1}{B_{path}} \; + \; C_3 \cdot PER_{path}$$
$$(1 = C_1 + C_2 + C_3, \; 0 \leq C_1, C_2, C_3) \tag{2.3}$$

A.2.2 Multi-Radio. To take full advantage of multi-channel communication, each node of the WMN can be equipped with multiple radios. This allows a node to operate in different channels simultaneously. In the last few years, a number of routing protocols have been proposed to explore this radio diversity. Many researchers have seen in the multi-radio approach a simple and relatively low-cost [5] approach to address the limited capacity of the WMNs due to interference. As result, nearby nodes can use the radios on distinct orthogonal channels, which permits effective use of the frequency spectrum, thereby, reducing interference and contention. Therefore, routing protocols should be aware of the radio diversity when calculating the best network paths.

The *Multi-Radio Ad-hoc On-Demand Distance Vector* (AODV-MR) routing protocol proposed by Pirzada et al. [119] is a multi-radio extension to the AODV protocol that incorporates the iAWARE routing metric. As its parent protocol, the AODV-MR is an on-demand (or reactive) protocol which sets up routes only when it is requested. Although iAWARE is non-isotonic, routing loops are avoided by using of sequence numbers in AODV control packets. Ramach et al. [120] proposed another AODV-based routing protocol, called

[5] Nowadays it is not so expensive to deploy nodes with multiple wireless network interface cards (WNICs). Actually, most of commercial mesh products already brings multiple WNICs as default.

Ad-hoc On-Demand Distance Vector Spanning Tree (AODV-ST), that uses ETX and ETT routing metrics rather than traditional hop count metric. It also pro-actively creates and maintains spanning trees having the mesh gateways as roots. The use of these spanning trees allows to reduce the route discovery latency. It gives to the AODV-ST characteristics of a hybrid routing protocol as it uses a proactive strategy to discover routes to the gateways (by using the information kept in the spanning trees) while for routes to less-commonly used end-points it relies on the traditional reactive discovery strategy from AODV. Both AODV-MR and AODV-ST are designed for multi-radio mesh networks. However, in the AODV-ST a subset of radios of the nodes is used only to relaying packets to the nearest Internet gateway. Results from simulation in [121] show a significant improvement by the AODV-MR, in terms of packet delivery ratio and latency, over AODV-ST and single-radio AODV, specially under high load conditions.

Das et al. [122] proposed the *Directional OLSR* (DOLSR) as a routing protocol developed along with a channel assignment algorithm in order to take advantage of directional antennas setup. DOLSR extends the OLSR protocol to aid in physical formation of trees using directional antennas, set up and maintain corresponding routing state, and perform channel assignment. The proposed architecture has been evaluated using both simulation and experiments ran over a mesh network testbed. Results in [122] shown that, compared with the omni-directional/multi-channel configuration, the proposed architecture improves packet delivery ratio and throughput, and drastically lowers average per-packet delay.

Hyacinth [123] is a multi-channel static wireless mesh network protocol that uses multiple radios and channels to improve the network performance. It implements a routing protocol and supports a fully distributed channel assignment algorithm, which can dynamically adapt to varying traffic loads. Hyacinth's channel assignment algorithm breaks a single-channel collision domain into multiple collision domains, each operating on a different frequency.

The Multi-Channel Routing (MCR) protocol, proposed by Kyasanur and Vaidya [81], has been developed for dynamic WMNs where nodes have multiple wireless interfaces and each interface supports multiple channels. The protocol makes use of an interface switching mechanism to assign interfaces to channels. Two types of interfaces are assumed: fixed and switchable. Switching is carried out depending upon the maximum number of data packets queued for a single channel. The switching mechanism assists the MCR protocol in finding routes over multiple channels. MCR uses a new routing metric which is computed as a function of channel diversity, interface switching cost and hop-count. The diversity cost is assigned according to the least number of channels used in a route. Thus a route with a larger number of distinct channels is considered to have lower diversity cost. The switching cost is used to minimize the frequent switching of wireless interfaces.

The *Multi-Radio Link Quality Source Routing* (MR-LQSR), was proposed by Draves et al. [76] for static community wireless networks. The protocol was implemented in the ad-hoc framework called *Mesh Connectivity Layer* (MCL), from Microsoft. Actually, the MR-LQSR is a multi-radio implementation of the *Link Quality Source Routing* (LQSR) [124] using the WCETT as routing metric. The LQSR is a source-routed link-state protocol derived from DSR [100]. The MR-LSQL protocol consists of four main components: (a) a component to discover the neighbors of a node, which is similar to the Route Discovery component of the DSR, (b) a component to assign the weights to the links, (c) a component to propagate information about the weights to other nodes, which is also similar to the equivalent component in DSR, and

(d) a component that uses the links weights to compute the best path to a given destination. In practice, the component (d) combines the links' weights to derive a path metric in order to choose the best path.

B. Anycast. Anycast is communication between a single sender and several receivers topologically nearest in a group. It is a routing model that can increase service scalability and provide efficient load distribution. Park and Macker [125] discusses the anycast routing in context of mobile ad hoc networks. They illustrate how several different classes of unicast routing protocols can be extended to provide efficient construction and maintenance of anycast routes. They show that anycasting approach instead of unicasting is efficient in such scenario. According to the same authors in [126], the anycast routing provides significant improvements to mobile network architectures, mainly regarding to the management of mobile nodes and servers under dynamic conditions.

B.1 Opportunistic Routing. More recently, researchers [127–129] have proposed opportunistic routing for mesh networks. Opportunistic routing differs from traditional routing in that it exploits the broadcast nature of wireless medium and defers route selection after packet transmissions [130]. The core idea behind the opportunistic routing is that, instead of predetermining a single specific node as the next-hop for a packet, multiple neighbor nodes are elected as candidates (by using some metric) which can potentially act as the next-hop and forward the packet. So, all candidate forwarder nodes that receive the packet successfully will coordinate with each other to determine which one would actually forward the packet according to some criteria (e.g. only the one that is closest to the destination). Then the remaining nodes will drop the packet. As a result, opportunistic routing can take advantage of the multiple (however, unreliable) wireless paths provided by the mesh network to improve the throughput [131]. In [132] the authors discuss the potential gain of opportunistic routing in multi-hop wireless networks. It has been shown that opportunistic routing can significantly improve the performance of wireless networks [127, 133].

The *Extremely Opportunistic Routing* (ExOR), proposed by Biswas and Morris [127], is considered as a seminal opportunistic routing protocol. ExOR is a combination of routing protocol and media access control for multi-hop wireless networks, such as a WMN. Instead of previously determining the route, ExOR forwards packets in a node-by-node fashion, deferring the routing decision (the choice of the next-hop) until the previous node has finished its transmission. The source node initiates the transmission by selecting the candidate forwarder set of nodes which may bring a packet closest to its destination and prioritizes them based on some criteria (e.g. shortest number of hops or transmission rate). The source node then includes, in the data frame, the list of candidate forwarders and broadcasts the packet. Only then does ExOR determines which node, among all candidate forwarders nodes that successfully received the transmission, is the closest node to the destination. Only the closest node forwards the packet. ExOR is more efficient with blocks of packets. As a drawback, ExOR requires tight node coordination, which is difficult to be implemented in large networks [134]. The *Resilient Opportunistic MEsh Routing* (ROMER) [129] is another opportunistic routing protocol which aims to forward packets along multiple paths. ROMER focuses on resilience and high throughput. Its design builds a per packet runtime forwarding mesh to improve the resilience against channel outages, errors, and attacks. ROMER introduces a credit based scheme to limit the number of transmissions that a packet is allowed to be forwarded before reaching the destination, analogous to the Time-To-Live of the Internet Protocol. Even with the credit-based scheme, there is still significant overhead since a packet is allowed to be forwarded by multiple nodes at each hop. Also, setting the credit is non-trivial [130] and static credit has difficulties in coping with different topologies. Because it operates on packets, unlike ExOR, ROMER can react faster to medium variations.

B.2 Opportunistic and Network Coding. Network coding is another approach that has been used in order to improve the routing in multi-hop wireless networks. With network coding, instead of simply relaying a single received packet, a network node may take several packets and combine them together for transmission. Likewise, a node may receive a combined packet and detach the part that interests to it. Network coding can be used to achieve the maximum possible communication flow in a network. Both opportunistic routing and network coding techniques use unreliable 802.11 broadcast as the hop-by-hop forwarding technique, which is a significant departure from traditional routing protocols. The use of broadcast is a necessity for opportunistic routing as well as effective network coding. Since the MAC now does not have to deal with retransmissions and exponential backoffs, it can send at much higher packet rates than in the unicast mode; it is essentially limited only by carrier sensing [135].

The COPE mechanism, proposed by Katti et al. [136], is taken as the first practical network coding mechanism employed to increase the throughput of a WMN. COPE considers a WMN with multiple unicast flows and it shows, via implementation and measurement, that network coding can increase the throughput of a WMN. In COPE every node is in promiscuous mode and overhears the transmission of all other nodes and a pseudo-broadcast approach is used to transmit a packet. Pseudo-broadcast packets are unicast packets that include an XOR-header listing all intended next-hops for the packet. Since all nodes are in promiscuous mode, they can overhear the packet and then accept the packet if its address is in the listing of next-hops for the packet. This pseudo-broadcast technique is more reliable than simple broadcast, as it relies on the mechanisms of acknowledgment and retransmission of unicast packets. It uses reception report in their neighborhoods to let the neighbors learn about the packets they currently have received. COPE may leverage the (ETX) values from the routing protocol to guess whether a neighbor has a particular packet. However routing in COPE is independent of coding opportunity.

Le et al. [137] pointed out two limitations of COPE: a) the coding opportunity is crucially dependent on the established routes and b) its opportunistic overhearing scheme limits the entire coding structure within a two-hop region. The authors then proposed an on-demand *Distributed Coding-Aware Unicast Routing Protocol* (DCAR) to overcome these limitations of the COPE protocol. Instead of using ETX, COPE introduces the *Coding-aware Routing Metric* (CRM), which jointly incorporates topology, traffic load, and interference information about a path. The use of CRM allows to select a high throughput path with more potential coding opportunities. In addition, DCAR can detect coding opportunities on an entire path.

The *Coding-aware Opportunistic Routing mEchanism* (CORE), proposed by Yan et al. [128], combines hop-by-hop opportunistic forwarding and localized inter-flow network coding to improve the throughput of a WMN. In CORE, the opportunistic forwarding is done in a way that the candidate node with the higher network coding gain is chosen to forward the packet. Through localized inter-flow network coding, CORE tries to maximize the number of packets that can be carried (coded) in a single transmission. Thus, in CORE, when a node has a packet to send, it simply broadcasts the packet, which may be received by some of the forwarder candidates in its neighborhood. This packet may encode multiple packets. Upon receiving the packet, a forwarder candidate node must cooperatively select among the other forwarder candidates that one which will actually forward the packet. As aforementioned, it will be that one with higher network coding gain. To calculate the gain or coding opportunity for a node, the authors in [128] assume that every node is equipped with a GPS device or some other localization mechanism, and there is no limitation of power or processing capability.

Chachulski et al. [133] presented the *MAC independent Opportunistic Routing & Encoding* (MORE) as an opportunistic and networking coding routing protocol for stationary WMNs, in which the nodes have ample CPU and storage resources. MORE combines network encoding and opportunistic routing to support multiple simultaneous flows. The source node creates random linear combinations of packets and broadcasts the coded packets continually. The relay nodes combine the independent packets and forward them. MORE employs fast network coding techniques to produce efficient coding to ensure that routers can achieve high bit rates.

According to [138], although MORE eliminates the overhead of node coordination as in ExOR, the list of forwarders is computed by assigning credits to each forwarder candidate and this assignment is purely based on previously measured link delivery probabilities (using the ETX metric). Therefore, if the link-level measurements are inaccurate or cannot adapt quickly enough to the current network condition, forwarders may receive too few (or too many) credits, leading to insufficient (or overloaded) transmissions and hence degraded throughput.

Yan et al. [134] proposed the *Coding Aware Opportunistic Routing* (COAR) mechanism, which is essentially an opportunistic forwarding mechanism that aims to optimize the selection of the forwarder on a per-hop basis. The core idea in COAR is in how all nodes in the forwarder set can agree on which one of them has the most coding opportunities using only local information. In COAR, all nodes in a forwarder set exchange their knowledge not only about the packets that they have stored in their buffers but also in their neighbors' buffers. This information gives to each node a 2-hop local view of all the packets stored in its neighbors. Therefore, all these nodes can compute the same coding opportunities for a particular packet (or block of packets) and then agree which one is the best forwarder. COAR adopts the same periodic reception report procedure used in COPE.

B.3 Field and Gradient-based Routing. Seeking further throughput improvement, other researchers have looked into exotic techniques, which largely abandoned the traditional routing principles, to propose new approaches for routing in WMNs. For example, HEAT is a routing protocol based on temperature fields similar to thermal physics in the sense that a gateway represents a heat source and to each node a temperature is assigned, and also each node conducts heat from the gateway to each other node [139]. Therefore, the higher the temperature of a node, the closer it is to a gateway and the greater is the diversity of paths to this gateway. Based on this temperature field, packets are always forwarded to the neighboring node with the highest temperature. It was proposed by Baumann et al. [140], as an anycast routing protocol. HEAT only requires communication between neighboring nodes (i.e., every node calculates its own temperature by evaluating solely the temperature of its immediate neighbors) and hence has good scalability properties due to its fully distributed implementation.

In another work, Baumann et al. [141] presented a proactive field-based routing protocol similar to HEAT, called *Field-Based Routing* (FBR). In FBR, every mesh node maintains a scalar field that is propagated by beacon messages through the mesh network. Routing towards a specific mesh node is achieved by forwarding along the steepest gradient of the field of the destination node.

2.2.4 The Hybrid Wireless Mesh Protocol (HWMP) Performance and Scalability Issues

There are many distinct reasons for reduced performance and scalability in WMNs, most of them are strongly related to the inherent inefficiency of the underlying IEEE 802.11 mechanisms [142]. Srivathsan et al. [8] have listed and discussed some of these reasons, namely co-channel interference, routing protocol overhead, half-duplex nature of radio antennas, difficulties in handling multiple frequency radio systems, deployment architecture, Medium Access Control (MAC), topology (denseness of nodes, degree of nodes), and communication pattern (locality and number of hops). It is important to highlight that not all these factors are mutually exclusive (actually, most of them are interrelated), for example, in a single-channel WMN, the overlapped areas may cause co-channel interference [143] and degrade the routing protocol and MAC performance (and, consequently, the scalability) no matter the deployed topology. Therefore, any proposed approach to deal with network scalability may not take into account the effect of only one of these factors and neglect the impact either in or of another.

Due to the multi-hop nature of mesh networks, they tend to experience high restrictions on network capacity. In fact, most of proposed path selection protocols are often bounded by ad-hoc approaches, do not taking advantage of the multi-hop architecture of WMNs. The HWMP protocol is a clear example of this restriction, as it is an adaptation of the well-known Ad hoc On-Demand Distance Vector (AODV) protocol.

The low scalability in these networks is also caused by the under-performance of the path selection[6] scheme, which causes a substantial control overhead. It is the case of the Hybrid Wireless Mesh Protocol (HWMP) - the standard IEEE 802.11s path selection - that still relies on traditional IEEE 802.11 medium access mechanisms and protocols, which present low scalability. Detailed description of HWMP operation can be found in [5, 46, 48, 52, 61, 144].

According to Carrano et al. [52], unless the path discovery overhead is drastically reduced by increasing the efficiency of flooding mechanisms, the new standard may present a suitable behavior just for small scale scenarios. Moreover, scalability is one of the major deciding factors for any network to be accepted and industrially deployed [144].

The HWMP performance has drawn considerable attention, and many works have compared it with other protocols. For example, Ghannay [60] conducted a performance comparison of the HWMP and Radio Aware Optimized Link-State Routing (RA-OLSR) [7] path selection protocol. The findings of this work corroborate that both protocols were designed for IEEE 802.11s mesh networks, however, none of them focused on scalability or stability

[6] Path selection is the expression used in the 802.11s standard for the equivalent functionality of routing, but at layer 2. For the same reason - to differentiate from the layer 3 routing - the standard refers to path instead of route.

[7] Until the IEEE 802.11s draft version 1.06, every mesh STA should support two path selection protocols: the HWMP [48] as the default routing protocol and the RA-OLSR [49] as an optional one.

issues. Nassereddine et al. [144] evaluate the scalability of the HWMP routing protocol regarding the traffic load and the number of nodes. Simulation results show that the selected performance metrics are very sensitive to the network traffic and size, i.e. the protocol is hardly scalable.

All previously cited works share the conclusion that the HWMP is not scalable enough and needs to be improved to deal with larger networks. Moreover, although the mesh topology provides multiple paths, that could be used to improve its performance, HWMP itself does not provide any multi-path selection mechanism. Likewise, there is no mechanism to handle multi-radio implementations, nor any metric suitable for those environments.

Up to date, few proposals targeting these HWMP issues can been found in the literature. The most relevant ones are briefly described as follows, and summarized in Table 2.5.

Although the following studied solutions present very distinct approaches, few characteristics can be extracted to allow the reader to better compare the various arguments in favour of and against each proposed solution.

Each solution possesses some advantages, drawbacks, and features. Several criteria can be used to classify the path selection and forwarding protocols proposed in the literature and discussed above. A fair comparison of them must take into account the most important architectural features that have impact on both the performance and the scalability of the mesh network.

The most basic classification regards the network structure: flat or hierarchical. Briefly, in flat routing, every node has the same role (i.e. they all do the same tasks). In hierarchical routing, nodes have a different role. Moreover, there is a hierarchy between them and the tasks they perform. A flat view from the network simplifies the protocol design, but overloads all network nodes. Unlike, a hierarchical view turns the protocol design a complex task, but distributes the load among the network nodes.

In Wireless Mesh Networks (WMNs) the interference awareness has a significant impact over the solution design. The impact of interference on the capacity of wireless networks has been broadly studied by researchers [9, 72, 73]. The interference can be depicted into two types: inter-flow interference and intra-flow interference. In wireless networking, the intra-flow interference is the interference caused by intermediate nodes sharing the same flow path. The intra-flow interference limits the achievable throughput in multi-hop wireless networks [74]. Inter-flow interference refers to the interference caused by neighboring nodes of distinct flow paths, but competing for the same channel (i.e. in the same interference zone). Besides capturing the interference on the medium, a good interference-aware solution must implement mechanisms to allow spatial reuse to mitigate the interference. Likewise, as most of WMN clients are mobile, the mobility support is an important feature of classification in WMNs.

Also, the metric used for path selection and forwarding is another important classification feature. Although the IEEE 802.11s standard recommends the use of the ALM as default metric, the architecture may be adapted to use any other metric.

In this thesis, the forwarding strategy is taken as one of the most important classification criteria. The forwarding strategy regards the scheme used to decide the next-hop to such a target of each frame. The strategy chosen will severely affect the protocol design and its performance in a way. The improvements and drawbacks of each strategy can be summarized as follows.

- **More accurate metrics.** Although the ALM is suggested by the IEEE 802.11s standard, it is unlikely that a single metric will be suitable for all mesh network settings. Therefore, new metrics might be proposed. A good routing metric accurately captures the quality of the network links and allows the computation of the best quality paths. Regarding the measuring method, a routing metric can be classified as active (e.g. using probe frames) or passive (e.g. using local information). Although active probing can provide much more updated and useful information, it suffers from its associated overhead.

- **Multiple radios and Multiple channels.** In principle, every path selection and forwarding protocol can be extended to work with multiple wireless interfaces, multiple channels, and distinct (or even multiple) routing metrics. However, it can become a very complex work, potentially requiring substantial extensions to the protocol.

- **Message piggybacking.** It consists in temporarily delaying outgoing frames (usually control frames) so that they can be inserted in the next outgoing data frame, reducing the overhead over the access and utilization of the medium.

- **Protocol tuning.** The main idea is to improve the protocol scalability by tuning its parameter values, seeking to optimize them. The control message periodicity adjustment is a common example of this type of strategy.

- **Quality of Service (QoS).** The goal of the QoS aware forwarding is to find best routes that meet the application requirements. It can be deployed either in the core of the protocol by changing its mechanisms to deal with QoS requirements or as a new metric QoS-aware (hence changes in the protocols are not required).

- **Greedy Geographical forwarding.** It is also called location-based forwarding as nodes' positions are exploited to forward data in the network. Unlike most of traditional approaches, greedy geographical forwarding does not require any information on the global topology, but requires that any node must be capable to provide its location (or geographical position), usually relying on GPS devices [145]. In other words, this strategy uses the nodes position information to send the frame to the neighbor closest to the destination.

- **Clustering.** Serving as the basis for many large-scale network solutions, clustering is basically the process of partitioning a set of network nodes into groups (clusters) that share a common characteristic. The most common grouping criteria is the node's proximity. Nodes within a cluster can play distinct roles: one node is chosen as cluster head, others can be gateways, and the remaining are ordinary nodes. The cluster head controls the formation of the cluster and the communications intra-cluster. Gateways are nodes that are in radio range of overlapping clusters (i.e. they can communicate with nodes in one or more distinct clusters) and allow inter-cluster communication. Besides providing an hierarchical structure, this strategy allows to reduce unnecessary communication. However, to keep providing stable service, clustering requires some level of topological stability. This is the most challenging issue for using clustering forwarding in WMN environments.

- **Distributed Hash Tables (DHT).** The DHT concept arises from the Structured *Peer-to-Peer* (P2P) overlay networking's field. Briefly, using this strategy, each node keeps a DHT structure to supply contents and a forwarding table with the address of some other nodes in the overlay network. The main idea behind DHTs is to apply a hash function to distribute content among a group of nodes in a network. The same hash function must be used to locate the node that stores the desired content. This method allows the efficient publication/lookup/retrieval of data, using a key-based map to address each node or data. Originally designed to create an overlay network that allows more scalable and faster to search and to recover information over the P2P systems, now its use is proposed to increase the network scalability and speed up the overall network performance [43].

- **Frame aggregation.** It is a feature of the IEEE 802.11e and 802.11n standards that increases throughput by sending two or more data frames in a single transmission. Also called A-MPDU, frame aggregation allows the transmission of multiple frames, called subframes in a row, with the overhead for medium access and physical header transmission of a single frame.

- **Smart antennas and Directional antennas.** The core idea behind this strategy is to exploit both time diversity and frequency diversity to send frames over high quality channels [146], increasing the capacity and the range of communications in mesh networks, reducing the collisions occurrence. Briefly, directional antenna takes advantage of the physical geometry of the antenna to provides a transmission power gain since energy is focused in a narrow direction rather than spread (e.g. in omnidirectional antennas). Furthermore, the transmission scheme to be used is related with the network conditions. For example, beamforming enables directional transmission with extended range thus being suitable to sparce networks, whereas spatial multiplexing enables high bit rate omnidirectional transmission with lower range, which makes it more suitable for dense networks. To effectively exploit directional antennas requires some intelligent mechanism to discern where to point the antennas and to physically point them in the chosen direction. In such a case, the antenna is considered smart. However, creating the conditions that allow this strategy to be effective is difficult. An interesting review of these necessary conditions for smart antenna exploitation is presented in [147]. Additionally, an interesting overview on using directional/smart antennas in wireless networks is given by [148].

- **Opportunistic forwarding.** It exploits the broadcast nature of the wireless medium. The core idea is: instead of selecting a single predetermined node as the next-hop for a frame, multiple neighbor nodes are elected as candidates (by using some metric) to act as the next-hop and forward the packet. So all forwarder candidate nodes that successfully received the frame will coordinate with each other to determine which one will actually forward the received frame, according to some criteria, e.g. only the node closest to the destination (the others nodes will drop the frame).

- **Network coding.** It combines algebraically several data frames to construct an encoded frame that transports more data in a single wireless transmission, reducing the control overhead (from headers). In other words, instead of simply relaying a single received frame, a network node may take several packets and combine them together, by using some algebraic operation, for transmission. Likewise, a node may receive a combined frame and detach the part that interests in it, using some inverse algebraic operation. Thus, this strategy exploits the wireless broadcast property to increase the network capacity [149] and to achieve the maximum possible communication flow in a network [44].

- **Cognitive radios.** This strategy takes advantage of available frequency opportunities that occur in multi-channel deployments in order to coordinate concurrent multiple data transmissions, hence increasing the overall network performance. This strategy requires modifications on the MAC layer to recognize and use the frequency opportunities. Up to date, few proposals using cognitive radios can be found on the IEEE 802.11s literature, such as [150, 151].

- **Field-based forwarding.** The core idea on the field-based forwarding is to assign a scalar value to each node in the network, based its proximity to some target (e.g. an Internet gateway, a root node etc.). The target is expressed as the maximum value and the data frame is forwarded along the gradient field to the target, similarly to potential fields in physics [152].

It is important to note that the forwarding strategies presented above can be also combined to maximize the protocol performance and improve the network scalability. For instance, clustering can perform frame aggregation in its cluster and decrease the control overhead and the number of frames to send. Another example is to combine Clustering and DHTs, as presented in [39, 40]. The combination of Clustering and Multi-radio and Multi-channel strategies may allow to schedule neighbor clusters to operate in distinct channels and radio, mitigating the impact of simultaneous communications in neighbor clusters. In this sense, many other combinations can be envisioned to achieve more scalable WMNs.

Description of some proposed solutions for the lack of scalability and poor performance presented by the standard HWMP protocol are discussed below.

Lim et al. [153] introduce the *Root Driven Routing* (RDR) mechanism that uses HWMP in proactive mode as path selection protocol. The RDR protocol aims to provide the optimum route by the root for any source-destination pair of intra-mesh traffic. With this, the RDR protocol outperforms the network performance of *Tree-Based Routing* (TBR) protocol. The most important is that RDR provides a solution to the lack of optimized paths for intra-mesh traffic presented by the TBR, which forwards this type of traffic through the root. To do so, upon receiving a RANN message, each node piggybacks its neighbor addresses list and the corresponding metric into the RREP message. This procedure allows to create the network topology (in addition to the tree topology) which enables to compute the best path for any intra-mesh traffic. Although this protocol alleviates the amount of traffic in the root node and outperforms the HWMP/TBR, it is not very scalable, as it requires that the root stores information about the topology of the entire network. Moreover, as most of tree-based protocols, it takes too long to react to link breakages. Wenjiang et al. in [154] present an improvement to the centralized approach of RDR [153] with the *Optimized Tree-Based Routing* (OTR), which logically separates the proactive tree into pieces, forcing the path selection to be partially computed by brunches instead of a central root.

Error recovery for the HWMP proactive RANN mode has been studied by Bae & Ko [155] that also propose a scheme to adjust the period of RANN messages for reducing the overhead of the tree topology creation. Additionally, it proposes two weight values α and β to be applied to the ALM for the alternative parent selection (path recovery) and to the *Time-to-Live* (TTL) field of PREQ messages (repair process), respectively. Simulations results show the performance increase by tuning the HWMP protocol. Regarding the tuning of the IEEE 802.11s standard mechanisms, it is still unclear how much this strategy can improve both the performance and scalability of the network. In order to reach a conclusion about that, many other standard parameters must be studied to find a best set of values that provides the best optimization.

Ueda & Baba [156] propose an initial routing establishment method based on a greedy forwarding, that uses a new address space based on the link state, using addresses as positional information. Also they proposed a forwarding method based on addresses in the address space. The source traffic mesh station chooses a mesh station closest to destination one. Although the proposed method is based on nodes' location, no additional device (such as GPS) is required. Simulation results on scaling the number of mesh stations show that the number of messages does not increases drastically as the number of mesh stations increases.

Lin et al. [157] propose the *Dynamic Aggregation Selection and Scheduling* (DASS) algorithm to reduce the MAC layer control overhead by dynamically adopting the appropriate aggregation mechanism to aggregate multiple frames into a single transmission. The frame aggregation is proposed based on the assumption that wireless channel condition is commonly dynamic and error-prone and hence transmission error (causing retransmissions) significantly impact the network performance. Frame aggregation can be performed at different sub-layers. In this sense, DASS considers three mechanisms: (1) *aggregate multiple MAC service data unit* (A-MSDU), in which MSDUs can be aggregated into a single *MAC protocol data unit* (MPDU) with a single MAC header; (2) *aggregate MPDU* (A-MPDU), which aggregates a number of MPDU to form a *PHY service data unit* (PSDU), and (3) *aggregate PHY protocol data unit* (A-PPDU), which concatenates multiple PSDUs together and adds a PHY header. The main difference between the mechanisms is the overhead introduced. Also, DASS employs four frame aggregation transmission schemes, namely *single destination single receiver* (SDSR), *multiple destination single receiver* (MDSR), *multiple destination multiple receiver* (MDMR) and *single destination multiple receiver* (SDMR). The usage of a frame aggregation mechanism varies with the roles of the communication pair, as shown in Table 2.4 [157]. Simulation results demonstrate that DASS could improve the overall throughput of 802.11s mesh network by 95% compared with the case with no aggregation.

Rafique et al. [158], introduce the *Modified HWMP* (MHWMP), which uses smart antennas to overcome scalability and stability issues, by avoiding link outages, and to improve the overall network performance. Smart antennas (an improvement of directional antennas) allow to explore the channel diversity efficiently. MHWMP nodes maintain two path tables: an *Omnidirectional Path Table* (OPT) and a *Directional Path Table* (DPT). The metrics used for these tables are modifications of the standard ALM - the C_{OPT} and C_{DPT}, respectively. Likewise, HWMP also defines two distinct sets of control frames. The proposed approach exploits the advantages of smart antennas by adaptively using spatial multiplexing or beamforming for data transmission and *Simple Space Time Block Codes* (STBC) to send control frames prior to beamforming. The high complexity of using smart antennas, forcing the use of additional control messages to deploy it (i.e. additional control overhead), is the main drawback of this approach.

Table 2.4: The adaptive frame aggregation mechanisms among different transmission pairs. Redrawn from [157].

	MP-to-MP				STA-to-MAP		MAP-to-STA	
	SDSR	MDSR	SDMR	MDMR	SDSR	MDSR	SDSR	MDMR
A-MSDU	◯				◯		◯	
A-MPDU	□	◯			□	◯	□	
A-PPDU	△	△	◯	◯	△	△	△	◯

◯: Most suitable, □: Replaceable but less efficient, △: Replaceable but inefficient.

* The authors used a deprecated nomenclature of the IEEE 802.11s elements.

** MP: mesh station, MAP: AP collocated with a mesh station, and STA: non-mesh station.

In another work, Rafique and Bauschert [159] propose the *Path Selection Protocol for Smart Antennas* (PSPSA). PSPSA is actually an enhanced version of the MHWMP. Multiplexing and beamforming are employed to take advantages of smart antennas. The major change is the reduced overhead of the PSPSA when compared with MHWMP, due to the use of the same path discovery for both transmission schemes (multiplexing and beamforming). The simulation results suggest that PSPSA performs better than MHWMP for random link degradation scenarios. Moreover, its overhead is significantly lower.

Lee et al. [160] present a modified version of the HWMP for *Multi-Interfaces and Multi-Channels* (MIMC) WMNs, compatible with the standard IEEE 802.11s. The proposed solution increases the overall network capacity and performance by exploiting the channel diversity. The solution basically utilizes the HWMP and the ALM for compatibility reasons. However, the authors introduce the concept of path throughput which is used as addition to the ALM to select the high performance path in the MIMC environment. The path throughput is defined as an end-to-end delay for a path, considering the channel diversity. To calculate this additional metric, PREQ and PREP messages are extended to accommodate additional fields about the nodes in the path, such as the ALM value and channel number. In order to reduce the broadcast of control messages (i.e. the control overhead), the proactive PREQ is distinguished into two new messages: $PREQ_F$ (which is rebroadcasted to all interfaces) and $PREQ_R$ (which is selectively rebroadcasted to the necessary interfaces). The messages are sent in distinct intervals, the $PREQ_F$ is sent in a I_F interval and the $PREQ_R$ is sent in a I_R interval between consecutive I_F intervals. The number of $PREQ_R$ updates is configurable as the I_F and I_R the intervals. Simulation results shown performance improvements in comparison with HWMP, using TCP traffic. Moreover, the results support the efficiency of MIMC forwarding strategy as it shows the increasing performance as the number of interfaces increases.

Yang & Chung [161] introduce the HWMP+, which is another modified version of the standard HWMP protocol. Actually, HWMP+ is the name of an enhanced airtime metric, which takes into consideration the link's quality and also improves the frames forwarding based on the monitored traffic flow information. Regarding the new metric, the authors modify the Frame Error Rate (e_f) term in the ALM computation (see equation 2.1) - in this paper the Packet Error Rate (PER) notation to e_f term is used[8]). Therefore, the PER value is computed as the ratio of the frames resent and frames sent. To allow that, they propose to extend the information exchanged for peering with additional fields about the metric and traffic flow. The additional information is used to compute and store historical information about the links' quality (PER) as well as information about the traffic conditions. The proposed forwarding scheme then uses the historical and real-time information about the links and traffic to better select the paths, improving the throughput. Simulation results show the reduction of packet loss ratio and end-to-end delay, whereas achieving significant throughput gain compared to HWMP.

Thaalbi & Tabbane [162] introduces the *Geographical Hybrid Wireless Mesh Protocol* (GHWMP). GHWMP proactively forwards frames based on a localization database maintained by the root mesh STA. The database contains geographic information received from all mesh STAs (non-root) in the network. The information is exchanged into extended RANN or proactive PREQ messages. Thus, when a mesh STA has data to send, it examines its cache for a valid path for the destination. In the absence of such path, it requests the root mesh STA for the destination location. After the destination location is received (encapsulated into a PREP message), if the destination is outside the MBSS, GHWMP will forward the frame in a similar way to HWMP, through the root mesh STA. Otherwise, GHWMP will use the geographic coordinates to reactively find a better path to destination. Simulations results show that GHWMP outperforms HWMP in terms of higher throughput, lower packet loss rate, and lower transmission delay. Moreover, GHWMP provides efficient forwarding in high mobile environments. The main drawbacks are the assumption that all mesh STAs must be equipped with a GPS and the centralized geographic database in the root mesh station, which can lead to congestion and reduce the reliability of the proposed solution.

Chakraborty et al. [163] propose an opportunistic path selection protocol over the HWMP for multi-radio WMNs. The main objective is to avoid channel interference by searching for the best pair of radios that allow better forwarding performance. To do so, the proposed scheme works in two phases: (1) proactive HWMP is used to construct the set of potential forwarders for each mesh STA from its one-hop neighborhood; and (2) during the data transmission, a candidate mesh STA from the set of potential forwarders is selected, based on the channel interference and ALM value of the potential forwarder and the current channel characteristics. The authors suggested to limit the broadcast of PREQ messages through only a set of necessary radios (such that all mesh STAs receives at least one copy of the PREQ), as an optimization for the first step. Simulation results show the effectiveness of the proposed scheme, outperforming the conventional HWMP (for both reactive an proactive modes) in terms of availability, average packet delivery rate, average jitter, and end-to-end delay. However, the assumptions that all mesh STA implements a centralized channel assignment scheme and also implement the Mesh Coordinated Channel Access (MCCA) are the main drawbacks of the proposed solution.

A QoS-aware path selection solution is proposed in [164]. The *QoS-aware HWMP* (Q-HWMP) aims to find a best route based not only in the airtime but also using the end-to-end delay as additive metric to satisfies the QoS requirements imposed by the intended application. To achieve that, a new flag (QosTag) is incorporated into PREQ frames, signalling the presence of other QoS-related additional fields. The information carried out in

[8]According to the current IEEE 802.11s standard document, the Packet Error Rate (PER) terminology is deprecated.

these fields is used on path discovery. Although simulation results show a better performance in comparison with the HWMP, the introduced overhead is doubtful (even that the authors argue that it is not significant). Even through the performance improvements of using Q-HWMP it will hardly bring significant improvements on the network scalability. Nevertheless, the combination of this solution with some other forwarding strategy may improve the overall network performance.

A previous version of the DCRP was introduced in [39, 40]. The DCRP uses Distributed Hash Tables (DHTs) and clustering techniques to minimize the broadcast storm, consequently reducing the Path Discovery and Selection, and Forwarding overhead on the network. The DCRP integrates clustering with DHTs to enhance the scalability of routing in 802.11s networks. Clustering allows hierarchical forwarding and therefore reduces the amount of routing traffic. The forwarding information that is not exchanged through the path selection protocol is kept in DHTs, which supports a rather efficient access. The main advantages are the reduction of the broadcast range, improving of the path discovery and forwarding using clustering and DHTs. Although architecturally similar to the current version, the main distinction is the use of RA-OLSR as underlay protocol in the previous version. The current version uses the HWMP. The use of RA-OLSR was the downside of this approach, incurring an increasing amount of maintenance information as the networks size increases due to its proactive nature.

Although this section does not exhaustively reviews the proposed solutions for the HWMP scalability issues, the examples discussed above are enough to support the need to develop new scalable path selection and forwarding protocols and metrics. In this sense, the combination of forwarding strategies can cope with the WMN characteristics, such as high intra and inter-flow interference.

Complementing the comparison drawn in Table 2.5 it is important to note that: (1) regarding the forwarding strategy, up to date, not all types listed above have been effectively employed for this specific purpose, (2) most of the solutions still rely on flat topology, (3) also, most of solutions are not aware of the interference on the channel, and (4) all the studied proposals neglect the mobility on the network.

Finally, three important observations must be highlighted from the discussed works: (1) although some of them partially address the scalability problem in IEEE 802.11s networks, a ’one-size-fits-all’ solution for this issue is very unlikely; (2) the mobility is neglected by most proposals, but it becomes a real issue in large deployments, with a large number of mobile clients; (3) each proposal makes use of one or a combination of forwarding strategies to achieve better performance and scalability; however there are still many other potential combinations that can be devised.

2.2.5 The Airtime Link Metric and Path Stability Issues

Unstable path weights can be very harmful to the performance of any network [82], especially in WMNs. Path fluctuation leads to a high volume of path update messages, increasing the overhead of the path selection protocol. It can also disrupt normal network operations as some network protocols, as well as some applications, may not converge under frequent path changes.

Table 2.5: Comparison of relevant path selection protocols proposed to improve both HWMP scalability and performance.

Proposed	HWMP Mode support						Forwarding
Protocol	Reactive	Proactive	NS	IA	MS	Metric	Strategy
HWMP [45]	yes	PREQ & RANN	F	○	○	airtime	Standard
RDR [153]	no	RANN	F	○	○	best-metric	Piggybacking
OTR [154]	no	RANN	F	○	○	airtime	Piggybacking
— [155]	no	RANN	F	○	○	airtime	Protocol tuning
— [156]	Not specified.		F	○	○	distance	Greedy geographical
DCRP [39, 40]	RA-OLSR is used.		H	○	○	airtime	Clustering and DHT
DASS [157]	Not specified.		F	○	○	airtime	Frame aggregation
MHWMP [158]	yes	no	F	●	○	C_{OPT} and C_{DPT}	Smart antennas
MIMC [160]	no	PREQ & RANN	F	●	○	airtime[1]	Multiple radios
HWMP+ [161]	yes	PREQ & RANN	F	○	○	HWMP+	More accurate metric
GHWMP [162]	no	PREQ & RANN	F	○	●	airtime	Greedy geographical
— [163]	no	PREQ	F	○	○	airtime	Opportunistic and multiple radios
PSPSA [159]	yes	no	F	●	○	airtime[2]	Smart antennas
Q-HWMP [164]	yes	no	F	○	○	mean delay[3]	Quality of Service

* The metric value *best-metric* means any link metric, such as hop-count, airtime cost, etc.

** NS: Network structure - F (flat) or H (hierarchical); IA: Interference-aware; MS: Mobility support.

[1] The path throughput (end-to-end throughput) is used as an additive metric to the ALM.

[2] PHY layer transmission rate parameter is computed in a different way for spatial multiplexing.

[3] The end-to-end delay is used as an additive metric to the ALM.

By nature, links in multi-hop wireless networks have an unpredictable behavior, which directly affects the stability of routes [165]. This section presents the ALM as one cause of instability in IEEE 802.11s networks. Formally [45], the airtime cost (c_a) for each peer link is given by the Equation 2.1 (see Section 2.1.3).

According to Ghannay et al. [57], the ALM metric is well adapted to single-radio single-channel mesh networks due to its simple design. Ghannay et al. [60, 61] present a comparison of hop count and radio aware path selection protocols specified in the IEEE 802.11s draft standard at the time. The authors consider two simulation scenarios: in the first, the authors compare the OLSR and the Fisheye State Routing (FSR) applied to the Optimized Link-State Routing (OLSR) - the Fisheye OLSR (FOLSR) - with its radio-aware version, the RA-OLSR; in the second scenario, the Ad-hoc On-demand Distance Vector (AODV) with its radio-aware version, the Radio Metric AODV (RMAODV), is compared. The results for both simulation scenarios show that radio-aware metrics outperform hop count metrics. Starting with these studies, the path selection metric has been the object of several other research studies.

Different research works have identified different causes for path instability, including the link metric computation, the size of frames, and the adaptation rate, as follows. Nevertheless, as there is no widely accepted explanation, these issues are still open research problems that deserve to be further investigated in order to clarify its real impact over the IEEE 802.11s networks. It is important to highlight that the standard does not specify any mechanism to estimate e_f, leaving its implementation as an open issue.

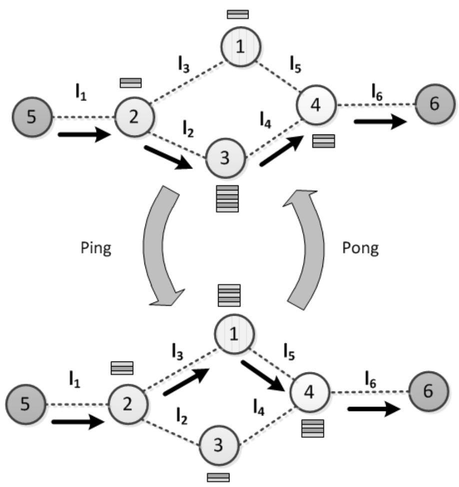


Figure 2.13: ALM "ping-pong" effect illustration.

ALM computation and the "Ping-Pong" phenomenon. A major issue related with radio-aware metrics is that they may be the cause for path instability issues. Arguably, the most studied instability issue is the "ping-pong" effect [166], which may occur when paths have similar metrics, especially under a triangular configuration. Shortly, the phenomenon occurs when there is a situation similar to that illustrated in Figure 2.13. Assume that at some time t_1 the best path from node *5* to node *6*, according to the HWMP path selection, is through nodes *5-2-3-4-6*, as l_2 offers a lower air-time cost than l_3. Sending frames through this link can potentially degrade l_2's metric[9] in a way that l_3 momentarily offers a lower cost. Thus, HWMP will select path *5-2-1-4-6* as current best path. Again, by sending frames through this new path, it will suffer a similar metric degradation to the point that l_2 will again have a lower cost than l_3, and HWMP will switch back to the previous path, leading to a path oscillation phenomenon. In other words, the phenomenon occurs when an unloaded (or just less loaded) path momentarily offers a better metric, so a mesh STA selects that path to send frames and suddenly the selected route becomes more loaded.

Garroppo et al. [166] address this problem by proposing a significant change to the airtime metric cost computation - although they used the expression "a slight change". More specifically, as shown in Equation 2.4, they replace the transmission rate by the *signal to noise ratio* (SNR) and introduce a set of constants (k_1, k_2, and k_3). Regarding to the set of constants, the authors claim that it was used to balance the relationship between the SNR

[9] A possible reason is that the added traffic may increase the error rate of links involved in the path and thus the path cost also increases.

and the frame error ratio (e_f). The introduction of SNR on the computation was used to alleviate the dependence on the frame loss percentage due to collisions (most common reason for frame losses in WMNs). The authors argue that with this modification, the metric becomes less dependent on the frame loss rate. The main drawback of the proposed approach is the poor definition and absence of computation method for the k_i constant values. To handle this problem, the authors just point out "a good set of values" ($k_1 = 3.2$, $k_2 = 250$, and $k_3 = 1$), based on their observations, to smooth out the airtime metric fluctuation effect.

$$c_a = \left[k_1 + \frac{k_2}{SNR}\right] \cdot \frac{1}{k_3 - e_f} \tag{2.4}$$

Another issue regarding the ALM specified in the standard is the estimation of the frame error rate (e_f) parameter in Equation 2.1. The problem is that the standard does not specify how to estimate its value, leaving this task as an "implementation choice".

In this sense, Garroppo et al. [53] analyze the implementation of ALM for a Linux-based implementation of the IEEE 802.11s standard - the *open802.11s* project [167], for both kernel versions 2.6.31 (so-called pre-31 ALM implementation) and 2.6.32 (so-called post-32 ALM implementation). According to the authors, the pre-31 ALM implementation used Equations 2.5a and 2.5b to estimate the frame error rate. It is based on discrete time instants (t_k), which are internally handled by the network device driver, and that must be (ideally) separated by at least 13 milliseconds. It estimates the frame loss probability p_f as the ratio between the number of failed frame transmissions (n_f) and the number of transmitting frames (n_{tx}). The frame error rate is then computed as a weighted average, where the present frame loss probability estimate has a weight of $1/9$ and the latter a weight of $8/9$.

$$e_f[t_k] = \frac{p_f[t_k] + 8 \cdot p_f[t_{k-1}]}{9} \tag{2.5a}$$

$$p_f = \frac{n_f}{n_{tx}} \tag{2.5b}$$

According to the authors [53], the post-32 ALM implementation uses a different formula to evaluate the frame error rate (see Equation 2.6). This formula, which is also based on discrete time instants (t_k), introduces a new parameter $\delta[t_k]$ which is equal to 1 if the last transmission failed, and 0 otherwise. This introduces a weighted average between the present p_f value and the past one. In this method, the e_f is updated after every frame transmission. Note that, for both pre-31 and post-32 ALM implementations, the HWMP samples e_f on each path addition or update. Note also that the latest version of the *open802.11s* project still applies Equation 2.6 to compute the ALM.

$$e_f[t_k] = \frac{80.e_f[t_{k-1}] + 5}{100} + 20 \cdot \delta[t_k] \tag{2.6}$$

The authors also argument [53] that Equation 2.6 smooth out the fluctuations in the value of e_f. Their results suggest that the post-32 ALM computation method is more efficient than the previous one.

Similarly, Jung et al. [27] address path stability in Smart Grid environments, later extended by Kim et al. [25]. In both works, the authors point out two issues with the IEEE 802.11s standard: the airtime link metric and the route instability in HWMP. With respect to the first issue, the authors point out that the standard leaves open the estimate of the frame error rate. To overcome this issue, they propose that the frame error loss (e_f) should be estimated using the total number of frames (P) submitted to the MAC for transmission, the total number of MAC transmissions (M) of these frames, i.e. including retransmissions, and the maximum retransmission count (R_{max}), according to Equation 2.7:

$$e_f = \frac{M \times \frac{1}{P}}{R_{max}} \tag{2.7}$$

The authors also suggest that, for environments such as smart grids, where the size of frames may vary widely, Equation 2.7 should be modified to take into account the size of the frames as follows:

$$e_f = \frac{\sum_{i=1}^{P} M_i \times \left(1 - \frac{B_i}{B_{max}+B_i}\right)}{P \cdot R_{max}} \tag{2.8}$$

Where M_i is the number of times that frame i is transmitted at the MAC level, B_i is the size of the frame i in bytes and B_{max} the maximum size of a frame in the network (also in bytes). Therefore, the contribution of each MAC transmission is weighted according to its size: each transmission of a maximum sized frame is weighted 0.5, whereas the transmission of very short frames is close to 1. The rationale behind this is that larger frames are more likely to be lost than smaller frames, and therefore ignoring the frame size would penalize links used with larger frames.

Unlike other listed works, other authors [168, 169] point out other reason for path instability in IEEE 802.11s networks rather than the metric computation. Abid [168] investigated the “ping-pong” phenomenon in his PhD thesis and later in [170]. The author points out the underlying rate control algorithms as the primary reason for this phenomenon. After simulating different rate control algorithms (e.g., *Auto Rate Fallback* (ARF), *Adaptive ARF* (AARF), ONOE, *Adaptive Multi Rate Retry* (AMRR) and Constant rate), he concludes that transmission rate adaptation is the principal cause for this phenomenon. Unlike Garroppo et al. [166], Abid suggests that this behaviour may have a positive effect of balancing the load in a mesh network. Following the same idea, Wu et al. [171] introduce a new rate adaptation scheme for IEEE 802.11s networks: the *Effective Rate Adaptation* (ERA). ERA takes advantage of fragmentation in IEEE 802.11 to detect frame loss cause, not relying on *Request to Send* (RTS)/*Clear to Send* (CTS) mechanism as others. When some loss is detected, ERA responds promptly to channel degradation by adjusting the data rate to address the channel degradation and the collision, instead of waiting until the end of a window or period.

An important finding in [53] is that the metric computation is only a partial solution for the path instability problem. Seeking for a complete answer, the authors perform an extensive set of experiments, concluding that a substantial gain can be achieved by fine tuning the behavior of HWMP. Based on these findings, the author’s argument that the most critical factor for path instability is not the link metric computation itself, but how the metric is used by HWMP (or by any other path selection protocol in use). Following this conclusion, up to date, few researches have addressed the path instability of the HWMP protocol by proposing modified (or only based) versions of the HWMP protocol.

Both works [25, 27] suggest a set of adaptations to the standard HWMP operation, introducing a modified version of the HWMP, named *HWMP-Reliability Enhancement* (HWMP-RE). The authors propose to create a "reserve route table" to maintain a set of paths that were previously announced using RANN elements (using the HWMP in pro-active mode) or PREQ elements (using the HWMP in on-demand mode).

The standard HWMP takes into consideration only the current link cost. Conversely, HWMP-RE takes into account multiple reserved paths that have lost the competition to the primary path at that moment, i.e. the new path cost is compared with historical data. Therefore, the authors claim that the HWMP-RE reduces the path fluctuation by selecting a new path only when the current path cost is excessively degraded when compared with the reserved paths in the reserve route table. This table is updated (as a First-In First-Out queue), as well as a better path is selected.

A distinct approach to study path instability in WMNs is introduced by Bezahaf et al. [165]. This work is based on the concepts of dominance and persistence of a path. A path is dominant if it is the most used route between a source-destination pair. The persistence of a dominant path is the average time a path is used before being replaced by another path. In general, their results show a high degree of instability in the dominant paths in the testbed. In other words, the mesh STAs do not use the same path for short periods of time. Another finding is that the larger the number of hops separating a pair of source-destination nodes, the larger the number of different selected paths, losing the notion of dominant path. The drawback of their work is the use of DSDV, which is not suitable for highly dynamic networks. The main reason is that whenever the topology of the network changes, it takes too much time until the network re-converges.

The path instability is only part of the study of routing instability (also called "route flapping") in WMNs. More details about this problem can be found in Ramachandran et al. [172] and Ashraf et al. [173, 174]. These works are not covered in this thesis as they are focused on general WMNs and not specifically in the IEEE 802.11s standard.

2.2.6 Clustering

A generic and widely accepted definition of clustering, in the context of computer networks, is the process of organizing nodes into groups whose members share some properties. In the specific case of wireless networks, the properties are usually related with the distance or transmission range. Regarding the scalability, clustering helps to organize large-scale networks in well-defined groups according to specific properties, allowing to distribute tasks and necessary resources in an optimized way.

As already mentioned, WMNs tend to grow in number of connected nodes, which requires maintenance at all times to guarantee connectivity and efficiency. A successful way to deal with the maintenance of WMNs is to partition the network into clusters which will make the network to be more manageable [175]. Clustering approach has been used broadly in computer networking to reduce the control overhead by imposing a sense of locality among nodes within a cluster. In this thesis, the clustering approach is used as a key building block by locally constraining most of the control overhead. In fact, clustering is applied to path selection and message forwarding protocol, helping to achieve smaller routing tables and fewer route updates. Further, in our solution design (see Chapter 3), cluster concept is treated as a single entity (representing a set of nodes) to improve the message forwarding using a DHT.

Although the solution proposed in this thesis is able to work as many distinct clustering algorithms discussed below, its overall efficiency will be directly affected by the clustering algorithm design. In this sense, algorithms that take into consideration properties such as scalability and low overheads (as it concerns WMNs) are more desirable.

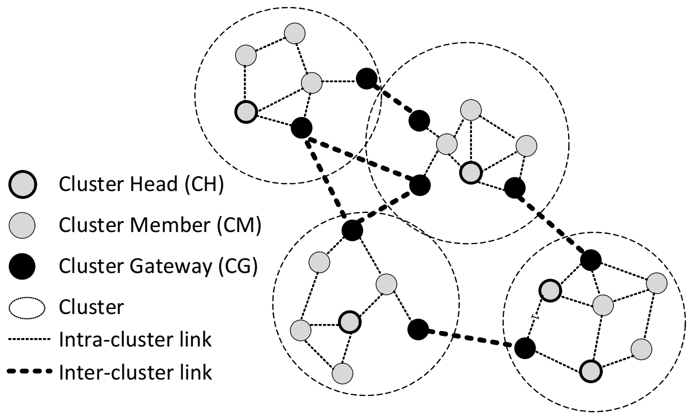


Figure 2.14: Common cluster structure illustration.

For sake of clarity and for better understanding of the cluster algorithms briefly surveyed in this section, general clustering concepts must be revised. Under a cluster structure (see Figure 3.2), mobile nodes may be assigned a different status or function, such as *Cluster Head* (CH), *Cluster Gateway* (CG), or *Cluster Member* (CM) [176]. A CH usually serves as a local coordinator for its cluster. Depending on the algorithm, CHs are also responsible for performing intra-cluster transmission arrangement, and data forwarding; CG is a non-clusterhead node with access (in wireless networks it means that is in the reception range) to neighboring clusters and perform inter-cluster communication; and CM (or just ordinary node) is any non-CH and non-CG node within a cluster. Popular clustering algorithms for wireless networks in use are following surveyed.

Most of the work in clustering for wireless networks has it roots on the works of Ephremides et al. [177] and Parekh [178]. In their works, two simple (but effective in many application domains, such as sensor networks) clustering algorithms are introduced: the *Lowest-ID* (LID), and the *Highest Connectivity Cluster* (HC), respectively. Later Gerla and Tsai [179] extended and compared those two approaches. Both algorithms are based on the assumption that to each node is assigned a distinct *Identifier* (ID). The cluster formation using the LID algorithm is very simple [179]: (i) periodically, each node brodcasts the list of nodes that it can “hear” (in your radio range), including itself; (ii) the node which hears nodes with ID higher than its own ID, it becomes a CH, otherwise the node with the lowest ID (if it is not in case iv) in the list will become its CH and the node becomes a CM; (iii) a node wich can hear two or more CHs becomes a CG; (iv) to guarantee the convergence of algorithm, a node which has already elected another node as CH gives up its role as a CH. Almost the same rules apply to the HC algorithm, except by the CH election decision. Using the HC algorithm, a node is elected CH only if it is the “most highly connected” node (i.e. it has the highest number of neighbor nodes). In case of a tie, the lowest ID rule prevails. Although these algorithms are quite old, their basic ideas are still used in recent dynamic clustering formation works [180]. But their disadvantage is that the clusters are limited, in size, to one hop away. One-hop clusters are not suitable to large networks as a large number of clusters will be created.

Seeking to overcome this limitation, allowing cluster of k size, a new family of so-called "k-hop" algorithms emerged. *Cluster Based Routing Protocol* (CBRP) [181] is a routing protocol designed for use in mobile ad hoc networks that applies such type of cluster formation algorithm. CBRP divides the nodes of the ad hoc network into a number of overlapping or disjoint 2-hop clusters in a distributed manner. An enhanced version of the CBRP to mesh network scenarios was presented in [182] - the *Mesh Cluster Based Routing Protocol* (MCBRP). The main changes includes: the assumption of bi-directional links; a new cluster node state to address the gateway role; and the use a mechanism for dynamic address assignment with duplicate address avoidance. To hold this assumptions, most of control frames had to be changed. The general concept of k-hop clustering was introduced by Krishna et al. [183]], in which a k-cluster is a subset of nodes that are mutually reachable by a path of at most k hops. By this definition, k is the distance between any pair of members within a cluster. Moreover, the algorithm produces overlapped clusters without a CH node rule. In [184] the authors describe several k-hop clustering algorithms for mobile ad hoc networks. The authors assume the presence of a CH node to generalize the k-cluster definition so that a cluster contains all nodes that are at distance at most k hops from the clusterhead, which also implies in the use of CG nodes to provide connectivity between CHs. Most of the recent research in clustering for wireless networks uses this second definition, this work included. In their work, the authors also proposed an unified framework for a clustering algorithm in wireless networks, where each node has a weight that indicates its suitability for a CH role, based on a general set of weighted parameters (namely speed, degree, power and energy-left) configurable according to the application.

In summary, clustering has several advantages over flat networks, especially for large-scale setups. In a clustered network, a clusterhead can coordinate transmission events within the cluster range (for example, limiting the scope of messages by controlling its time-to-live counter) to reduce transmission collisions, it can also serve as a virtual backbone for inter-cluster routing, reducing the routing overhead outside the cluster. Therefore, when topology changes, only the nodes in the corresponding clusters need to update the topology information. As a consequence, local changes are not propagated through the entire network, reducing the amount of information exchanged between nodes and thus greatly improving the scalability. Is exactly under this perspective that clustering is applied in this thesis.

An exhaustive survey of clustering algorithms in wireless networks is out of the scope of this thesis. For more detailed information, interesting surveys can be found in [175, 176, 185–188].

2.2.7 Distributed Hash Table (DHT)

The Distributed Hash Table (DHT) concept arises from the Structured P2P overlay networking's field. In contrast to Unstructured P2P systems, in which the content is placed at random peers, in the Structured P2P overlay networks, the content is placed at specified (by some deterministic calculation) locations. This feature makes it more efficient to retrieve the content. In this context, a DHT is used as a substrate of the overlay network to provide a number of functionalities such as information distribution, location service, and location-independent identity. DHT overlays have been established as an effective solution for data placement and exact match query routing in scalable network infrastructures.

The main idea behind DHT is to apply a hash function to distribute content among a group of nodes in a network. The same hash function must be used to locate the node that stores the desired content. Examples of commonly applied hash functions are the *Secure Hash Algorithm version 1* (SHA-1) and the *Message-digest algorithm version 5* (MD5). This method allows the efficient publication/retrieval of data, through the association of a key, or identifiers, to each data element. The space of identifiers is divided among the nodes that form the DHT and the pieces of information are mapped into that space, typically using a hash function. Each network node is responsible for all the information pieces mapped to its identifier.

The nodes participating in a DHT use a physical communication network, such as the Internet, to exchange messages. However, they also create a new network, superimposed upon this physical network, called the overlay network. This overlay network has its own topology and routing protocols that are specified by the DHT. Thus, each node has its own neighbors in the DHT, that is, nodes to which they are directly connected in the DHT, even if in the underlying network the nodes are several hops away. In essence, DHTs are multi-hop networks, where each node forwards a message to the neighbor node that is closer to the message's destination.

A DHT is a scalable structure that allows to find the host of desired content rather quickly. It guarantees that if the content exists in the system, its host will be found. However, to manage and maintain a DHT requires extra effort. In particular, nodes usually have to maintain a neighborhood table. As the number of entries in that table increases, the performance of the search on the DHT also increases, but so does the cost to maintain the DHT. In order to balance the cost of these operations, the neighborhood table may keep $\log N$ entries, where N is the number of nodes on the network, ensuring that the search cost will be $\log N$.

In the last decade, much effort has been put in the development of new scalable structured P2P overlay networks. In this context, DHT networks have gained popularity as they are the underlying support for the organization of these networks. Among a number of proposals, the most prominent are *Content Addressable Network* (CAN) [189], Pastry [190], Chord [191], Tapestry [192], Kademlia [193], and Viceroy [194]. The key differences among all these proposals are the data structure geometry, the distance function, and the routing/searching algorithm. The geometry is a graph structure that inspires a DHT design. For example, Chord maintains a ring geometry; Tapestry and Kademlia use a tree-like data structure; Viceroy emulates a butterfly structure; CAN employs a $d-dimensional$ Cartesian space, also know as Hypercube; while Pastry implements a hybrid tree-ring geometry. The distance function depends on the geometric structure and determines the distance between two nodes in the DHT. The routing/searching algorithm specifies the rules for selecting neighbors and for routing queries based on the distance function. A detailed survey and comparison of P2P overlay network schemes, including all DHT aforementioned, can be found in [195].

Beyond the P2P's field of study, many researchers [196–200] have proposed to make use of the scalable properties of a DHT in providing an efficient implementation for routing and discovery in wireless networks. As a result, many approaches have proposed the integration of DHT with ad hoc routing protocols to provide indirect routing in MANETs. Saumitra et al. [201] compares the most common design choices of integration: the layered approach and the integrated approach. In the former, the DHT scheme is directly layered on top of the MANET in the same way it is layered on top of the Internet stack (i.e. as an application). In the latter, the DHT scheme is coupled to the routing protocol. When it comes to the wireless network field, a straightforward layering usually leads to low performance and scalability, mainly due to the expensive maintenance of traditional DHT schemes. A complementary cross-layer approach is presented in [202].

There are a few proposals to integrate the routing protocol (physical network) and the DHT structure (overlay network) in order to create a scalable indirect routing functionality at the network level for MANETs Zahn and Schiller [196]. *Mobile Ad-Hoc Pastry* (MADPastry), proposed in [196], integrates the reactive AODV routing protocol and the Pastry DHT at the routing layer. Like in Pastry, MADPastry considers the physical location of the nodes in the MANET. MADPastry combines nodes in clusters, where each cluster has its own overlay id, and keeps three routing tables (Pastry Routing Table, Pastry Leaf Set and AODV Routing Table). To mapping the cluster concept, the DHT address space is previously segmented into slots of ids using Random Landmarking [203]. Caesar et al. [197] proposed the *Virtual Ring Routing* (VRR). VRR is a DHT-inspired routing protocol that works directly on top of the link layer (but still at routing layer, applying a crosslayer approach) providing both point-to-point network routing, and DHT functionalities. The VRR maps physical nodes into a virtual ring ordered by node identifiers, and keeps only one routing table. Ekta [204], like MADPastry, is based on Pastry, but it uses DSR [100] for route discoveries. Actually, Ekta is taken as the first attempt at merging the application and network layers to improve the performance of a DHT. Unlike MADPastry, Ekta does not explicitly consider physical proximity in its DHT. DHT-OLSR [205] is another example of attempt to merge the routing protocol and the key-based lookup. DHT-OLSR utilizes MADPastry as DHT substrate integrated with the OLSR protocol.

Fuhrmann et al. [198] proposed the *Scalable Source Routing protocol* (SSR), which like VRR tries to integrate the overlay network in the network layer. The difference is that whereas VRR does not assume the use of any specific routing protocol, SRR combines the DSR routing protocol in the physical network with Chord routing in the overlay network. A similar approach, called MA-Chord, applied to cluster-based routing is proposed by Meng and Ji [199]. MA-Chord is a DHT substrate particularly designed for mobile Ad hoc networks that combines AODV routing and Chord overlay routing at the network layer to provide efficient key-based routing in MANETs.

MeshChord, proposed in [200], is a Chord specialization applied to WMNs, where characteristics of this type of networks, such as the availability of a wireless infrastructure, and the 1-hop broadcast nature of wireless communication are taken into account while performing key lookup. In MeshChord, routers are assumed to be stationary. In the MeshChord architecture, when a mesh client needs to find a certain resource, it sends a key lookup message to its reference mesh router (a mesh router within its transmission range). Upon receiving a lookup message, the reference router forwards the resource request in the DHT overlay according to the rules specified by the Chord protocol.

In native structured P2P overlay networks, the lookup is performed at the application level. Early DHT-based routing protocols proposed to ad hoc networks usually follows the same approach. More recent proposals integrate the DHT to the routing protocol at the routing layer. Considering the architectural design of the IEEE 802.11s standard, where the path selection and message forwarding are performed at the link layer, the solution presented in this thesis (see Chapter 3) integrates the DHT lookup at the MAC level.

An interesting survey on scalable DHT-based routing protocols for ad-hoc networks can be found in [206].

2.3 Summary

The related works described herein lays the foundation for the contributions of this thesis. The analysis of related literature revealed that the problem of scalability in wireless networks becomes even more critical in WMN deployments, mainly due to the higher node density that increases the interference. Although the IEEE 802.11s standard has been developed for small/medium scale networks, a set of works aforementioned suggest the potential use of this technology for large application scenarios, with proper adaptations. The contributions from this thesis are build on gathering well-known concepts such as Clustering and DHT. In this chapter, some previous works that successfully explored theses concepts to scale ad hoc networks were presented. It must be highlighted, that most of the works targeted MANETs, and applied these concepts separately.

CHAPTER 3

DHT-based Cluster Routing Protocol (DCRP) Design

"The price of success is hard work, dedication to the job at hand,
and the determination that whether we win or lose,
we have applied the best of ourselves to the task at hand."

Vince Lombardi

This chapter introduces the DHT-based Cluster Routing Protocol (DCRP) architecture. DCRP is a Path Selection and Message Forwarding protocol explicitly designed for use in IEEE 802.11s Mesh Networks. DCRP integrates the functionalities of the Distributed Hash Tables (DHTs), the scoped communication provided by the clustering scheme, and the Hybrid Wireless Mesh Protocol (HWMP) to provide a scalable solution to these networks.

3.1 Architectural Overview

The proposed DHT-based Cluster Routing Protocol (DCRP) resorts to a three-layer architecture to provide a scalable solution for IEEE 802.11s wireless mesh networks, as illustrated in Figure 3.1. The first layer represents the physical IEEE 802.11s WMN itself. At this layer, nodes (or mesh STAs) are identified by their unique MAC address and implement most of the mechanisms recommended in the standard with a slightly enhanced version of the HWMP protocol (to be further explained). At the second layer, nodes are organized in clusters of k-hop ratio (i.e. by nodes up to k-hops away the central node, the cluster head). Here, clusters are allowed to overlap and hence share boundary nodes (hereinafter called as border nodes). At the top layer, the DHT layer, nodes are organized into a DHT structure which is used as a lookup service. At this layer, nodes are identified by a virtual unique identifier, created by a hash function applied to its physical address. In other words, the MAC addresses of the underlay network are mapped to the space address of the overlay network (DHT).

DCRP integrates clustering with DHTs to enhance the scalability of routing in 802.11s networks. Clustering allows the use of hierarchical routing and therefore to reduce the amount

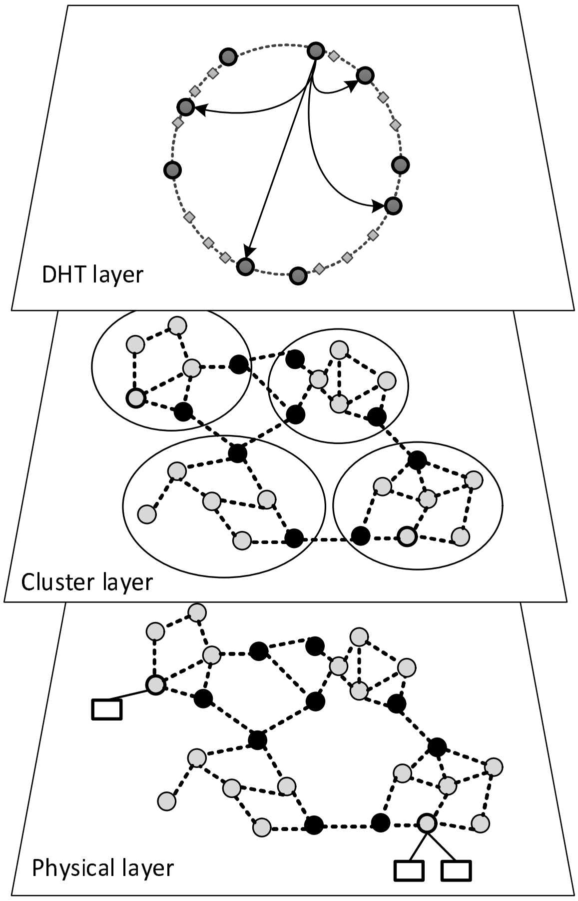


Figure 3.1: DCRP depicted in a three-layer architecture.

of routing traffic. The routing information that is not exchanged through the routing protocols is kept in DHTs, which supports a rather efficient access.

Although at a high level the DCRP architecture can be represented as in Figure 3.1, at an operation level all layers are integrated as explained in the following sections.

3.2 The Physical Layer

At this layer the nodes perform the tasks recommended in the standard document [45] to create an IEEE 802.11s WMN, such as the peering task. In DCRP, a parametrised timeout is defined before the clustering phase start. The purpose of this delay is to give time to the nodes peering with their neighbors (i.e. wait until the network topology has been considered stable enough). This approach is needed because the clustering algorithm to be applied must consider only neighbor peers instead of all the node's vicinity.

Regarding the protocol operation, in this layer, all mesh STAs runs an enhanced version of the Hybrid Wireless Mesh Protocol (HWMP), as further explained below.

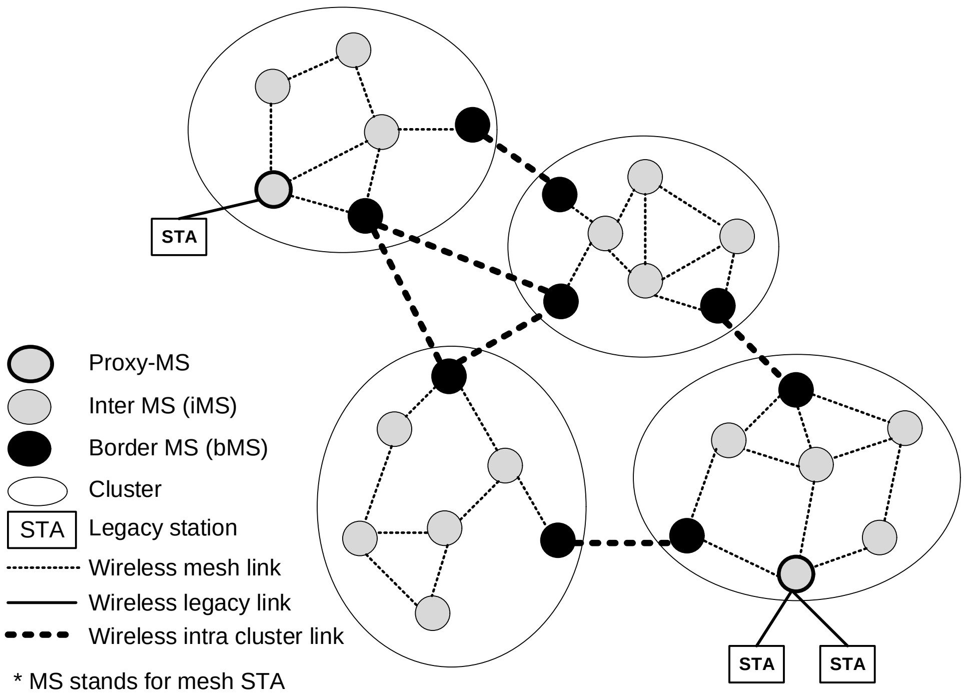


Figure 3.2: DCRP architecture elements.

3.3 The Cluster Layer

The performance of cluster-based routing protocols to MANETs have been well studied (as mentioned in Session 2.2.6). Although there exist several cluster schemes proposed to MANETs, only few proposals to WMNs can be found. A desirable clustering scheme for WMNs should take into account the heterogeneity of node types and most importantly be able to identify and prioritize stable links and nodes. Unfortunately, this requirement cannot be achieved in a few communication rounds, as the instability becomes observable after some time of network operation (mainly due to the interference caused by multi-hop simultaneous transmissions). For that reason most proposed clustering approaches to WMNs are adaptations from MANETs.

Recent work in MANETs clustering usually address the mobility of nodes, which require sophisticated and complex algorithms. In the design of the DCRP there is the assumption that nodes have limited or (usually) no mobility at all. This assumption is quite fair and is also taken by the IEEE 802.11s standard and most of the related research work. Therefore, in practice, DCRP architecture is very flexible regarding the clustering scheme to be adopted. There are only three main requirements: the cluster scheme must create clusters with more than one-hop size, it must create overlapped clusters, and only peers must be considered neighbors. The first requirement is needed to avoid creating a large number of small clusters as the network size increases. The second is needed to implement our proposed inter-cluster communication through border nodes (also known as gateways). Finally, the third requirement is needed to ensure that the neighbor is reachable according to the IEEE 802.11s Mesh Peering Management (MPM).

To create the clusters, DCRP uses a generalization of the cluster algorithm described in [184] so that a cluster contains all nodes that are at distance of, at most, k hops from the

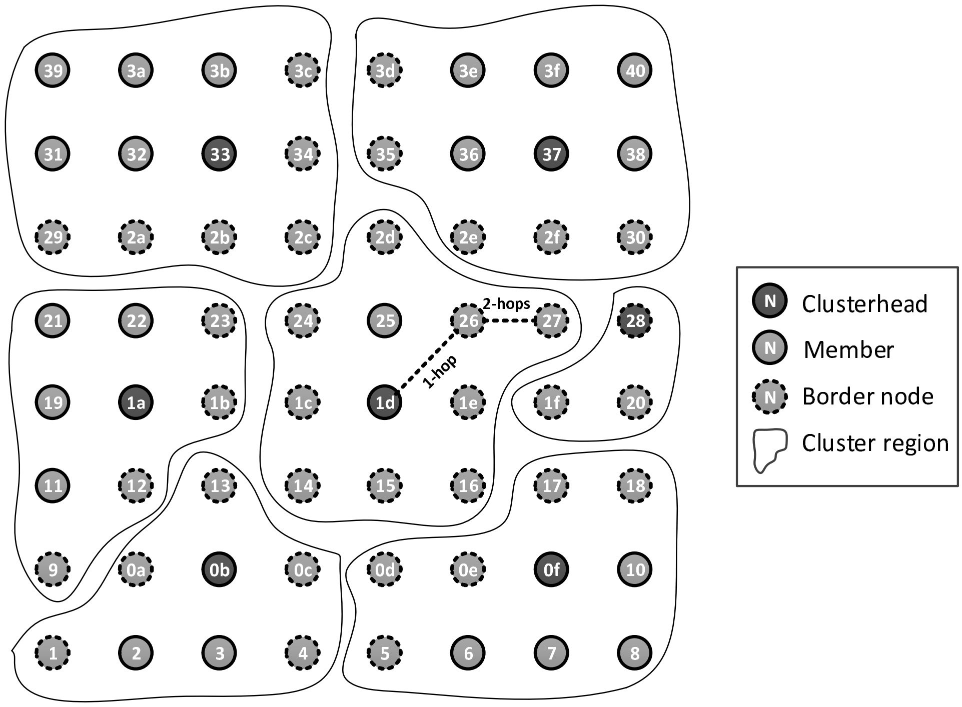


Figure 3.3: Illustration of a set of DCRP clustered nodes in a grid topology with k=2.

clusterhead (considering that each pair of nodes at 1-hop is a valid IEEE 802.11s peer). The Figure 3.3 illustrate a set of DCRP clustered nodes in a grid topology, using $k = 2$. In our protocol, there are four possible states for the node: MEMBER, ISOLATED, CLUSTERHEAD and BORDER. A cluster head (a node in CLUSTERHEAD state) is hierarchically the most important node in the cluster and its primary responsibility is to communicate with all the nodes of its own cluster. Moreover, as we have overlapped clusters, this node must be also able to communicate with the nodes of other clusters, which can be done directly or through border nodes (a node in BORDER state). Thus border nodes act as gateways to other clusters. A member (a node in MEMBER state) is a regular clustered node that is neither a cluster head or a border node (i.e. they do not have neighbors belonging to different clusters). A node in the ISOLATED state means that it is a non-clustered node. Initially all nodes are in the ISOLATED state.

As shown in Figure 3.2, mesh STAs physically close are grouped in clusters. Most mesh STAs in a cluster communicate only with mesh STAs in the same cluster, whereas a few mesh STAs in a cluster communicate both with mesh STAs in the same cluster and mesh STAs in other clusters. Additionally, the cluster related notation used in DCRP is illustrated in Figure 3.3. *Internal mesh STA* (iMS) is an ordinary node in the cluster (with MEMBER status). *Border mesh STA* (bMS) is a border node (with BORDER status), connecting its own cluster to one or more neighbor nodes. *Proxy mesh STA* (pMS) is an AP collocated with a gate or portal (as explained in Figure 2.1). This type of node acts as proxy to non-mesh STAs (just STA in DCRP notation).

Cluster formation is triggered by the addition of a new node at any time. When a node starts-up, the node waits for a defined random time period (in order to avoid collisions) and then sends a broadcast (it can also send in multicast) cluster head query. This query is sent to the k-neighbouring nodes, i.e., to the k-hops away nodes (e.g. k being set to 3 by default in our experiments). In a parallel way, the new node initialises its topology data table. If after a defined timeout no reply is received (the topology data table is empty), the node changes its status ISOLATED to CLUSTERHEAD, promoting itself to cluster head. This situation of an isolated cluster head is the worst case in any cluster scheme. It can be alleviated through network planning to ensure that no node becomes isolated. Alternatively, after checking its parameters, a cluster head either refuses or admits the node in question into its cluster. In the second case, the cluster head reserves a place for the member and responds with an acceptance message.

To provide additional reliability and better performance, it is desirable to have cluster heads in adjacent clusters at most $2k$-hops from each other and a small degree of overlap between clusters. Although border nodes increase the reliability by providing multiple paths to inter-cluster communication, a high number of border nodes in the same cluster can jeopardize the overall performance. After the cluster formation phase, it is assumed that all nodes are aware of its *Cluster Identifier* (CID) and its related cluster head. This version of DCRP uses the MAC Address of the cluster head as CID.

3.3.1 Cluster Tables

DCRP clustering scheme relies on a set of cluster tables that are used to support both the cluster creation and maintenance, and intra-cluster communication as well, as illustrated in Figure 3.4. Each DCRP node maintains at least two tables: a NeighborTable[1] and a MemberTable. The former is used to store information about neighbors in the range of k-hops. This table is mainly used for cluster formation and cluster election. Considering that, as aforementioned, in the DCRP only peer neighbors are considered, and the content of this table can be fulfilled by information from the Mesh Peering Management (MPM) module. The latter stores information of the effective known neighbor members of the same cluster. To avoid the excessive exchange of control messages in the cluster, this table stores the direct (1-hop) neighbors. Additionally, to improve the performance of the intra-cluster communication, new entries about members far from this can be added by overhearing frames from other directly connected peers. That is the case of the entry for node 27 at the MemberTable of the node 25 in the Figure 3.3, which was added by overhearing frames sent through node 26.

Border nodes must maintain an additional table: the BorderTable. Every time that a border node receives (or simply overhears) a frame from a peer of another cluster, a new entry is created in this table. In other words, in this table the border nodes store information about all clusters that it overlaps with, and the address of the peer belonging to the other clusters (used as next hop in direction to this cluster). It must be noted that this table can store more than one entry for the same cluster. When combined with a metric of link quality, congestion, or distance in hops to the cluster head (in the overlapping cluster), this table can be useful to balance the loading in the inter-cluster communication. These enhancements have not been explored in this thesis.

Cluster head nodes keep a complete version of the ClusterMemberTable. Additionally, cluster head nodes maintain a NeighborClusterTable with informations about its neighbor clusters. In fact, this table is a compilation of the informations kept by all border nodes in their

[1]This table is not illustrated in Figure 3.3, however its content is very intuitive.

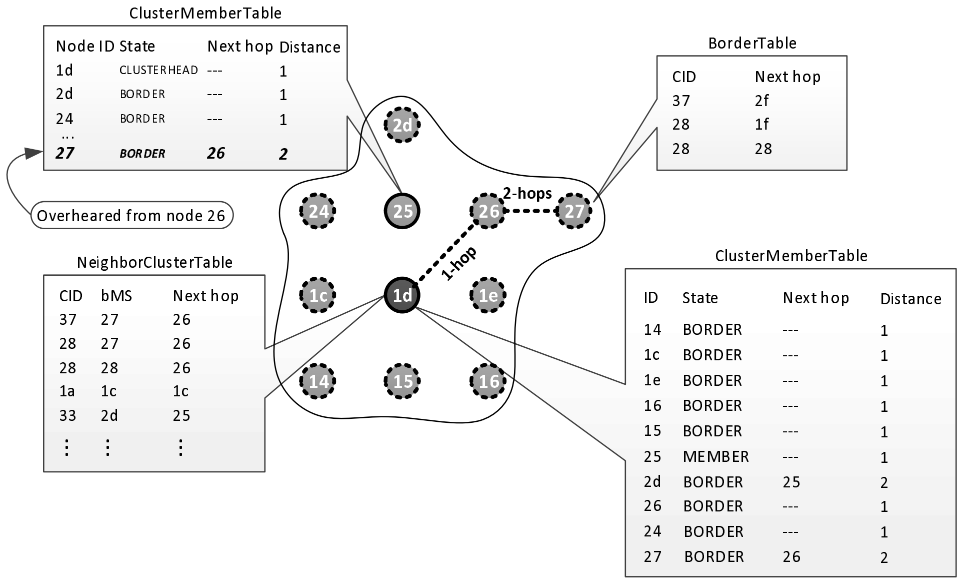


Figure 3.4: Example of tables kept by DCRP nodes within the cluster which have the node $1d$ as cluster head.

BorderTable, but including the gateway (the border node address) and the next hop in that path.

3.4 The DHT Layer

The current version of DCRP is inspired in a Chord [191] DHT scheme, which is considered to be one of the earliest P2P algorithm based on a DHT[2]. Therefore, DCRP inherits the shape of the key space and the rules used to allocate objects onto participant nodes. It must be noted that DCRP does not replicate key values over the DHT due to the prohibitive cost of such operation in a wireless environment. This means that only one DHT node with the closest key on the ring will store this value.

In order to form a Chord ring, usually the SHA-1 algorithm is used to hash and map the node IDs and also to hash the values and distribute the resulting keys to the nodes. The result is a seemingly random and of consistent distribution (consistent hashing) of keys and node IDs, making this scheme quite desirable to use. IDs for data items to be stored in the DHT are created by applying the same consistent hashing function and therefore both node and data IDs fall into the same address space. Based on consistent hashing, each node keeps a small routing table, also known as a finger table. The finger table will be automatically updated as nodes enter or leave the Chord ring, without needing to re-hash and re-map the entire ring structure. This arrangement allows a DHT to scale to extremely large numbers of nodes and to handle continuous node arrivals, departures, and failures.

Although the original Chord has been designed to run at the application layer, in the DCRP it was integrated at layer 2. Briefly, in a Chord DHT, each data item and node is associated

[2]The DHT scheme likewise the clustering scheme is designed as a building block, thus can be easily decoupled and replaced by any other scheme.

to an identifier using a hash function (usually a consistent hashing, as explained above). The data item identifier is named key. To forward resource requests, nodes form an overlay routing network by maintaining neighboring keys. In a Chord scheme, nodes are ordered and linked based on its IDs, forming a ring with clockwise increasing nodes' IDs. Each Chord overlay network is responsible for all preceding keys. Therefore, any object with key k is mapped to (and maintained by) node $successor(k)$ (the successor of the key k) whose ID_{node} is the smallest identifier such that $ID_{node} \geq k$. In order to guarantee the consistency of the ring, each overlay node maintains few local information about its successor nodes[3]. This table, called finger table, has a maximum of m rows (for a $m-bit$ identifier), where each row i stores a finger to the $ID + 2^{i-1}$ successor of the node, where $1 \leq i \leq m$ (using modular arithmetic). Every client searches the keys by using its finger table, as illustrated in Figure 3.5. A complete description of the Chord scheme and its routing tables maintenance is not the focus of this thesis. More detailed information about it can be found in [191].

To create and assign IDs to the nodes, first the MAC address of each node is hashed. This produces a message digest that has a fixed size of 160 bits using SHA-1. It does not matter where any of the nodes are physically located; they are placed along the ring structure according to their 160-bit address space. For sake of simplicity, hereinafter all figures and descriptions regarding the DHT node IDs will be represented using a CRC-32 hash function, which produces a smaller ID. For example, the result of *hash(00:00:00:00:00:01)* is the ID *2EFD52FA* using CRC-32, while the SHA-1 produces the ID *DE8190E673F06CA7781447C0B3210560327FEA8D*.

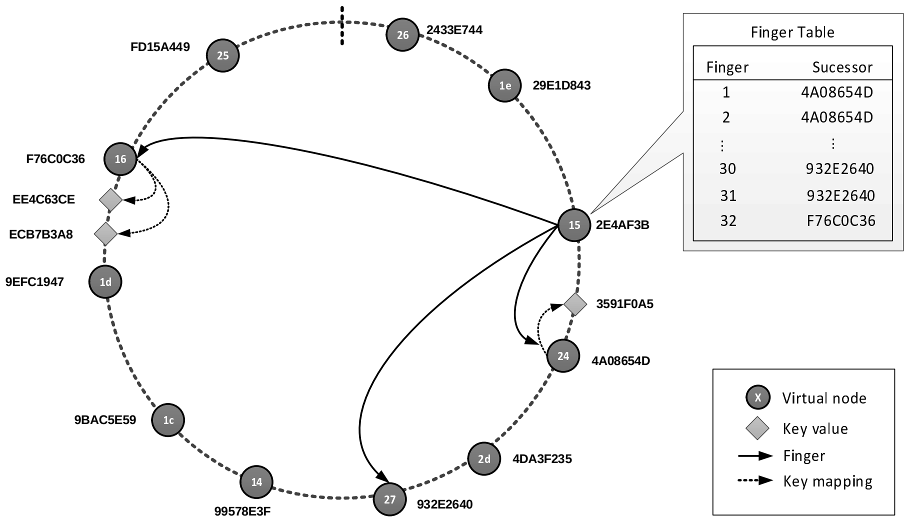


Figure 3.5: Illustration of a DHT overlay with the finger table for the node 15 with overlay ID 2E4AF3B.

Whenever a node in the network searches for the key k using a LOOKUP operation, the network address (physical address in the underlay network) associated with the successor node will be necessary. For this reason, the underlay network runs a routing protocol. In DCRP, the HWMP protocol is used.

[3]Some enhanced versions of Chord uses a bi-directional search and therefore maintains two finger sets with informations about successor and predecessor nodes.

3.4.1 DHT Tables

Seeking to answer the research question *"How to manage non-mesh station information in an efficient and robust way?"*, presented in Session 1.2, the DCRP proposes that any information about non-mesh STAs (including information about its proxy mesh STA) must be stored at DHT structures. The main reason is to replace the expensive current standard mechanism (and other proposals found in the literature) by an elegant and efficient mechanism of distributed lookup. Following, the current standard mechanism and other proposals found in the literature are briefly explained.

	Element ID	Length	PXU ID	PXU Originator MAC Address	Number of Proxy Information (N)	Proxy Information #1	...	Proxy Information #N
octets:	1	1	1	6	1	11,15,17 or 21		11,15,17 or 21

	Flags	External MAC Address	Proxy Information Sequence Number	Proxy MAC Address	Proxy Information Lifetime
octets:	1	6	4	0 or 6	0 or 4

Figure 3.6: Standard PXU information element format.

	Element ID	Length	PXU ID	PXU Recipient Mac Address
octets:	1	1	1	6

Figure 3.7: Standard PXUC information element format.

According to the IEEE 802.11s standard document [45], mesh STAs only exchange path selection and forwarding information that contain addresses of mesh STAs that belong to the MBSS. However, the destination station may be outside of the MBSS, and therefore a proxy mechanism is required. For this purpose, the standard document defines a basic mechanism that introduces two new IEs, and the corresponding frames, to carry proxy information: the *Proxy Update* (PXU) (see Figure 3.6) and the *Proxy Update Confirmation* (PXUC) (see Figure 3.7). Briefly, the PXU element contains one or more mappings of an external address to a mesh proxy address. PXUC is used to acknowledge a received PXU. The PXU and PXUC IEs are transmitted in a Proxy Update and Proxy Update Confirmation frames, respectively. These frames must be individually addressed. These frames may contain multiple IEs when needed.

Although PXU IEs can comprise multiple mappings and can be incorporated in HWMP messages (i.e. proxy information can be conveyed in PREQ/PREP/PERR IEs), the mechanism is still not scalable enough, as it can potentially create a large number of proxy information messages (or simply large HWMP frames for the case of proxy information to be included in the HWMP IE) as the number of external stations increases.

Early draft versions of the IEEE 802.11s standard document defined a proxy information maintenance scheme for RA-OLSR, which was at the time an optional path selection mechanism: the so-called *Association Discovery Procedure* (ADP). The ADP uses two sets of proxy information: the *Local Association Base* (LAB), which stores a list of external addresses (external STAs) which are associated to the AP collocated with mesh gate STA or behind a portal; and the *Global Association Base* (GAB), which is a sort of all LABs merged in only one table. The construction of GAB is based on dissemination (using flooding) of *LAB Advertisement* (LABA) messages. The cost of maintenance for the LAB and GAB tables is prohibitive to large deployments.

The RA-OLSR proxy information maintenance scheme inspired other works [207–209]. Okada et al. [207] proposed a handling scheme, in which every mesh gate and portal keep only the part of association information, in an on-demand manner, rather than maintaining the whole association information in the mesh network, as in the original RA-OLSR scheme. In order to populate the LAB and GAB, the scheme relies on the exchange of unicast messages containing *STA Request* (SREQ) and *STA Reply* (SREP) elements. Liang in [208, 209] introduced the *Simple yet Effective Scheme* (SimYES) as a simple scheme for the maintenance of the proxy information. The SimYES takes advantage of the piggybacking strategy to include proxy information on ordinary frames, reducing the control overhead.

A distinct approach is introduced in Yang and Kim [210]. In this work, the authors proposed a method for station association and frame forwarding based on MAC subnet addressing, without the use of any proxy information or frames. The main idea is to create virtual MAC addresses consisting of two parts, one derived from the proxy mesh gate and another derived from the AP collocated with the proxy mesh gate.

The proxy information maintenance in the 802.11s standard is still an open research question. This thesis addresses this issue by proposing to store and manage proxy information through the use of DHTs. For this purpose, and considering the locality of the information, DCRP proposes the use of two structures: the intra-DHT and the inter-DHT.

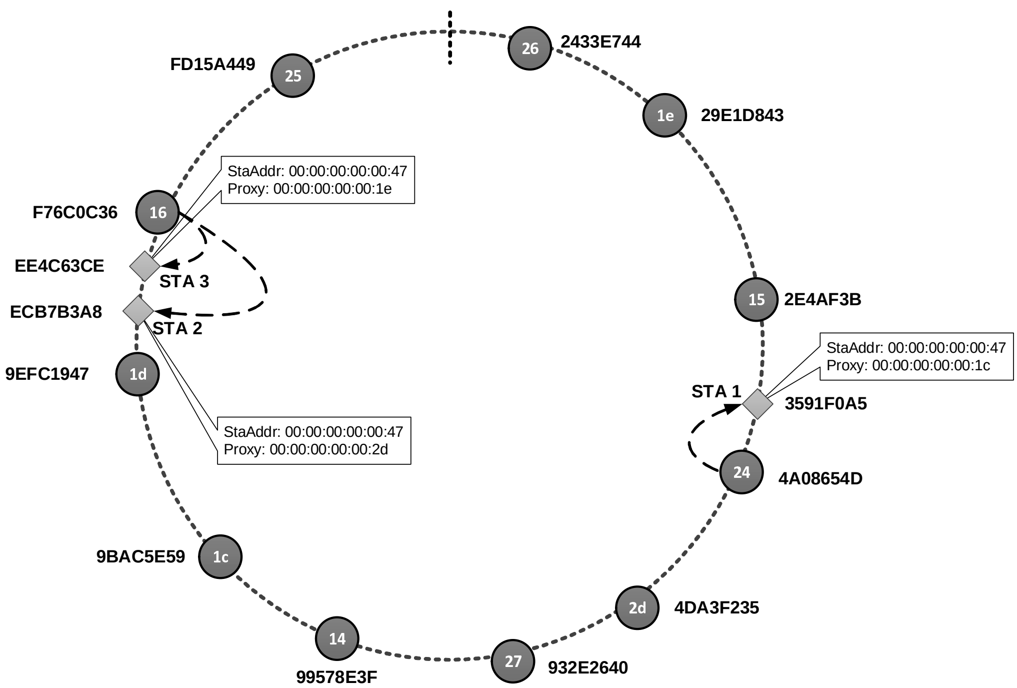


Figure 3.8: Illustration of a DCRP intra-DHT where mesh STAs are virtual nodes in the DHT and non-mesh STAs are stored as key values. In this example, the DHT node with ID FD15A449 (the mesh STA 25) is responsible for the keys 2433E744 and 2433E744.

Intra-DHT Table. Each mesh STA in a cluster is a node of the intra-cluster DHT (Intra-DHT) for that cluster and keeps the entries (as key values) for the non-mesh STAs of which it is the *Key mesh STA* (kMS), in this case the intra-kMS. The keys maintained in the intra-DHT map the id of a node to the MAC address of its Proxy mesh STA (pMS). An example of intra-DHT for a DCRP cluster is illustrated in Figure 3.8.

Inter-DHT Table. To enable the inter-cluster communication, each bMS is also a node of a mesh-wide DHT overlay: the inter-DHT. In this overlay, nodes maintain entries for nodes (either mesh STAs or non-mesh STAs) of which it is the kMS, more specifically the inter-kMP. The entries of the inter-DHT map the id of a node to the MAC address of its proxy-bMS, i.e. a bMS in that node's cluster.

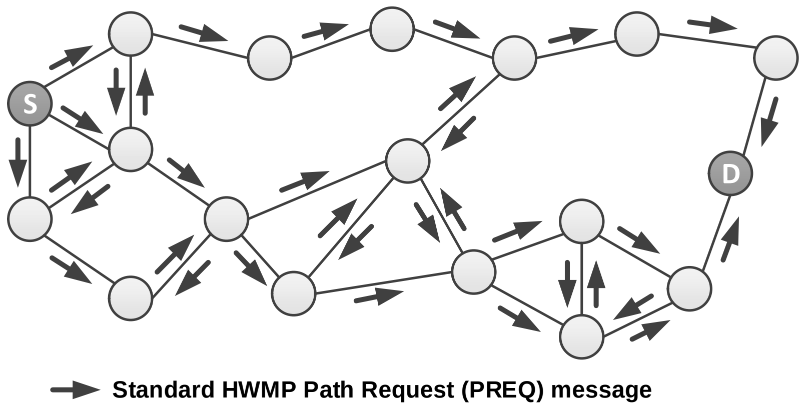
In DCRP, populating these DHTs with entries is very simple. When a mesh STA finishes its cluster membership, it adds itself in its intra-kMP, by sending to that inter-kMP an ADD-ENTRY message. When a non-mesh STA associates with a mesh STA (acting as an AP collocated with a mesh gate, or a mesh portal) the latter adds the entries for proxy mapping to both the intra-DHT and the inter-DHT, by sending an ADD-ENTRY message to each of the intra-kMP and the inter-kMP of that station respectively.

In order to support the forwarding of messages (e.g. ADD-ENTRY, and LOOKUP) in DHT overlay networks, a mesh STA relies on its HWMP instance, setting the appropriate scope (global or local). Most likely, neighbor nodes in the overlay network are several physical hops away. Thus, forwarding of messages between two neighbor nodes in the DHT overlay network is done by forwarding the message from one node to the next along the path between the two DHT nodes in the physical network.

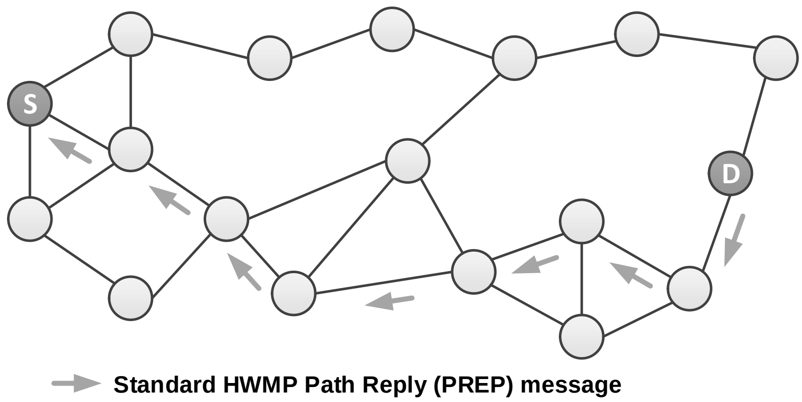
3.5 Path Selection

As aforementioned, DCRP implements the principles of HWMP for path selection and forwarding of messages. In this thesis only the reactive mode of HWMP (see Section 2.1.4.1) is used. Further optimizations must be done in order to integrate the DHT scheme with the pro-active mode. The major scalability issue with HWMP in reactive mode is the excessive use of broadcasted control messages.

Excessive broadcast communication is one of the major concerns in large-scale WMN deployments. The Figure 3.9 illustrate a common path discovery mechanism used in HWMP. Figure 3.9(a) illustrates the scenario of a source node S trying to discover and stablish a path to a destination node D. As illustrated, following the protocol, a Path Request (PREQ) message is sent in broadcast from S towards D. In the WMN, every intermediary node (neither source or destination of the message) rebroadcasts the message to its peers. This creates a broadcast storm that can reduce and limit resources such as channel resources and device resources in the WMN [211]. Moreover, by reducing control traffic, more data traffic can be transmitted. Although, in response to a PREQ, a Route Reply (RREP) is sent in unicast (see Figure 3.9(b)), the multi-hop nature of a WMN can result in multiple PREP messages (with distinct metric values). Additionally, in case of error in the path discovery (caused by an invalid route entry, or the destination is simply unreachable) a Path Error (PERR) message is sent back to inform the error.



(a) PREQ is sent in broadcast.



(b) PREP is sent in unicast using the reverse path.

Figure 3.9: Illustration of path discovery of an unknown destination using standard HWMP in reactive mode.

Although this request/reply scheme has been proved to be acceptable for a small number of nodes, when it comes to large-scale WMNs it has a significant impact on the scalability of the network. As a solution to reduce the overhead caused by the HWMP control messages, DCRP explore the structure provided by the Cluster layer to allow a query localization and the local repair of the HWMP.

However, instead of introducing new messages to the standard HWMP, an enhancement of this messages is proposed. The main idea is to control the locality of the messages with minimal modifications. Therefore, additional fields regarding the Cluster Identifier (CID) and the locality were introduced to PREQ (see Figure 3.10),and PREP (see Figure 3.11) Information Elements (IEs). Actually, to indicate the locality, DCRP uses the already existing field Flags of HWMP messages. More specifically, only one Reserved "bit" is used as flag for locality, where the value 0 indicates a local scope and the value 1 indicates a global one. The PEER IE (see Figure 3.12) remained original as any error must be always globally reported. For this first version of DCRP the MAC Address of the cluster head node is used as Cluster Identifier (CID). Here, the CID is used to control the intra cluster communication instead of the simple manipulation of the Time-to-Live (TTL) field value (such as in [205]). The reason to that clusters are not a perfect region with ratio of k-hops.

These modifications allows to reduce the number of network-wide PREQ messages initiated by the source node if both the source and destination nodes belong to the same cluster. The control of the HMWP messages scope (Local or Global) reduces the possibility of having broadcast storms.

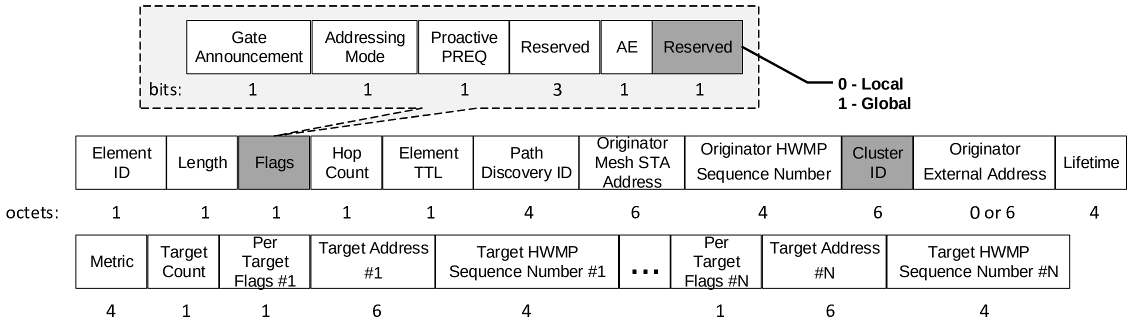


Figure 3.10: Enhanced PREQ information element format.

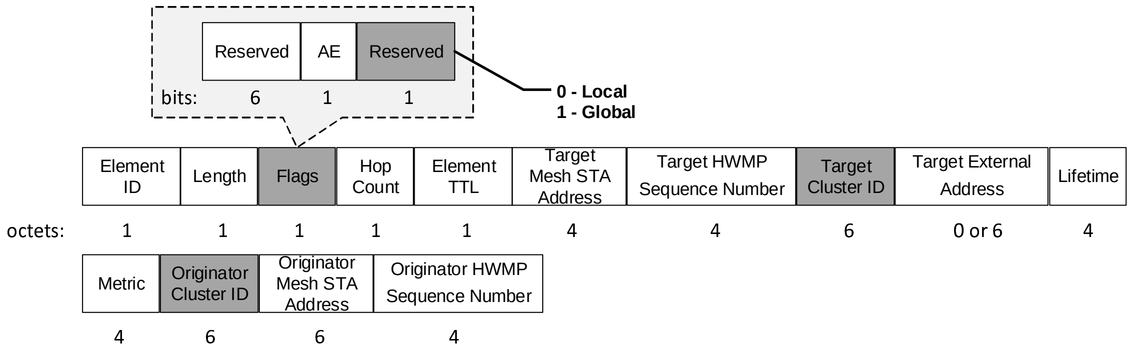


Figure 3.11: Enhanced PREP information element format.

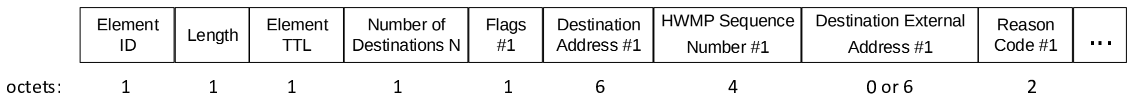


Figure 3.12: PERR information element format.

In DCRP, only border nodes are allowed to set the locality flag to Global value in the Path Selection. The other nodes within a cluster always address its frames as Local. When the locality flag of a message is set to Local, mesh STAs only forward the message if the message's CID field is the same of its own CID. Otherwise, they just drop the message. Local scoped messages allows to constrain the messages in the range of the cluster, minimizing the interference between clusters. From the cluster point of view, using local messages, the physical layer (in DCRP architecture) operates as an isolated IEEE 802.11s WMN. Local messages allows to create the necessary paths between mesh STAs within the cluster.

Upon receiving a message with the flag set to Local and the message CID distinct of its own CID, a mesh STA must drop it.

Global scoped messages are used to cross multiple clusters in wide-range (inter-cluster) communications. In practice, these messages are local messages that are received by some mesh border for which a local path is unknown and then the border node decides to employ an inter-cluster lookup. These global messages allow to create the paths between border nodes (which likely involves intermediary nodes), providing the inter-cluster communication at the DCRP's physical layer.

3.6 Forwarding

Forwarding is the process executed by each mesh STA when receiving a frame whose final destination is not itself. In the context of IEEE 802.11s networks, it comprises the modification of the appropriate address fields and the re-transmission of the frame to the next hop in the path to the final destination. In DCRP, to determine the appropriate values of the address fields, the mesh STA must perform a lookup for the destination in any of the forwarding tables it maintains.

As explained in Session 2.1.2, IEEE 802.11s frames carry four or six addresses. The former is applied to communication within the WMN (i.e. between two mesh STAs). The latter is used for communications involving any non-mesh STA. In such a case, six addresses are needed to properly address the frame, setting the Addr5 and Addr6 fields to indicate the MAC addresses of the final target and of the originator of the frame. Thus, these fields are set at the proxy-MS of the originator, and are not modified until they reach the proxy-MS of the target. Address fields Addr1 and Addr2 always contain the MAC addresses of the nodes at the end of the physical link, (i.e. of the physical hop), and therefore are modified at every hop in the path. Address fields Addr3 and Addr4 contain the MAC addresses of the destination mesh STA and source mesh STA respectively of a path that may be comprised by several physical hops. These addresses are modified only at some mesh STAs in the end-to-end path. To make it clear, when these addresses are modified the expressions *relays to XXX* and *transmits to YYY* are used with very precise meanings. The former means that the Addr3 field of the frame is set to the MAC address of node XXX and Addr4 field of the frame is set to the MAC address of the node that is relaying the frame. The latter means that the Addr1 field of the frame is set to the MAC address of node YYY and Addr2 field of the frame is set to the MAC address of the node that is transmitting the frame.

The following subsections detail how DCRP forwards frames.

3.6.1 Intra-cluster Forwarding

The intra-cluster forwarding is the process of transmitting a frame, in a multi-hop fashion, towards its target, considering that both originator and target mesh STAs (or non-mesh STA associated to any proxy-MS) belong to the same cluster.

Figure 3.13 illustrates an intra-cluster forwarding in the case where the proxy-MS of the target is different from the one of the originator station. Solid arrows are paths followed by the frame in its end-to-end path from station STA1 to station STA2. The meaning of the dashed arrows is provided below. The numbers associated with some of the arrows are meant to help follow the description of the forwarding process.

- In step 1, a non-mesh STA1 (previously associated with the mesh STA 1c that acts as an AP, providing access to the WMN) sends a frame addressing the non-mesh STA2 as target;

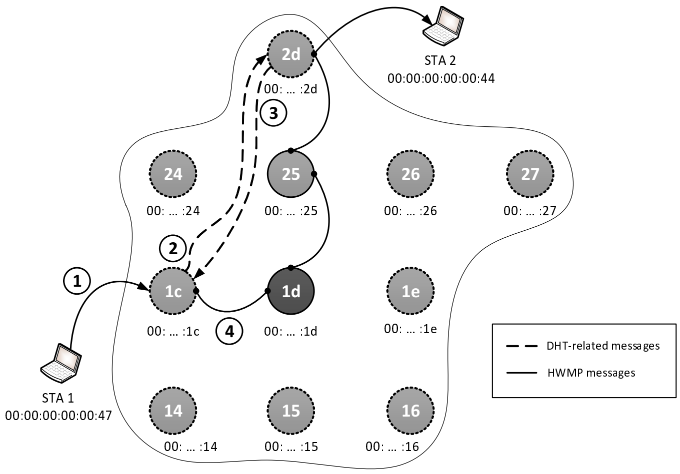


Figure 3.13: Illustration of a DCRP intra-forwarding.

- In step 2, after consulting its internal tables, the mesh STA 1c does not find a path to the target. Then it starts a lookup in its intra-DHT. After hashing the target address, based on its intra-DHT entries (key-based routing), the resultant ID (ECB7B3A8) is mapped to the mesh STA 2d (4DA3F235) in the overlay, using the finger table. Thus, the mesh STA 1c relays a LOOKUP message to the mesh STA 2d;
- In step 3, upon receiving the LOOKUP message, the mesh STA 2d identifies the target ID as one of its related key values. Then after storing the mapping for the originator (for further communication), it relays a LOOKUP-RESULT message back to the source mesh STA (1c) in the overlay (with ID 9BAC5E59) containing the target address and its proxy-MS address;
- In step 4, after receiving a successfully LOOKUP-RESULT message, the mesh STA 1c starts the transmission on the mesh network using the six-addresses frame format (acting as proxy-MS to STA1).

It must be noted that the dashed arrows in Figure 3.13 represent a key-based routing in the intra-DHT. These communication will likely result in some hops in the underlay network. In this example, all messages exchanged in the DCRP's physical layer are flagged as Local.

For this theoretical example of pure intra-cluster forwarding, it is not expected to have a lookup operation failing in step 4. If the target is unknown, an inter-cluster forwarding is started as explained in the following subsection. Therefore, the major benefit of the proposed intra-cluster forwarding scheme is that all the exchanges of messages involving nodes within the same cluster are constrained to the cluster.

3.6.2 Inter-cluster Forwarding

The inter-cluster forwarding is the process of transmitting a frame, in a multi-hop fashion, towards to its target, considering that both originator and target mesh STAs (or non-mesh STA associated to any proxy-MS) potentially are in distinct clusters.

Figure 3.14 illustrates an intra-cluster forwarding in the case where the proxy-MS of the target is different from the one of the originator station. Solid arrows are paths followed by the frame in its end-to-end path from station STA1 to station STA3. As in the previous example, dashed arrows mean DHT-related messages.

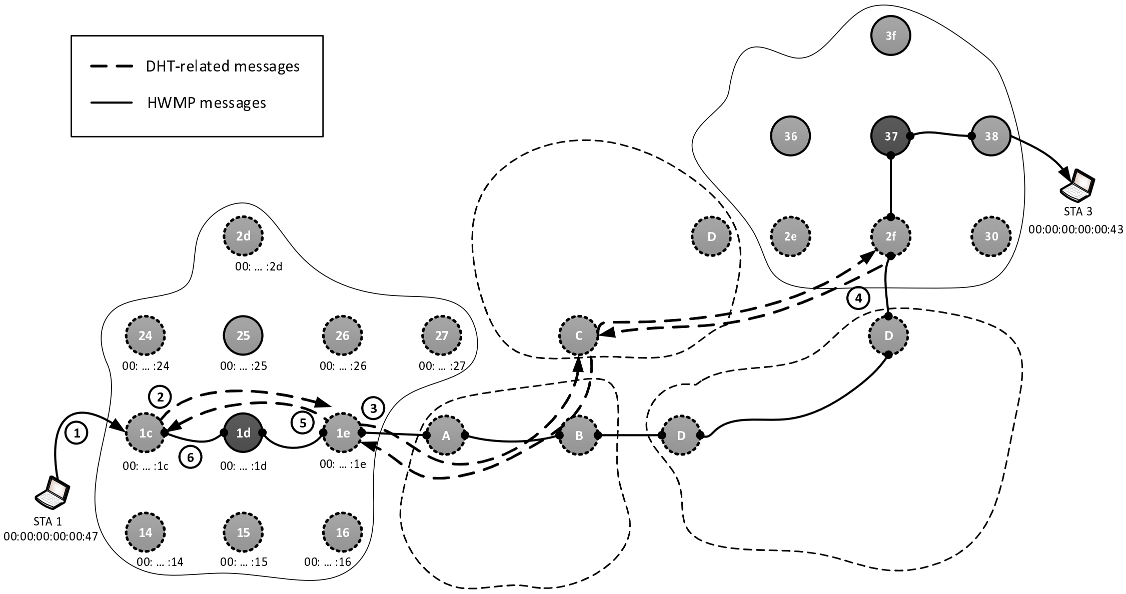


Figure 3.14: Illustration of a DCRP inter-forwarding.

- In step 1, a non-mesh STA1 (previously associated with mesh STA 1c that acts as an AP, providing access to the WMN) sends a frame addressing non-mesh STA3 as target;
- In step 2, after consulting its internal tables, mesh STA 1c does not find a path to the target. Then it starts a lookup in its intra-DHT. After hashing the target address, based on its intra-DHT entries (key-based routing), the resultant ID (E9E7F4B6) is mapped to mesh STA 1e (29E1D843) in the overlay, using the finger table. Thus, mesh STA 1c relays a LOOKUP message to mesh STA 1e;
- In step 3, upon receiving the LOOKUP message, mesh STA 1e looks up in its intra-DHT for the entry of the target ID, as in the case of intra-cluster routing. However, as non-mesh STA3 is in another cluster, no entry is found. Therefore, it starts a wide lookup, using its inter-DHT, setting the messages locality to Global;
- In step 4, upon receiving the LOOKUP message through the overlay, mesh STA 2f (2398703C) looks up in its intra-DHT for the entry of the target ID and finds the corresponding entry. Then it relays a LOOKUP-RESULT message back through the source overlay node (the mesh STA 1e);
- In step 5, the border mesh STA 1e that has performed the inter lookup (here the border node represents the cluster as a single entity) relays the LOOKUP-RESULT message to mesh STA 1c, setting the locality of messages to Local;
- In step 6, after receiving a successfully LOOKUP-RESULT message, mesh STA 1c starts the transmission on the mesh network using the six-addresses frame format (acting as proxy-MS to STA1).

The benefits of the proposed inter-cluster forwarding scheme are as follows. First, the use of unicast messages based on the inter-DHT lookup. Second, as the inter-forwarding is performed mainly by border nodes (with a few intermediate nodes), the inter-cluster traffic is also reduced. Finally, the distributed lookup is much more scalable in comparison with the standard mechanism.

3.7 Summary

This chapter described the DHT-based Cluster Routing Protocol (DCRP), a path selection protocol to increase the scalability of 802.11s WMNs. The main features of DCRP are the following. Firstly, the introduction of the notion of locality to the HWMP messages, which is later used to constrain the intra-cluster traffic. Secondly, a distributed management scheme of proxy-related information using DHT concepts. Thirdly, the novel forwarding scheme that integrates both previous features to efficiently forward messages in both local (intra-cluster forwarding) and global (inter-cluster forwarding) scopes. The key benefit of this approach is that it can significantly reduce the number of path selection and forwarding protocol messages. The main reason for this behaviour is that local communication (with both originator and target in the same cluster) will not be broadcasted to other clusters. Another improvement is the reduction of the number of messages exchanged among clusters, as it will mainly involve the border nodes. These features were assessed through simulation. The simulation results and discussion are presented in Chapter 4.

CHAPTER 4

DCRP Performance Assessment

"Where a new invention promises to be useful,
it ought to be tried"

Thomas Jefferson

This chapter presents a detailed simulation assessment of the DHT-based Cluster Routing Protocol (DCRP). To assess the proposed protocol, a simulation model of the DCRP was implemented using the ns-3 network simulator [212]. A set of simulations were carried out in order to evaluate the DCRP's scalability properties, claimed in the previous chapter, and to compare it with the standard Hybrid Wireless Mesh Protocol (HWMP). The simulation parameters and the experiment details are also presented. Finally, the assessment results are presented and discussed.

4.1 Introduction

In the previous chapter, the architectural design of the DHT-based Cluster Routing Protocol (DCRP) was presented. This thesis claims that DCRP is a potential solution for deploying large-scale IEEE 802.11s mesh networks. In order to support this claim, this chapter presents a simulation assessment of the DCRP performance, regarding the network scalability in IEEE 802.11s WMN scenarios.

4.2 Methodology

4.2.0.1 The ns-3 Network Simulator

The absence of an open-source and IEEE 802.11s standard compliant testbed, forces researchers to use simulation tools to asses their proposals [213]. To date, only a few simulators implement mechanisms that enable the simulation of IEEE 802.11s mesh networks, such as *Network Simulator 2* (ns-2) [214], *Network Simulator 3* (ns-3) [212], and Qualnet [215]. In the ns-2, just an implementation of the HWMP protocol is available through a patch developed by the Wireless Software Research & Development Group of Institute of

Information Transmission Problems of the Russian Academy of Sciences. The model for ns-2 is a basic realization of HWMP in accordance with the standard IEEE802.11s Draft 1.07 released in September 2007. Qualnet, developed by Scalable Network Technologies, implements most of the desirable features of an IEEE 802.11s WMN. However, besides being a proprietary software, there are still just a few research works using this simulation platform, which would put in cause the results validation. As a middle term between the open-source feature of the ns-2, and the implemented IEEE 802.11s features in Qualnet, there is the ns-3 implementation. After an extensive prospective study, the ns-3 platform was elected as the simulation tool for the assessment of DCRP. More detailed information about the ns-3 features are given below.

The ns-3 simulation system is a relatively recent, improved, and rewritten version of the older ns-2 simulator [214]. Its simulation engine is written in C++ programming language, with some Phyton support. As an event driven simulator, the ns-3 schedules all actions into a linked and ordered list, to be executed in a discrete timeline. It has been largely used by researchers to study and evaluate the performance of routing protocols (including their own proposals) in both MANETs and WMNs, including IEEE 802.11s [27, 42, 216–222].

The ns-3 version 3.19 was used for all simulations reported on this document. Although the current version being the 3.23, this gap between versions does not jeopardise the generality of the simulation results presented in this thesis, as none of the relevant ns-3 modules used for the DCRP simulation model have been modified.

Detailed information about the modules and features of the ns-3 can be found in [212, 213].

4.2.0.2 The Mesh Module

In any simulation tool the models are the base for creating a series of network events as realistic as possible. The ns-3 tool can be broken down into several models, such as core models with common functions, mobility, network, devices, nodes, and routing protocols. Likewise in ns-3, the IEEE 802.11s features are modelled in the *mesh model* (previously called *dot11s module*), implemented by Andreev et al. [223] and now distributed as part of the ns-3 default source code. The most important features are the implementation of the Peering Management Protocol (PMP), the HWMP and the ALM [224]. PMP includes peering establishment and beacon collision avoidance. HWMP includes proactive and on-demand modes, but the RANN mechanism is not supported and hence the proactive PREQ mechanism is used in the proactive mode. The ALM computation is implemented and used as the default metric for HWMP.

There are still some issues with the ns-3 mesh module, among them:

1. The current ns-3 implementation of the WiFi channel (implemented by the class WifiChannel) does not implement the co-channel interference, an important characteristic of real wireless communication. In fact, the simulator views each channel as a separated instance of the Channel class, without any co-relation. In addition, intra-flow and inter-flow interferences are not modelled;

2. Nodes have no individual physical properties. The physical properties are represented only in the WifiPhy layer model. Thus, individual characterization of physical node properties (e.g. distinct radio properties) are not possible;

3. Although the model allows to install multi interfaces in a mesh node, no channel assignment protocol is proposed;

4. The current mesh model is a mixture of many IEEE 802.11s draft versions (D2.07, D3.0, and D11B), and includes the Peer Management Protocol and the HWMP implementations. The HWMP still lacks important features to be fully compliant with the current standard, such as: support to multi-hop frame forwarding, support to six-address frame, implementation of *Gateway Announcement* (GANN) element (used for announcing the presence of a mesh gate in the MBSS) and Root Announcement (RANN) (used for announcing the presence of a mesh STA configured as root mesh STA), inter-networking mechanisms (proxy), security (authentication) mechanisms, among others. Nevertheless, its open implementation allows to include these functionalities by directly changing the mesh model or creating workarounds. Despite its limitations, the mesh model enables a fair simulation of the majority of the IEEE 802.11s mechanisms;

5. The Mesh Coordinated Channel Access (MCCA) described in Section2.1.5 is not implemented;

6. Although ns-3 offers logging and tracing support in a more refined manner, there are still some issues with the mesh module in generating ASCII or PCAP trace results;

7. Security mechanisms are not implemented;

8. Power safe mode is not implemented.

Although issues 1 and 2 have impact on the reality degree of the simulated scenarios, they do not directly affect the comparative assessment of DCRP and HWMP. Regarding these issues, an interesting extension to the ns-3 model has been introduced in [225], in which the authors proposed an *Interference Emulator* based on a semi-Markov model of the possible channel status. As stated at Chapter 1, this work assumes single-radio and single-channel nodes and hence the issue 3, can be neglected. The issue 4 however includes features of paramount importance to the present study. Therefore, most of the cited limitations were implemented by extending the mesh model of ns-3. Extensions to the mesh model are described in the following section. Finally, issues 5,6,7 and 8 are not required for the development of the proposed work, thus were neglected.

The mesh model implemented in ns-3, is not fully compliant with the current IEEE 802.11s standard document [45]. Actually, this is an inherited limitation from the mesh model. As an example, some of the Information Elements (IEs) have their Element ID value distinct from those specified in *Table 8-54* of the standard document. As a consequence, these IEs can not correctly be decoded by Wireshark, which turns the debug of the implemented DCRP mechanisms (the same applies to the HWMP) into a complex task.

Besides the aforementioned limitations, both HWMP and DCRP performance behaviours **are still comparable**, and thus the simulation results reported in this thesis are valid. The main reason is that, as already explained, the DCRP simulation model was constructed over the ns-3 mesh model. Therefore, all the limitations affect the performance of both protocols. Analogously, any improvement on the ns-3 mesh module will benefit both protocols.

Detailed information about the ns-3 mesh module can be found in Andreev et al. [223], Andreev and Boyko [224], or in the official ns-3 website [212].

4.2.0.3 Extending the Mesh Model

The ns-3 mesh model code is still incomplete, as explained above, and is no longer maintained by its authors. Therefore, some features where implemented to allow the complete implementation of the DCRP. Seeking to overcome the issue 4 of the ns-3 mesh model, as discussed above, some of the missing features were implemented, as follows.

One of the most important additions made to the existing mesh model was a set of modifications to the HWMP, namely: implementation of six-addresses scheme, implementation of the proactive HWMP mode using RANN messages, and internetworking with stations outside the MBSS (non-mesh STAs).

Although already defined in the MeshHeader, the additional MAC six-addresses scheme is not used in the current ns-3 mesh model implementation. Therefore, an addition to the source code was made to implement this feature to allow non-mesh STAs to use the MBSS as a communication backhaul. Additionally, the mesh gate role with support to mesh Portal and collocated Access Point features was also implemented. The mesh gate functionality was implemented by the new class MeshGate (see Listing 4.1). This class includes methods to “listen” all packets[1] from/to mesh STA (ReceiveFromMeshDevice), collocated AP (ReceiveFromApDevice), and mesh portal (ReceiveFromPortalDevice) interfaces. Upon receiving a packet, a mesh gate acts as a bridge between these interfaces.

Listing 4.1: MeshGate implementation.

```
class MeshGate : public Object {
public:
  [...]
  MeshGate(Ptr<MeshPointDevice> mp);
  virtual ~MeshGate();
  virtual void DoDispose ();
  void ReceiveFromMeshDevice (Ptr<MeshPointDevice> incomingPort,
      Ptr<const Packet> packet, uint16_t protocol, Address const &src,
      Address const &dst, NetDevice::PacketType packetType);
  void AddCollocatedAp (Ptr<NetDevice> iface);
  void AddPortal (Ptr<NetDevice> iface);
protected:
  bool ReceiveFromApDevice (Ptr<NetDevice> incomingPort,
        Ptr<const Packet> packet, uint16_t protocol, Address const &src,
        Address const &dst, NetDevice::PacketType packetType);
  bool ReceiveFromPortalDevice (Ptr<NetDevice> incomingPort,
        Ptr<const Packet> packet, uint16_t protocol, Address const &src,
        Address const &dst, NetDevice::PacketType packetType);
private:
  Ptr<MeshPointDevice> m_meshIf;
  std::vector< Ptr<NetDevice> > m_ApIf;
  std::vector< Ptr<NetDevice> > m_PortalIf;
};
```

To enable internetworking between MBSS and non-mesh STAs, the IEEE 802.11s standard document defines a proxy mechanism based on the exchange of Proxy Update

[1]The ns-3 uses the nomenclature packet for any message transmitted over the channel. Although the IEEE 802.11s mechanisms operates in layer 2 (using frames), in this chapter, both terms frame and packet are often used interchangeably.

(PXU) and Proxy Update Confirmation (PXUC) messages (as explained in Session 3.4.1). As illustrated in the Listing 4.2 and 4.3, the ns-3 mesh model was extended with these new Information Elements (IEs). These IEs are used by the mesh gate.

Listing 4.2: Proxy Update (PXU) Information Element.

```
class IePxu : public WifiInformationElement
{
public:
  IePxu ();
  virtual ~IePxu ();

  [...]

  uint8_t GetPxuSequenceNumber ();
  Mac48Address GetPxuOriginatorMacAddress ();
  uint8_t GetNumberOfProxyInformation ();
  std::vector<Ptr<ProxyInformationField> > GetProxyInformationList ();
  [...]
private:
  uint8_t m_pxuSequenceNumber;
  Mac48Address m_pxuOriginatorMacAddress;
  uint8_t m_numberOfProxyInformation;
  std::vector<Ptr<ProxyInformationField> >  m_proxyInformationList;

  friend bool operator== (const IePxu & a, const IePxu & b);
};
```

Listing 4.3: Proxy Update Confirmation (PUC) Information Element.

```
class IePxuc : public WifiInformationElement
{
public:
  IePxuc ();
  virtual ~IePxuc ();

  void SetPxuSequenceNumber (uint8_t pxuSequenceNumber);
  void SetDestinationMeshStaAddress (Mac48Address destinationMeshStaAddress
      );

  uint8_t GetPxuSequenceNumber ();
  Mac48Address GetDestinationMeshStaAddress ();
  [...]
private:
  uint8_t m_pxuSequenceNumber;
  Mac48Address m_destinationMeshStaAddress;

  friend bool operator== (const IePxuc & a, const IePxuc & b);
};
```

Following the implementation model of the ns-3, the DCRP architecture illustrated in Figure 3.1 was implemented as follows. The DCRP's physical layer was implemented by modifying the existent HWMP code. Both cluster and DHT layers were implemented as separated protocol handlers that are later tied to the MeshPointDevice at the installation of the protocol stack, as illustrated in Listing 4.4. In the ns-3, a protocol handler (let it be

MyProtocol) must implement at least two classes: MyProtocol and MyProtocolMac. The MyProtocol class must implement all station-level protocol logic and data base. An instance of this class is tied to the mesh point device. An instance of the class MyProtocolMac, which is tied to each mesh interface MAC, must extend the MAC functions to support the corresponding protocol [223]. In other words, the class MyProtocol implements the protocol operation and its state-machine, while the class MyProtocolMac servers as an interface to the MAC layer by sending and receiving frames to be processed by the protocol.

Listing 4.4: Installing the DHT and PeeeClusterProtocol as plugins of the mes STA.

```

//Install Peer Cluster Protocol:
Ptr<PeerClusterProtocol> pcp = CreateObject<PeerClusterProtocol> ();
install_ok = pcp->Install (mp);
if (!install_ok)
  {
    return false;
  }
pcp->SetPmp (pmp);

//Install DHT Cluster Protocol:
Ptr<DhtClusterProtocol> dht = CreateObject<DhtClusterProtocol> ();
install_ok = dht->Install (mp);
if (!install_ok)
  {
    return false;
  }
```

As specified in the standard document [45], only a single active path selection protocol should be used in a single IEEE 802.11s MBSS. As aforementioned, HWMP is the default path selection protocol. In the current standard document, the Active Path Selection Protocol Identifier field value for the HWMP is set to 1, whereas values [0,2..254] are reserved for future use, and 255 is used to indicate that the active path selection protocol is specified in a Vendor Specific element (see Table 8-177 in [45]). So, we use the value 2 for DCRP in this field. This information is embedded in the Mesh Configuration IE. Specific values to identify the action frames used to carry DCRP information (for both DHT, and cluster related messages) were also defined.

4.2.1 General Simulation Parameters and Assumptions

The definition of a clear set of simulation parameters and assumptions aims to ensure the reproducibility of the simulation results. Although the assessment of the DCRP was performed using a set of distinct simulation scenarios in the ns-3 simulator, they still share some common assumptions and simulation parameters, as follows.

All simulations are based on the IEEE 802.11s mesh model, which means that the stack *ns3::Dot11sStack* is installed in all nodes. In other words, all node are enabled as devices of type MeshPointDevice instead of WifiDevice (IEEE 802.11). Device is the representation of a Network Interface Cards (NIC) in ns-3. MeshPointDevice device works as an interface to upper-layer protocols, providing functionalities hidden from upper-layer protocols, such as path selection and forwarding, by means of the class MeshL2RoutingProtocol. The task of

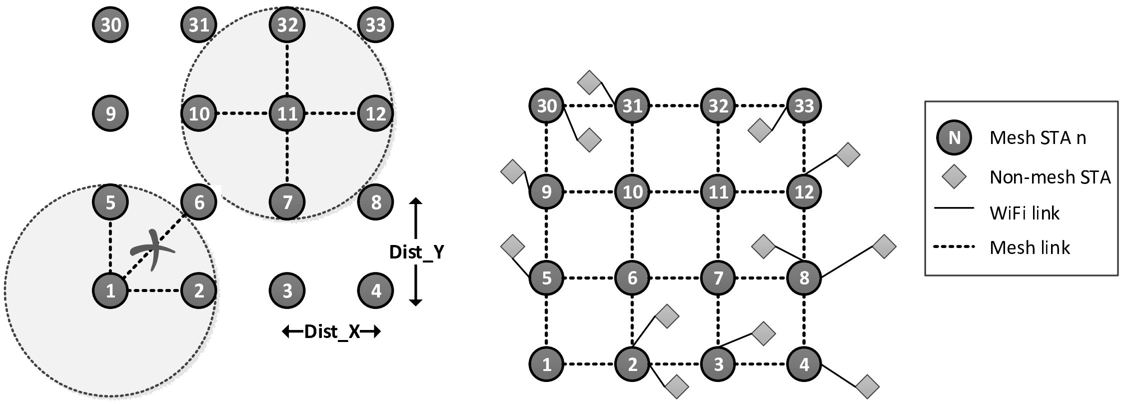
MeshPointDevice is to send, receive, and forward frames, while the task of MeshL2RoutingProtocol is to provide path selection and to forward frames. Following this model, any layer 2 "routing" protocol is implemented as a subclass of MeshL2RoutingProtocol, including the HWMP protocol.

For modelling the wireless channel, for all simulation experiments, the Constant Speed Propagation Delay Model, and the Log Distance Propagation Loss Model were used. This propagation model assumes an exponential path loss over the distance from sender to receiver [226]. Log Distance Propagation Loss Model is a radio propagation model that predicts the path loss a signal encounters inside a building or a densely populated areas over distance. Considering the application scenarios targeted by DCRP (see Section 1.1.2), where the distance between the nodes is usually short and static, and the measurements are conducted in a city-wide environment, the Log-Distance Propagation Loss Model was considered to be the most suitable and adaptive. This model calculates the reception power (received signal strength) using the following equation:

$$L = L_0 + 10\; n\; log_{10}\left(\frac{d}{d_0}\right) \tag{4.1}$$

where L is the path loss (dB), L_0 is the path loss at reference distance (dB), n is the path loss distance exponent, d is the distance (m), and d_0 is the reference distance (m). When the path loss is requested at a distance smaller than the reference distance, the *tx power* is returned.

UDP (User Datagram Protocol) traffic streaming was established between a certain number of senders to a certain numbers of receivers. The traffic transported by UDP was CBR (Constant Bit Rate) traffic which allows simulating real time multimedia applications. The application OnOffApplication was used to generate traffic. Constant Bit Rate (CBR) was assumed to generate traffic flows between source and destination nodes with a constant data packet size of 512 bytes. In order to create enough traffic, the default data rate value used was set to 1024 kbps.



(a) Mesh backhaul. (b) Mesh backhaul with clients.

Figure 4.1: Illustration of a static grid topology of 4x4 size.

In all simulation experiments, the nodes were arranged in a NxN grid topology. The value of N in some experiments varies in the set $[3, 4, 5, 6, 7, 8, 9, 10]$. The parameter N is used to scale the IEEE 802.11s WMN in terms of number of nodes that form the backhaul, which means that the network size is scaled from a total of 9 to 100 mesh STAs forming the mesh network. The nodes are equally spaced in the grid, as illustrated in Figure 4.1(a).

Table 4.1: General ns-3 parameter values used for the simulations.

Parameter	Value
Topology	Grid (NxN)
Number of mesh STAs	9,16,25,36,49,64,81,100
Mobility Model	ns3::ConstantPositionMobilityModel
Stack	ns3::Dot11sStack
PHY Standard	WIFI_PHY_STANDARD_80211a
Remote Station Manager (RSM)	ns3::ConstantRateWifiManager
RSM DataMode	OfdmRate6Mbps
RSM RtsCtsThreshold	2500
Packet size	512 bytes
Delay Model	ns3::ConstantSpeedPropagationDelayModel
Propagation Model	ns3::LogDistancePropagationLossModel (with exp=2.7)
Traffic Generator	OnOffApplication (CBR)
CBR Bitrate	1024 kbps
Random Start	0.1 s
Simulation Duration	700 s
Stabilization Time	50 s
Number of runs	50
Simulation Seed	1408
Run Seed	1..50

As illustrated in Figure 4.1(b), non-mesh STAs (or clients) are randomly distributed along the square area of the grid. Each non-mesh STA connects to its closest mesh STA which will act as mesh gate to the mesh backhaul. It means that all mesh STAs in the backhaul also act as an AP collocated with a mesh gate.

Such backhaul mesh networks in real-world deployments are normally formed neither in a self-organized fashion, nor in a grid shape. Instead, the location and placement of each mesh STA, AP collocated with a STA, and mesh Portal is carefully planned, applying network planning [227] or Genetic Algorithms (GA) [218]. Nevertheless, grid shape has been widely used by researchers to evaluate the scalability of IEEE 802.11s mechanisms [39, 40, 144, 228, 229] as it provides a simple and controlled environment, allowing a fair comparison of reproducible results.

For each run, the same number of non-mesh STAs are created and randomly distributed in a square area covering the grid. After a random start time, each non-mesh model associates with a closer mesh STA (the selection criteria follows the normal IEEE 802.11 standard).

Moreover, 50% of the total clients were configured to generate traffic. The choice of the source and destination for the traffic flow is taken randomly at run time to create more realistic scenarios.

Each simulation batch had a duration of 700 seconds and was repeated 50 times (with distinct seeds) in order to obtain a higher confidence degree. It is important to note that to avoid packet loss due to either network warm-up time or premature ending, in all simulations the source nodes start to generate data traffic only after $StabilizationTime$ (in seconds) and stop a $StabilizationTime$ before the end of the simulation. This procedure ensures a fair comparison of the protocols, waiting until the mesh network reaches its topological steady state and giving time to late packets to find their way to its destination. The $StabilizationTime$ was set to 50 seconds.

Three different elements were established in a random manner: sender and receiver node, communication start time, and duration of each connection. The procedure to select pairs of sender and receiver nodes ensures that the sender is not the receiver in a pair. The connection start time is given by $UniformValue(StabilizationTime, SimTime - StabilizationTime)$, and the stop time by $SimTime - StabilizationTime$ The random values are generated from a fixed uniform distribution, using the UniformVariable class.

The simulation results were plotted based on average values of all runs. Seeking to obtain highly meaningful results, each run is independent from all others. To ensure that, each set of simulations was conducted using an unique simulation seed and a different seed for each run. The first ensures the repeatability of the experiment, whereas the second ensures the statistical independence of the results.

Table 4.2: Mesh module parameter values used for the simulations.

Parameter	Value
Dot11MeshHWMPactivePathTimeout	100 s
Dot11MeshHWMPactiveRootTimeout	100 s
Dot11MeshHWMPmaxPREQretries	5
UnicastPreqThreshold	5
UnicastDataThreshold	5
DoFlag	True
RfFlag	False
MaxBeaconLoss	20
MaxRetries	4
MaxPacketFailure	5
EnableBeaconCollisionAvoidance	false

General simulation parameters are presented in Table 4.1, while the most relevant parameters for the ns-3 mesh module are presented in Table 4.2. The *Beacon Collision Avoidance* (BCA) mechanism of HWMP is used to detect and mitigate collisions among beacon frames transmitted by other stations on the same channel within the range of 2-hops. However, the implemented procedure produces very limited advantages and reduces the throughput. Thus, it was disabled to not drop down the performance of HWMP. Other important parameter that had to be changed was the Max Beacon Loss in HWMP. Its default value is set to 2 (which is extremely low) and sometimes due to the propagation loss model, some connections are set as not valid beforehand.

4.2.2 Performance Metrics

As discussed in Section 1.1.1, the network scalability can be evaluated under different metrics. The following metrics were considered to compare both the performance and scalability of DHT-based Cluster Routing Protocol (DCRP), and Hybrid Wireless Mesh Protocol (HWMP).

Packet Delivery Ratio **(PDR).** PDR can be defined as the ratio of data packets received by the destinations to those generated by the sources. PDR can be computed using Equation 4.2, where n_d is the number of packets successfully delivered and n_s is the number of sent packets. This metric is usually presented in terms of percentage.

$$PDR = \frac{n_d}{n_s} \;\; , or \;\; PDR(\%) = \frac{n_d}{n_s} * 100 \tag{4.2}$$

Aggregate Throughput or System Throughput **(ST).** It can be defined as the cumulated throughput for all flows in the network. In other words, is the ratio between the amount of packets successfully received over the activity time for all flows. In this work, the throughput is computed using Equation 4.3, where $n_{d,f}$ is the number of packets successfully delivered to the flow f, $Size(\,)$ is a function which returns the size (in bytes) of each packet $p_{i,f}$, $F_{i,f}$ is the arrival time of the first packet successfully received (in seconds), and $L_{i,f}$ the arrival time of the last packet successfully received (in seconds) for the flow f.

$$ST = \sum_{f=1}^{n_f} \frac{\sum_{i=1}^{n_{d,f}} Size(p_{i,f}) * 8}{L_{i,f} - F_{i,f}} \tag{4.3}$$

Average End-to-End Delay **(EED).** This metric can be defined as the average transmission delay of all delivered packets. It includes all possible delays caused by buffering during path discovery latency, queuing at the interface queue, retransmission delays at the MAC, propagation and transfer times. EED is computed using Equation 4.4, where n_d is the number of packets successfully delivered, $T_{rx(i)}$ is the time that the packet was received at the destination, and $T_{tx(i)}$ is the time that the packet was transmitted (or the first attempt of) by the source.

$$EED = \sum_{i=1}^{n_d} \frac{T_{rx(i)} \; - \; T_{tx(i)}}{n_d} \tag{4.4}$$

***Normalized Routing Overhead or Routing Load* (NRO).** The routing overhead is usually defined as the number of routing bytes required by the routing protocol to construct and maintain its routes. Although this metric has its significance, it is disconnected from the data delivery. For example, in a comparison of two protocols a high overhead of one protocol seems to be undesirable, but it can compensate this by increasing the amount of delivered data. Therefore, the Normalized Routing Overhead is a better metric to analyse the protocol overhead. This metric represents the total number of routing packets divided by total number of delivered data packets. In other words, it indicates the extra bandwidth consumed by overhead to deliver data traffic. NRO is computed using Equation 4.5, where n_{rs} is the total number of routing packets sent by the nodes, n_{rf} is the total number of routing packets forwarded by the intermediate nodes, and n_d is the total number of data packets successfully delivered.

$$NRO = \frac{n_{rs} \ + \ n_{rf}}{n_d} \tag{4.5}$$

Equation 4.5 is quite unbalanced if different packets sizes are considered. In other words, a protocol A that generates a large number of small routing messages would be penalized by NRO metric in comparison to another protocol B that uses less but larger routing messages. Therefore, alternatively, the NRO can be analysed in term of bytes using Equation 4.6, where n_{rs} is the total number of routing packets sent by the nodes, n_{rf} is the total number of routing packets forwarded by the intermediate nodes, $Size(\ )$ is a function which returns the size (in bytes) of each packet p_x, and n_d is the number of data packets successfully delivered.

$$NRO_{[bytes]} = \frac{\sum_{i=1}^{n_{rs}} \ Size(p_i) \ + \ \sum_{i=j}^{n_{rf}} \ Size(p_j)}{\sum_{k=1}^{n_d} \ Size(p_k)} \tag{4.6}$$

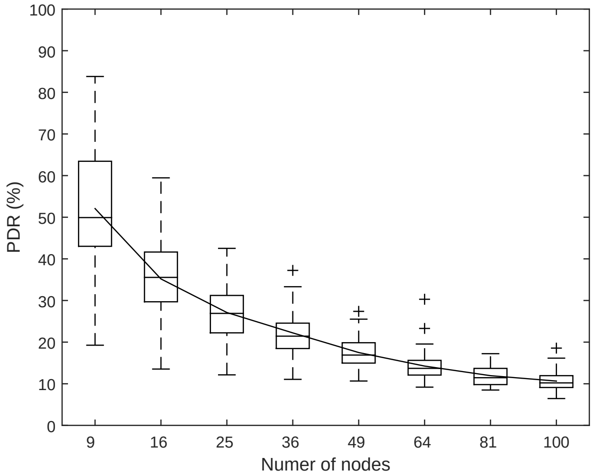
The performance metrics listed above were collected by using a double-checked approach: first, the FlowMonitor [230] module was applied to generate the metrics' values, and then these values were compared with the values recorded during the simulation using the tracing subsystem of ns-3, and callbacks. This approach aims to ensure the reliability of the data analysed in the following subsections.

4.3 Simulation Results

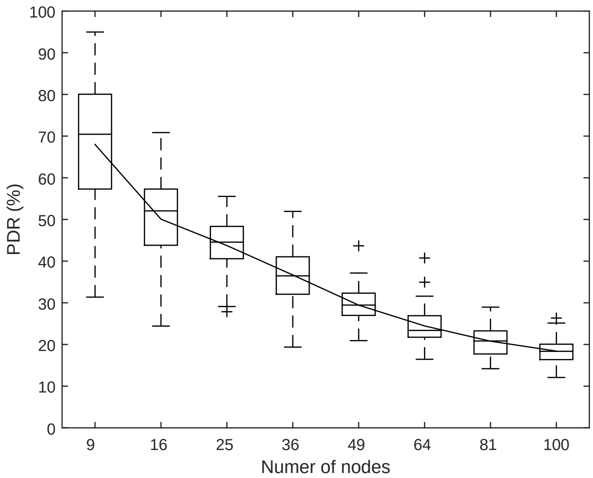
In this section, the results for the comparative simulation assessment between the DCRP and the HWMP, regarding their scalability properties, are presented and discussed.

4.3.1 Scaling the Number of Nodes

In a first and obvious experiment, the scalability of the protocols was evaluated regarding the number of nodes. This study was set out to investigate the effects of varying the network size (number of mesh STAs) over the set of performance metrics previously defined in Section 4.2.2. The simulation results regarding this experiment are plotted in Figures 4.2, 4.3, 4.4, and 4.5.



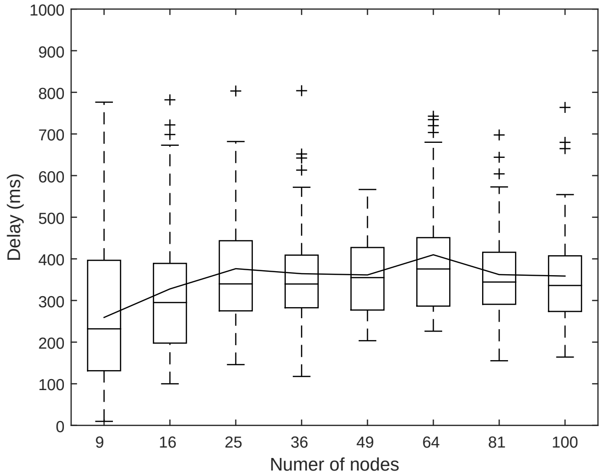
(a) HWMP



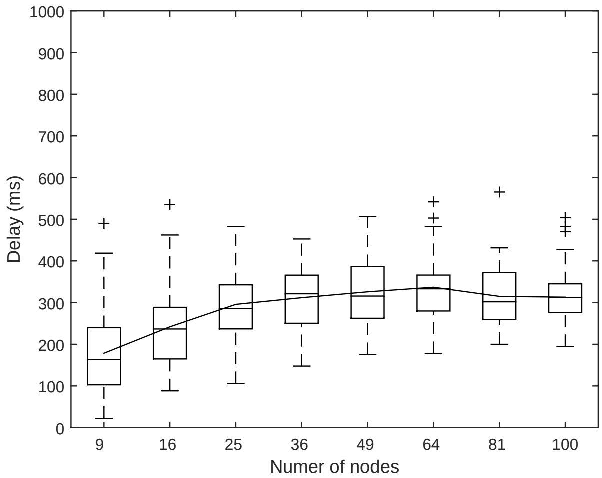
(b) DCRP

Figure 4.2: The effect of the number of nodes over the PDR.

The results of the effect of the number of nodes over the Packet Delivery Ratio (PDR) are ploted in the Figure 4.2. The PDR values for both the HWMP (see Figure 4.2(a)) and DCRP (see Figure 4.2(b)) protocols decrease as the number of nodes increase. This is an expectable result, as the number of mesh STAs has a significant impact upon the PDR due to the increasing inter-flow interference caused by the number of concurrent connections. However, regarding the PDR values, DCRP scales much better than HWMP. In average, in the simulated scenario DCRP provides PDR values 60% higher than the related HWMP values. The difference becomes even higher for a large number of nodes, where DCRP overcomes HWMP in up to 73%. This behaviour can be explained by the use of HWMP messages with local scope for many communications in the DCRP protocol.



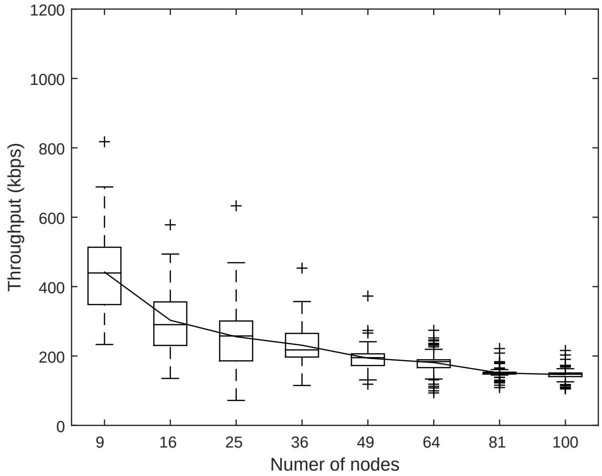
(a) HWMP



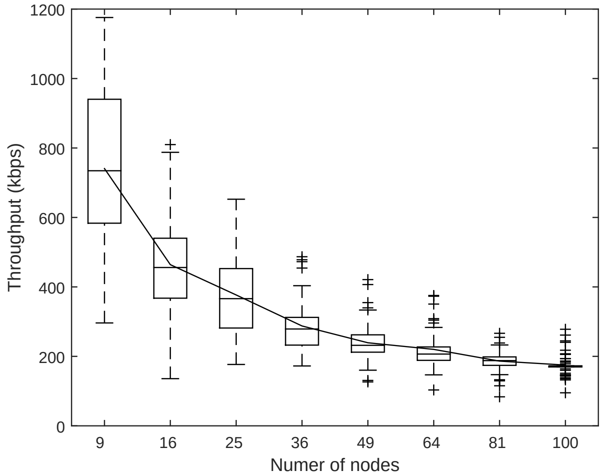
(b) DCRP

Figure 4.3: The effect of the number of nodes over the Delay.

Figure 4.3 illustrates the effect of scaling the number of nodes over the Delay. Analysing the obtained results, both DCRP (see Figure 4.3(b)) and HWMP (see Figure 4.3(a)) presented a close tendency curve in terms of delay. A closer look at the Figure 4.3(b) reveals that the DCRP is more resilient to the increasing of the network size, presenting slightly lower delay values with a lower standard deviation. Therefore, the DCRP also reduces the communication jitter.



(a) HWMP



(b) DCRP

Figure 4.4: The effect of the number of nodes over the Throughput.

Figure 4.4 illustrates the effect of scaling the network size over the Throughput and Normalized Overhead metrics, respectively. Checking DCRP throughput results (Figure 4.4(b)), it clearly outperforms HWMP (Figure 4.4(a)). The descendent exponential curve behavior for the throughput can be explained by the increase of simultaneous connections among the non-mesh STAs that increases the interference. The low throughput of HWMP is partially explained by the high number of transmission outages due to concurrent flows generating traffic at higher data rates, which leads to long transmission queues (in some cases resulting in the dropping of the packet). As the network load increases, the channel condition and interference varies with time, and this cannot be captured with the standard ALM metric (as explained in Section 2.2.5).

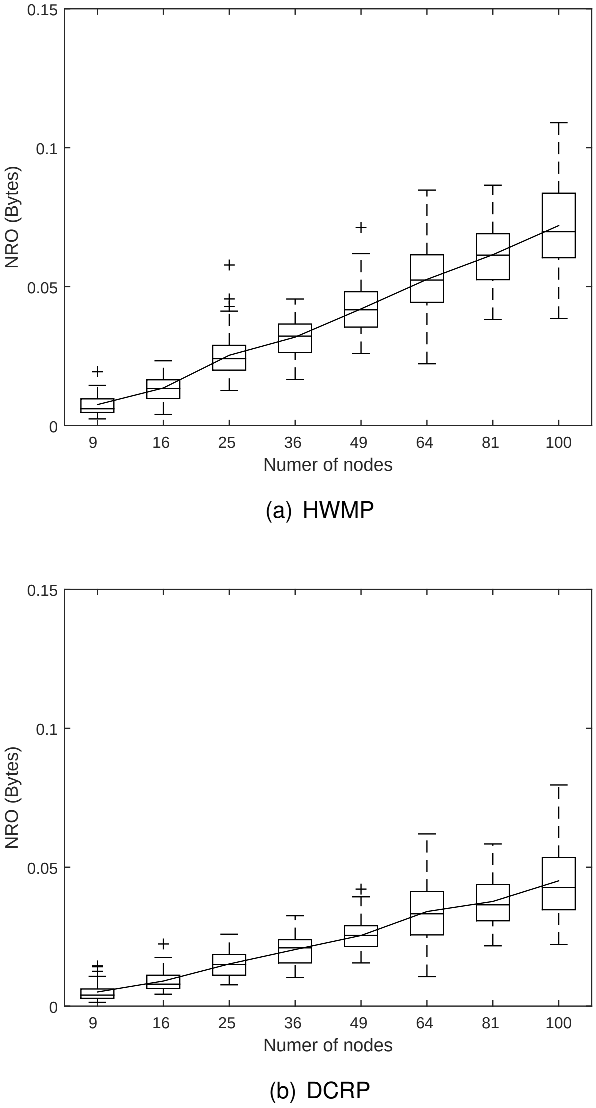
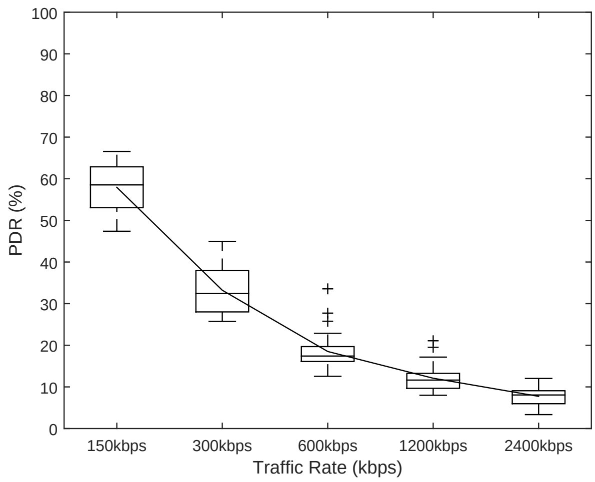


Figure 4.5: The effect of the number of nodes over the Normalized Routing Overhead.

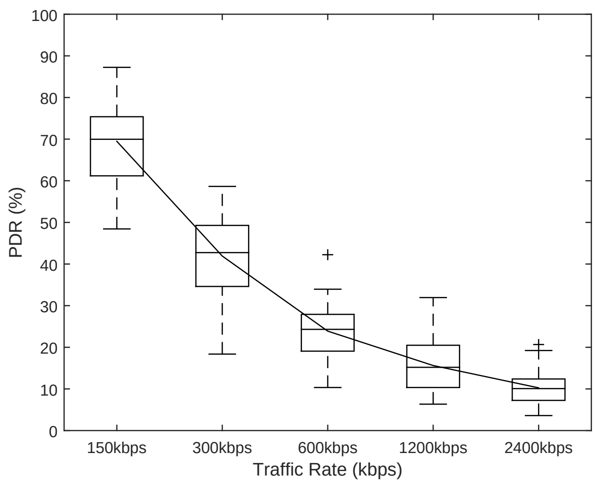
Finally, Figure 4.5 illustrates the effect of scaling the network size over the Normalized Overhead metric, and revels an interesting finding. Considering a small network with 9 or 16 nodes, for a DCRP clustering scheme with k=3 in a grid topology, a single cluster will be created. In such a case, it would be expected a network behaviour very similar to the HWMP case (or even worse), because of the increased overhead of the cluster and DHT maintainance. Instead, Figure 4.5 shows that even for small size networks, DCRP presents smaller values for NRO. The explanation is that the addition of 6 bytes used to identify the Cluster Identifier (CID) in the HWMP messages (the locality bit is already part of the standard frame), and the overhead associated with the DHT is compensate by the efficiency of the intra-cluster forwarding, which proved to be less costly than exchanging proxy messages (PXU and PXUC).

4.3.2 Scaling the Data rate

A second set of simulation experiments was setup to analyse the effect of varying application data transmission rate in the IEEE 802.11s WMN for both protocols. This second simulation experiments were carried out by varying the CBR traffic with the values 150kbps, 300kbps, 600kbps, 1200kbps, and 2400kbps. Seeking to reproduce a fair comparison between these two protocols, for this experiment, the node grid was sized to 8x8 (i.e. 64 nodes). The simulation results are presented in Figures 4.6, 4.7, and 4.8.



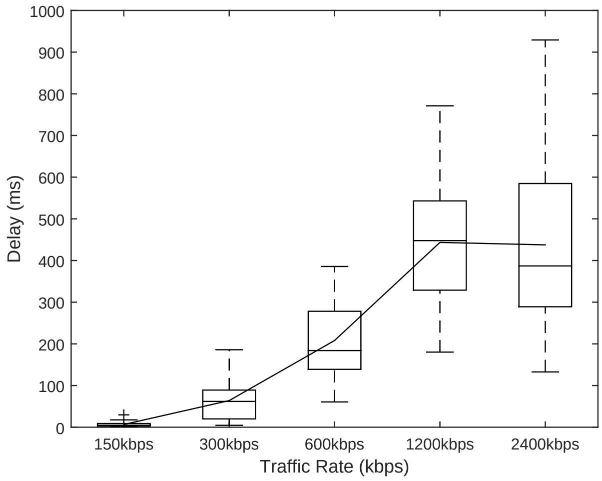
(a) HWMP



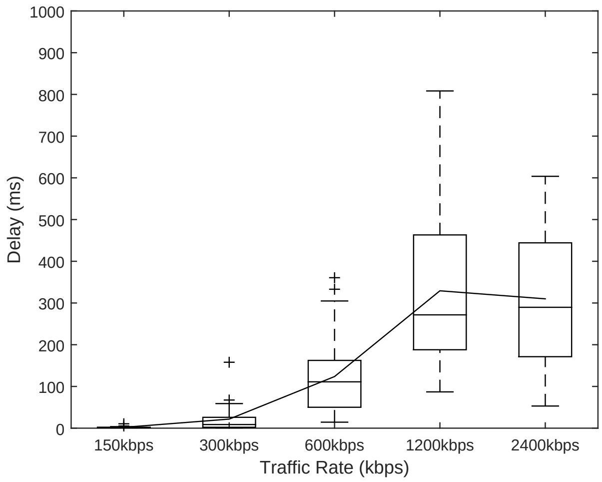
(b) DCRP

Figure 4.6: The effect of the transmission rate (traffic load) over the PDR.

Figure 4.6 illustrates the effect of scaling the transmission rate. Checking the results, DCRP (see Figure 4.6(b)) clearly overcomes HWMP (see Figure 4.6(a)) in terms of packet delivery. This was an expected result due to the increased number of packets drops caused by the interference and path length (in number of hops). Moreover, by containing local communication within the cluster, DCRP tends to reduce the interference with data flows having other cluster either as source, or destination. The use of unicast messages (through the inter-DHT) to locate and forward messages between distant (in hops) nodes also contributes to achieve better PDR results.



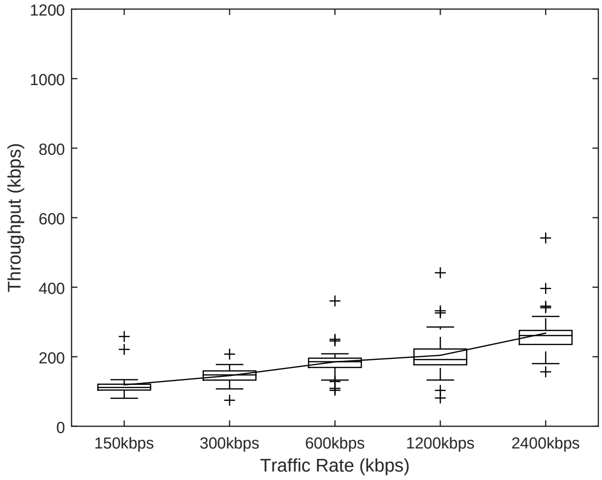
(a) HWMP



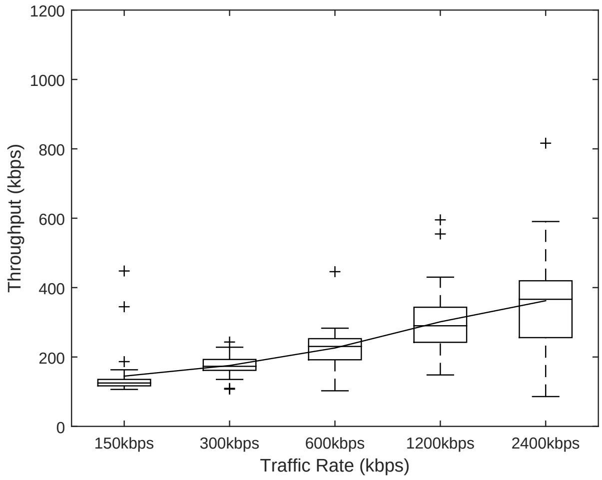
(b) DCRP

Figure 4.7: The effect of the transmission rate (traffic load) over the Delay.

Figure 4.7 illustrates the effect of scaling the transmission rate over the Delay. Although similar, the Delay curve for the DCRP (see Figure 4.7(b)) presents values lower than the HWMP curve (see Figure 4.7(a)). For both protocols, the standard deviation values are considerable. This variation will affect the jitter values for both protocols.



(a) HWMP



(b) DCRP

Figure 4.8: The effect of the transmission rate (traffic load) over the Throughput.

Similar observations are valid for the effect of varying the transmission rate on the throughput, as illustrated in Figure 4.8. Checking the results, it is clear that throughput values for both protocols reduce as the data rate increase. These results are consistent with those from Figure 4.6 that highlights the PDR behavior. Even so, DCRP (see Figure 4.8(b)) clearly outperforms HWMP (see Figure 4.8(a)) in what concerns its throughput. This can be attributed to several factors. Obviously, the reduction of congestion provided by the reduction of broadcasted messages, and a higher PDR clearly contribute to this result.

Finally, it is important to note that the simulation results observed in this experiment are strongly consistent with those obtained in the previous experiment for the same grid size and data rate.

4.4 Discussion of the Results

This section sums up the simulation assessment results and presents the main findings from the experiments described above.

As the network becomes larger by scaling the number of mesh STAs, or increasing the data rate, the Packet Delivery Ratio (PDR) decreases for both DCRP and HWMP protocols. However, the PDR values decrease is significantly slower for the DCRP curve than for the HWMP, in both experiments.

Regarding the Average End-to-End Delay (EED), in the first experiment, besides clearly outperforming the HWMP, the DCRP results also registered a standard deviation consistently smaller than those for the HWMP as the network scales. This is a desirable behavior, as it significantly impacts on the delay jitter. In the second experiment, the opposite was observed. The results reveals that the DCRP (and the HWMP as well) presents a high variation of delay values in response to the increasing of the data rate.

In terms of the Aggregate Throughput or System Throughput (ST), the results from the simulation experiments can not be directly correlated. In the first experiment, the network was scaled in terms of number of nodes, but with constant transmission data rate. Obviously, in such a scenario it was expected that the throughput decreases as the network size increases. The main justifications for this behavior are the increasing of the average path length for the data flows, and the increase of both inter and intra-flow interferences. Even so, the DCRP provides better results in terms of average values, and presents a smoother degradation of its curve.

The Normalized Routing Overhead or Routing Load (NRO) is a critical metric to prove the viability of the DCRP design. The results for this metric suggest that the overhead introduced by the creation of the clusters, creation of the DHTs, and the proposed enhanced HWMP messages have payed off, allowing to achieve better performance metrics, as discussed above.

Overall, DCRP achieved significantly better performance metric values (see Appendix B) for all simulated scenarios with markedly less generated overhead than the standard HWMP. These simulation results support the initial thesis that *it is possible to improve the scalability of IEEE 802.11s mesh networks by integrating both Clustering and Distributed Hash Table (DHT) concepts*. The simulation results presented in this chapter provide an initial and encouraging look at the performance of the DCRP.

4.5 Summary

In this chapter, a detailed simulation assessment of the proposed DHT-based Cluster Routing Protocol (DCRP) was presented.

The DCRP model was implemented using the Network Simulator 3 (ns-3). A comparative simulation assessment was made, using the existent Hybrid Wireless Mesh Protocol (HWMP) implementation (it is part of the mesh module described in Section 4.2.0.2). Simulations results reported in this chapter suggest that the DCRP provides significant improvements when compared with the HWMP in terms of scalability, providing a reasonable gain in performance for the conducted experiments and evaluated metrics. These results were expected and can be explained by the use of unicast messages (trough DHT) combined with the reduction of the number of broadcasted messages (by using the notion of cluster locality and inter-cluster lookup).

Finally, the reported simulation results are a clear indication that exploiting the properties and synergy of DHT and Clustering concepts can provide a promising solution for larger WMN deployments.

CHAPTER 5

Conclusion and Future Work

"Life's tragedy is that we get old too soon and wise too late."

Benjamin Franklin

"A conclusion is the place where you get tired of thinking."

Arthur Bloch

In this chapter, the major findings reported in this thesis are presented and contemplated regarding how clearly the research targets have been achieved. Following, some directions for future work are highlighted. Finally, some concluding remarks are presented.

5.1 Thesis Summary

This thesis has focused on the problem of low scalability of current IEEE 802.11s Wireless Mesh Networks. In this section, we briefly review the contributions and main conclusions of this thesis.

From the state-of-the-art study summarized in Chapter 2, we have identified a set of major scalability issues of the IEEE 802.11s WMNs: (1) as an adaptation of the well-known AODV protocol, widely applied to ad hoc environments, the HWMP also heavily relies on broadcasting of messages, not scaling beyond a few tens of nodes; (2) the standard Airtime Link Metric (ALM) still lacks of improvements to be able to deal with both inter-fow and intra-flow interference; (3) the computation of the ALM cost itself can be improved to avoid the so-called "Ping-Pong effect", which causes path instability; (4) The path instability is also caused due to limitations on the mesh peering selection protocol, such as the indistinct selection of peers, which can lead to topological instability; (5) Finally, the lack of support to mobility of nodes, especially the non-mesh stations.

Unfortunately, a deeper study and the proposal of potential solutions for each of the mentioned issues would clearly take an amount of time and effort that is not compatible with a single PhD thesis. So, it was decided to focus on issue (1). Thus, this thesis seek to answer the main research question "How to overcome the scalability issues of the standard path selection and forwarding protocol (HWMP) in order to allow the implementation of larger IEEE 802.11s deployments?".

Previous approaches in the literature (as surveyed in Chapter 2) fall short of meeting scalability requirements in IEEE 802.11s. The main reason is that the majority of proposals which claim to be scalable for larger WMNs still rely on ad hoc or MANETs technologies, while only a few truly consider the multi-hop nature of IEEE 802.11s mesh networks and the associated challenges. The solution proposed in this thesis was presented in Chapter 3. Instead of relying on traditional approaches, the DHT-based Cluster Routing Protocol (DCRP) exploits the traffic contention from hierarchical clustering routing with the key-based lookup provided by DHTs.

The current design of DCRP considers a basic DHT scheme based on Chord. DCRP defines two distinct DHT structures: one local to each cluster (intra-DHT), and another global but containing only border nodes (inter-DHT). The simulation results from the DCRP assessment suggested that this strategy can significantly reduce the overhead of creating and maintaining a single DHT with all nodes.

The use of clusters along with the notion of locality into the HWMP messages proved to be efficient to confine the local traffic (i.e. source and destination are in the same cluster) within the cluster. There are still space for research and improvements in the clustering scheme proposed by the DCRP.

In fact, the architectural design of the DCRP protocol introduced in Session 3.1, allows new features to be added in a modular fashion. For example, new DHT substrates, or clustering algorithms can be used to improve the overall scalability. Even the modifications proposed on the HWMP messages can be mapped to other protocols in a straightforward manner.

In an overall comparison, the DCRP approaches the scalability issue highly better than the standard HWMP protocol. The simulation results presented and discussed in Chapter 4 corroborates that. The DCRP produced better results for most of the evaluated performance metrics defined in Section 4.2.2.

In a wider evaluation, the reported results are a clear indication that exploiting the properties of DHT and Clustering concepts can provide a promising solution for larger Wireless Mesh Network (WMN) deployments in general. Although the DCRP has been designed having the IEEE 802.11s WMNs in mind, its concepts can be easily mapped to other mesh standards. In addition, it must be highlighted that the key-based lookup structure provided by the DCRP can be also used as an efficient and multi-purpose building block for the implementation of distributed services on top the path selection and forwarding mechanism. In this direction, services such as *Address Resolution Protocol* (ARP), *Domain Name Service* (DNS), and *Dynamic Host Configuration Protocol* (DHCP) can be envisioned.

Besides the DCRP itself, we believe that this work contributes to the advance of the state-of-the-art of IEEE 802.11s WMNs by discussing objectively the status of scalability in the standard as well as the existing approaches proposed in previous research works. In addition, the summary of the principles, mechanisms, and techniques for achieving scalability in IEEE 802.11s WMNs will serve as a reference for future research and deployments.

5.2 Future Work

Although the simulation results presented in Chapter 4 reveals a significant improvement of the scalability of IEEE 802.11s WMNs, the proposed solution still has potential for further improvements. Regarding the proposed DCRP architecture and the IEEE 802.11 WMNs research field, several points remain to be addressed as part of future work.

In this section some of these points are highlighted, and some directions for future research works are presented.

Mobility. The current DCRP architecture is based on the assumption that mesh STAs have limited (or none) mobility. This assumption is also taken by the standard IEEE 802.11s document. However, when thinking in large-scale deployments (e.g. wide-city mesh networks) this assumption does not hold for laptops and cellphones that might be used as mesh STA and not only as end points of communication. In such a mobile scenario, the presented work must be extended to address the mobility problem. The major potential impact here is the high churn (i.e. nodes joining and leaving the underlay network at unpredictable rates) over the DHT, which increases the maintenance overhead. Although the proposed clustering approach will also be affected by the mobility of some of its members, it is expected the impact to be diminished by the use of local repair mechanisms. Mobility impacts the network scalability in the sense that increasing the number of external mobile STAs which are communicating through the MBSS, will increase the additional overhead and handoff delay. Handoff management is a determining factor for the successful deployment of such environment [231, 232]. From our best knowledge, few works have addressed mobility issues in IEEE 802.11s WMNs [233–236]. These works may serve as an interesting start point for further research on this point.

Multi-channel and multi-interface mesh STAs. Another assumption made along this work is the use of single-channel and single-interface mesh stations for the mesh backbone formation. To consider multi-channel and multi-interface mesh stations brings in one hand new research challenges to the protocol design, such as the efficiency of the channel assignment, and the exploitation of multiple paths and multiple flows with reduced interference. In another hand it also brings new opportunities. The clustering scheme can take advantage of multi-channel to reduce the interference between neighbor clusters, by assigning non-overlapping channels to neighbor clusters. Additionally, it allows the use of multi-path with simultaneous communication, thus improving the network performance. This research path includes devising mechanisms of channel assignment and multi-path selection and forwarding, as the current IEEE 802.11s standard does not cover these topics.

Improving the DHT scheme. One limitation of DCRP is its simple DHT scheme. We have used a Chord substrate as prove of concept for our architecture. However, DHT literature provides many other structures, such as CAN, Pastry, and Tapestry - and many other optimizations for these classical structures. To improve the DCRP, more study on scalable DHT substrates such as Ekta [204], and MADPastry [196] is necessary. Both are example of Pastry-based schemes, which presents as major advantage taking into consideration the proximity of nodes. It means that nodes physically close in the underlay tend to be also virtually close on the overlay. However this mapping is based on IP addresses and the assumption of local LANs sharing a same network prefix. As in the IEEE 802.11s the path selection and forwarding is performed in the link layer, using MAC addresses, the original notion of proximity does not hold. So optimizations must be made to accommodate this new assumption. Concepts from MeshChord [200] can be potentially applied to DCRP, as it uses Chord as DHT structure. Anyway, due to the modularity of the proposed DCRP architecture, any other DHT scheme can be easily deployed as replacement to the current scheme. In this sense, a comparison of different versions of DCRP - by replacing the DHT scheme - can be envisioned. Moreover, much more work on the efficiency and reliability of the id-based lookups performed by the DCRP must be conducted. The set of simulations reported in the Chapter 4 also reveals a high stretch (ratio of the overall sum of hops on the overlay path, divided by the number of hops). But it was investigated not in deeper in this thesis. Still regarding the DHT scheme, the performance of the DCRP in scenarios with high level of churn can also be studied.

Selecting stable peers. Both DHT and Clustering schemes proposed in the DCRP architecture demand for stable links, which regarding the IEEE 802.11s leads to the efficiency of the peering selection and management mechanism. In order to be more efficient, avoiding high delays on peer establishment and to reduce the network load induced by this task, the 802.11s standard MPM suggests to limit the number of neighbor peer links that can be established by a mesh STA. Clearly, this parameter value, will directly affect the cluster formation in DCRP. Increasing the number of established peers will increase the connectivity of the mesh STA but also increase its receiver and transmitter queues load (due to message exchange for peering), as well as the path discovery delay (due to the multiplicity of alternative paths). Although the IEEE 802.11s standard clearly indicates that the number of neighbor peer STAs must be limited, it does not define any procedure to identify and select a candidate peer mesh STA [237]. Selecting a peer regardless of its load, resources or interference range can lead to poor performance in large or dense networks. To the best of our knowledge, to date, few works studying or proposing new MPM solutions have been published [237, 238]. The authors in [237] introduced three schemes in which the decision to stablish a peering is defined by a selection criteria, usually based on the spatial diversity. In [238], the authors proposed two strategies: the *MPMP with Unconditional Confirmation* (MPMP-U) and the *MPMP with Conditional Confirmation* (MPMP-C). The former is based on the reception of a number r of beacons. The latter differs from the first by introducing a statistical strategy to decide when to accept or to reject a Peering Open/Peering Close frame from a peer candidate STA. The receiver node, using MPMP-U, always agrees with the sender, accepting the messages. The receiver node, using MPMP-C, accepts these messages only if it has received not less than l beacons from the sender; otherwise, the frame is rejected. The MPMP-C aims to establish more reliable and stable links. Incorporate a peer selection scheme into the DCRP will bring advantages in terms of cluster instability.

Experimental assessment. Lastly, a natural development would be to implement a real testbed allowing to make statements about the real-world applicability of the DCRP. The big challenge here is the network size. In other words, the question is "How many nodes must be deployed to create a meaningful setup?". The answer might be statistically easy to find out, however hard to execute in practice. Hence, in this thesis, simulation assessment has been used. Regarding real world deployment of IEEE 802.11s networks, we strongly recommend starting from the actual application requirements, followed by a detailed network planning before the deployment of the mesh topology. Moreover, hardware configuration, such as tuning its parameters for maximum performance, and security considerations must be taken into consideration. To date, many operational WMNs testbeds have been deployed at universities and research institutes around the world. Well-known examples of WMN testbeds are [106, 109, 239–244], among others. Nonetheless, there are still few initiatives toward creating an IEEE 802.11s WMN testbed [245–249]. Nevertheless none of them has been in operation for neither a long time or in a large scale enough, thus the long term outcomes for this type of mesh technology is still unclear.

5.3 Concluding Remarks

To date, over three years have passed since the IEEE 802.11s-2011 amendment to IEEE 802.11 standard was ratified and incorporated into the IEEE 802.11-2012 standard. Based on the development and standardization process, review of the research on early draft versions and the final standard version, and with the growing maturity of the IEEE 802.11s, we have very positive expectations for the future of IEEE 802.11s mesh networks.

From a research point of view, it is expected, in the next few years, an increasing number of works around the scalability and overall performance of IEEE 802.11s mesh networks. Although most of the assessment of the proposed approaches has been (so far) done in simulators, it is expect that testbeds become preferred by many researchers for further assessment as opposed to simulators [250], mainly due to the decreasing costs and wide availability of wireless equipments. More deployments and testbeds will certainly arise even more questions related to the scalability and topological stability of these networks than the aforementioned in this thesis.

From a commercial point of view, it is expected that manufacturers will start to develop an entire new set of 802.11s devices quite soon. Those devices should be tested for compatibility and interoperability before being established in the market. This whole production process will take time. Meanwhile, in the running for market share, it is also expected and highly probable that some companies will produce early products that come close enough to a standard compliance, betting that minors differences can be easily fixed with firmware updates. In one hand, that would mean that 802.11s-capable devices can be available in stores in a short time from now. But, in the other hand, it may lead to private solutions with no interoperability at all. Although the IEEE 802.11s does not appear to have been adopted by device makers at this time, it seems to follow a path similar to the IEEE 802.11n. However, unlike the IEEE 802.11n, the IEEE 802.11s has the advantage that when it gets adopted, the companies can make profit by not only releasing a new family of products, but also improving legacy devices with mesh capabilities (by easily providing firmware upgrade as opposed to replacing the entire infrastructure).

To conclude this thesis, we believe that the IEEE 802.11s standard will play a very important role in future large-scale WMNs, serving as entry point for future highly scalable and long-range backhauls (.e.g. using WiMAX or any other technology; or even a mix of communication technologies organized in layers in an hierarchical fashion) due to its support to legacy IEEE 802.11 devices. In other words, we envision a modular, multi-standard, radio agnostic, multi-radio, and multichannel wireless mesh network.

APPENDIX A

List of Publications

A list of publications produced during this PhD is presented below.

A.1 Publications in Journals

Silvio Sampaio, Francisco Vasques, and Pedro Souto, "A review of scalability and topological stability issues in IEEE 802.11s Wireless Mesh Networks", International Journal of Communication Systems, John Wiley & Sons, 2015. DOI: 10.1002/dac.2929. [IF=1.106] (**IN PRESS**, published online: 16 JAN 2015. Online version available at: http://onlinelibrary.wiley.com/doi/10.1002/dac.2929/full).

Silvio Sampaio, Francisco Vasques, and Pedro Souto, "DCRP: a Scalable Path Selection and Forwarding Scheme for IEEE 802.11s Wireless Mesh Networks.", EURASIP Journal on Wireless Communications and Networking, Springer, 2015. (**SUBMITTED**).

A.2 Book Chapters

Sampaio, S. & Vasques, F. Routing Protocols for IEEE 802.11-Based Mesh Networks. Encyclopedia of Information Science and Technology, Third Edition. IGI Global, 2015. 6295-6306. Web. 26 Aug. 2014. DOI: 10.4018/978-1-4666-5888-2.ch619.

Sampaio, S. & Vasques, F. Exploiting DHT's Properties to Improve the Scalability of Mesh Networks. Encyclopedia of Information Science and Technology, Third Edition. IGI Global, 2015. 6177-6185. Web. 26 Aug. 2014. DOI: 10.4018/978-1-4666-5888-2.ch609.

A.3 Publications in Conferences

C.M.D. Viegas, **S. Sampaio**, F. Vasques, P. Portugal, and P. Souto. *Assessment of the interference caused by uncontrolled traffic sources upon real-time communication in IEEE 802.11-based mesh networks*. In Factory Communication Systems (WFCS), 2012 9th IEEE International Workshop on, pages 59–62, 2012. DOI: 10.1109/WFCS.2012.6242541.

Pinheiro, M.; **Sampaio, S.**; Vasques, F.; Souto, P., "A DHT-based approach for Path Selection and Message Forwarding in IEEE 802.11s industrial Wireless Mesh Networks," Emerging Technologies & Factory Automation, 2009. ETFA 2009. IEEE Conference on , vol., no., pp.1,10, 22-25 Sept. 2009. DOI: 10.1109/ETFA.2009.5347111.

M. Pinheiro, **S. Sampaio**, F. Vasques, and P. Souto. Pinheiro, M.; Vasques, F.; Sampaio, S.; Ferreira Souto, P., "DHT-based Cluster Routing Protocol for IEEE802.11s Mesh networks," *Sensor, Mesh and Ad Hoc Communications and Networks Workshops, 2009. SECON. Workshops '09. 6th Annual IEEE Communications Society Conference on* , vol., no., pp.1,6, 22-26 June 2009. DOI: 10.1109/SAHCNW.2009.5172928.

Silvio Sampaio, Francisco Vasques, Pedro Souto and Marcos Pinheiro. *Improving the Scalability of IEEE 802.11s Networks*. Proceedings of the 5th Doctoral Symposium in Informatics Engineering DSIE 2010, pp93-105, Porto, Portugal, January 2010. ISBN 978-972-752-119-7. (**Best Paper Award**). Proceedings available at: http://paginas.fe.up.pt/ dsie10/proceedings.pdf

A.4 Other Outcomes

The DHT-Mesh Project. Inspired by the preliminary studies and results of this thesis, in 2009 the DHT-Mesh Project was in the context of the Wireless Mesh Networks (WMNs) targeting study and propose solutions for the lack of scalability in the IEEE 802.11s WMN. The "DHT-Mesh: DHT-based services for increasing the Scalability of Highly available Wireless Mesh Networks" project was approved and financially supported by FCT/COMPETE/QREN/EU funds through COMPETE program under the reference SFRH/BD/61427/200.

Although the project has been approved in 2009, it was carried out between 2011-01-01 and 2013-31-12. The research team was composed by researchers from three institutions: University of Porto, University of Aveiro, and Micro I/O Serviços de Electrónica Lda (Microio). The project was headed by Professor Francisco Vasques from University of Porto.

Some of the results presented in this thesis was also published in the Project Final Report.

APPENDIX B

Simulation Results: Average Values

The average values used to plot the simulation results presented in Chapter 4 are reproduced in this appendix. In the following set of tables is therefore possible to quantify the improvement brought by the DCRP protocol over the current HWMP standard protocol.

B.1 Scaling the Number of Nodes

Table B.1: Average values for the PDR metric.

PDR			
Nodes	HWMP	DCRP	Improvement (%)
9	52,0814	67,9917	30,54891
16	35,1794	50,0664	42,31738
25	27,1154	43,7394	61,30833
36	22,2200	36,6766	65,06121
49	17,5003	29,4372	68,20969
64	14,2496	24,4507	71,58868
81	11,9432	20,7897	74,07144
100	10,6465	18,4086	72,90753
		Average	60,75164

Table B.2: Average values for the EED metric.

Delay			
Nodes	HWMP	DCRP	Improvement (%)
9	259,3090	178,4621	-31,1778
16	327,7996	241,8487	-26,2206
25	376,4052	295,7265	-21,4340
36	364,3811	311,7647	-14,4399
49	361,4150	325,8361	-9,84433
64	409,8299	336,8218	-17,8142
81	362,1669	314,8899	-13,0539
100	358,7176	313,0233	-12,7382
		Average	-18,3404

Table B.3: Average values for the ST metric.

Throughput			
Nodes	HWMP	DCRP	Improvement (%)
9	441,9974	740,7870	67,59985
16	303,0058	464,0987	53,16496
25	255,5824	376,8378	47,44278
36	231,0211	287,5559	24,47170
49	193,7951	239,1858	23,42201
64	181,1572	220,1371	21,51717
81	151,0123	186,3369	23,39187
100	146,5291	174,9738	19,41232
		Average	35,05283

Table B.4: Average values for the NRO metric.

NRO			
Nodes	HWMP	DCRP	Improvement (%)
9	0,0076	0,0051	-32,8947
16	0,0135	0,0090	-33,3333
25	0,0253	0,0152	-39,9209
36	0,0318	0,0204	-35,8491
49	0,0420	0,0254	-39,5238
64	0,0526	0,0340	-35,3612
81	0,0615	0,0377	-38,6992
100	0,0720	0,0451	-37,3611
		Average	-36,6179

B.2 Scaling the Data Rate

Table B.5: Average values for the PDR metric.

PDR			
Data rate	HWMP	DCRP	Improvement (%)
150kbps	57,9354	69,475	19,91805
300kbps	33,2244	41,9161	26,16059
600kbps	18,5088	23,8868	29,05645
1200kbps	12,0856	15,6217	29,25879
2400kbps	7,7312	10,2628	32,74524
		Average	27,42782

Table B.6: Average values for the EED metric.

Delay			
Data rate	HWMP	DCRP	Improvement (%)
150kbps	6,6054	1,9853	-69,9443
300kbps	63,9040	21,7043	-66,0361
600kbps	208,0759	123,7155	-40,5431
1200kbps	443,4020	329,2670	-25,7407
2400kbps	437,5569	309,9864	-29,1552
		Average	-46,2839

Table B.7: Average values for the ST metric.

Throughput			
Data rate	HWMP	DCRP	Improvement (%)
150kbps	119,1039	144,8549	21,62062
300kbps	145,6550	175,4599	20,46267
600kbps	185,1788	225,9664	22,02606
1200kbps	204,0990	301,4806	47,71292
2400kbps	267,8510	362,1665	35,21193
		Average	29,40684

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