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Cross-Layer Optimizations in Multi-Hop Ad Hoc Networks

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Abstract

Unlike traditional wireless networks, characterized by the presence of last-mile, static and reliable infrastructures, Mobile ad Hoc Networks (MANETs) are dynamically formed by collections of mobile and static terminals that exchange data by enabling each other's communication. Supporting multi-hop communication in a MANET is a challenging research area because it requires cooperation between different protocol layers (MAC, routing, transport). In particular, MAC and routing protocols could be considered mutually cooperative protocol layers. When a route is established, the *exposed* and *hidden* terminal problems at MAC layer may decrease the end-to-end performance proportionally with the length of each route. Conversely, the contention at MAC layer may cause a routing protocol to respond by initiating new routes queries and routing table updates.

Multi-hop communication may also benefit the presence of pseudo-centralized virtual infrastructures obtained by grouping nodes into clusters. Clustering structures may facilitate the spatial reuse of resources by increasing the system capacity: at the same time, the clustering hierarchy may be used to coordinate transmissions events inside the network and to support intra-cluster routing schemes. Again, MAC and clustering protocols could be considered mutually cooperative protocol layers: the clustering scheme could support MAC layer coordination among nodes, by shifting the distributed MAC paradigm towards a pseudo-centralized MAC paradigm. On the other hand, the system benefits of the clustering scheme could be emphasized by the pseudo-centralized MAC layer with the support for differentiated access priorities and controlled contention.

In this thesis, we propose cross-layer solutions involving joint design of MAC, clustering and routing protocols in MANETs.

As main contribution, we study and analyze the integration of MAC and clustering schemes to support multi-hop communication in large-scale ad hoc networks. A novel clustering protocol, named *Availability Clustering* (AC), is defined under general nodes' heterogeneity assumptions in terms of connectivity, available energy and relative mobility. On this basis, we design and analyze a distributed and adaptive MAC protocol, named Differentiated Distributed Coordination Function (DDCF), whose focus is to implement adaptive access differentiation based on the node roles, which have been assigned by the upper-layer's clustering scheme. We extensively simulate the proposed clustering scheme by showing its effectiveness in dominating the network dynamics, under some stressing mobility models and different mobility rates. Based on these results, we propose a possible application of the cross-layer MAC+Clustering scheme to support the fast propagation of alert messages in a vehicular environment.

At the same time, we investigate the integration of MAC and routing protocols in large scale multi-hop ad-hoc networks. A novel multipath routing scheme is proposed, by extending the AOMDV protocol with a novel load-balancing approach to concurrently distribute the traffic among the multiple paths. We also study the composition effect of a IEEE 802.11-based enhanced MAC forwarding mechanism called Fast Forward (FF), used to reduce the effects of self-contention among frames at the MAC layer. The protocol framework is modelled and extensively simulated for a large set of metrics and scenarios.

For both the schemes, the simulation results reveal the benefits of the cross-layer MAC+routing and MAC+clustering approaches over single-layer solutions.

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A mia madre

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Chapter 1

Introduction

Mobile Ad Hoc Networks

Mobile ad Hoc Networks (MANETs) can be defined as autonomous systems of mobile nodes connected via wireless links without using an existing network infrastructure or centralized administration [JNC04, Ger04]. The nodes composing a MANET are free to move and to organize themselves arbitrarily: thus, the topology of the network may change rapidly and unpredictability. In *multihop ad hoc* networks, every node acts also as a router and forwards each others' packets to enable the communication between nodes not directly connected by wireless links. The benefits and commercial potentials of the ad hoc architecture have attracted considerable attention in different application domains. Historically, MANETs have been used for tactical network-related applications to improve battlefield communications and survivability. Actually, the introduction of short range wireless technologies such as Bluetooth and IEEE 802.11 [dcf] has greatly facilitated the deployment of MANETs outside of the military applications, including personal area networking, sensor networks, vehicular services, location-aware services.

The basic characteristics of MANETs may be identified as follows [JNC04]:

- **Absence of infrastructures**. MANETs do not require any fixed intrastructure to support their operations: wireless devices join the network on the fly.

Lack of infrastructures means the network management has to be distributed across different nodes, bringing added difficulty in fault detection and management.

- **Mobility**. Each node is free to move while communicating with other nodes. The network topology can change frequently and unpredictability due to the mobility of the wireless nodes, resulting in route changes, network partitions and packet losses.
- **Multihop routing**. In single-hop ad hoc networks, each node is able to communicate directly with any other node that resides within its transmission range. However, if the communication involves two nodes not direct connected, *multihop routing protocols* should be used, by exploiting some intermediate nodes to relay the messages hop-by-hop.
- **Self-configuration**. Nodes composing a MANET must autonomously determine their own configuration parameters, including: addressing, routing, clustering, power control.
- **Energy conservation**. MANETs are formed by nodes with limited power supply and no capability to generate their own power. Processing power becomes an important issue, specially in multi-hop environments where the longevity and the connectivity of the network should be preserved.

History and Current Trends

Historically, MANETs have primarily been used in tactical network-related applications to improve *battlefield* communications and *survivability* [Ger04]. Early ad hoc network application can be traced back to the DARPA Packet radio network project (PRNET) in 1970s, which evolved into the Survivable Adaptive Radio Networks (SURAN) program in the early 1980s. The PRNET project used a combination of ALOHA and CSMA approaches to support the dynamic sharing of the radio resources, and featured multi-hop communication among nodes by introducing several distance-vector routing protocols. The main contributions coming from the SURAN project were the proposals and developments of distributed link-state routing protocols for large-scale wireless networks. In the early 1990, the U.S. Department of Defense continued to support research programs such as Global Mobile Information Systems (GloMo) and the Near-Term Digital Radio program (NTDR). The recent advances in device miniaturization, and the proposal of open standards (Bluetooth, IEEE 802.11, RFID) for wireless communication, have greatly facilitated the deployment of ad hoc networks outside of the military applications. Natural scenarios for MANETs are all the ones characterized by the need to have a practical, inexpensive, fault tolerant communication support in extremely dynamic environments, such as university campuses, conference locations, home/office networking and so on. Moreover, MANETs are expected to become an important component of the next generation 4G wireless networks, by favoring the proposals of new services and applications based on cooperation and on "*spontaneous networking*" [Rhe02] among the mobile users.

Table 1.1 shows the classification of present and future applications, as well as the list of services they provide. In the following, we describe three sample scenarios demonstrating the potential of MANETs [Ger04].

Battlefield. MANETs are expected to be applied in all the scenarios characterized by the absence of fixed infrastructures, such as battlefield or disaster recovery. These scenarios typically involve teams of mobile agents performing coordinated tasks, whose result depends on the cooperation among the wireless agents.

Campus Grid. Ad hoc networking is considered a fundamental technology to support new services and applications for vehicle drivers assistance and safety, whose implementation guidelines are the mission of the worldwide

Applications	**Possible Scenarios/Service**
Tactical Networks	Military communication and applications Automated battlefields
Emergency Services	Search and rescue operations Disaster recovery Replacement of fixed infrastructure
Education	Universities and campus setting Virtual classroom Ad hoc communication during meetings
Commercial and civilian environments	Vehicular services (VANETs) E-commerce Context-aware and information services
Sensor Networks	Home Applications Body area networks (BANs)
Entertainment	Multi-user games Wireless P2P networking Outdoor Internet access

Table 1.1: Mobile Ad Hoc Network Applications

Intelligent Transportation System (ITS) program [MCG02, NOW]. Inside a car, short range wireless technologies could be used for monitoring and controlling vehicle's components, as well as for providing driver assistance (automatic breaking). Another set of applications stems from ad hoc communications among cars to provide traffic monitoring, alert messaging, infotainment services (see Chapter 5).

Urban Grid. The term "campus" may be applied to every place where people congregate for various cultural and social activities (parks, universities, conferences). Although typical campus today exploit infrastructure-based WLAN, not all the areas of a campus might be covered by the APs. Multi-hop ad hoc networks may provide Internet connectivity by extending the coverage of the APs, and may also support "spontaneous networking" applications among people interacting in the same area (file exchange, gaming, chat, etc).

Design Challenges

The wide spectrum of applications demonstrate that MANETs have some distinct advantages over wired networks, mainly due to their fault-tolerant and self-organizing characteristics. At the same time, wireless ad hoc networks present a number of complexities and design constraints that are not existent in wired networks. The most important factor characterizing a MANET is the high variability of the network state. We use the term *network state* to refer to the wide range of communication conditions a node can experience in a MANET. The most important factors characterizing the network state are the link connectivity, the power control and the mobility effect [Bis05].

1. *Link Connectivity.* In a wired environment, the link connectivity is a binary decision, i.e. a link exists between two nodes when they are connected by a physical medium like optical fiber or coaxial cable. In a MANET, the

broadcast nature of the communication allows each node to be connected with multiple receiver nodes. Small-scale channel variations due to fading, scattering and multipath can change the quality of a link within a few milliseconds. A variable link connectivity increases the number of packet dropped for transmissions errors and has a direct impact on all the network protocols. The MAC layer may assume that packet drop is caused by collisions and therefore increases its backoff window. At transport layer, the TCP sender may misinterpret losses as congestion, and may react invoking congestion control and entering slow start recovery, thus reducing the end-to-end performance of the current flow.

2. *Power Control.* The broadcast nature of the wireless communication determines that each node may increase/reduce the number of neighbouring nodes by tuning its transmitting power. Thus, the topology of the network as perceived by each node is strongly dependant by the transmit power of each node. Increasing the transmission power also increases the effect of hidden/exposed terminal at MAC layer and affects the congestion level of the wireless channel.

3. *Mobility Effect.* The nodes belonging to a MANET are free to move and organize themselves arbitrarily. The mobility effect affects the performance of the network protocols. At the MAC layer, the mobility factor governs how long the measurements regarding channel state and inference remain valid. At routing layer, the mobility factor governs the performance of routing protocols. At transport layer, route failures can be misinterpreted as congestion effects and produce performance decay.

Meeting the requirements of the application despite variable link connectivity, network topology and power levels implies two issues in protocol design:

- *information sharing*: each layer of the protocol stack should be able to access the information about the current network state;

- *protocol cooperation*: performance gains may be obtained if joint solutions at multiple network layers are considered.

Unfortunately, the layered open system architecture (OSI) does not seem to support these requirements. The networks layered architecture is remarkably successful for networks made up of wired links, where the key assumptions and abstraction boundaries work well. The strict layering approach reveals to be suboptimal in many application domains of MANETs [SM05, CMT04, Bis05]. The main drawback of the ISO/OSI model is the lack of cooperation among non-adjacent layers: each layer works in isolation with few information about the network. Moreover, the strict modularity does not allow to design jointly solutions optimized to maximize the overall network performance.

Cross-layer design is an emerging proposal to support flexible layer approaches in MANETs [SM05, CMT04, Bis05]. Generally speaking, cross-layer design refers to *protocol design done by allowing layers to exchange state information* in order to obtain performance gains. Protocols use the state information flowing throughout the stack to adapt their behaviour accordingly. For example, given current channel and energy conditions, the physical layer may adapt rate, power and coding to meet the application requirements. The cross-layer design introduces the advantages of explicit layer dependencies in the protocol stack, to cope with poor performance of wireless links and mobile terminals, high error rates, power saving requirements, Quality of Service. Many interesting cross-layer design solutions have been proposed in literature, together with some critical works addressing the risks of an unbridled cross-layer design leading to uncoordinated interactions [Yin04, FMBT05, CP02], fluctuations, and system instability [VP05].

Contributions of the Thesis

The mutual interactions between MAC, clustering and routing layers raise the possibility of improving the performance of multi-hop communication in a MANET by considering joint design of MAC, routing and clustering protocols. To this aim, the cross-layer approach appears a viable paradigm to overcome the strict separation into modules of a layered architectures and to enable layers to exchange state information about the context of the communication. By using a cross-layer perspective, the main contributions of our work may be identified as follows:

- *MAC and Clustering Integration for distributed management in highly mobile networks.* In [FBD03], a solution for the mutual support of distributed MAC and clustering schemes in MANETs is investigated. A new clustering protocol, named *Availability Clustering* (AC), is defined under general nodes' heterogeneity assumptions in terms of connectivity, available energy and relative mobility. At the same time, [FBD03] considers the design and analysis of a distributed and adaptive MAC protocol, named Differentiated Distributed Coordination Function (DDCF) supporting the cluster organization created by the AC scheme. The DDCF scheme implements adaptive access differentiation based on the node roles assigned by the upper-layer's clustering scheme, and it dynamically adapts to the presence (absence) of the cluster organization inside the network.

  By considering the guidelines defined in [FBD03], we consider another application scenario where the integration of MAC and clustering protocols may be useful, i.e. the efficient propagation of alert messages in a VANET. A distributed dynamic clustering algorithm is proposed in order to create a dynamic virtual backbone inside the vehicular network [FB07a]. The vehicle-members of the backbone are responsible for efficient support to messages propagation. A fast multi-hop MAC forwarding mechanism is defined to exploit the role of backbone vehicles, under a cross-layered approach. Contributions and results about MAC and clustering integration are discussed in detail in Chapters 3, 4 and 5.

- *MAC and Routing Integration for effective support to multi-hop communication in large scale networks.* In [FB06, FB07b], a combined MAC and routing scheme is investigated for multi-hop topologies that (i) favours the spatial reuse of the channel by using multiple disjoint paths at routing layer and (ii) exploits channel reservation beyond one-hop at MAC layer. A novel multi-path routing scheme is proposed, by extending the AOMDV protocol with a novel load-balancing approach to concurrently distribute the traffic among the multiple paths. In order to provide an efficient support to the proposed routing scheme at the MAC layer, we also study the composition effect of a IEEE 802.11-based enhanced MAC forwarding mechanism called Fast Forward (FF), used to reduce the effects of self-contention among frames at the MAC layer. Contributions and results about MAC and routing integration are discussed in details in Chapters 6 and 7.

Thesis Plan

This document is structured as follows. The overall structure is divided in three parts. In Part 1, we sketch the main characteristics of MANETs and we discuss the basis of cross-layer protocol design. In particular:

Chapter 1: we briefly sketch the main characteristics of MANETs, the application domains and the design challenges which justify the use of a cross-layer approach in the protocol design for MANETs.

Chapter 2: we focus on cross-layer design for MANETs, by analyzing benefits and criticisms of the cross-layer approach and by providing an exhaustive review of the cross-layer solutions and architectures proposed in literature.

Parts 2 and 3 describe our contributions on cross-layer optimizations of multi-hop communication in a MANET. In Part 2, we focus on MAC and clustering integration for distributed management in highly mobile ad hoc networks. More in detail:

Chapter 3: we discuss the motivations supporting the joint design of MAC and clustering solutions in a MANET. At the same time, we describe the state of the art in the area of clustering protocols and MAC protocols with priority access schemes for MANETs. The state of art constitutes the background to our proposals described in Chapter 4 and 5.

Chapter 4: we present our proposal for the joint design of clustering and MAC solution in a MANET [FBD03]. The AC clustering and the DDCF MAC scheme are described in detail. Moreover, the simulation analysis includes a comprehensive evaluation of the cross-layer framework under varying mobility models, nodes' role distribution and offered load.

Chapter 5: we present our proposal for the joint design of clustering and MAC solution for efficient data broadcast in a VANET [FB07a]. The proposed scheme follows the guidelines defined in the previous chapters, but also exploits a novel approach to handle the specific characteristics of the vehicular mobility.

In Part 3, we focus on MAC and routing integration to support multi-hop communication in large scale ad-hoc networks. In particular:

Chapter 6: we discuss the motivations supporting the joint design of MAC and routing solutions in MANETs. At the same time, we sketch some existing routing protocols for MANETs. The state of art constitutes the background for our proposal described in Chapter 7.

Chapter 7: we present our proposal for the mutual support of distributed MAC and routing schemes in MANETs [FB06, FB07b]. We provide a complete description of the routing scheme (CS-AOMDV) and of the MAC scheme (FF). Moreover, we include a complete evaluation of our framework for a large set of metrics and scenarios.

Chapter 2

Cross-Layer Design in Wireless Ad Hoc Networks

2.1 Layered vs Cross-Layer Approach

Traditional packet-based network architectures assume that communication functions are organized into nested levels of abstraction called *protocol layers*, and that the metadata controlling the packet delivery are organized into *protocol headers*, one for each protocol layer. Actually, the network functionalities and services are commonly classified and modelled through the well-known Open System Interconnection (OSI) network model. Standardized in 1984, the ISO/OSI model establishes a 7-layer protocol stack where each layer defines the specifications for a particular network aspect and provides services to the upper layers (Figure 2.1). The main characteristic of the OSI model is the modularity [VP05]. Each layer implements a specific service: the architecture forbids direct communication between non-adjacent layers, while the communication between adjacent layers works by using standard interfaces.

Alternatively, protocols can be designed by violating the reference architecture, by allowing interactions and state information flowing among non-adjacent levels of the protocol stack. Generally speaking, cross-layer design refers to *protocol design done by allowing layers to exchange state information in order to obtain perfor-*

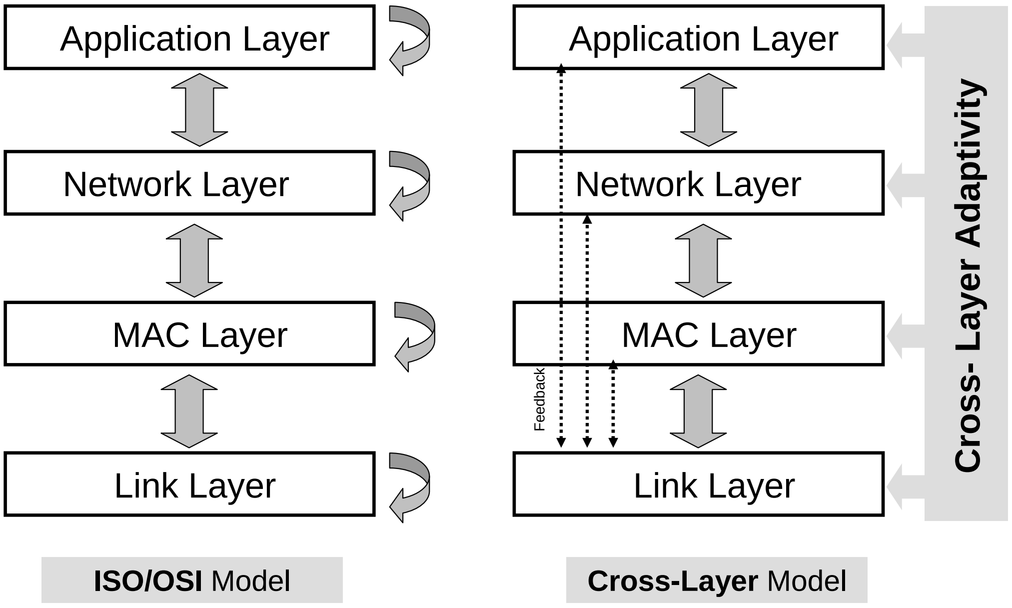


Figure 2.1: The ISO/OSI (left) and the cross-layer architecture (right)

mance gains [SM05, CMT04, Bis05, YSZ+04, MVP05]. The differences between the cross-layer architecture and the layered one are shown in Figure 2.1. The sharing of information enables each layer to have a global pictures of the constraints and characteristics of the network. Moreover, the network protocols are jointly designed and integrated in a hierarchical framework.

Several definitions of cross-layer design have been proposed in literature [SM05, CMT04, Bis05, YSZ+04, MVP05]. In most cases, cross-layer design is referred both as a general protocol design methodology as well as a mean to identify protocols designed with this approach. In [SM05], the authors identify four different approaches of cross-layer design, classifying each approach according to the possible violations of the layered architecture: (i) creation of new interfaces between the levels, (ii) merging of adjacent layers, (iii) coupling without new interfaces and (iv) vertical calibration across layers. In the following, we provide the general motivations supporting the adoption of cross-layer design in MANETs, together with the analysis of possible risks raising when a cross-layer approach is followed. A survey of cross-layer proposals for MANETs is provided in section 3. In section 4, we focus on the cross-layer approach from an architectural standpoint, sketching the common proposals to allow runtime information sharing among the protocol layers. Open issues on cross-layer design follows in section 5.

2.2 Motivations and Criticisms

There are three main motivations supporting the adoption of cross-layer design in protocol design for MANETs: the need by protocols to be adaptive to network dynamics, to support the requirements specified by the applications and to tackle the energy and security constraints. We observe that several design challenges in MANETs (security, energy issue, topology control) cut across the layers, and requires joint solutions involving multiple protocol layers.

Adaptivity and Self-Organization. Network protocols for MANETs must be adaptive to many factors to effectively support fair sharing of devices and resources and to hide the system dynamics to the upper layers. The *system dynamics* include a wide range of communication conditions a wireless node can experience inside a MANET, including changing topology, shared medium contention, varying traffic patterns and distributions. The adaptive behaviour can be implemented if the following requirements are met:

- *context awareness*, i.e. the knowledge of the parameters affecting the network state (channel condition, congestion, traffic demands, etc);
- *protocol tuning*, i.e. the possibility for each protocol to adjust his behaviour according to the current network state.

For example, given the current channel state condition (BER level), the MAC protocol may adjust some parameters (for example the length of frame) in order to reduce the energy consumption [EW99]; the routing layer may use the channel state information in the route discovery process, in order to dynamically select the most stable routes [FMBT05].

Context awareness sometimes requires to re-design the way protocols are organized and interact each other. Cross-layer architectures have been proposed to guarantee protocols cooperation with sharing of network-status information while still maintaining separation among the layers [CMT04].

QoS and Applications Requirements. QoS is a guarantee by the network to provide certain performance for a flow in terms of bandwidth, delay, jitter, packet loss probability, etc. At the MAC layer, QoS is related to the fraction of time a node is able to successfully access and transmit a packet. Actually, the 802.11e protocol extension provides mechanisms to support different priorities in WLAN networks: the 802.11e EDCF [edc] protocol supports 8 different service priorities, mapped on 4 different access categories. Each category defines a set of parameters governing the access to the shared medium. In multi-hop environments, QoS must be addressed by considering the QoS requirements on the end-to-end path as well as on each hop. Wireless channel fluctuations, self-contention, limited bandwidth and dynamic topology make the QoS appear a strong issue for MANETs [YSZ+04]. What appears clear is that the QoS requirements can not be met in MANETs unless they are supported across all the layers of the network. For these reasons, many recent works investigate the joint optimization of physical layer power allocation, MAC layer link scheduling, and network layer flow assignment [YSZ+04, WZ05].

Energy Conservation. Energy efficiency is a limiting factor in the successful deployment of MANETs, because nodes are expected to rely on portable, limited power sources. Moreover, energy conservation is extremely challenging in multi-hop environments, where the wireless nodes should also consume energy to route packets for other nodes and to guarantee the connectivity of the network. At the MAC layer, some techniques can be used to reduce the energy consumed during transmission and reception; additionally, a careful policy may turn off the wireless communication device when the node is idle. At the network layer, the route selection process should be performed by minimizing the total power needed to forward the packet ([BR04]); if the network layer may have access to energy information, battery-level metrics can be used in the routing process.

Security. Because nodes in MANETs communicate each other via open and shared broadcast channel, they are more vulnerable to security attacks. Moreover, the support for multi-hop communication implies that the network has to rely on individual solutions from each mobile nodes, resulting vulnerable to infiltration, eavesdropping, interference, DoS attacks. Many research efforts have mostly concentrated on secure data forwarding: secure routing protocols face the attacks that intentionally disrupt the routing protocol execution, and guarantee the acquisition of correct topological information [MM04]. On the other hand, data-link security solutions are implemented as parts of wireless standards (WEP/WPA for 802.11) to provide authentication and privacy issue on infrastructured single-hop wireless networks [AB05]. The solutions proposed at MAC, routing and transport layer only cover a subset of all possible threats; a cross-layer design of MAC, routing and transport protocols allows to take into account the security issues in all the stages of protocol design.

Although the ad hoc research community recognizes that a cross-layer approach can provide significant performance benefits, some recent works observe that the layered design has provided a key element in the Internet's success and proliferation, and warns the risk for unbridled stack design. In [VP05], the authors examine holistically the issue of cross-layer design and its architectural ramifications. They contend that a good architectural design leads to proliferation and longevity of a technology, and illustrate this with some historical examples, starting from the John von Neumann's architecture for computer systems to the Shannon's architecture for communication systems. The main disadvantages of an undisciplined cross-layer design are identified as tight coupling, unbridled stack design and uncorrect system implementation [MVP05, VP05].

Tight coupling. The layered architecture enables protocol designers to focus on a specific layer without considering the effects on the rest of the protocol stack. The design of cross-layer optimizations may cause the involved protocols to become tightly-coupled, and therefore mutually dependent. Sometimes, the mutual interactions among protocols may affect the whole system, leading to negative consequences such as instability.

Unbridled stack design The absence of modularity may affect the design improvements and innovations, because modifying one layer or adding new layers into the stack may require changes in the whole systems. For these reasons, the authors of [VP05] address the need to identify a reference cross-layer architecture [CMT05, BFH02, CPN07].

Uncorrect system implementation Cross-layer design may create adaptation loops caused by interacting protocols. In some cases, the dependencies are caused by an uncorrect system implementation and are not essential for the specific functionalities to be reached [VP05].

2.3 Cross Layer Optimizations

Many cross-layer solutions have been considered in literature, so that a complete classification results out of the scopes of this discussion. In the next section we follow the approach presented in [RI04], by providing some examples of cross-layer solutions involving Physical (PHY), Medium Access Control (MAC), Network (NET) and Transport (TRA) layers. In most of them, cross-layer feedbacks are used to enable state information flow from upper to lower layers or viceversa, while the traditional layered structure is preserved.

PHY+MAC Cross-Layer Solutions. In a wireless network, each device has a transmission radius and an interference radius. The relation between the transmission and interference radius depends on the underlying physical layer, and affects the contention level perceived at MAC level. In [NR03], the authors analyze the impact of the physical layer on the performance of MAC protocols, by demonstrating the importance of physical layer parameters (SNR) in designing efficient MAC protocols. The authors of [CL06] propose a carrier-sensing scheme that use MAC state information to alleviate the problem of Hidden Terminals (HT) and Exposed Terminals (ET): the addresses of transmitter and receiver of a packet are incorporated into the PHY header. Making use of address information for its carrier-sensing operation, a node can declare the channel busy or idle on the basis of transmitter-receiver pairs. The scheme described in [GCA06] attempts to mitigate the effect of EN and HN by using directional antenna: a novel MAC protocol (MAC-EDAMA) is proposed to exploit the directionality of the communication. A complete analysis of protocol harmonization between MAC and physical layer is investigated in [EW99], by focusing on the effects of packet length, transmit power and bit-error rate on system performance. The results shown in [EW99] demonstrate that the optimal transmit power is proportional to the packet length. Moreover, if the length of the packet is varied at MAC Layer accordingly with the current BER level, the energy consumption may be drastically reduced.

PHY+NET Cross-Layer Solutions. In [CP02], the authors evaluate the impact of the physical layer on the performance of five different routing protocols for MANETs. The results in [CP02] demonstrate that the performance obtained when physical layer properties such as path loss and shadowing are considered are drastically different when compared with the results provided by a simple free propagation model. For these reasons, the authors conclude that the hop-count may not be an

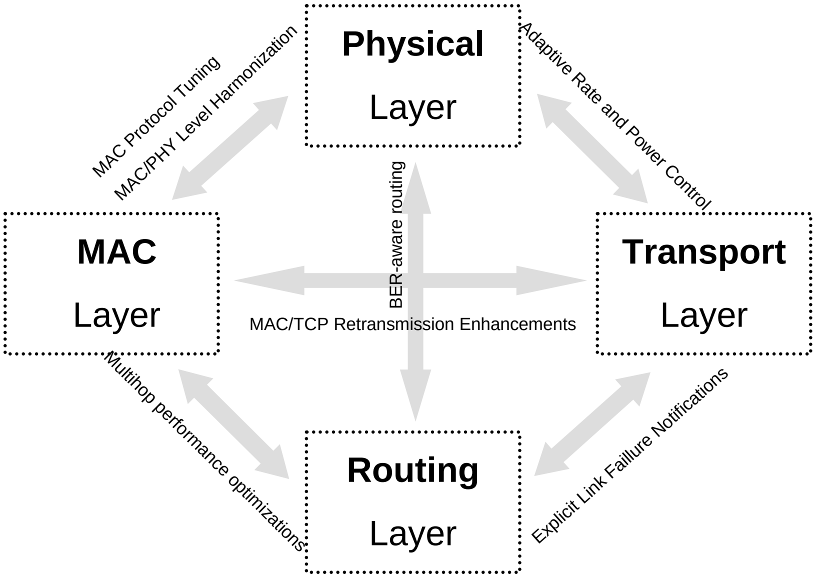


Figure 2.2: Cross-layer optimizations involving Physical, MAC, Routing and Transport Layers

optimal metrics for the routing process and that the routing metrics for MANETs should take into account the current state of the channel as well as the quality of each link. In [FMBT05], the AODV protocol is extended by considering the Bit Error Rate (BER) of each link in the route selection process: the resulting protocol (named MAODV) leads to the selection of the route minimizing the end-to-end BER.

PHY+TRA Cross Layer Solutions. Power control can often influence the transmission rate of mobile nodes. In [Chi05], the authors examine the possibility to enhance multi-hop communication in wireless ad hoc networks by balancing power control in the physical layer and congestion control in the transport layer. The authors present a distributive power control algorithm (JOCP) that couples with the original TCP protocols to increase the end-to-end throughput and energy efficiency of the network. The key idea of JOCP is that, during congestion periods, nodes will try to transmit packets faster at the bottleneck links by updating their transmission power. More specifically, at each time slot the transmission power at a transmitter i will increase proportionally to its packet queuing delay λ and will decrease proportionally to its current power level P_i. The analytical model described in [Chi05] proves the convergence of this coupled system to the global optimum of joint power control and congestion control, for both synchronized and asynchronous implementations.

MAC+NET Cross Layer Solutions. In [BDM02], the authors analyze the interaction of the routing and MAC layer protocols on multi-hop MANETs topologies. Simulation results obtained in different scenarios confirm that routing protocols can significantly affect the performance of MAC protocols and viceversa. For example, the paths selected by the routing protocol directly affect the spatial contention among the involved nodes at the MAC layer. At the same time, the contention at the MAC layer can cause routing protocol to respond by initiating new route queries and route table updates. The authors conclude that it is not meaningful to consider MAC or routing protocols in isolation, and suggest that a cross-layer approach may produce effective enhancement to multi-hop communication in a MANET. Some recent works addresses the joint design of MAC and routing solutions for MANETs. A cross-layer design is investigated in [RS03]: a combined MAC and routing solution is illustrated aiming to obtain effective load balancing using maximally node-disjoint routes and directional antennas. In [FB06, FB07b], a novel multipath routing scheme -called Concurrent Separate AOMDV protocol - for mobile ad hoc networks is proposed. The CS-AOMDV scheme extends the Ad Hoc On-demand Multipath Distance Vector (AOMDV) routing protocol, by introducing a load-balancing scheme to concurrently distribute the traffic among the available paths. The traffic-path allocation scheme is based on cross-layer measurements of path statistics reflecting the congestion level of each path.

MAC+TRA Cross Layer Solutions. The inability of TCP to distinguish between packet loss caused by congestion and packet loss caused by other factors (mobility of nodes, wireless link fluctuations) is the main cause of the poor performance of TCP in multihop ad hoc networks [HAN03]. While several proposals in literature attempt to solve the problem by modifying the MAC level or the TCP in isolations, some other solutions explore joint strategies with a vertical calibration of MAC and TCP layers. In [MD02], the authors show that increasing the number of MAC retransmissions decreases the risk of TCP timeout, and improves the overall performance of the network.

NET+TRA Cross Layer Solutions. The Explicit Link Failure Notification (ELFN) scheme [HV02] is a a feedback based approach to handle route failures in MANETs. The ELFN technique is based on the interaction between the routing and transport layers: when a link failure is detected by a mobile router, an ELFN message is notified to the TCP sender, which responds by disabling its retransmission timers and enters a "standby" mode. Ad hoc TCP (ATCP) [LS01] utilizes network layer feedback too. In addition to route failure notification, ATCP exploits Explicit Congestion Notification (ECN) messages from network layer which notify the occurence of congestion: upon reception of ECN, TCP congestion control is invoked normally without waiting for a timeout event. The ATCP protocol monitors the received ACKs to detect packet losses due channel errors. When three duplicate ACKs have been received, the ATCP protocol does not forward the third duplicate ACK but puts TCP in the "persistent" state and quickly retransmits the lost packet from the TCP buffer. After receiving the next ACK, ATCP will resume TCP to the normal state [LS01].

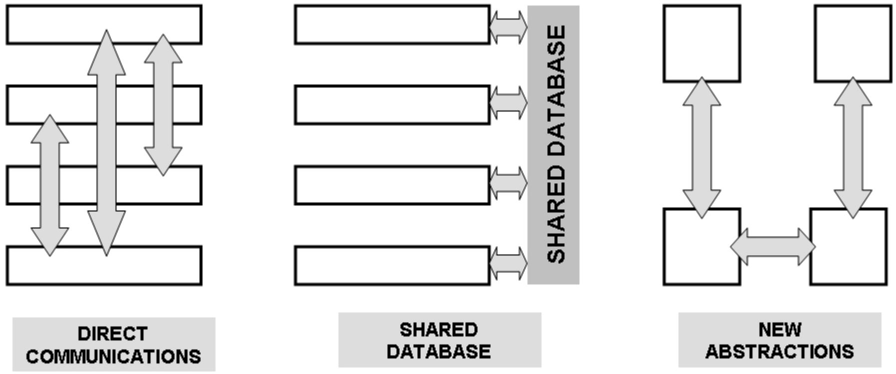


Figure 2.3: Cross-layer architectures proposals in literature

2.4 Cross Layer Implementations

Cross-layer solutions typically require an effective communication support for sharing the information among cooperative nodes. Alongside the cross-layer protocols discussed earlier, initial proposal on how cross-layer interactions can be implemented are being made in literature. The authors of [SM05] distinguish among three categories of cross-layer architectures:

- Direct communication between layers
- Shared database architectures
- Heap architectures or completely novel approaches

2.4.1 Direct Communication between Layers

Using the approach of direct communication, the network layers communicate with each other by using shared variables, internal packets or layer triggers. Layer triggers are predefined signals which are used to notify special events between protocols. An example of layer trigger is the Explicit Congestion Notification mechanism [HV02], used by intermediate routers to notify the TCP senders about congestion. Another

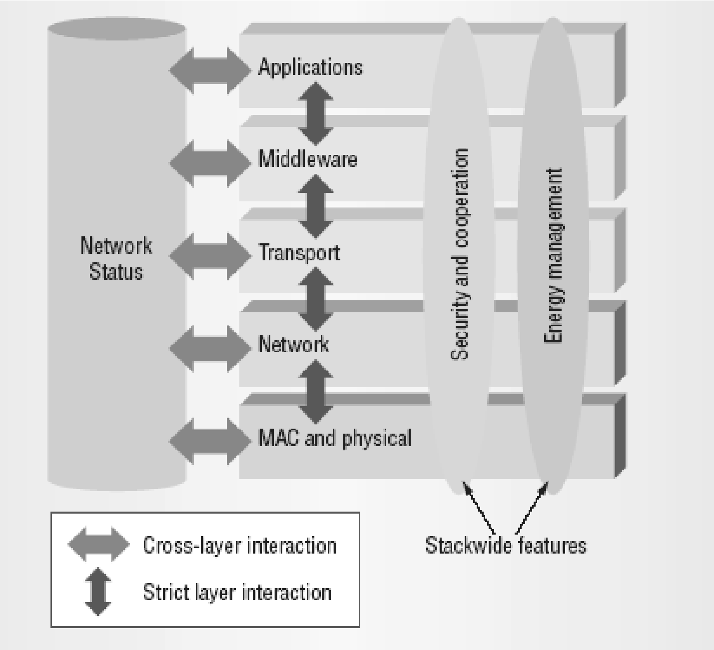


Figure 2.4: The MobileMAN reference architecture

examples are the L2 trigger, added between the link and Internet protocol layer to efficiently detect changes in the wireless links' status. Layer triggers is the most common cross-layer implementation, mainly because it does not require to modify the layered structure.

2.4.2 Shared Database Architecture

Another class of proposals use a shared database that can be accessed by all the layers, as illustrated in Figure 2.3. The common database plays the role of storage of shared information. The architecture also provides common methods to retrive/insert data from/into the database. An example of shared database cross-layer architecture is the MobileMAN project [CMT04, CMT05].

MobileMAN Architecture The MobileMAN project[CMT04] started in February 2004 with the primary aim to exploit a full cross-layer design for MANETs. The architecture presents a core component, Network Status (NS), that works as an information repository. Whenever a protocol in the stack collects information, it publishes it to the repository, thus making it available for the other network protocols (see Figure 2.4). Layer separation is achieved by means of standard interfaces to access the network repository. The MobileMAN architecture provides two possible models of interaction [CMT05]: synchronous and asynchronous. Protocols interact synchronously when they share private data: a request for private data takes place on-demand, with a protocol issuing a query to retrieve data produced at other layers, and waiting for the result. Asynchronous interactions characterize the occurrence of specified conditions, to which protocols may be willing to react. The XL-interface to the shared repository includes 5 different methods. The *seize* and *access* methods allow to insert and retrieve information from the repository respectively. The remaining functionalities of the XL-interface cope with asynchronous interactions by means of a publish/subscribe paradigm. With the *subscribe* method, a protocol declares its interest to receive notification of a specific event. The *notify* method is used by the protocol inserting data in the NS to notify event occurrences. Data gathering and monitoring are performed by the *monitor* method. The authors claim that the main benefits of the MobileMAN architecture are (i) cross-layer optimization for all the network functions, (ii) improved local and global adaptation, (iii) full context awareness for all the layers and (iv) reduced overhead. However, they also observe that the only way to obtain such benefits is to redesign protocols at each layer of the protocol stack: some example of cross-layer protocols using the MobileMAN architecture can be found in [CMT05].

2.4.3 Heap architectures or completely novel approaches

Another set of cross-layer implementations exploit completely new abstractions for protocol organization and protocol information sharing. The authors of [BFH02] propose a completely new architecture called *role-based architecture* or RBA. Instead of using protocol layers, RBA organizes communication using functional units that are called *roles*. Roles are organized in heaps instead of stacks. Another example is the EventHelix protocol design [Eve].

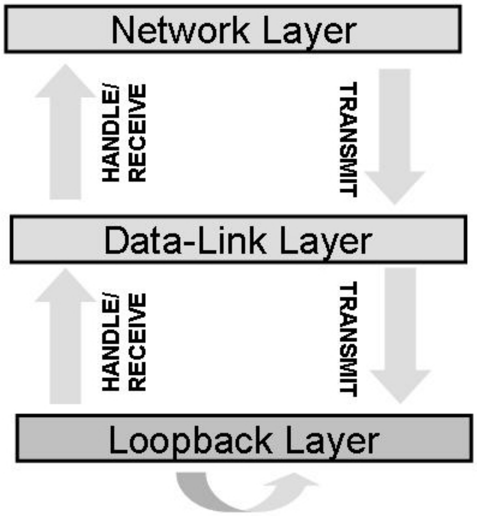


Figure 2.5: EventHelix protocol design

EventHelix protocol design. EventHelix [Eve] is a streaming protocol which uses a standardized interface among different layers. The protocol architecture is a variant of the layer trigger approach described previously, but also allows the dynamic adding and removal of protocols on the fly. The modularity of each layer is still garanteed, but a single layer can interface with any number of upper or lower layer protocols by using the same interface. The EventHelix framework is still under development: an examples of EventHelix implementation is illustrated in Figure 2.5.

2.5 Open Issues

The wide spectrum of cross-layer proposals demonstrates the popularity of the cross-layer approach in the research community. However there are also some open research problems limiting the development of systematic techniques for cross-layer design in wireless ad hoc networks [MVP05]. Again, we consider two kinds of issues in the open challenges: questions about which cross-layer protocols should be considered in a standard reference architecture and questions about how to implement a standard cross-layer architecture.

While many cross-layer architecture proposals have been proposed, a complete analysis showing benefits and drawbacks in terms of complexity and performance improvement is not addressed in literature. Finding a reference architecture becomes a challenge in order to standardize the organization of layers and the interfaces for information sharing among layers [SM05, MVP05]. Another important question is how cross-layer and traditional layered architecture can coexist with one another. For example, it should be preserved the possibility to use the legacy TCP protocol without cross-layer optimizations when a node implementing a cross-layer architecture communicates with a node implementing the traditional layered architecture.

From the protocol design point of view, existing studies on cross-layer optimizations are mostly focused on jointly solutions involving at most two protocol layers. In many cases, the network planning in wireless ad hoc networks can be modelled as an optimization problem involving physical, MAC, and routing layers [WZ05].

Part II

Joint Design of MAC and Clustering solutions

Chapter 3

Motivations and State of The Art

3.1 Motivations

Nodes belonging to MANETs may be heterogeneous in technology, performance resources and mobility characteristics. To support reliable and efficient network communication, and to dynamically optimize the resource management, the protocols for network management should be distributed in their design and implementation. The distributed paradigm is the most affordable management approach for an "ad hoc" environment, to face the unpredictable dynamics and best effort communication characteristics of MANETs. On the other hand, distributed protocols must be made adaptive to many factors, to hide the system dynamics to the upper layers, and to provide the best effort support for communication, possibly conditioned to dynamic availability and distribution of devices and resources. For these reasons, distributed management protocols may benefit of network infrastructures to implement general communication services under the optimal exploitation of the nodes' heterogeneity.

One of the most promising methodologies for trading-off pseudo-centralized virtual infrastructures and distributed management, in dynamic scenarios, is obtained by grouping nodes into *clusters* [YC05, LC00, Kri97, LG97] - i.e., by creating a hierarchy among hosts. Under a cluster structure, each mobile node may be assigned a different status reflecting the specific role inside the cluster (clusterhead, gateway, member, ...). Each node should decide, in a distributed way, the cluster formation and membership issues. Under this point of view, the heterogeneity and mobility features of MANETs nodes should be specifically taken into account by clustering schemes designed for the wireless MANET scenario. The overhead for cluster creation and management should be balanced by persistent advantages in (i) spatial reuse, (ii) communication coordination and (iii) stability and efficiency.

Spatial Reuse. A cluster structure may facilitate the spatial reuse of resources by increasing the system capacity. For example, two non-overlapping clusters may deploy the same frequency or code set if they are not neighbouring clusters.

Communication Coordination. The hierarchy inside the network may be used to coordinate transmission events inside the network with the help of special mobile nodes (clusterheads). Moreover, intra-cluster routing protocols may be designed by exploiting the backbone structure formed by some clustering schemes ([DBL02]).

Stability and Efficiency. A cluster structure makes a MANET appear more stable in the view of each mobile terminal. When a mobile node changes its attaching cluster, only mobile nodes residing in the corresponding clusters need to update their data structures.

By extending this discussion on the protocol issues and protocol architecture viewpoint in MANETs, the Medium Access Control (MAC) layer protocols are still challenging the research community, and are deeply investigated in the effort to obtain a good design and adaptive, tunable compromises among distributed and centralized implementation, communication performance and reliability, resources utilization and system scalability [dcf, edc, KRD06]. MAC protocols and clustering schemes could be considered mutually cooperative protocol layers: the clustering scheme could support MAC layer coordination among nodes, by shifting the distributed MAC paradigm towards a pseudo-centralized MAC paradigm

[FBD03, FB07a]. On the other hand, the system benefits of the clustering scheme could be emphasized by the pseudo-centralized MAC layer with the support for differentiated access priorities and controlled contention.

From these considerations, we can conclude a MAC protocol supporting a cluster organization should meet the following requirements:

- *Differentiated Channel Access.* Several clustering schemes work by assigning different roles to each node of a cluster. Special roles usually involve specific tasks to be performed: for example, clusterhead and spine nodes may be asked to support intra-cluster routing. At MAC layer, clustering roles should be mapped into different classes in accessing the shared medium, where special nodes should have higher priority in accessing the channel than common nodes [WYY03, AC01, XL01, YYH03].

- *Adaptivity.* The MAC layer could not rely on the assumption of a reliable cluster organization, like in infrastructure-based networks. For this reason, the MAC layer coordination function should transparently adapt to the presence (or absence) of the clustering node roles, by mutating its coordination scheme from pseudo-centralized to fully distributed (in presence and absence of clustering, respectively). This adaptation should be obtained without introducing any critical issue, management bottleneck and resource wastage in the system operation.

In the following, we sketch some existing clustering schemes proposed in literature for MANETs, which constitute the milestones of the AC clustering scheme described in Chapter 4. Section 3 focuses on existing solutions at MAC layer. The legacy 802.11 DDCF protocol is described in section 3.1, together with the 802.11e EDCA extension to support QoS on MANETs. Priorities access schemes support differentiated service at MAC layer by adjusting the parameters regulating the channel access in the legacy 802.11 DCF scheme. At least five different factors may be considered to provide channel access differentiation at MAC layer: section 3.3.3

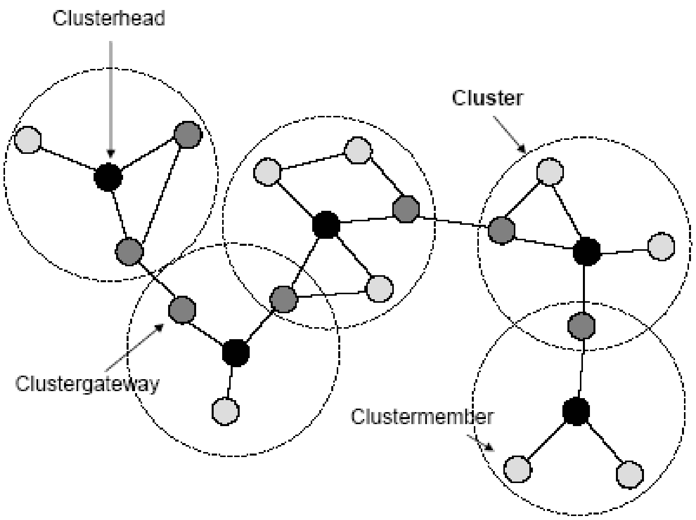


Figure 3.1: Cluster structure

sketches the existing MAC protocols which provide priority channel access schemes. All these schemes have been taken into account in the definition of our solutions described in chapters 4 and 5.

3.2 Clustering Schemes for MANETs

A great number of different clustering algorithms have been introduced, generally different in the kind of hierarchical infrastructure and topology they establish [YC05, LC00, Kri97, LG97].

From the architectural point of view, we can classify clustering algorithms as *1-hop clusterhead* based, *multi-hop clusterhead* based and *non-clusterhead based.* Clusterhead based algorithms select a node into each cluster as the ClusterHead (CH, i.e. the group leader), which may act just as the cluster representative or, in more complex approaches, as the coordinator of intra and inter-cluster communications. In clusters with a cluster leader, some schemes (e.g. [BKL01, AP00, CDT00]) let nodes joining a set only when they have direct wireless links with target clusterheads

(1-hop clustering), while other schemes (e.g. [LC00]) create multihop paths between nodes and related cluster leaders (see Figure 3.1). In such cases, a virtual backbone -called *Spine*- is created inside the networks. On the other side, non-clusterhead based algorithms let every single node decide, in a distributed way, which sets have to be formed and what group they have to join without assigning any particular role to nodes themselves [Kri97, LG97].

Many different clustering metrics can be defined for a wide range of scenarios, including MANETs. A ”one fits all” solution for clustering schemes is hard to find, and a careful examination of the peculiarities of the target scenario is essential to design effective protocols. We can classify clustering algorithms depending on the clustering metrics in four different categories [YC05]: (i) *mobility-aware* clustering, (ii) *energy-efficient* clustering, (iii) *load-balancing* clustering and (iiii) *combined-metrics* clusterings.

3.2.1 Mobility-Aware Clustering

The mobility of wireless nodes may be considered as one of the most important scenario characteristics to be considered under the protocol design and the cluster organization. The design choices impact cluster stability (that is, the way the cluster infrastructure is influenced by nodes' mobility) which in turn may determine the system performance. Mobility-aware clustering schemes attempt to group mobile terminals with similar speed in the same cluster, in order to reduce the overhead of cluster formation and maintenance [YC05]. The MOBIC [BKL01] scheme uses an aggregate local mobility metric so that the best clusterhead candidates are the nodes with the lowest relative speed. The mobility metric is calculated as the variance of the relative mobility value of a mobile node with respect to each neighbour. For cluster maintenance, the MOBIC scheme uses a timer (CCI) to avoid the risk of frequent re-clustering procedures when two clusterheads incidentally move in the same transmitting range. Re-clustering procedures are invoked only when two clusterheads remain in the transmitting range of each other longer than the CCI time period.

3.2.2 Energy-Efficent Clustering

Mobile nodes in a MANET normally depend on battery-power supply during operation, hence the energy limitation poses a severe challenge for network performance. Moreover, clusterhead and spine nodes consume more energy than ordinary nodes because they have to perform some extra tasks, such as intra-cluster routing. For these reasons, some clustering schemes tackle energy-consideration in the clustering formation process [YC05]. In the IDLBC protocol [AP00], each node maintains a local counter (VID) limiting the maximum time units a node can serve as clusterhead continuosly. Initially, the VID value is set as the ID number. Mobile nodes with the highest VID win the contention and become clusterhead. The VID counter is updated each time a mobile node becomes clusterhead: when a clusterhead exhausts its duration budget ($Max\ Count$), it resets its VID to 0 and becomes a non-clusterhead node.

3.2.3 Load-balancing Clustering

Load-balancing schemes attempts to find an optimal trade-off between clustering overheads and performance improvements by limiting the number of mobile nodes that a cluster can handle. An upper and lower limits on the cluster size are introduced. When a cluster size exceeds these limits, re-clustering procedures are invoked to adjust the number of mobile nodes in that cluster. The DLBC scheme [AP00] periodically invokes re-clustering procedure in order to keep the number of mobile nodes around a system parameter (ED). A clusterhead degrades to an ordinary node if the the difference between ED and the current number of affiliates exceeds a threshold value ($Max\ Delta$). The system parameter (ED) should be carefully chosen because it represents the optimal size of a cluster: too-large clusters mean excessive overhead for cluster-creation and maintenance, too-small clusters result in long hierarchical routes and high end-to-end delay.

3.2.4 Combined Metrics Clustering

Combined metrics schemes use all the metrics described so far by taking into account the node degrees, mobility and energy factors in the cluster formation. One advantage of this approach is that the weighting factors for each metric may be adjusted in order to adapt to different scenarios. On-demand WCA [CDT00] protocol considers four parameters in the clusterhead election procedure: degree-difference, D_v, local distance from all neighbours, P_v, average mobility speed, M_v and clusterhead serving time T_v. The ranking of each mobile node, I_v is computed as follows:

$$I_v = c_1 D_v + c_2 P_v + c_3 M_v + c_4 T_v \tag{3.1}$$

with $c_1 + c_2 + c_3 + c_4 = 1$. A similar combined-metrics is introduced in the AC clustering scheme [DBL02], which takes into account the connectivity, energy and mobility factor of each mobile node composing the cluster.

3.3 IEEE 802.11 MAC and priority access schemes

In recent years, the IEEE 802.11 Standard has emerged as a prevailing technology for the wireless LANs. The IEEE 802.11 WG is currently designing a new supplement of the current legacy 802.11 MAC sub-layer to support Quality of Service (QoS) needs [dcf, edc]. In this section we illustrate the main design issues of legacy IEEE 802.11 MAC, and QoS-enhanced IEEE 802.11e MAC, whose concepts will be considered as the milestones for the design of the proposed Differentiated Distributed Coordination Function (DDCF) access scheme, for cluster-based MANETs.

3.3.1 IEEE 802.11 DCF and PCF

The IEEE 802.11 MAC [dcf] describes two medium access functions, namely, the mandatory Distributed Coordination Function (DCF) which provides a distributed, contention-based shared access to the medium, and the Point Coordination Function (PCF), which is optional and offers a centralized access for an infrastructure-network. The legacy IEEE 802.11 DCF MAC protocol is based on a Carrier Sensing Multiple Access scheme with Collision Avoidance mechanism (CSMA/CA). Before starting a transmission, each station senses the channel to determine if another station is transmitting. If the channel is idle for a minimum duration called DCF InterFrame Space (DIFS), the station is allowed to transmit, otherwise the node defers the current transmission attempt until the end of the ongoing transmission. A deferring node executes a Binary Exponential Backoff (BEB) procedure. The BEB is implemented by assigning a local counter named Backoff Counter (BC) with a random value. The BC represents the number of empty slots that must be counted on the idle channel before performing the transmission attempt. The BC is computed as:

$$BC = RND() \cdot CWSize \tag{3.2}$$

where $RND()$ is a function returning pseudo-random numbers uniformly distributed in [0,1] and $CWSize$ is the integer upper bound to the values used to initialize the BC. For each idle time-slot, the BC is decremented by one. When the channel becomes busy, the BC is frozen and re-activated after the station senses the channel idle for a DIFS time. As soon as the BC equals zero, the pending frame is transmitted. A collision may occur if two or more stations access the channel at the same time-slot: to reduce the collision risk, the BEB dynamically modifies the CW Size after each transmission, on the basis of the collisions experienced. Along with the Collision Avoidance scheme, the IEEE 802.11 DCF defines a basic two-way DATA+ACK handshaking, based on positive acknowledgement frames (ACK). All the frames sent by a node to a (unicast MAC) receiver must be acknowledged by the receiving node, otherwise a collision is assumed and the CW Size is doubled by the sender up to a maximum value is reached. The DCF optionally incorporates preliminary two-way RTS/CTS handshaking scheme to minimize collisions with hidden terminals. The transmitting node sends a Request to Send (RTS) frame to the receiver to reserve the channel. Upon reception of one RTS, if the receiver is available, it replies with a Clear To Send (CTS) frame. The DATA+ACK transmission follows the CTS reception on the sender. The RTS and CTS frames contain a time value (NAV) that alerts other stations to hold from accessing the medium for the time duration of the ongoing transmission.

3.3.2 802.11e Enhanced DCF (EDCF)

The IEEE 802.11e distributed, contention-based MAC is called the Enhanced DCF (EDCF), because it is defined as the enhanced version of the legacy DCF access scheme [edc]. The EDCF provides differentiated channel access to frame flows whose priority level is decided by the layers above the MAC layer. With the EDCF, a single MAC, implemented on a MANET node, may have multiple frame queues, each one assigned to a different priority level (Traffic Class, TC). The access differentiation of frames with different priorities is realized in distributed way by adopting different CSMA/CA contention parameters. With the EDCF, all the frames within each node, and the nodes themselves, contend for the channel access, called the EDCF Transmission Opportunity (TXOP). Nodes contending with frames belonging to the same TC would act as peer contending nodes, without any differentiated effect based on the node role. The emerging EDCF is designed to provide differentiated, distributed channel accesses for frames with 8 different traffic classes (from 0 to 7) [edc]. The EDCF is a part of a single coordination function, called the Hybrid Coordination Function (HCF), of the 802.11e MAC [edc]. The HCF combines the aspects of both DCF and PCF.

Each frame from the upper layer arrives at the MAC along with a specific priority value. An 802.11e node shall implement a set of access categories (called ACCs to distinguish them from AC clustering), where an ACC is an enhanced variant of the DCF. Each frame arriving at the MAC with a specific traffic class (TC) priority is mapped into an ACC. A node willing to transmit a frame belonging to the access category ACC uses opportunely designed Arbitration IFS and CW size parameters (AIFS[ACC], CW min[ACC], and CW max[ACC]), instead of generalized DIFS, CW min, and CW max parameters of the DCF. The AIFS[ACC] can be defined as a function of SIFS and SlotTime, [dcf, edc]:

$$AIFS[ACC] = SIFS + size[ACC] \cdot SlotTime \qquad (3.3)$$

where size[ACC] is an integer value greater than zero. Moreover, every access category owns a personal CW range [1, CW[ACC]-1], instead of the global [0,CW-1] range. The values of AIFS[ACC], CW min[ACC], and CW max[ACC], which are referred to as the EDCF parameters, are announced by the AP via beacon frames.

3.3.3 MAC Priorities Access Schemes

The 802.11 DCF legacy MAC is designed to provide channel accesses with fair probabilities to all peer nodes contending for the channel access, in a distributed way. It does not support the generalized differentiation of nodes and frames with different priorities. At least five possible MAC factors can be adopted to introduce differentiated priorities on the basis of the IEEE 802.11 DCF CSMA/CA access scheme [WYY03]:

- *exploitation of variable IFS*: higher priority nodes may have smaller IFS than the low priority stations, thus obtaining more immediate time-priority to seize the medium;

- *variable CW ranges* for the selection of the backoff counter: higher priority nodes may have smaller window size, and then smaller average backoff time to wait before each transmission attempt;

- *variable PBF*: the scaling factor may affect the way the CW increases after a collision, which translates in the way the average backoff time increases before each new retransmission attempt;

- *variable size of transmitted frames*: given a channel capture, a long frame is a way to gain throughput with respect to peer nodes contending for short frames transmissions;

- *non-uniform random backoff distribution*: each priority level may have a biased probability distribution in the selection of the backoff slot within their respective CW range, so that high-priority nodes are more probable to select early slots in the CW range.

Backoff Management

As described in section 3.3.1, each deferring node in the legacy 802.11 DCF scheme executes a Binary Exponential Backoff (BEB) procedure. The BEB is implemented by assigning a local counter named Backoff Counter (BC) with a random value:

$$Backoff\_Time = [2^{2+i} \cdot rand()] \cdot Slot\_Time \tag{3.4}$$

Differentiated channel access may be implemented by replacing in equation 3.4 the term 2^{2+i} with two possible alternatives:

- P_j^{2+i}, where P_j is the priority level of node j (also called *Persistent Factor*, PB). In this case, when a station detects a collision, it increases the current CW range according to its current priority level. Higher priority classes may have smaller value of P_j.

- 2^{2+P_j}, where P_j represents the priority level of the node j. In this case, higher priority classes have smaller CW size, and experiment smaller average backoff delay in accessing the wireless channel.

In [AC01], the authors study the impact of varying P_j^{2+i} factors on system differentiation for IEEE 802.11 ad hoc networks. Simulation results reveals that varying P_j factors translates in a considerable priority differentiation effect when UDP traffic is considered. Results are completely different when TCP traffic is evaluated [AC01]. In such case, varying PBs is not able to differentiate TCP flows mainly because TCP is an adaptive transport protocol based on a feedback control embedded in the reception of ACK packets. In both *Slow Start* and *Congestion Avoidance* states, the TCP protocol sends new data packet only when the ACK packets are received. So, if an high-priority TCP sender sends DATA to a low-priority TCP receiver, the performance of the receiver also affects the transmission rate of the sender node.

Variable Interframe Spaces (IFS)

As described in section 3.3.3, IEEE 802.11 ACK packets get higher priority than RTS packets because they are transmitted after a SIFS which is shorter than a DIFS (for RTS). The same concept may be exploited to introduce priorities among different data frames or among different nodes' classes. In particular, each priority class gets a different $DIFS$, i.e. $DIFS_j$ where $DIFS_{j+1} < DIFS_j$. In this way, the nodes with priority j will wait $DIFS_j$ idle period before accessing the channel, obtaining more immediate time-priority to seize the medium than nodes with priority $< j$. Simulation results shown in [AC01, XL01] confirm that varying the IFS may offer a wide range of channel differentiation effect without affecting the efficiency of the communication. Moreover, the differentiation effect is effective for both UDP and TCP flows [AC01].

Variable Frame Length

The third mechanism that can be used to introduce service differentiation into IEEE 802.11 networks is to limit the maximum frame length (MFL_i) used by each node according to the current priority level i. Nodes with higher priority have higher MFL_i, and so they may use the channel for more time after they have accessed the medium. Simulation results shown in [WYY03] confirm that data rate shares are directly proportional to the maximum frame lengths allowed for each node. That is, for a given priority j:

$$\frac{B_j}{\sum_{i=1}^{N} B_i} = \frac{MFL_j}{\sum_{i=1}^{N} MFL_i} \tag{3.5}$$

where B_j and MFL_j are the throughput and the maximum frame length for a node with priority j.

Backoff Distribution

In [AC01], service differentiation is produced by using different biased probability distribution according to the current priority level of the node. In particular, the prioritized backoff time is based on the OPNET exponential distribution model, for which the mean is $1/\lambda$. Two different classes are considered, with different value of λ: high priority nodes (with $\lambda = 0.1$) and low priority nodes (with $\lambda = 0.4$)[AC01].

Chapter 4

MAC and Clustering Integration in MANETs

4.1 Overview

This chapter proposes and analyzes a solution for the mutual support of distributed MAC and clustering schemes in MANETs, by following the guidelines defined in Chapter 3. Contributions and results of this work are described in detail in [FBD03].

In [DBL02] a new clustering protocol, named *Availability Clustering* (AC), is defined under general nodes' heterogeneity assumptions in terms of connectivity, available energy and relative mobility. The AC clustering scheme takes into account the scenario peculiarities by combining multiple metrics into the clustering formation process. From the architectural point of view, the AC scheme identifies a hierarchy of nodes -called *Spine*- inside the network.

Our contribution consists in the design and analysis of a distributed and adaptive MAC protocol, named Differentiated Distributed Coordination Function (DDCF) supporting the cluster organization created by the AC scheme. The DDCF scheme is based on the IEEE 802.11 DCF access scheme, and inspired to the IEEE 802.11e design. The DDCF scheme implements adaptive access differentiation based on the node roles assigned by the upper-layer's clustering scheme, and it dynamically adapts to the presence (absence) of the spine in the network.

Section 4.2 contains an overview of the AC clustering scheme, while in section 4.3 we focus on the DDCF scheme at MAC Layer. We extensively simulate the proposed clustering scheme by showing its effectiveness in dominating the network dynamics, under some stressing mobility models and different mobility rates (section 4.4). Clustering simulation has been used as guidelines for the extensive performance evaluation of the DDCF access scheme, presented in section 4.5. The analytical model of the DDCF scheme under network saturation assumptions is described in section 4.6.

4.2 Overview of the AC Clustering Scheme

The design of the AC sheme is focused on three main targets: i) to identify a feasible virtual infrastructure topology, ii) to exploit nodes heterogeneity to enhance structure stability, and iii) to identify nodes having more resources as those implementing the leading roles required by the cluster hierarchy. In the following, a brief overview of AC clustering protocol is given; in [DBL02] a more exhaustive description can be found.

From the infrastructure topology point of view, AC creates a multi-hop cluster-based organization. In each cluster, one node elects itself as clusterhead (CH in the following), and other stations may become members of a cluster only if they are at most R hops away from the CH (R is defined as *cluster radius* in hops units). Each member selects one of its neighbors as the Next Hop (NH in the following), that is, the preferred node through which the CH can be reached. The selected NHs (including the CH itself) form the *intra-cluster spine*, that is, a virtual backbone able to support the main networking functions. The organization created by the AC clustering is shown in Figure 4.1.

The clusterhead selection is guided by a local parameter named *Availability Factor* (AF in the following). Informally, the AF parameter estimates the ”goodness” of each node to assume leading roles. The AF is computed as follows:

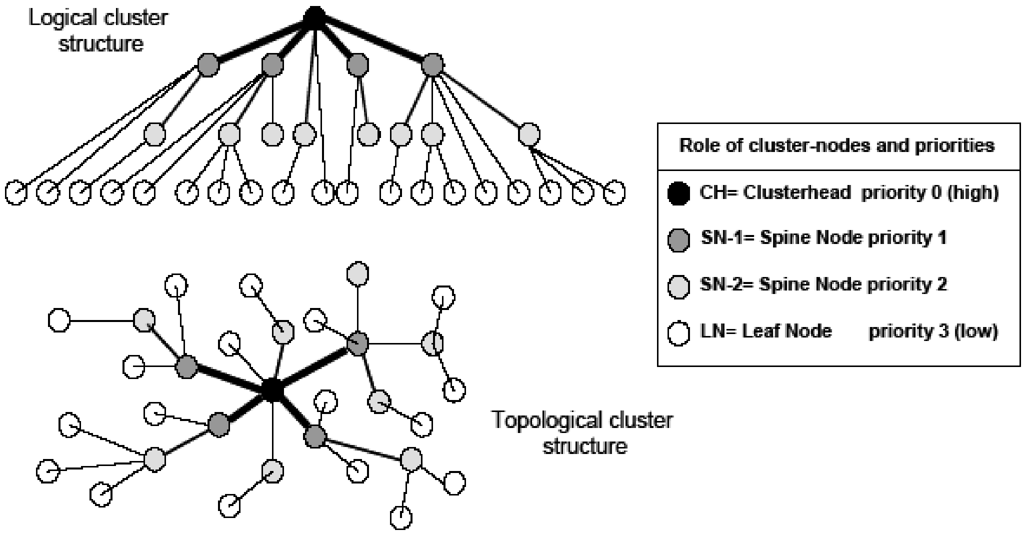


Figure 4.1: AC clustering organization

$$AF = \alpha \cdot CF + \beta \cdot EF + \gamma \cdot MF \tag{4.1}$$

where the Connectivity Factor (CF), the Energy Factor (EF) and the Mobility Factor (MF) are ranging in [0,1]. The CF, EF and MF parameters are local estimates of the connectivity, energy and mobility factors of each node, respectively. The Connectivity Factor is considered to minimize the number of selected NHs, while energy and mobility are used because the leading roles should be assigned to nodes having more energy and less relative mobility than others. The Mobility Factor is an estimate of the relative speed of each node, as proposed in [BKL01]. The three parameters α, β, γ may be arbitrarily assigned to tune the impact of the features of each node.

In general, AC has been thought to be communication "lightweight": it requires only a periodic information exchange among neighbors through broadcast packets called *beacons*. The protocol operations are supported by two data structures (local to each node):

1. a *status array* with clustering-related information, i.e. the node IDentifier, the node AF, the identifier of the CH of the node, the AF of the current CH, the identifier of each NH, the MINimum AF within the path towards the CH, the number of hops on the path towards the CH;

2. a *neighbors table*, storing the data received from neighboring nodes and also the power levels of the last beacons.

The algorithm behavior is driven by a periodic information gathering and role evaluation process controlled by a *Waiting Timer*: the node collects beacons coming from its neighbors, by refreshing the related neighbors table entries. Each beacon carries the node status array, the current energy level and the number of neighbors. When the timer expires, the node processes all the current information, evaluates its own AF, decides its role in the clustering structure, and assembles and transmits its beacon.

The role decision process includes three possible node states: Initial (INst), Normal (NMst) or Clusterhead (CHst). All nodes start in INst state, meaning that the node still has not joined any cluster. In CHst the node has elected itself as the cluster leader. In NMst the node is member of a cluster, and it is either a NH or a leaf node (that is, it has neighbors that have chosen it as NH or not, respectively). State transitions are driven by the AF value and the state of the node in relation to AF values and states of its neighbors. The target is to enhance as much as possible the quality and stability of the hierarchy organization, by avoiding any unnecessary structure change.

Initial State

In the INst state, the node affiliation to a cluster follows a novel approach, oriented to the infrastructure stability: one node selects the CH providing the best path connecting the CH to the node. The best path is selected among all the paths (if any) towards all the reachable CHs, as the path that maximizes the following generic target function:

$$AFtarget = f(AF(CH), AF(NH), AFmin) \tag{4.2}$$

where AF(CH), AF(NH) and AFmin are, respectively, the AF of the candidate CH, the AF of the candidate NH and the smallest AF on the path. The AF of the CH maximizing the 4.2 is compared with the AF of the node: if the AF of the CH is greater or equal to the AF of the node, then the node joins the CH cluster, by entering the NMst state. Otherwise, the node checks the current state of its neighbours: if at least one node in INst state, with AF greater than the AF of the node is found, then the node remains in INst, and waits for another node to become CH; if not, the node changes the state to CHst. Here, like in [CDT00], f(·) of 4.2 is equal to the sum of the three arguments.

Normal State

In NMst, the node goes into INst if it has lost its NH towards the previous CH and if it is unable to find another suitable NH to the same or any other CH. If the node belongs to the spine, the node is forced to maintain its affiliation, by limiting spine changes and enhancing the infrastructure stability. Conversely, it tries to find a new cluster aggregation (hopefully more stable). In other words, the node looks for a new NMst-node, candidate NH towards the same or other CH, which maximizes (4.2) and satisfies the following condition:

$$AFtarget, new - AFtarget, old \geq \tau \tag{4.3}$$

where the threshold τ has been introduced to limit hierarchy variations that may result in wasteful fluctuations: higher τ values translate in less aggregation updates. Before performing any affiliation change, any node must verify whether the new spine connection is better than the old one, up to a given lower bound threshold τ that would motivate the possible re-routing and channel re-allocation overheads due to the cluster variation.

Clusterhead State

In CHst, the node turns back to INst when it has no neighbors, or when one or more CHs with a higher AF become a neighbor.

4.3 The DDCF Access Scheme

As described in Chapter 3, the 802.11 DCF legacy MAC [dcf] does not support the generalized differentiation of nodes and frames with different priorities. Optimistically, the DCF is designed to provide channel accesses with fair probabilities to all peer nodes contending for the channel access, in a distributed way. However, equal access probabilities are not desirable among nodes with different priority, like the nodes belonging to a cluster-based infrastructure. The 802.11e EDCA legacy MAC scheme [edc] provides access scheme differentiation exploiting the concept of access categories and transmission opportunities. However, the basic efforts of the EDCA scheme are quite different from our perspective because differentiated channel accesses are provided for each packet on the basis of the packet flow and not of the role of each node.

Our proposal for the design of a Differentiated Distributed Coordination Function (DDCF) access scheme is based on the aforementioned EDCF description (section 3.3.2), and on the AC clustering assumptions. The DDCF channel access differentiation is obtained by applying different IFSs and CW sizes to the CSMA/CA MAC adopted for node accesses, whose values are defined by the node role in the cluster infrastructure. We assume that the node role has been mapped to an integer *priority level* (PL) value. The definition of a generalized hierarchy of nodes, with no limitations to the number of priority levels (PLs) can be obtained by extending the AIFS and CW design. Anyway, by taking into account the spine structure created by the AC clustering, and simulation results in [DBL02], we can limit the number of node-priority classes to four: PL=0 is the highest priority level (for clusterheads) and PL=3 is the lowest (for Leaf Nodes) (see Figure 4.2 and Table 4.1) . Prototype

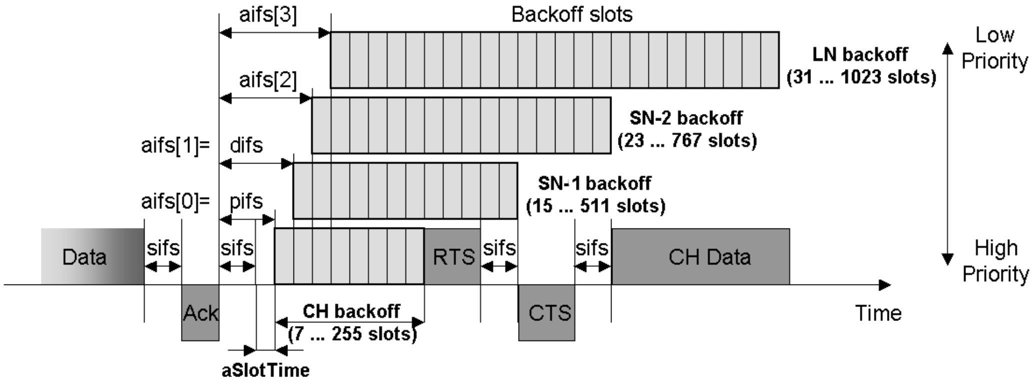


Figure 4.2: Interframe spaces in the DDCF protocol

arbitration IFS (AIFS) and CW ranges defined for DDCF have been summarized in Table 4.1.

The use of AIFS[PL] and CW ranges in the DDCF is quite similar to the EDCF's. The definition of values in Table 4.1 is driven by the need to maintain a compliance with legacy IEEE 802.11 design. By substituting the ACC with the PL in equation 3.3, the size[PL] argument may be considered as a tuning knob for the definition of slot ranges in the backoff phase, whose accesses would be additively reserved to the subset of spine nodes. Variable values for the size[PL] parameter in equation 3.3, adopted for the definition of AIFS[PL], could result in more wide separation among the contention slots devoted to be used by many leading node roles.

In current design, we fixe the size[PL] = (PL+1) value, by obtaining a single slot as the difference between consecutive AIFS[PL], also for compliance with IEEE 802.11. At this level, we assume that the Persistence Backoff Factor (PBF) is constant (i.e. Binary Exponential Backoff with PBF=2, for compliance with IEEE 802.11).

The DDCF parameters are defined in Table 4.1. It is worth noting that the CH assumes the role similar to the AP for legacy IEEE 802.11, while SN1 nodes would behave like legacy DCF nodes. This would also preserve the semantics of

Priority	**Node Role**	**Airbitration IFS** (AIFS[PL])	CW_{min}	CW_{MAX}
0	Clusterhead(CH)	AIFS[0]=SIFS+SlotTime	7	255
1	Spine Node1 (SN1)	AIFS[1]=AIFS[0]+SlotTime	15	511
2	Spine Node2 (SN2)	AIFS[2]=AIFS[1]+SlotTime	23	767
3	Leaf Node (LN)	AIFS[3]=AIFS[2]+SlotTime	31	1023

Table 4.1: DDCF Parameters

the SIFS used to piggyback context-related transmissions. The choice of the ranges for backoffs has been defined in order to maintain the upper bound limit consistent with the legacy IEEE 802.11 DCF. Currently, the AIFS, CW_{MAX}, CW_{min} and PL parameters of DDCF have been designed as static global values.

4.4 Simulation Results

In this section, we illustrate the simulation analysis of the AC clustering scheme adopted on a MANET scenario characterized by different mobility models. The AC clustering analysis is oriented to evaluate the AC clustering capability to exploit the system heterogeneity, and to adapt to the mobility of the nodes. The guidelines and clustering characterization obtained in this preliminary analysis are adopted as target factors for the specific analysis of the DDCF MAC protocol.

4.4.1 AC Clustering simulation

In the following, we analyze the performance of the AC scheme under dynamic MANET scenarios. The AC scheme is compared with the the DR scheme [LC00] because they produce a similar spine-based cluster structure. The main characteristics of simulations for both AC and DR schemes are briefly reported in Table 4.2. In the following set of experiments, the MAC is considered as ideal, because we are interested in the evaluation of pure clustering effects.
Two performance metrics are considered:

Simulated Areas	500x500m
Nodes Number	100
Nodes Composition	60% Mobile (M) 30% Fixed (F) and Unplugged (U) 10% Fixed (F)
Max Velocity (Vmax)	[1:3]m/s
Initial Energy Level	[100:1000] J
Cluster Radius (R)	3 hops
τ Threshold	[0:2.5]

Table 4.2: Simulation Parameters

- the *aggregation time*, which is the average time for a node to be aggregated to a CH or to a NH towards a CH;
- the *permanence time*, which is the average time for a node to retain its role.

Two mobility models are considered: the uncorrelated Random Waypoint Mobility (RW) and the Reference Point Group Mobility (RPGM) [Hon99], which introduces mobility correlation between node groups. All the simulation metrics are measured for both AC and DR with the aforementioned mobility models, parameterized by $Vmax$. Extensive simulations have been considered by combining several values of velocity, and of the τ threshold. Due to space limitation, only a subset of the obtained results is reported here.

In the following, the first collection of metrics is shown, by using τ as a varying parameter and by considering a minimum value for $Vmax$ (i.e. 1 m/s). The same metrics are shown in section 4.4.3 by varying $Vmax$ and by fixing a suitable value for the parameter τ.

4.4.2 Topological Metrics using RW

Figure 4.3 shows the average number of CHs and spine nodes (i.e. NHs) for both AC and DR clustering schemes. The mobility factor is fixed ($Vmax$=1 m/s). In the fol-

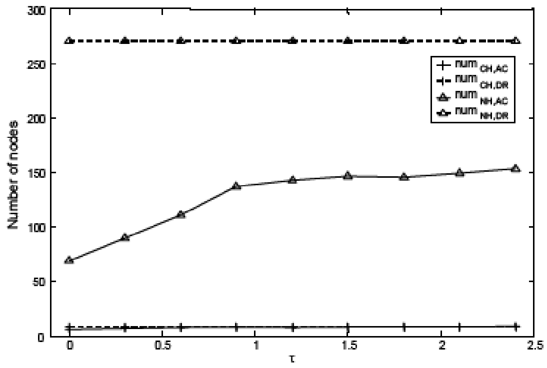


Figure 4.3: Average number of CHs and Spine Members (NHs), RW, $Vmax$=1 m/s

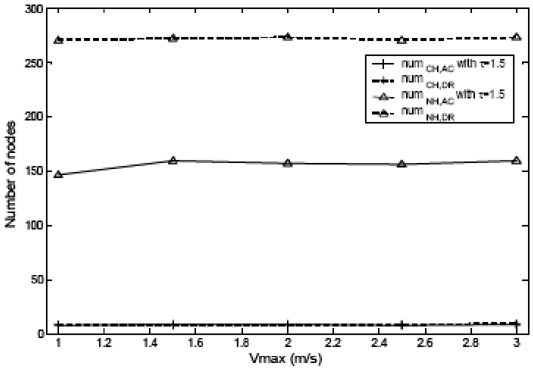


Figure 4.4: Average number of CHs and Spine Members (NHs)

lowing, the topological metrics are hereafter briefly indicated as $num_{<role>,<scheme>}$ with $< role >$ in {CH,NH} and $< scheme >$ in {AC,DR}.
By looking at the AC curves, no appreciable variations of $num_{CH,AC}$ can be observed, whereas $num_{NH,AC}$ linearly increases with τ (up to 1.2- 1.5), as expected. Since τ is the threshold of "convenience" in changing affiliation, the greater τ, the higher the number of nodes holding their actual affiliation. Moreover, the AC and DR schemes create about the same number of clusters, but the AC scheme uses less spine nodes than the DR scheme.

The Figure 4.4 shows the same metric of Figure 4.3 when $Vmax$ is variable and τ =1.5. As shown in Figure 4.4, $Vmax$ does not sensibly affect the performance of either AC or DR (with respect to the metrics under examination), while the AC scheme still outperforms the DR scheme in terms of (reduced) number of spine nodes, with the same number of CHs. The negligible effect of the motion speed could be caused by the specific characteristics of the RW model: in the RW model, the nodes tend to concentrate in the middle of the network area, by resulting in less mobility effects.

The percentage of plugged (P), unplugged (U), and mobile (M) CHs and spine nodes are weakly affected by the mobility factor. In the AC scheme, the nodes pro-

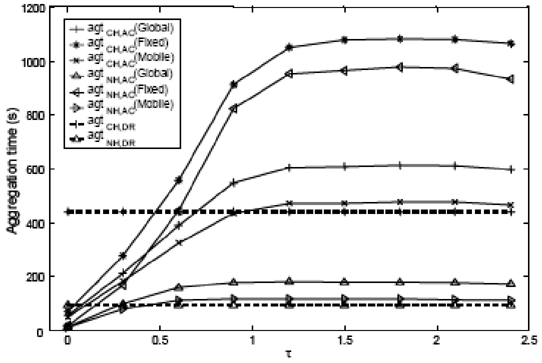


Figure 4.5: Average aggregation time to a CH or to a NH, Vmax=1m/s

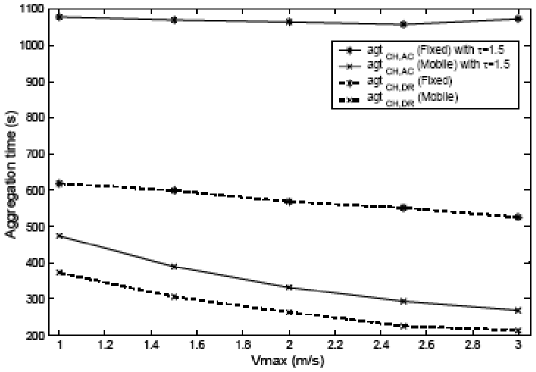


Figure 4.6: Average aggregation time to a CH or to a NH using RW

vided with the best characteristics (e.g. unlimited energy, static positions) are most likely selected as spine members. In quantitative terms, the CHs "per-role" distribution is about (P=89%; U=8%; M=3%), without appreciable variations as τ changes. On the other hand, the spine per-role distribution is about (P=45%; U=29%; M=26%) when τ is greater than 1.2-1.5. Below a threshold value ($Vmax$ <1.5), the top role distribution is even more unbalanced, in favor of fixed, and plugged nodes. With DR, the spine role distribution reflects the node role distribution in the network, as expected, (P=10%; U=30%; M=60%). This happens because DR does not take into account the nodes heterogeneity in the clustering formation process. The same considerations may be extended when the $Vmax$ speed factor increases.

4.4.3 Aggregation Time Metric using RW

In Figures 4.5 and 4.6, the following formalism is used to refer to the curves of the aggregation time: $agt_{<role>,<scheme>}(< type >)$ with $< role >$ in {CH,NH}, $< scheme >$ in AC,DR, and $< type >$ in {fixed, mobile, global}. The $agt_{<role>,<scheme>}(< type >)$ metric is an estimation of the average aggregation time curve between nodes of type $< type >$ in their role $< role >$, under the clustering $< scheme >$.

Figure 4.5 shows the average aggregation time with average speed $Vmax$=1 m/s. As shown in Figure 4.5, the average aggregation time of the AC scheme increases linearly when $\tau < 1.5$, and remains quite constant if τ=1.5. From these results, the choice of a reference value for τ= 1.5 can be motivated. As shown in Figure 4.5, the mobile nodes experience lower aggregation times than the static ones, and AC outperforms DR under the same scenarios. When τ=1.5 the Figure 4.5 shows that $agt_{NH,AC}$(fixed) is comparable with $agt_{CH,AC}$(fixed). With the AC scheme, the spine paths are composed mainly by fixed nodes, and are highly stable: such stability might be exploited by spine-based routing schemes. This observation constitutes the main motivation supporting the assumption to consider only static clustering scenarios in the DDCF MAC analysis. Moreover, under the same scenarios, $agt_{\cdot,AC}(\cdot)$ outperforms $agt_{\cdot,DR}(\cdot)$, by confirming that the AC spine paths are more stable than those obtained under the DR scheme.

Figure 4.6 shows the average aggregation time when τ =1.5 is fixed and $Vmax$ vary. As shown in Figure 4.6, the parameter $Vmax$ has little influence on the $agt_{CH,AC}$(fixed), while $agt_{CH,AC}$(mobile) decreases as $Vmax$ increases. By looking at the DR curves, both the $agt_{CH,DR}$(fixed) and $agt_{CH,DR}$(mobile) values decreases as $Vmax$ increases. This effect may be justified considering that the DR scheme does not exploit the nodes characteristics, including the mobility degree, so that static nodes may be affiliated to mobile nodes with high probability.
Similar comments can be expressed for Figure 4.7, where τ =1.5 and $Vmax$ is variable. Again, the mobility effect has little impact on $agt_{CH,AC}$(fixed) and $agt_{NH,AC}$(fixed), but negatively influences $agt_{NH,AC}$(mobile) and $agt_{NH,DR}(\cdot)$ (for both fixed and mobile nodes). In Figure 4.7, the AC scheme outperforms the DR scheme, and $agt_{NH,AC}(\cdot)$ is greater than $agt_{NH,DR}(\cdot)$.

4.4.4 Permanence Time Metric using RW

As shown in the previous figures, the AC scheme selects mainly fixed and plugged CHs, and most of them maintain their role for a significant time. On the other hand, the simulation results confirm that re-clustering procedures are very unlikely, i.e. a small percentage of nodes assume the CH role for a limited time. In Figure 4.8, we

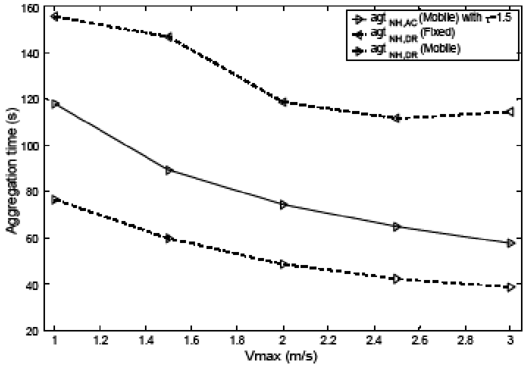


Figure 4.7: Average aggregation time to a NH using RW

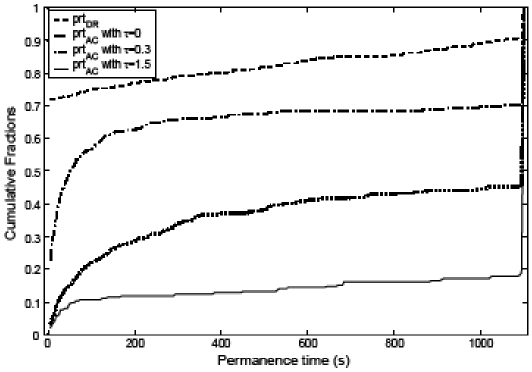


Figure 4.8: CH permanence time CDFs, Vmax=1 m/s

show the Cumulative Distribution Functions (CDFs) of the simulated permanence times for both AC and DR schemes, with $Vmax$=1 m/s. The CDFs are indicated as $prt_{<scheme>}$ with $< scheme >$ in AC,DR. In Figure 4.8, the CDFs of the AC scheme confirm that a small percentage of nodes assume the CH role for a limited time. Moreover, high values of τ prevent nodes to become CHs for short time intervals. In DR, the CH permanence time causes more frequent re-clustering operations, affecting the system performance. Similar conclusions for both AC and DR can be obtained when higher values of $Vmax$ are considered.

4.5 DDCF Simulation

In this section, we present the results of the DDCF simulations over a large number of scenarios, defined as variations of network topology and role distributions, by using the ns-2 simulator [ns2b]. The scenario and simulation parameters considered here are collected in Table 4.3. The physical parameters assumed for DDCF, and for the underlying IEEE 802.11 technology, can be found in Tables 4.1 and 4.3. The performance metrics considered in the analysis are: system throughput, per-node throughput differentiation, and per-node MAC delay differentiation percentiles (i.e. cumulative fractions).

To obtain the preliminary insight into the DDCF behavior, we have ran all the simulations with static nodes only. This choice was further motivated since previous simulations have shown that the AC clustering, by exploiting nodes heterogeneity, is able to select low relative mobility (and fixed) nodes as spine members. Under the channel access contention viewpoint, which is the main focus of this analysis at the MAC layer, two scenarios have been defined:

1. *Single Collision Domain* (SCD) where all nodes are in the range of each other;
2. *Multiple Collision Domain* (MCD) where the collision domains of the nodes may be different.

In all our experiments we have realized the analysis of the DDCF over a single cluster infrastructure. We have modeled wide ranges for both node population and node-roles distributions, and we have respected the guidelines provided in the previous experiments about the average cluster composition and formation properties. For many scenarios, a variable number of nodes (from 4 up to 100) and a wide collection of node roles distributions in the cluster are assumed. We have varied the percentage distribution of nodes in any role, and for space reasons we present results obtained only with the following two node distributions [FBD03]:

1. Distribution **A**: (1 CH, 20% SN1 nodes, 20% SN2 nodes, 60% LNs)
2. Distribution **B**: (1 CH, 10% SN1 nodes, 10% SN2 nodes, 80% LNs)

We notice that, however, DDCF performances are not heavily influenced by modifying these percentages: this demonstrates that the DDCF scheme is effective in supporting differentiated intra-cluster communication over a really variable range of node-roles' distributions. The effects of the DDCF scheme could give advantages and could be exploited in intra-cluster communications spanning multi-hop cluster scenarios.

Simulated Areas	500x500m
Number of nodes	variable [4:100]
Nodes Distribution	1 CH, 20% SN1, 20% SN2, 60% LNs 1 CH, 10% SN1, 10% SN2, 80% LNs
Frame size	1500 bytes
Reception Range	74m
Channel bitrate	2 Mbs
SlotTime	20 μs
SIFS Time	10 μs

Table 4.3: DDCF Simulation Parameters

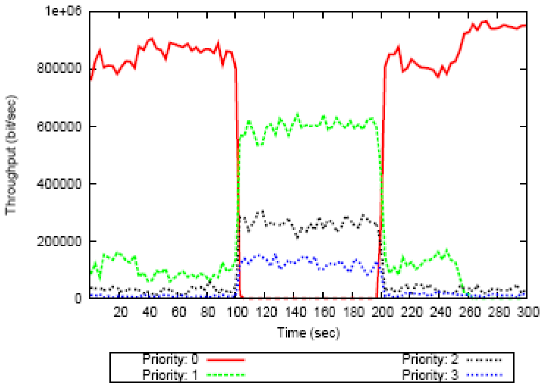


Figure 4.9: DDCF Dynamic throughput, 4 nodes, SCD

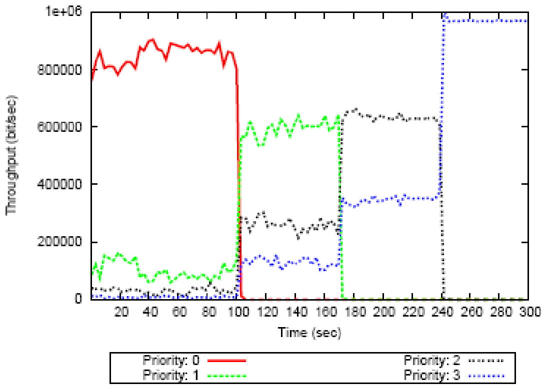


Figure 4.10: DDCF Dynamic throughput, 4 nodes, ON/OFF

4.5.1 Dynamic Throughput Differentiation

The following figures analyzes the dynamic throughput differentiation at MAC layer, when a clustering strucure is dynamically turning on/off. The dynamic throughput shown in these figures is the per-node runtime throughput, averaged over constant, separated and sequential time windows. The node load is asymptotic, i.e. every node always has one frame ready to transmit. The Figure 4.9 shows the dynamic throughput differentiation in a basic scenario (SCD), with only 4 nodes.

At the steady state, in the first 100 seconds, the CH node (PL=0) obtains more than 80% of the channel throughput, while the SN1, SN2 and LN, respectively, share the remaining 20% throughput (still in differentiated way). In the middle 100 seconds, the CH is switched OFF (e.g. it has no frames) and the SN1, SN2 and LN adaptively gain the throughput available, still in differentiated way. When the CH restarts (after 200 seconds) the system returns to the original steady state behavior. This figure demonstrates that the DDCF scheme adaptively and dynamically allocates the available channel to nodes, based on their role priority and space distribution. The Figure 4.10 shows the same effect with low priority nodes gaining in throughput when the highest priority node (from CH to SN2) is sequentially switched OFF. This demonstrates that the DDCF mechanism is able to dynamically differentiate the throughput based on the node role, and the local scenario, for any subset of node roles, without fluctuations, with reduced overheads and with fast convergence. This behavior would also demonstrate the effective and adaptive access differentiation in underload scenarios, i.e. when the channel throughput is not saturated, and only one low priority node is present in the system.

4.5.2 MAC Delay Differentiation

The Figure 4.11 shows the MAC delay percentiles for frames transmitted by 10 nodes with different priorities (Distribution A): the DCF scenario gives good performance, but it is unable to differentiate accesses and all nodes assume the same flat delay distribution. With the DDCF, the CH obtains almost immediate transmission (under asymptotic load for all the nodes) while the low priority nodes obtain differentiated access delay, as expected. Figure 4.12 shows the MAC delay percentiles, based on the standard DCF, in a SCD, when the contention level is increased (with 10 and 100 nodes, respectively). The increasing contention also increases the MAC delay, as expected, in a flat way, that is, without being affected by the node priority levels.

The effectiveness of the DDCF scheme is not much influenced by the node-roles' distribution: for example, Figures 4.13 and 4.14 show the delay differentiation in a

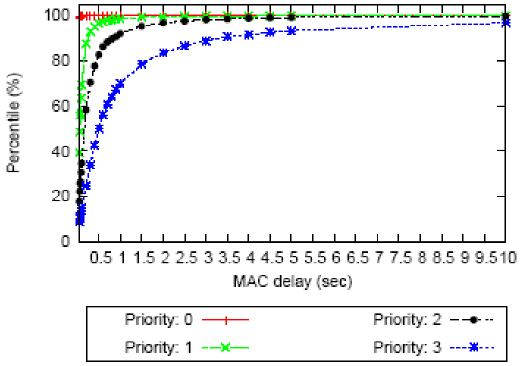


Figure 4.11: DDCF MAC delay percentiles, SCD, 1 CH, 2 SN1, 2 SN2, 5 LN

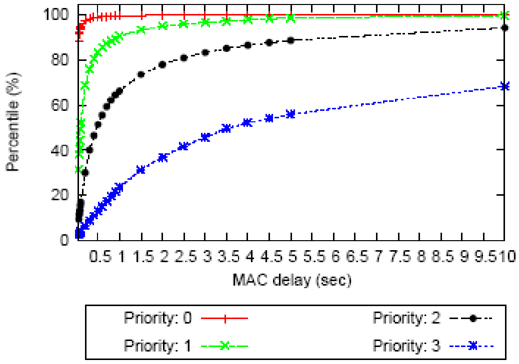


Figure 4.12: DDCF MAC delay percentiles, SCD, 1 CH, 20 SN1, 20 SN2, 59 LN

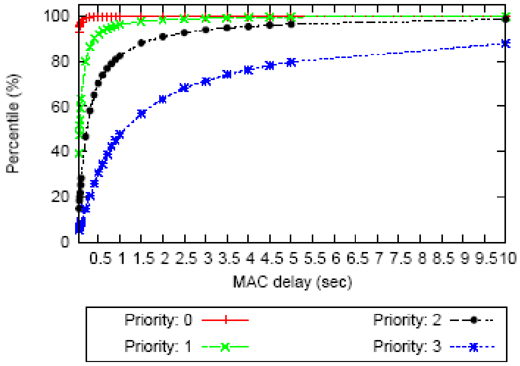


Figure 4.13: DDCF MAC delay percentiles, SCD, 1 CH, 1 SN1, 1 SN2, 7 LN

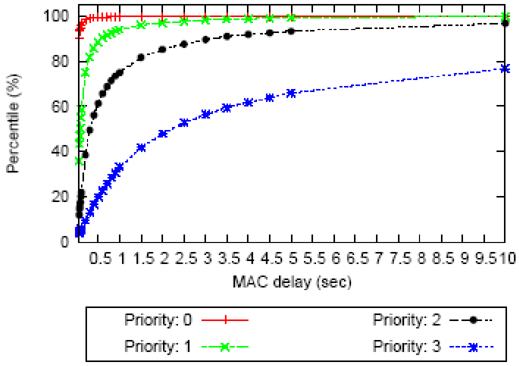


Figure 4.14: DDCF MAC delay percentiles, SCD, 1 CH, 10 SN1, 10 SN2, 79 LN

SCD scenario with 10 nodes (Figure 4.13) and 100 nodes (Figure 4.14) characterized by an higher percentage of LNs (10% SN1, 10% SN2, 80% LN).

4.5.3 Steady State Throughput Differentiation

Figures 4.15 and 4.16 show the steady state throughput differentiation obtained with a variable number of nodes, and with different priority levels, in a SCD. The distribution of the node roles is reported in Table 4.3.

In the DCF scenario (Figure 4.15), the steady-state system throughput is uniformly

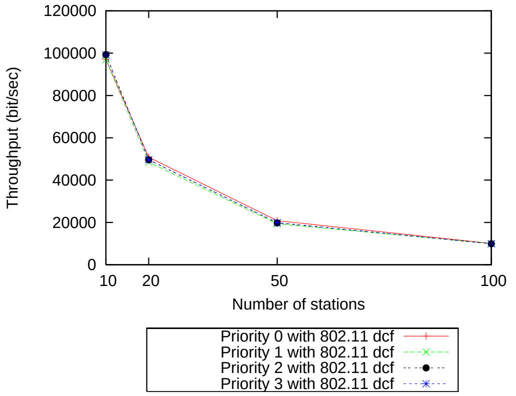


Figure 4.15: DCF, Steady state per-node throughput, Distribution A)

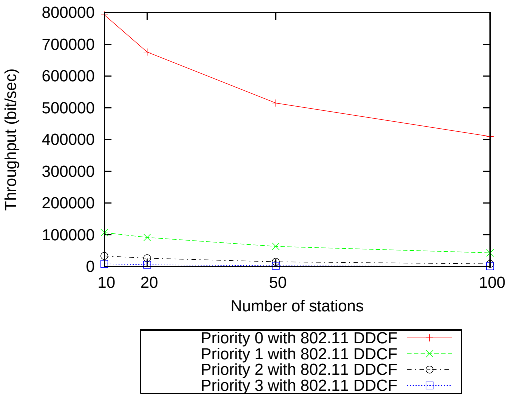


Figure 4.16: DDCF, Steady state per-node throughput, Distribution A

shared among nodes, and it reduces with the increasing number of sharing nodes, as expected. In the DDCF (Figure 4.16) the steady-state system throughput reduces when the number of nodes increases, but the CH and Spine nodes still maintain differentiated throughput levels. Figure 4.17 shows that the DDCF scheme allows the CH and Spines nodes to have a differentiated throughput level also in extreme configurations, with high percentage of low-priority nodes (80%). Both Figure 4.14 and Figure 4.17 would describe how the DDCF can ensure that node roles are dynamically mapped on throughput and delay differentiation levels, in the worst scenario (i.e. with maximum contention over a SCD, and with asymptotical load).

Additional preliminary results (not reported here) show that by playing with the DDCF parameters like AIFS[PL], CW_{min} and CW_{max}, the differentiation gap between node roles can be tuned both for throughput and for MAC delay. Priority mechanisms over backoff schemes like in [WYY03, AC01] may also contribute to enhance priority control and adaptation.

4.5.4 System Throughput in MCD: Channel Reuse

All the additional results obtained in MCDs, not shown for space limitations, confirm the effective expected behavior of the DDCF access scheme. The only relevant issue

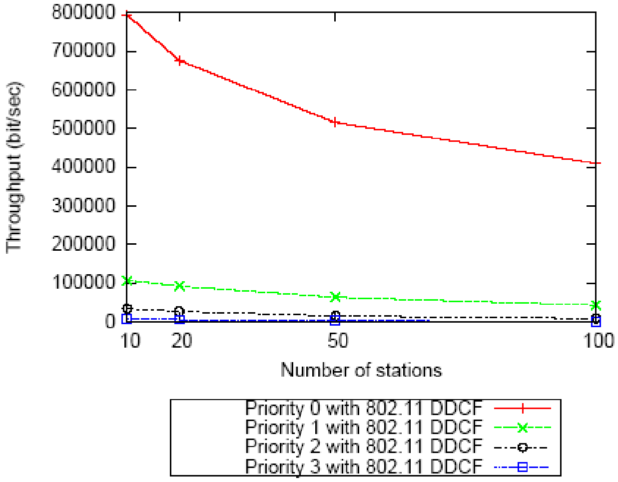


Figure 4.17: DDCF, Steady state per-node throughput, Distribution B

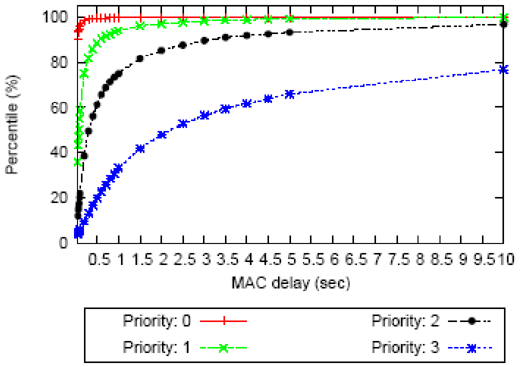


Figure 4.18: DDCF, Steady state per-node throughput with 1 CH, N nodes (20% SN1, 20% SN2, 60% LN), MCD

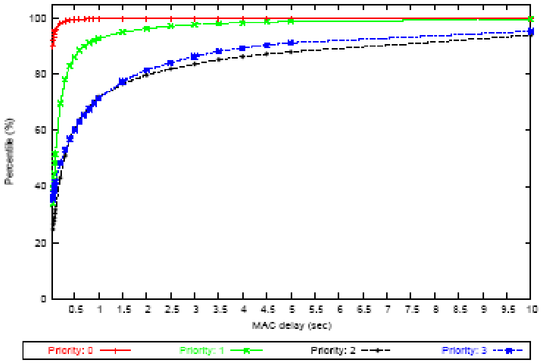


Figure 4.19: DDCF MAC delay percentiles, MCD, 1 CH, 10 SN1,10 SN2, 79 LN (total 100 nodes), MCD

of DDCF in MCDs emerged when, with high number of nodes, the MAC delay percentiles of SNs and LNs have shown a convergence of delay values, as shown in Figure 4.18 and in Figure 4.19. On the other hand, the CH and the SN1 nodes still maintain a strong differentiation.

Figure 4.20 shows the increasing steady-state system throughput obtained in

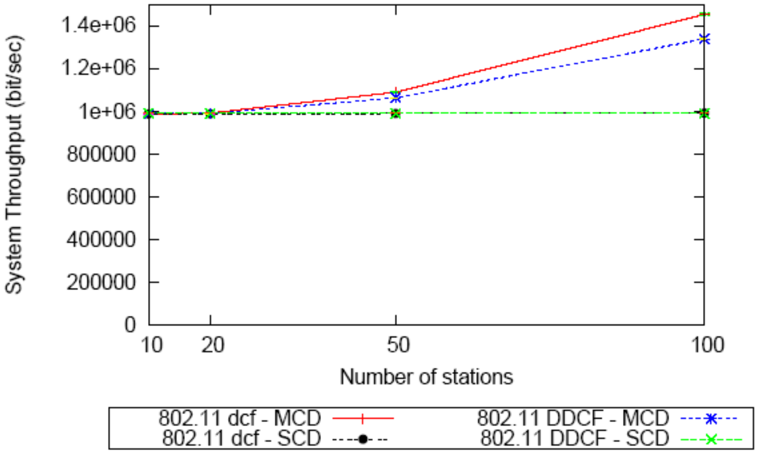


Figure 4.20: DCF vs. DDCF System throughput, MCD

the MCD, with respect to the SCD, for both the DCF and DDCF schemes. The figure indicates that the channel reuse is favored by spatial node distribution. The fact that DCF outperforms DDCF is explained because the space reuse in a MCD is more probable under peer-to-peer transmissions of space-separated nodes (under the DCF). With the DDCF, the CH and spine nodes are typically located in central positions within the cluster, and they own a great percentage of the spatial channel control with respect to subordinate nodes, by reducing the channel reuse.

4.5.5 DDCF Analytical Model

In this section, an analytical model of the DDCF protocol is proposed. The DDCF priority mechanism assigns different MAC parameters (contention window, inter-frame space) to each node according to the role assigned by the clustering scheme. The DDCF scheme works in a similar way than the 802.11e EDCA scheme, although it provides differentiated access between *nodes* rather than between *data flows*. For this reasons, the analytical model proposed here follows the same approach of the 802.11e EDCA analytical model described in [Xia04, EO05].

Most of the recent analytical models on the performance of the 802.11e EDCA stem from the model proposed by Bianchi [Bia00] to calculate saturate throughput of the legacy 802.11 DCF protocol. Xiao [Xia04] proposes an analytical model of the 802.11e EDCA MAC protocol, by taking into account the role of variable contention windows, but without considering the role of variable interframe spaces. The analytical model described in [EO05] enhances the Xiao's model by considering the role of variable interframe spaces, and by predicting the performance in both saturated and non-saturated network conditions.

The analytical model of the DDCF scheme is based on the works described in [Xia04, EO05]. Without loss of generality, the model proposed here uses the following assumptions:

- all the nodes are inside a *single domain of collision*. The multi-hop environment is not taken into account;
- each node has always a packet to transmit, i.e. only the *saturation* case is considered;
- the effect of the *retry retransmission limit* is not evaluated, i.e. each packet is retransmitted just one time after the contention window has reached the CW_{MAX} value;
- the *post-backoff* mechanism is not modelled;

Let i={0,1,2,3} denote the Priority Levels (PL) defined in Table 4.1 and assigned by the AC Clustering scheme. We consider a network composed by N nodes, where n_i represents the number of nodes of priority i, and $\sum_{i=0}^{3} n_i = N$. $W_{i,j}$ denotes the the contention window size for a node of class i in the backoff stage j, i.e. after the j-th unsuccessful retransmission. Hence, $W_{i,0} = CW_{min,i}$, where the value of $CW_{min,i}$ and $CW_{max,i}$ are shown in Table 4.1.

Figure 4.21 illustrates the Markov chain for a node with priority i. Each state of the Markov chain is represented by a tuple $< i, j, k >$, where:

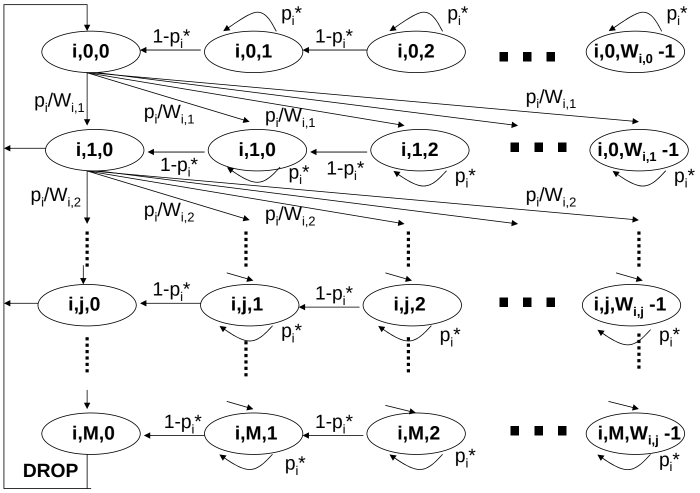


Figure 4.21: DDCF Markov chain

- i is the class priority assigned by the clustering scheme;
- j is the current backoff stage;
- k is the current value of the backoff window in stage j.

Let τ_i indicate the probability of transmission in a slot, p_i the probability to find the channel busy while transmitting and p_i^* the probability to find the channel busy during the backoff procedure. The probability p_i^* depends on the setting of the interframe space ($AIFS[i]$), and can be approximated as [EO05]:

$$p_i^* = min\left(1, p_b + \frac{AIFS[i] \cdot p_b}{1 - \tau_i}\right) \tag{4.4}$$

The probability p_i captures the condition where a node of class i attempts to transmit while at least one node is transmitting:

$$p_i = 1 - \left[(1 - \tau_i)^{n_i - 1} \cdot \prod_{j=0, j \neq i}^{3} (1 - \tau_j)^{n_j}\right] \tag{4.5}$$

In general, let p_b indicate the probability the channel is busy:

$$p_b = 1 - \prod_{j=0}^{3} (1 - \tau_j)^{n_j} \tag{4.6}$$

Based on p_i, $p_{i,s}$ denotes the probability that a packet from any of the node with class i is transmitted successfully in a time slot:

$$p_{i,s} = \frac{n_i \tau_i}{(1 - \tau_i)} \prod_{c=0}^{3} (1 - \tau_c)^{n_c} \tag{4.7}$$

The probability of a successful transmission for all the priority levels is p_s, with $p_s = \sum_{i=0}^{3} p_{i,s}$.

Let $b(i, j, k)$ denote the state distribution for state $< i, j, k >$. From chain regularities, we get:

$$\begin{aligned} b(i,j,k) &= \frac{p_i}{W_{i,j}} \cdot b(i, j-1, 0) + (1 - p_i^*) \cdot b(i, j, k+1) \qquad (4.8) \\ b(i,j,0) &= p_i \cdot b(i, j-1, 0) \qquad (4.9) \end{aligned}$$

from which $b(i, j, k) = \frac{W_{i,j} - k}{W_{i,j} \cdot (1 - p_i^*)} \cdot p_i^j \cdot b(i, 0, 0)$. At the same time, τ_i represents the probability to be in a state $< i, j, 0 >$, and can be derived as follows:

$$\tau_i = \sum_{j=0}^{7} b_{i,j,0} \tag{4.10}$$

The value of τ_i, p_i, p_i^* for each $i \in \{0, 1, 2, 3\}$ can be numerically computed by solving the system composed by equations 4.5, 4.10 and by the conditions $\sum_{i,j,k} b(i, j, k) = 1$.

For each priority class i, the throughput for class T_i can be written as the average real-time duration of a successfully transmitted packet by the average real-time duration of a "logical" slot [Xia04, EO05]:

$$T_i = \frac{p_{i,s} \cdot T_s}{(1 - p_b) \cdot \sigma + p_s \cdot T_s + (p_b - p_s) \cdot T_c} \tag{4.11}$$

where the value of σ, T_s, T_c denotes the value of an empty slot, the average time to transmit a data packet and the average time of a collision.

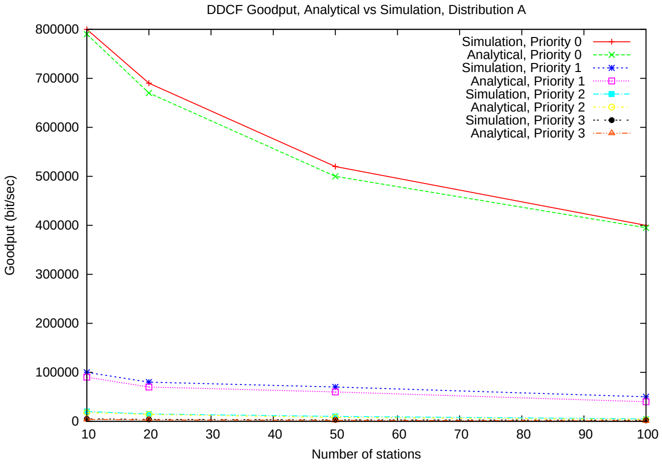


Figure 4.22: DDCF, Analytical Model vs Simulation, Distribution A

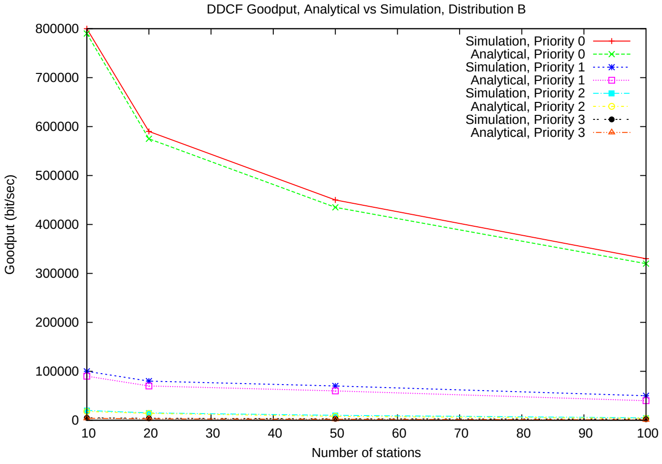


Figure 4.23: DDCF, Analytical Model vs Simulation, Distribution B

The exact values of σ, T_s, T_c depend by the physical layer, and are not reported here for space reasons. The reader may find the exact value of σ, T_s, T_c in [Bia00, Xia04, EO05].

We have compared numerical computations of the model described above with the simulation results obtained with the ns2 simulator. Figure 4.22 compares the analytical model with the simulation results in a configuration with 1 CH, 20% SN1 nodes, 20% SN2 nodes, 60% LNs (Distribution A). We can observe that the analytical model gives a qualitatively good match when compared with simulations. The accuracy of the analytical model is also confirmed by Figure 4.23, where a configuration with 1 CH, 10% SN1 nodes, 10% SN2 nodes, 79% LNs (Distribution B), is considered.

Chapter 5

MAC and Clustering Integration for Efficient Data Broadcast in VANETs

5.1 Overview

In this chapter, we propose and analyze the mutual support of distributed MAC and clustering schemes in an application scenario, i.e. the broadcast of alert message in a Vehicular Ad Hoc Network (VANET). Contributions and results of this work are described in [FB07a].

Vehicle-to-vehicle communication (IVC) for satety related applications has been recently addressed by several consortium and research institutes [MCG02, NOW, MJK00]. In a typical safety applications, a vehicle detecting a problem on the road broadcasts an alert message to a group of potential receiver in the *Risk Zone* (RZ). Since the Risk Zone may be larger than the transmitting range of a single device, the message should be relayed by the intermediate vehicles to extend the horizon of the message. *Multi-hop broadcast protocols* [XMK04, Adl06, KEO04, TMJH04, CFF05] have been proposed to support fast dissemination and to guarantee highly effective message delivery ratio among the vehicles in the Risk Zone.

In [FB07a], we exploit a cross-layer approach with joint design of MAC and Clustering protocols for supporting the fast propagation of alert messages inside the

VANET. A distributed dynamic clustering algorithm is proposed in order to create a dynamic virtual backbone inside the vehicular network. The vehicle-members of the backbone are responsible for efficient support to messages propagation. The backbone creation and maintenance are proactively performed aiming to balance the stability of backbone connections as well as cost/efficiency trade-off and hops-reduction when forwarding broadcast messages. A fast multi-hop MAC forwarding mechanism is defined to exploit the role of backbone vehicles, under a cross-layered approach. The MAC scheme follows the guidelines defined in Chapter 3 and in [FBD03]: it provides differentiated channel access based on the clustering roles, and the same time it adapts to the presence (or absence) of the clustering infrastructure. However, the specific characteristics of vehicular mobility pose new issues in the design of clustering algorithms for VANETs, so that a complete new approach is defined for cluster creation and maintenance.

In the next section, we briefly sketch the characteristics of nodes mobility in a VANET, together with a complete analysis of the requirements of safety-applications and of the existing solutions for data dissemination inside a VANET.

5.2 Vehicular Ad Hoc Networks

5.2.1 Design Challenges

Vehicular Ad Hoc Networks (VANETs) may be considered as a subclass of MANETs, where the mobile nodes are identified by vehicles equipped with short and medium range wireless technologies [BEH04, Nek05]. However, in addition to the similarities with Mobile ad Hoc Networks such as short radio transmission range, low bandwidth and low storage capacity, VANETs present some unique characteristics, that may be identified as follows:

- **High mobility**. The environment in which vehicular networks operate is extremely dynamic, and includes extreme configurations: in highways, relative speed of up to 300 km/h may occur, while density of nodes may be 1-2 vehicles per kilometer in low busy roads. Because of the relative movement of the vehicles, the connectivity among nodes could last only few seconds, and fail in unpredictable ways.

- **Partitioned network**. VANETs will be frequently partitioned. The dynamic nature of traffic may result in large inter-vehicle gaps in sparsely populated scenarios, and in several isolated clusters of nodes. The degree to which the network is connected is highly dependant on two factors, such as the range of wireless links and the fraction of participant vehicles, since only a fraction of vehicles on the road could be equipped with wireless interfaces. Maintaining end-to-end connectivity, packet routing, and reliable multi-hop information dissemination is extremely challenging in such kind of networks.

- **Geographically constrained topology**. Unlike general Mobile ad Hoc Networks, where it is hard to predict the nodes' mobility, vehicles normally run along roads with fixed topologies. Given the average speed, current speed, and road trajectory, the future position of a vehicle can be predicted, and the driver's behaviour be simulated by using realistic car-following and lane-changing models [FBBC06, FBD+07]. However, the presence of obstacles and buildings prevents wireless signals from traveling between roads, and contributes to make more unreliable the communication among the mobile nodes.

- **Large scale**. Despite frequent partitioning, and low density, VANETs may in principle extend over large areas, and include many nodes.

5.2.2 Applications

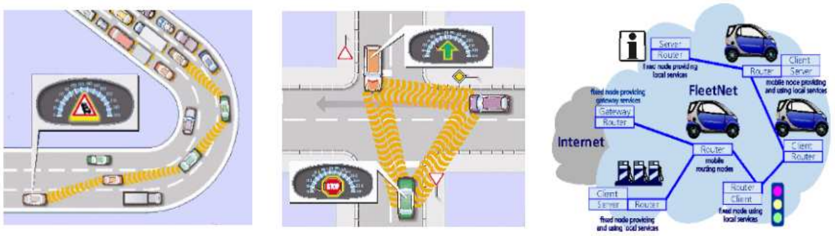
The opportunities and areas of applications of VANETs are growing rapidly, with many vehicle manufacturers and private institutes actively supporting research and development in this field. The integration with on-board sensor systems, and the progressive diffusion of on-board localization systems (GPS) make VANETs suitable for the development of active safety applications, including collision and warning systems, driver assistant and intelligent traffic management systems. On the other hand, inter-vehicular communication (IVC) also fuels the vast opportunities in online vehicle entertainment (such as gaming or file sharing), and enables the integration with Internet services and applications.

The main applications of VANETs, as summarized by [MH05], may be roughly categorized into three classes:

- **Safety management**. These applications exploit the "look-through" capability of IVC to help avoiding accidents and dangerous situations. In the Cartalk2000 project [MCG02], a co-operative collision warning and avoidance system has been developed to support the driver in longitudinal control of the vehicle; the proposed system generates warnings based on acceleration, velocity and inter-vehicle headway data, and includes mechanisms for automatic breaking. Other possible safety applications, developed within some European projects (PReVENT, INVeNT) include automatic systems for passing assistance, security distance warning and coordination of vehicles entering and keeping a lane.

- **Traffic monitoring and management systems**. Traffic and travel information systems currently in use are based on a centralized structure, in which some sensors along the roadsite monitor the traffic density and transmit the results to a central unit for further processing. Alternative approaches based on vehicular ad hoc networks are currently investigated by several projects, including Network on Wheels (NOW) [NOW, WEL03] and CarTalk2000 [MCG02, NDL04]. In a peer-to-peer approach, each vehicle monitors density and mean speed of surrounding vehicles , performs local traffic analysis and broadcast periodic messages to all vehicles in the neighbourhood.

- **User communications and Information Services**. Some architectures and projects provide also capabilities to access Internet from vehicle by using stationary gateways services, short range wireless devices and multi-hop



Cooperative Assistence Driver Applications

Decentralized Floating Data Car Services

User communication and Information Services

Figure 5.1: Applications based on inter-vehicular communication

communication. The CarNet project [MJK00] supports IP connectivity from vehicles, as well Internet services and applications.

TrafficView [NDL04] and SOTIS [WEL03] are scalable traffic information systems based on inter-vehicular communication. They include both safety management and traffic monitoring functionalities. Each vehicle equipped with such systems gathers and broadcasts information about the other vehicles. The records about the other vehicles are stored in a local validated repository, and merged with local sensor data. Periodically, the system performs data analysis and generate traffic reports to be broadcasted. A navigation module is responsible of accessing the validated repository and displaying a map of the road annotated with dynamic and real time traffic information.

5.2.3 Multi-hop Data Dissemination Protocols

The timely information exchanged by safety-related applications may determine strong communication requirements: few tenths of a second delay may have a significant impact on the effectiveness of a safety application (e.g. braking assistance). For these reasons, several probabilistic and deterministic multi-hop broadcast protocols have been proposed in literature, but only few of them relies on the presence of a virtual infrastructure inside the VANET.

Flooding [dcf] is a simple way to disseminate information within a IEEE 802.11 VANET: each vehicle receiving the first occurrence of a new message retransmits it after a MAC backoff to the neighbour vehicles. The drawback of this approach is the amount of potential useless retransmissions, resulting in the high number of hops needed to cover the risk zone, and the MAC contention caused by the broadcast storm problem, introducing high risk of message dropping (due to collisions) and high average end-to-end delay.

Most multi-hop broadcast protocol considers 802.11 variants in the context of intervehicular communication. In [XMK04], authors try to increase the reception probability of the IEEE 802.11 DCF, by broadcasting a message several times within a lifetime limit. *Location based* broadcast protocols [Adl06] exploit local position information to decide whether a certain node should broadcast a message or not. As a result, location-based broadcast protocols can quickly adapt to topology changes in vehicular ad hoc networks: the next hop transmitter (possibly the farthest with respect to the previous transmitter) is selected with a biased contention-phase, in a distributed way. In [KEO04], a contention-based MAC protocol for the urban environment is proposed: when an alert message is received, a jamming signals whose duration is proportional to the source distance is transmitted by receivers to individuate the farthest one within the source transmission range.

In other schemes [TMJH04, CFF05, PFR07], hops minimization is achieved by opportunely adjusting the parameters governing the channel access at MAC level, such as the contention window [dcf] in the 802.11 DCF backoff scheme. Specifically, in [PFR07] each vehicle dynamically adjusts the contention-window size upon receiving a broadcast message from the front-car. The contention window size is made inversely proportional to the distance from the sender, so that far vehicles statistically obtain the access differentiation to efficiently re-broadcast the received message, in distributed way. In addition, a distributed scheme to allow vehicles to estimate communication ranges on-the-

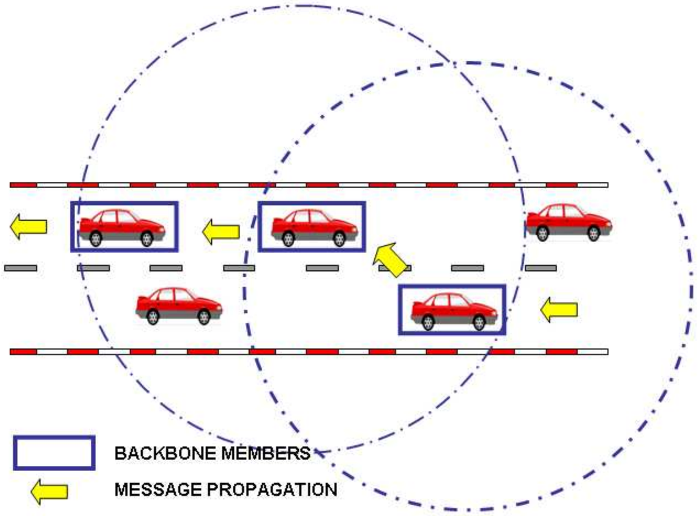


Figure 5.2: Backbone creation inside a VANET

flight is proposed in [PFR07], to support realistic scenarios where transmission ranges are frequently changed due to physical obstacles, vehicle density, and mobility factors. A solution based on a dynamic adjustment of the contention window at the MAC layer is described in [CFF05], which is based on estimation of network contention by analyzing packet sequence numbers. In [TMJH04], the IEEE 802.11e Enhanced Distributed Channel Access (EDCA) priority class differentiation is investigated in VANETs: vehicles are mapped on priority levels depending on their distance from the previous one forwarding the message.

Cluster-based solutions may be a viable approach in supporting efficient multi-hop message propagation among vehicles. In this approach, only nodes members of a the cluster infrastructure are enabled to relay broadcast messages. A distributed cluster infrastructure may be defined by providing nodes with a distributed protocol to proactively form a backbone. The term *backbone* is used here to identify a virtual chain of vehicles in a vehicular scenario (e.g. a highway). Each node of the backbone must be connected to previous and next hop of the backbone chain, as shown in Figure 5.2.

Under ideal assumptions, this goal could be achieved by allowing to relay a broadcast message only to nodes in the *Minimum Connected Dominating Set* [ZPM04] of vehicle flows. As proposed in [ZPM04], the MCDS may be recursively obtained, starting from the broadcast message source, by including in the MCDS the farthest node within the covering range of the previous MCDS node, step by step. Unfortunately, building a MCDS in a vehicular environment implies that all the vehicles must have a strong real-time knowledge of the vehicle positions and radio characteristics.

The directional information propagation protocol (DPP) [LA05] is composed of four main components including a cluster formation and maintenance protocol, a custody transfer protocol, an intercluster routing protocol, and an intra-cluster routing protocol. The clustering algorithm selects a clusterhead and trailer-nodes located at the front/rear of each cluster of vehicles. The cluster head is responsible for propagating the alert messages, by communicating with the trailer vehicles of other clusters, by using acknowledged transmissions. On the other hand, cluster creation and maintenance are not explored in [LA05]. Although several clustering schemes have been proposed for MANETs [YC05], much effort should be done to support the specific dynamic nature of the VANET environment. In [FHD06], single-hop clustering algorithms are evaluated in the context of vehicular environments, by focusing on the leader election processes.

5.3 System Modelling and Assumptions

The target scenario considered in [FB07a] is a multi-lanes highway scenario, with vehicles travelling in both directions. In general, considered values for model factors will be defined in the simulation. Vehicles are assumed to be equipped with sensing, wireless communication, computation and storage capabilities. IEEE 802.11 devices are considered the target wireless technology. Vehicles obtain data provided by on-

board sensors (acceleration and speed) and by GPS devices (location).
When a vehicle senses a critical condition on the road, it broadcasts an alarm message to inform the other vehicles. In general, the content of a message is application-dependent. Each alert message involves:

1. a direction of propagation (in [FB07a], without loss of generality, backward message propagation with respect to the vehicle flow direction is assumed);
2. a maximum time-to-live (TTL) limiting the temporal validity of the message;
3. a risk zone RZ limiting the space horizon of the message. Only nodes in the risk zone are allowed to relay the message.

5.4 Clustering Scheme

A clustering structure devoted to support the information dissemination of alert messages in a VANET should take into account the following issues:

- *backbone stability*: a minimum expected connectivity-duration threshold is required for a node to become part of the backbone;
- *fairly high nodes distance*: if hop reduction is to be achieved, relaying nodes should be as much distant as possible;
- *management overhead*: the backbone creation should be distributed and based on light communication overhead. Moreover, the effects due to vehicle mobility and backbone disruption should be under the control of parameters, like the frequency of backbone refresh procedures.

Following these guidelines, a fully distributed clustering algorithm is proposed, whose implementation requires cross-layer interactions among MAC and clustering schemes. A backbone structure is not required to be monolithic. In general, the target backbone might be composed by multiple non-overlapping chains of interconnected backbone vehicles. Each vehicle device has a unique ID (as an example, a

MAC address). Each chain member has at most two neighbours (previous and next hop, *prev_hop*, *next_hop*) and a sequence number (*chain_seq*) in the chain obtained as the vehicle hop-count in the chain itself.

Under a clustering viewpoint, vehicles can be in two states: normal vehicle (NV) or backbone member (BM). Each backbone member has a backbone-record (BR) information with the following structure:

$$< ID; state; prev\_hop; next\_hop; chain\_seq > \tag{5.1}$$

A backbone creation process starts whenever a vehicle misses to receive backbone beacons for a time interval $RefTim$ (defined in the following). In this case, it elects itself as a backbone member, and it broadcasts a BEACON message. The BEACON message has the effect to propagate the impulse of a backbone creation process. The BEACON message contains the following sender information:

$$< ID; (x; y); R; speed; dir; horizon > \tag{5.2}$$

where ID is the unique sender identifier, (x,y) are the GPS coordinates, R is the transmitting range (or, equivalently, the transmission power in dBm), *speed* is the average speed, *dir* is the direction of the vehicle, and *horizon* is the space limit of the risk zone, respectively.

Vehicles receiving the BEACON message from a node with ID=1 (and travelling in the same direction) are potential next-hop candidates of the backward backbone creation. A distributed, contention-based MAC access phase is implemented by receiver nodes to select the candidate that (*i*) is expected to stay connected with backbone node 1 for at least a minimum threshold duration (BB_REFR), and (*ii*) is expected to be the farthest node from 1 after a BB_REFR interval.

The notion of *ResidualTime* (RT) of a connection between two nodes A and B is used to indicate the time during which A will remain in the transmitting range of B without overtaking it. The RT of a connection between two nodes RT(A,B) could be computed (under some assumptions) from the information about current positions, relative speed and transmitting range R. To relax the assumptions at the basis of the adoption of parameter R (that is, homogeneous wireless propagation and sensitivity of wireless devices) the available link budget of the receiver (in dB) could be used in the place of the distance metric R. In detail, RT can be computed as:

$$RT(A,B) = \frac{[max(0; sign(\Delta v))] \cdot R - dist(A;B)}{\Delta v} \tag{5.3}$$

where R is the transmission range of the sender vehicle, Δv is the difference between the average speed of vehicles A and B, and $dist(A,B)$ is the current estimated distance among nodes A and B, respectively. Upon reception of a BEACON message from vehicle B, a vehicle A computes the RT(A,B) of the connection: if the residual time is lower than the duration threshold (BB_REFR), this means that the vehicle A is not a good candidate to be the next backbone-hop of the backbone node B. This is because A is expected to move out of the range of node B within the next BB_REFR interval. Vehicles with $RT(A,B) > BB\_REFR$ can join the contention phase whose winner will be the next backbone member. A generic vehicle A receiving a BEACON enters the contention phase to become backbone member, and performs the actions shown in Figure 5.3.

This three-phases handshake protocol (BEACON-CANDIDATURE-ACK WINNER) selects one single next-hop backbone member for extending the backbone. A cross-layer technique is used to reduce the number of CANDIDATURE messages generated in the contention phase and to select the best candidate for backbone extension. A local parameter named *Fit Factor (FF)* is locally calculated by every candidate node as a goodness evaluation metric to become the next backbone-hop of previous backbone-node B. The FF for candidate node A is defined as follows:

$$FF(A) = \frac{dist(A;B) + \Delta \cdot BB\_REFR}{R} \tag{5.4}$$

where R is the transmission range of B. Namely, the FF is an estimation of the residual distance among node A and backbone-node B after a BB_REFR interval.

```
When a node does not receive a BEACON message for RefTime
    1. Elects itself as backbone member
    2. Broadcasts the BEACON message

When node B receives a BEACON message from node A
    1. Compute RT(A,B)
    2. If (RT(A,B))> BB_REFR) {
        1. Compute the Fit Factor (FF)
        2. Send the CANDIDATURE message to A
        3. Wait to receive the ACK_WINNER message from A
        }

When node A receives a CANDIDATURE message from node B
    If (next_hop==0) {
        1. Sets next_hop to B
        2. Sends the CANDIDATURE message to B
    }

When node B  receives an ACK_WINNER message from node A
    1. Elects itself as backbone member
    2. Broadcasts the BEACON message
```

Figure 5.3: Backbone creation algorithm

The FF is used to dynamically control the contention window of the backoff scheme implemented at the MAC layer. A node with high value of the FF parameter obtains short backoff values, hence it would win the contention with limited delay, statistically. During the backoff phase, nodes perform carrier sensing: if a node C detects an early CANDIDATURE message from another vehicle A towards backbone-node B, than C aborts its own backoff phase and remains in the NV state.

Since the backbone creation process may be initiated in asynchronous way by multiple nodes, many virtual sub-chains may be created in the highway scenario. Virtual chains may remain disjoint or may be interconnected when a backbone member A with a backbone chain sequence equal to 1 (that is, the header node A of a sub-chain) receives a BEACON request from a front-head vehicle B (that is, the trailer node B of a sub-chain): in this case, the node A replies immediately after a SIFS with a CANDIDATURE message to B, by trying to realize a concatenation of two adjacent backbone sub-chains. The complete algorithm of backbone creation is shown in Figure 5.3.

5.4.1 Backbone Maintainance

The high mobility of nodes in a VANET may produce frequent changes in the backbone topology. For this reason: (*i*) links among nodes of the backbone may be broken and (*ii*) the value of local connectivity factors (*ResidualTime*) and node distance (*FitFactor*) among backbone members may dynamically vary. A reactive scheme for repairing the backbone would need break-detection capability and overheads, and would probably result in fragile patched backbones. To cope with these issues, our mechanism proactively refreshes the backbone, under the control of a refresh timer. To limit the number of nodes restarting the process of backbone-refresh, and to exploit the memory-effect of already existing backbone sub-chains, each node of the backbone maintains a refresh timer ($RefTim$) which is a multiple of the BB_REFR parameter, and it is defined as:

$$RefTim = (chain\_seq\%MAX\_Chain\_Size) \cdot BB\_REFR \tag{5.5}$$

The effect of the formula above is to randomize the distribution of backbone creation-refresh events, by increasing the frequency of refreshes coming from nodes ahead to the existing chains. This has the effect of reducing the occurrence of synchronous backbone creation processes activated by neighbour nodes.

5.5 MAC Layer Support

At the MAC Layer, the proposed cross-layered forwarding scheme (i) exploits the presence of a backbone structure in the VANET, (ii) favours the fast propagation of multi-hop broadcast messages, and (iii) dynamically adapts to network load and cluster variations. For these reasons, the scheme is called Dynamic Backbone Assisted MAC (DBA-MAC). The DBA-MAC protocol provides differentiated channel access reflecting two priority classes (Backbone Member, Normal Vehicle) defined in the backbone creation algorithm. Backbone members (BM) have higher priority in accessing the channel and relaying the broadcast messages. This is supported by the MAC scheme called *Fast Multi-Hop Forwarding* (FMF). In addition, a new multihop broadcast transmission concept - called *Basic Forwarding Scheme* (BFS)- is introduced to allow the fast advertisement propagation of alert messages when the backbone propagation fails or when no backbone is available.

5.5.1 Fast Multi-Hop Forwarding Scheme

All messages relayed by backbone members are broadcast messages: in this way, every node will receive the advertised message information. On the other hand, by exploiting a cross-layered approach, backbone members (BM) react to broadcast messages with a non-standard way defined in the following.

As long as the backbone is working, when BM_{i+1} receives a broadcast information message from BM_i it immediately sends back and acknowledgment (as for unicast messages), after a SIFS. Then BM_{i+1} immediately broadcasts the message towards BM_{i+2} (if any) without releasing the channel control, by realizing the FMF access scheme. If the ACK is not received, the BM_i leaves the FMF scheme and enters the Basic MAC Forwarding Scheme (see below).
The FMF approach achieves two important goals:

- *enhanced reliability*: all the backbone-assisted broadcast transmissions are acknowledged (only while messages are carried by BMs) as in the unicast 802.11 DCF protocol definition. In this way the BM sender can immediately retransmit a message that failed (e.g. due to backbone failure). The retransmission will be forwarded with the help of normal vehicles NV (if any, see below).

- *fast multi-hop forwarding (FMF)*: as long as backbone members receive a message, they forward it immediately after a SIFS. As a result, the medium control is inherited and propagated over pre-defined multi-hop IEEE 802.11 nodes, without introducing backoff delays, as long as the multi-hop backbone is connected and no collisions occur.

5.5.2 Basic Forwarding Scheme

This scheme is similar to the one defined in [PFR07], and it is adopted as a worst case scheme when backbone assisted FMF fails: if a vehicle receives an alert message from any node AND i) it is not a BM implementing FMF, OR ii) it is a BM performing the second attempt (that is, no ack received after the first attempt), it dynamically adjusts its contention window (CW) that controls the MAC backoff. In particular, if the vehicle is a backbone member (BM), the CW size is initialized to a low value (4). If the vehicle is a normal vehicle (NV), the dimension of the contention window is inversely proportional to the distance from the sender, like in [PFR07]:

$$CW = \frac{R - Dist}{R} \cdot (CW_{MAX} - CW_{Min}) + CW_{Min} \tag{5.6}$$

At this point, the vehicle implements a standard IEEE 802.11 backoff scheme and broadcasts the message. In the worst case, the MAC works like the mechanism in [PFR07], by performing long-range broadcasts via a biased backoff scheme. Eventually, if the message is received by a BM node, then the FMF re-starts by riding the multi-hop backbone of vehicles.

5.6 Performance Evalutation

To analyze the performance of our solution, we consider an highway scenario of 8 Km with three uni-directional lanes. In our target application, a subset of vehicles broadcasts one alert message per second. Each alert message has a Risk Zone (horizon) covering a distance of 1 Km. Each vehicle is assumed to be equipped with 802.11 devices, with a homogeneous transmission range of 250 meters. We have considered different scenarios by varying the vehicle density (from 200 up to 600) and the percentage of vehicles generating alert messages (from 5% up to 50%).

Simulated Areas	8 Km (3-lane highway)
Vehicles speed	[20,30] m/s
Vehicles density	200, 400, 600 vehicles
Transmitting Range	250 m
Message size	100 Byte
Message Risk Zone	1 Km

Table 5.1: Simulation Parameters

The tool used is the ns-2 simulator [ns2b] with the extension provided by [ns2a] to produce realistic mobility traces of highway scenarios. The parameters used in the simulations are shown in Table 5.1.

In the simulation analysis, we have compared our solution with three similar proposals.

Flooding. As a basic case, we have considered a simple MAC 802.11 flooding scheme: each vehicle receiving an alert message rebroadcasts it by using the standard IEEE 802.11 backoff scheme.

Fast Broadcast MAC. The second solution is the Fast Broadcast protocol [PFR07]. The reason of this choice is that our MAC scheme may be considered an extension of the MAC scheme described in [PFR07]. when the transmission among vehicles of the backbone fails or no backbone nodes are present to relay the message, a contention phase is started to select the forwarding vehicle: each vehicle dynamically adjusts its contention window according to the distance from the sender vehicle, by using the same formula proposed in [PFR07]. For these reasons, the Fast Broadcast protocol can be considered the worst case behavior of our DBA-MAC, when the backbone fails.

Static Backbone. As an ideal analysis scenario, we consider the backbone composed by statically allocated stations, like in a roadside infrastructure system. Nodes of the static backbone are placed in the scenario at the maximum

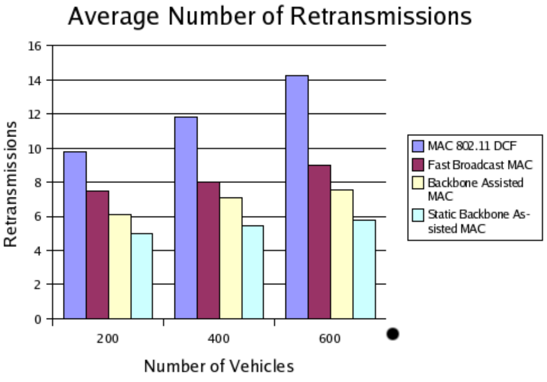


Figure 5.4: Average number of retransmission, Scenario A

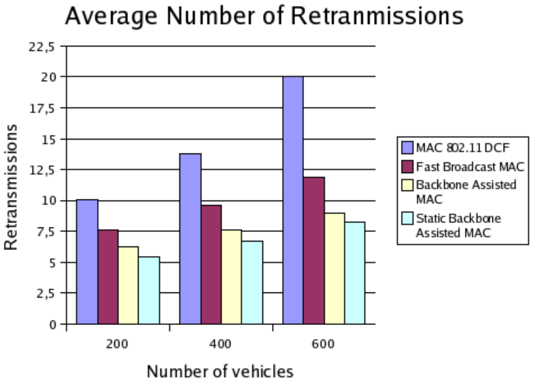


Figure 5.5: Average number of retransmission, Scenario B

distance preserving the connectivity (250 m in our simulations), resulting in a MCDS for this scenario. We call this scheme "*Static Backbone-Assisted MAC*", to emphasize the difference with our solution where backbone is created dynamically in the VANET. Both Static and Dynamic Assisted MAC use the forwarding scheme described in section 5.5.

To compare efficient forwarding of alert messages, we consider the following metrics: the total (average) number of retransmissions experienced by an alert message to span the horizon distance, the percentage of collisions at the MAC layer, the average end-to-end delay, the percentiles of the end-to-end delay, the clustering overhead. In the following, we show the simulation results in two scenarios:

- Scenario **A** Varying number of vehicles {200,400,600}, 5% of vehicles produces an alert message each second.
- Scenario **B** Varying number of vehicles {200,400,600}, 25% of vehicles produces an alert message each second.

5.6.1 Packet Delivery Analysis

Figures 5.4 and 5.5 shows the average number of retransmissions needed by an alert message to cover the horizon of the risk zone (1 km), as a function of the vehicle den-

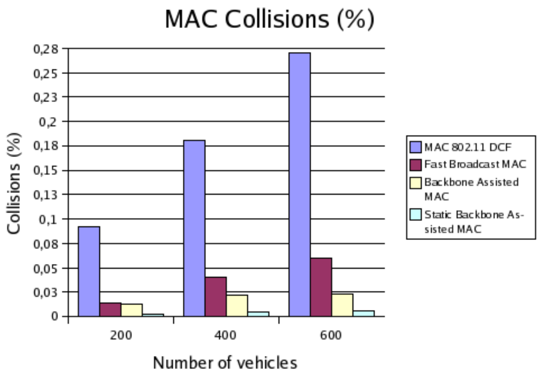


Figure 5.6: Average percentage of MAC Collisions, Scenario A

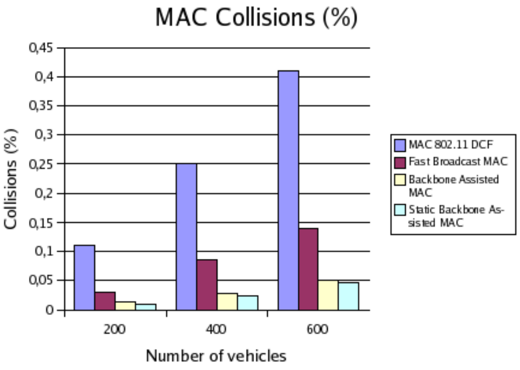


Figure 5.7: Average percentage of MAC Collisions, Scenario B

sity in the scenario A (Figure 5.4) and B (Figure 5.5) respectively. As expected, the basic 802.11-based flooding protocol requires the highest number of retransmissions to propagate the message, in both the scenarios: this effect is emphasized when the vehicle density increases. The average number of flooding retransmissions in the scenario with 600 vehicles is five times the optimal value (roughly defined as 1000/250m = 4 hops). When a static backbone is used, the alert message is often relayed by the backbone member vehicles, whose hop distance is the maximum transmission range (by construction, under our modeling choice). This is the reference scenario with an ideal backbone, to test the enhanced backbone assisted FMF MAC. The performance obtained is still sub-optimal with respect to the theoretical value 4, due to MAC collisions and hidden terminal effects, but it obviously outperforms all other schemes. When the backbone is dynamic, the DBA- MAC still produces a quite limited number of retransmissions, even if some more broadcasts are possible when the FMF backbone propagation fails. These results are sligthly worst than the static backbone results. On the other hand, the DBA-MAC outperforms the Fast Broadcast protocol, which is not backbone-assisted. This is due to the effect of the FMF scheme, which decreases the impact of contention during multi-hop backbone message propagation.

Figures 5.6 and 5.7 confirm this interpretation, by showing the average percent-

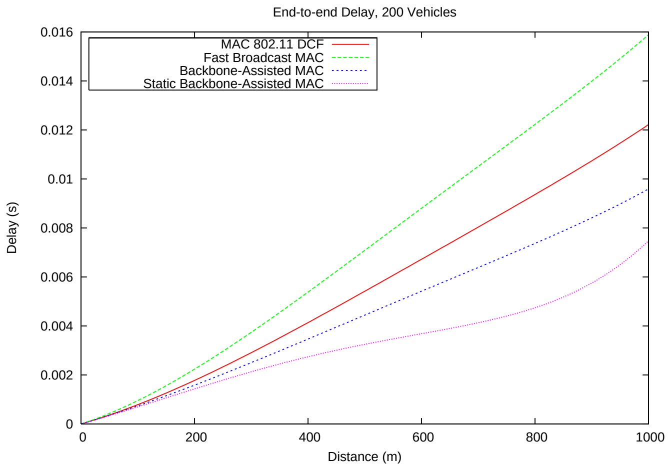


Figure 5.8: End-to-end Delay, 200 Vehicles, Scenario B

age of collisions obtained at the MAC layer in the VANET, with respect to the total amount of message transmissions performed. The 802.11-based flooding scheme produces a significant 10% up to 30% collision risk in the Scenario A and up to 40% in the Scenario B, as a function of the vehicle density range and transmission message load (that is, the MAC access contention level). The collision probability is reduced by Fast Broadcast MAC thanks to the priority-based effect of the biased backoff scheme, and it is drastically reduced when dynamic or static backbone assisted MAC is adopted, thanks to the reduction of contention-based accesses over multi-hop backbones.

5.6.2 Data Delay Analysis

In the following figures, we focuses on the analysis of the end-to-end delay experimented by alert messages to cover the Risk Zone. For space reasons, we describe only the results obtained in scenario B. Results on scenario A are not shown since they basically confirm the same trend.

Figure 5.8 shows the average end-to-end delay experienced by alert messages to cover a variable distance (x) in the scenario B when a low-density configuration (200 vehicles over 8 km) is considered. The Dynamic Backbone Assisted MAC falls in

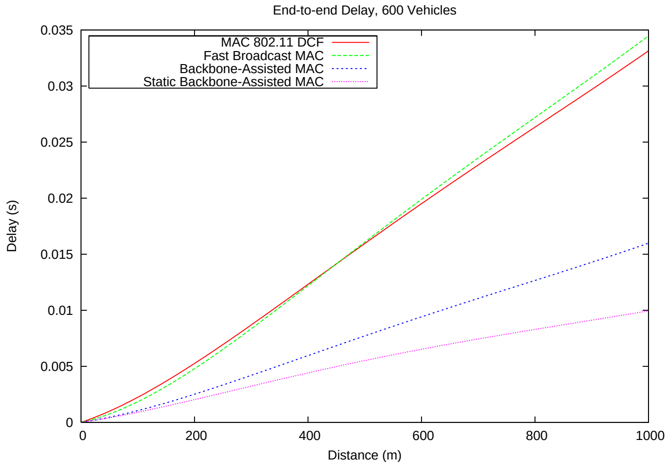


Figure 5.9: End-to-end Delay, 600 Vehicles, Scenario B

the range between the Static Backbone Assisted MAC and the 802.11-based flooding scheme. Quite surprisingly, the Fast Broadcast MAC protocol produces average delay worst than the flooding protocol. This problem is caused by the settings of the contention window. In the 802.11 DCF MAC protocol, the contention window size is set to the minimum value (CW_{Min}) for the transmissions of broadcast messages (since no feedback is obtained by missing acks to implement binary exponential backoff). Given the low vehicle density, most flooding transmissions are successful. In the Fast Broadcast protocol, the contention window is dynamically managed, resulting equal to CW_{Min} only for forwarding nodes located at the maximum transmission distance from the sender. Hence, in a low density scenario, it may happen frequently that the (farthest) forwarding vehicle uses a contention window $> CW_{Min}$, for each hop, resulting in high end-to-end delay.

Figure 5.9 shows the average end-to-end delay in a high-density scenario (600 vehicles over 8 km). In general, the effect of the increased message-load translates in higher end-to-end delay than Figure 5.8. However, the performance of the DBA-MAC scheme is close to the performance of the ideal static backbone assisted MAC. Figure 5.9 demonstrates the advantage of using a cross-layered MAC and backbone solution to support fast propagation of broadcast messages. Both 802.11 and Fast Broadcast MAC protocols show higher delays. By confirming the previous com-

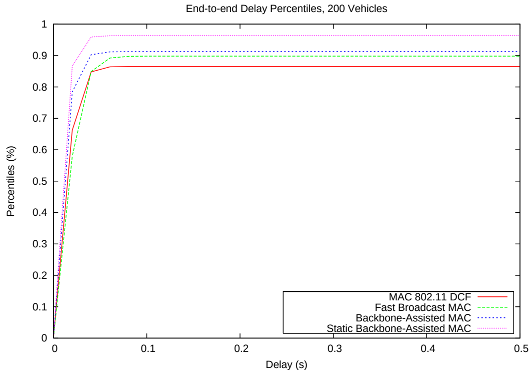


Figure 5.10: End-to-end MAC Delay Percentiles, 200 Vehicles

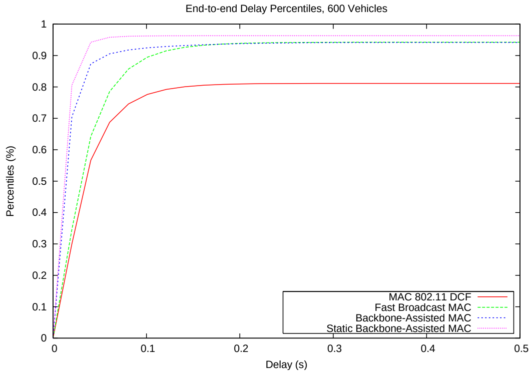


Figure 5.11: End-to-end MAC Delay Percentiles, 600 Vehicles

ments, Fast Broadcast MAC has now similar performance as IEEE 802.11 DCF flooding, due to the increased vehicles' density. In fact, a flooding incurs in more collisions, and farthest vehicles more likely exist near the transmission range border (to forward messages with CW_{Min} value).

Figures 5.10 and 5.11 show the MAC Delay Percentiles in a low density (Figure 5.10) and high density (Figure 5.11) scenarios, by taking into account the end-to-end delay of messages covering a risk zone of 1 Km. In the low-density scenario (200 vehicles), in Figure 5.10, more than 85% of generated alert messages successfully covers the risk zone. The distribution of delays shows small differences among the considered schemes, and a different schemes reliability testified by the asymptotic values of the distribution, which could be interpreted as the probability of message arrival. In Figure 5.11, (high-density scenario, 600 vehicles) the most relevant effect is the different slope of the curves, which demonstrates the "resistance" of the system to message forwarding. As expected, the flooding approach produces the worst performance. Both Fast Broadcast and Dynamic Backbone-Assisted MAC protocols deliver an high percentage of messages (90%). However, backbone assisted schemes outperform the Fast Broadcast protocol in terms of delay bound (Figure 5.11).

Part III

Joint Design of MAC and Routing solutions

Chapter 6

Motivations and State of The Art

6.1 Interactions between MAC and Routing protocols

The development of efficient routing protocols is a key issue in supporting multi-hop communication in MANETs. Because the wireless transmission range of nodes is often limited, source and destination nodes may typically not be within the direct transmission range of each other. Hence, the routing protocol must be able to discover multi-hop routes by using other intermediate nodes to forward the messages. Many routing protocols have been proposed over the last few years [CB94, KV98, MD01, PR99], each of them aiming at provide the issues required in ad hoc routing, i.e. simplicity, rapid route convergence, distributed nature, adaptivity. Although the approaches used may be different, most of them are based on similar sets of design goals, which may be identified as follows [BR04]:

- *Minimum control overhead.* Control messages consume bandwidth and battery power to receive and send a message. Routing protocols should not send more than the minimum number of control messages they need for their operations.

- *Dynamic topology maintenance.* The node mobility may cause route failures on a pre-established path. In order to preserve the connectivity, routing protocols should handle link breaks by discovering alternate paths and minimizing the route discovery latency.

- *Loop prevention.* A routing loop occurs when a node along a path select a next hop to a destination that also occurred earlier in the path. The cost of packet forwarding/processing in a MANET make appear routing loops extremely wasteful of resources and negative for the system performance.

On the other hand, several recent works also discuss the impact of spatial frame contention at the Medium Access Control (MAC) layer on the end-to-end performance of multi-hop topologies [BDM02, GF03, XS02]. In [BDM02], for example, the authors analyze the interactions of the routing and MAC protocols in a MANET. The mutual interactions between MAC and routing protocols may be described as follows:

- The paths selected by the routing protocol directly affect the spatial contention among the involved nodes at the MAC layer.
- The contention at the MAC layer can cause routing protocol to respond by initiating new route queries and route table updates.

The authors of [BDM02] conclude that it is not meaningful to consider MAC and routing protocols in isolation, and suggest that a cross-layer design of MAC and routing solutions may enhance the multi-hop communication in a MANET.

In the following section, we briefly sketch the traditional problems affecting the MAC protocols on multi-hop ad hoc topologies. In Section 3, we focus on the network layer, by presenting the common approaches in routing design for MANETs. Protocols and guidelines defined in section 6.2 and 6.3 are used as milestones for the design of our cross-layer MAC and routing framework defined in Chapter 7.

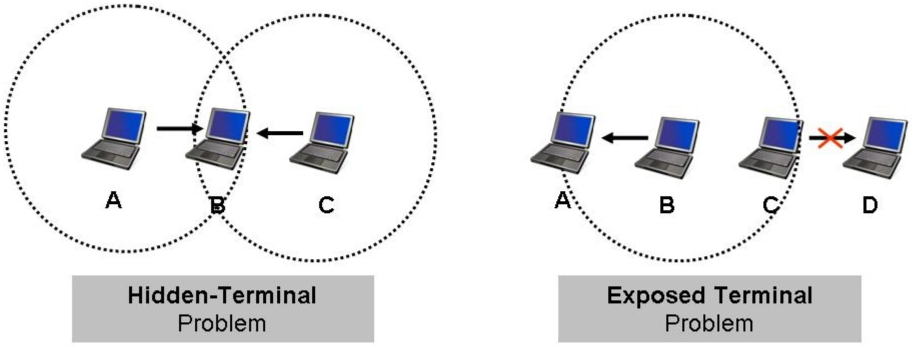


Figure 6.1: The hidden (left) and exposed terminal (right) at MAC layer

6.2 Common MAC problems on multi-hop topologies

Traditional problems affecting the MAC performance on multi-hop topologies may be identified as: the hidden problem problem, the exposed-station problem and the self-contention problem.

The Hidden Terminal Problem.

Figure 6.1 (left) shows a typical hidden terminal problem. Let us assume that station B is in the transmitting range of both A and C, but A and C cannot hear each other. Let also assume that A is transmitting to C. If C has a frame to transmit to B, according to the legacy DCF protocol, it senses the medium and it finds the medium free because it can not detect the ongoing transmission of node A. Therefore, it starts transmitting the frame causing a collision at the destination B.
The hidden-terminal problem may be alleviated by extending the DCF basic mechanism through the RTS-CTS handshake scheme (see section 3.3).

The Exposed Terminal Problem.

Figure 6.2: Self-contention at MAC layer

Figure 6.1 (right) depicts a typical scenario in which the exposed terminal problem may occur. Let us assume that both Station A and Station C can hear transmissions from node B, but Stations A can not hear transmissions from C. Let also assume that Station B is transmitting to Station A and Station C receives a frame to be transmitted to D. According to the legacy 802.11 DCF protocol, C senses the medium and finds it busy because of the transmission of B. Therefore, it does not transmit to node C, although this transmission would not cause a collision at A. The exposed terminal problem may thus result in a throughput reduction.

The Self-Interference Problem.

Traditional MAC protocols for wireless networks are not designed to handle the multi-hop coordination of the MAC layer when relaying data flows. A common assumption is that a node should contend for the channel for each transmission, regardless of the frame destination and of the traffic flow. As a result, the packets belonging to the same connection contend for the channel during transmission at neighboring nodes. This phenomenon, termed self-contention (Figure 6.2), is one of the key reasons for significantly lower goodput over multihop connections in wireless ad-hoc networks [GF03, XS02, YB04]. We distinguish between two types of self-contention, intra-stream and inter-stream contention:

- *Intra-stream* self-contention is caused by packets of the same stream competing for the shared medium. Contention caused by TCP-DATA packets on other

TCP-DATA packets is an example of intra-stream contention.

- *Inter-stream* self-contention is caused by the packets of the reverse stream on the packets of the forward stream. Contention caused by TCP-DATA packets on TCP-ACK packets is an example of inter-stream contention.

Self-contention arises due to distributed access of the shared media which is the role of the MAC layer. For these reasons, some MAC protocols work by considering that a packet has to be relayed over many intermediate peer nodes to reach its destination. Among multiple channel protocols, MCSMA [NZD99] and GRID-B [Tse02] exploit a multi-hop flat topology by favouring frequency channel reuse into the network. In single-channel solutions, MARCH [Toh00] is a receiver-oriented protocol, in which nodes on the next hop of the data path may implicitly invite the data forwarding without additional MAC contention, by anticipating the CTS messages. The utilization of RTS/CTS packets to alleviate self-contention and to provide fast forwarding of packets at relaying nodes is explored in other works [YB04, AMB02]: in [AMB02] the authors propose a simple mechanism of label-switching and fast-forwarding at the MAC layer, by evaluating such solution in string and random network topologies.

6.3 Routing Protocols

Several routing protocols have been proposed in literature, so that a complete description of each proposal is out of the scope of this work. Four different categories may be identified according to the routing strategy [BR04]: proactive routing, reactive routing, geographical routing, multipath routing.

6.3.1 Proactive Routing

Proactive routing protocols for MANETs are derived from the traditional link-state and distance-vector routing protocols used in the wireline Internet. Proactive protocols attempt to maintain up-to-date routing information between every pair of nodes by using a combination of the following techniques:

- *periodic updates*: routing information are exchanged periodically by the nodes of the network;
- *event-triggered updates*: external events such us link addition or removal may cause the transmission of routing updates.

The main advantage of the proactive scheme is that updated routes are always available when they are needed. At the same time, each node should periodically broadcast a routing update message, so that a significant control overhead may be originated in large-scale networks or in networks characterized by high nodes' mobility.

Destination-Sequenced Distance Vector Protocol (DSDV)

The Destination Sequenced Distance Vector routing protocol (DSDV) [CB94] is an extension of the conventional Routing Information Protocol (RIP) for MANETs. In DSDV, each mobile node of a MANET maintains a routing table, which lists all the available destinations, the metric and next hop to each destination and a sequence number generated by the destination node. Periodically, each mobile node advertises routing information by broadcasting a *routing table update message*. Each routing update is of the form:

$$< IP\_destination; sequence\_number; hop\_count > \tag{6.1}$$

After receiving the update message, the neighboring nodes update their routing table by incrementing the metric and then re-broadcast the message. The process will be repeated until all the nodes in the MANET have received a copy of the update message with a corresponding metric. If a node x receives multiple update message about a destination y, the message with the smallest metric is used, while the existing route is discarded or stored as a less preferable route.

The size of each update message may be critical over high-density scenarios because

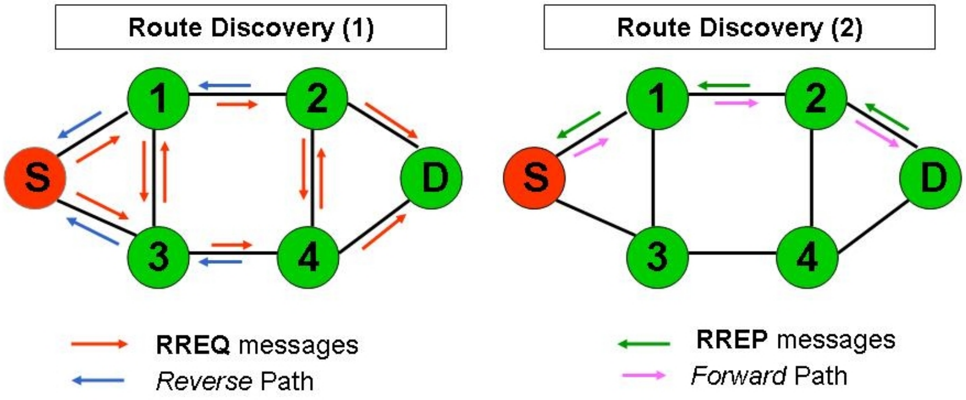


Figure 6.3: The AODV routing discovery process

the entire route table should be transmitted. For this reason, the DSDV protocol supports incremental updates that allow to include in the routing messages only those routing entries that have changed since the last update [CB94].

6.3.2 Reactive Routing

Reactive routing protocols, also called *on-demand routing*, attempt to reduce the control overhead by discovering routes only when needed [BR04]. When a source node S needs to send a data packet to a destination node D, it checks its routing table to determine whether it has a route toward node D. If no routes are available, a routing discovery process is started by network-wide flooding of request messages. The main advantage introduced by the reactive approach is the reduction of the control overhead, because no update packets are broadcasted. However, such convenience comes at the price of higher *route acquisition latency*. When a route is needed, the routing discovery process should be executed: some finite latency is required before the route is discovered.

Ad Hoc On-demand Distance Vector Routing (AODV)

The AODV protocol [PR99] is a reactive protocol. A route discovery process is initiated when a source node needs a route towards a destination node. Route discovery is started by the source node with a flooding of route request packets (RREQs) targeting the destination. The source node waits for a route reply (RREP) message testifying the discovered path, up to a given timeout limit. Each intermediate node receiving a RREQ packet checks its local routing table to see if there is a valid route towards the RREQ destination: if a route is available, a RREP packet is generated, otherwise the RREQ is propagated in broadcast. In both cases, the intermediate node saves the reverse path towards the source node, by setting a backward pointer to the previous hop of the current RREQ. Duplicate copies of RREQ messages are discarded. Eventually, if the destination node receives the RREQ, it produces the RREP message, which is routed back to the source by using the unicast reverse path established by the corresponding RREQ. Sequence numbers are used with messages in order to prevent cycles and to determine the time to live of each route. A detailed description of AODV can be found in [17].

6.3.3 Geographical Routing

Geographical routing protocols [BR04, KV98] extend the proactive and the reactive schemes by exploiting geographical information in the routing process. The geographical information can be in form of geographical coordinates or can be obtained by using reference points. The geographical information may enhance the performance of both reactive and proactive schemes:

- reactive routing protocols may reduce the number of entries in each update message, by considering only the destination nodes inside an area of interest;
- proactive routing protocols may avoid network-wide searches of the destination node, so that routing requests can be sent in the general direction of the destination node.

Location-Aided Routing (LAR)

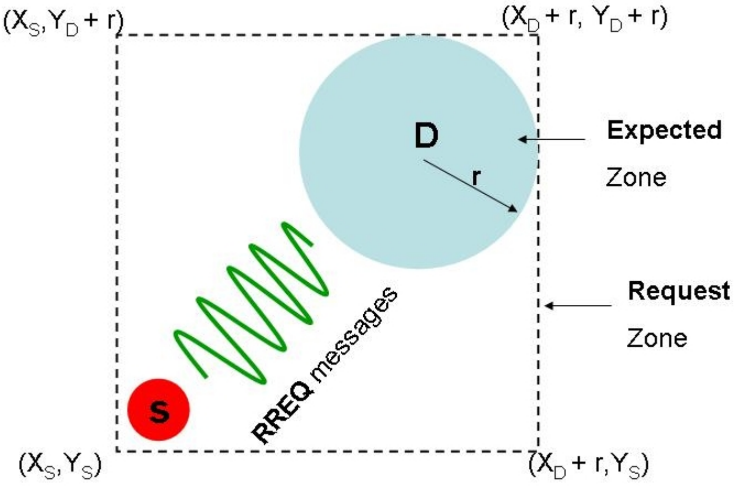


Figure 6.4: The LAR routing discovery process

The Location-Aided Routing protocol [KV98] utilizes geographical coordinates to direct route request messages to the previously known location of the destination. The protocol defines two areas: the *expected* zone and the *request* zone. The expected zone represents the area in which it is most likely to discover the destination. The expected zone may be computed if the following parameters are known:

$$< time0, location_{time0}, speed_{time0} > \tag{6.2}$$

where $location_{time0}$ and $speed_{time0}$ are the previous location of the destination and the speed of the destination at time $time0$. The request zone represents the area in which the route requests for the destination should be propagated.

The routing discovery process works as the other reactive protocols. When a source node S needs a path to a destination node D, it creates a route request (RREQ) message for that destination. If the source node has some information about the destination node, than it calculates the expected and the request zones and places the coordinates of the request zone into the RREQ message (see Figure 6.4). If the source does not have such information, a basic flooding discovery is used.

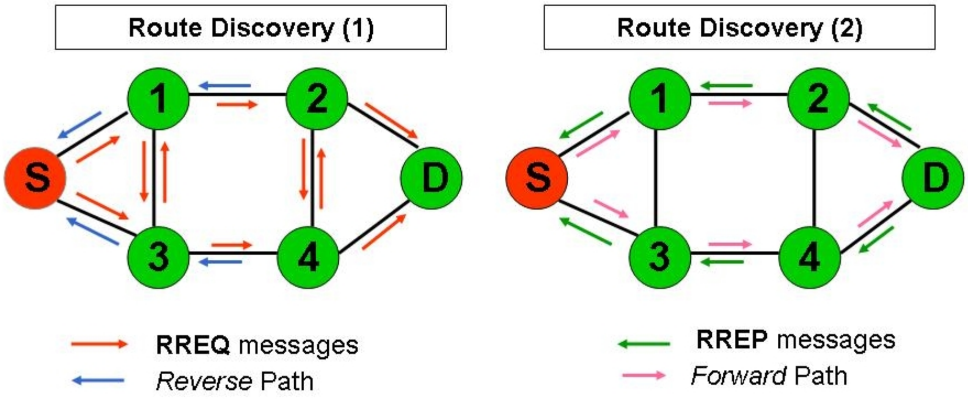


Figure 6.5: The AOMDV routing discovery process

6.3.4 Multipath Routing

On-demand protocols suffer of considerable route discovery latencies under intermittent-data applications, when a new route is requested in large networks and high-populated scenarios. Multipath on-demand protocols overcome this inefficiency, by allowing to discover multiple disjoint routes between any source and destination nodes. The presence of multiple paths may be exploited in two ways:

- *interchange routes*: multiple node-disjoint or link-disjoint routes are stored for each destination. When a link failure occurs in the active route, an alternate route is used to forward the data.
- *concurrent routes*: all the available routes toward a destination are used concurrently. Load-balancing schemes are used to allocate different amount of data proportionally to the performance of each route.

Ad Hoc On Demand Multipath Distance Vector (AOMDV)

AOMDV [MD01] extends the AODV protocol by computing multiple paths during route discoveries, with limited overhead and reduced complexity. To keep track of multiple routes, the routing entries in intermediate nodes contain a list of the next-hop nodes towards the destination node, and the corresponding hop-counts. Additional information is required to ensure loop freedom and to compute node-disjoint and link-disjoint paths (in particular, the maintenance of last-hop information for each route, in addition to next-hop information). As in AODV, the source starts the route discovery process by generating a RREQ packet when a route to a destination node is needed. RREQ messages are received by intermediate nodes, flooding the whole network. Different instances of RREQs are not discarded by intermediate nodes, because they may provide information about potential alternate reverse paths: if the new RREQ instance preserves the loop-free condition and comes from a different last-hop node, then a new reverse route towards the source node is logged in the intermediate node. If the intermediate node knows one or more valid forward paths to the destination, a RREP packet is produced and forwarded back to the source along the reverse path. If possible, the intermediate node includes in the new RREP a forward path that was not used in any previous RREP, for this RREQ. Otherwise, if the current RREQ is not a replica of a previously broadcasted RREQ, the intermediate node re-broadcasts the RREQ towards the destination. When the destination receives more RREQ instances, in order to get multiple link-disjoint routes, it replies with multiple RREP messages. Node-disjointedness may be computed from link-disjoint paths simply preventing intermediate nodes from having more than one path passing through them. A complete description of AOMDV can be found in [MD01].

Chapter 7

Cross-Layered MAC and Routing Protocols in MANETs

This chapter proposes and analyzes a solution for the mutual support of distributed MAC and routing schemes in MANETs. Contributions and results of this chapter are described in detail in [FB06, FB07b].

In [FB06, FB07b], a novel multipath routing scheme for wireless mobile networks is evaluated. The proposed scheme extends the Ad Hoc On-demand Multipath Distance Vector (AOMDV) routing protocol [MD01], by introducing a novel load-balancing approach to concurrently distribute the traffic among the multiple paths: for this reasons, the scheme is called *Concurrent Separate AOMDV protocol* (CS-AOMDV in the following). The traffic-path allocation scheme is based on cross-layer measurements of path statistics reflecting the size and congestion level of each path.
We also study the composition effect of a IEEE 802.11-based enhanced MAC forwarding mechanism called Fast Forward (FF) [YB04], used to reduce the effects of self-contention among frames at the MAC layer.

Section 2 contains a detailed description of the CS-AOMDV routing protocol, while the MAC layer support scheme is shown in Chapter 3. The protocol framework is modelled and extensively simulated for a large set of metrics and scenarios (section 7.3).

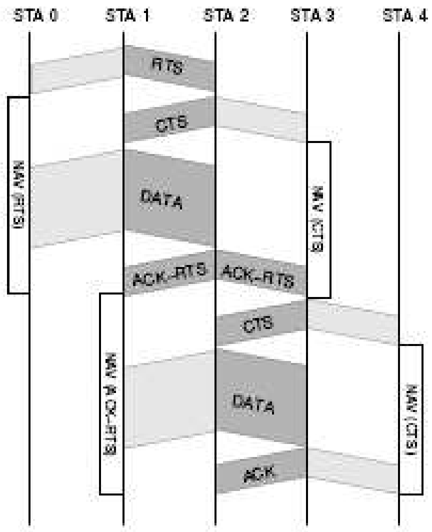


Figure 7.1: Fast Forward mechanism

7.1 MAC Layer: Fast Forward (FF) scheme

A MAC layer scheme, called Fast Forward (FF), is proposed in [YB04] to provide an effective support to end-to-end communication in IEEE 802.11 multi-hop wireless networks. The self-contention problem of data flows [GF03, XS02] has been shown to produce a direct impact on the throughput utilization of the system, and to affect the MAC interaction with transport protocols.

Once a route is established at the network layer (as an example, STA1, STA2 and STA3, respectively), the FF at the MAC layer works as shown in Figure 7.1: let us suppose that STA 1 starts with the basic access method to contend for the channel, and successfully sends a RTS frame to STA 2. After the correct reception, STA 2 immediately determines the next-hop MAC address for the frame and attempts to reserve the channel for the immediate relaying, by using a special frame, named ACK-RTS. The ACK-RTS frame combines two functions: it works as an ACK for STA 1 and as an implicit RTS for STA 3. The basic fourhandshake rules of the 802.11 IEEE DCF scheme is still valid: STA 3 replies with a CTS frame to STA 2, while the other stations in the collision domain simply update their NAVs for virtual carrier sensing.

To summarize, the FF mechanism is expected to produce an enhancement of the IEEE 802.11 DCF in a multi-hop environment, and to provide an effective support for the proposed multipath routing scheme, due to the following reasons:

- self-contention between adjacent nodes is reduced because the sender of a frame is prevented from injecting subsequent frames until the previous one has been forwarded out of its interfering range [GF03];
- the twofold nature of the ACK-RTS packet enables to reduce the control overhead, by suppressing a control packet and a new backoff contention [dcf] between neighbour nodes;
- as reported in the performance analysis section, FF may provide a more balanced access to the medium, for nodes involved in multiple flows, thus reducing the end-to-end delay. This could result in a proportional (that is, not flat) concept of fairness implemented by the MAC of nodes relaying multiple flows. In other words, nodes actively relaying more flows have more opportunities to gain the channel access, in a fair and transparent way;
- the FF is almost compliant with IEEE 802.11 DCF and it requires only a small modification to the RTS frame, which should include an additional field (the MAC address of the ACK receiver).

7.2 Network Layer: the CS-AOMDV Protocol

Although several paths may be available between a source and a destination, only a single active route is used by the AOMDV protocol. Alternate routes are adopted, if any, only when an active route failure occurs. In order to improve the system throughput and to favour the spatial reuse of the network resources, in [FB06, FB07b] we extend the AOMDV protocol with a novel load-balancing approach to distribute the traffic among the disjoint paths. Since our multipath routing protocol is based on AOMDV and exploits concurrent separated paths we call it CS-AOMDV.

The current performance and state of each link should affect the load distribution of pending traffic on the source nodes. To this end, a close cooperation and information sharing between protocol layers is required [CMT04]. In our scheme, we consider the queue length of intermediate nodes as a metric to reflect the path performance, called the path congestion. Consecutive packets from the transport layer are allocated on each path as a function of the congestion level and the hop-count of the path. Moreover, if multiple paths are available between a source and a destination, at least two paths are defined with opposite preferred directions. This would allow to reserve a different path for upstream and downstream transport layer traffic, in order to reduce MAC layer contention caused by frames travelling in opposite directions (as an example, TCP-DATA and TCP-ACKs). The main functions of the CS-AOMDV routing scheme are:

1. to compute multipath link-disjoint paths as the original AOMDV scheme;
2. to collect information about the congestion level of each path according to the queue length of the intermediate nodes;
3. to classify the available routes according to their performance;
4. to select the number of paths to use for each direction, by considering the incoming and outgoing traffic load, for both the sender and the receiver;
5. to balance the traffic load (pending packets) among the routes according to their classification and their performance, by reducing the transport-layer buffering and re-ordering overheads on the receivers.

Route Classification

The performance of each route is computed by considering the occupation of the queue at the LLC layer for each intermediate node. A node is said to be congested when the queue length is higher than a threshold limit. This information is conveyed

Bytes:	2	2	6	6	6	2	2	6	0-2312	4
	Frame Control	Duration	Address 1	Address 2	Address 3	CNC	Sequence Control	Address 4	Frame Boby	FCS

Figure 7.2: Structure of the modified MAC frame header for RREP and RINF packets

at the sender node both during the route discovery and route maintenance phases. During a route discovery, a new data frame format is used at the MAC layer for RREP messages forwarded by intermediate nodes of the path as a response to a RREQ message (see Figure 7.2). The MAC-header structure of the DATA packet is extended by including the CNC (Congested Node Counter) field as shown in Figure 7.2. The CNC field is initially set to value 0 by the destination node and incremented by each congested intermediate node.

When the source node receives a RREP message, it obtains additional information about the global congestion level of the routepath, to be saved in a local routing table. The mechanism for collecting information about route-congestion is very simple and works also when intermediate nodes anticipate RREP messages to RREQs, based on cached route information including the corresponding CNC value. Moreover, the management overhead introduced is limited because the additional information is managed at the MAC layer, without involving the network layer. Route maintenance in CS-AOMDV requires that the information about the congestion level of each path is provided periodically to the sender node. For this reason, a new routing packet has been defined, called Route Information (RINF), to convey information about the CNC value of each path from the destination to the source node. Since the proposed scheme executes route classification, the information collected about routes should include the preferred direction of each route. We have modified the basic structure of AODV's RREP packets by including a new field called Preferred Direction (PD). The value of this field may be: 0 (uplink), 1 (downlink) and -1 (not defined). Each intermediate node receiving a RREP message updates its routing table by recording the PD values.

Route Selection

Route classification and route selection for incoming/outgoing traffic are handled by the source node after the route discovery process. If a single route is available towards the destination, the route will be used in both directions. When AOMDV discovers several link-disjoint paths, a mechanism is used to classify the routes according to their performance. The performance metric of a route, called $Index_{route}$, depends on the number of hops and on the congestion level. It is computed according to the following formula:

$$Index_{route} = \left(1 - \frac{CNC_{route} + 1}{hop_{MAX} + 1}\right)^{hop_{route} - hop_{MIN} + 1} \tag{7.1}$$

where $Index_{route}$ is in $[0..1[$, hop_{MIN} and hop_{MAX} are respectively the MIN and MAX number of hops towards the destination, hop_{route} is the length of the current route and CNC_{route} represents the most recent CNC value obtained for that route. Intuitively, $Index_{route}$ has value zero for congested routes and value one for ideal routes, with a strong preference criteria for short routes. The decision about how many paths to use for each direction, and the selection of individual routes, depends on the information collected during the discovery phases, and on the amount of traffic generated to/from the destination. The proposed scheme uses a simple and intuitive approach to compute the number of incoming (and outgoing) routes with the following formula:

$$Routein = min\left(1, route_{TOT} \cdot \left(\frac{byte_{RECV}}{byte_{RECV} + byte_{SEND}}\right)\right) \tag{7.2}$$

where $route_{TOT}$ is the total number of routes available towards a certain destination, $byte_{SEND}$ (and $byte_{RECV}$) represent the amount of byte respectively sent to (and received from) the destination. $Route_{in}$ and $Route_{out}$ paths are marked among the $route_{TOT}$ available by updating their preferred direction (PD) value, and possibly preserving the current value of PD. A new routing packet called RTAB has been introduced to synchronize the source and the destination node about the preferred directions of each route.

Load Balancing

Generally speaking, load balancing should exploit the multiple routes available with an efficient interaction with other protocols. At the transport layer, UDP flows may have more advantages compared with TCP. TCP with multipath routing has been addressed, e.g. in [YKT04]. TCP includes mechanisms to provide reliability, flow and congestion control based on standard MAC and routing layer assumptions. Consecutive blocks of data should be sent on each route, according to the route throughput, in order to i) preserve the packet ordering on the receiver, ii) avoid cumulative retransmissions, iii) have less negative impact on sliding window management, and iv) avoid overheads, latency and buffer fluctuations.

These requirements have been considered in the CS-AOMDV scheme. First, consecutive blocks of data are allocated on outgoing routes proportionally to the $Index_{route}$ value. This would contribute to maximize the packet throughput while keeping under control receiver buffering and re-ordering overheads. The amount of bytes allocated over each route is:

$$byte_{route} = Index_{route} \cdot (Byte_{MAX} - Byte_{min}) + Byte_{min} \tag{7.3}$$

where $Byte_{MAX}$ and $Byte_{min}$ are parameters that define the maximum and minimum number of data bytes that could be allocated on each concurrent path. Specifically, $Byte_{min}$ can be used to control the insurgence of concurrent route-path overheads when few data are to be sent, while $Byte_{Max}$ can be used as upper bound factor for the buffering on the receiver side.

7.3 Performance Results

In the following, we illustrate simulation-based performance results of the new cross-layered protocol framework, compared with available solutions, under a wide range of tests, with different mobility and traffic scenarios. The simulation analysis has the following goals:

Simulated Areas	400x400m
Number of nodes	100
Mobility Model	Random Waypoint
Data Packet Size	512 Byte
Traffic Type	(UDP-CBR)/(TCP-FTP)
Channel nominal bitrate	2 Mb/s
$BYTE_{MAX}$	12000
$BYTE_{MIN}$	6000

Table 7.1: CS-AOMDV Simulation Parameters

1. to analyze the behaviour of single-path AODV routing solutions with respect to multi-path AOMDV solutions (exploiting one single path at a time) and multi-path CS-AOMDV solutions (exploiting concurrent paths, if any, under a cross-layered approach);

2. to provide a preliminary analysis of the Fast Forward (FF) MAC layer enhancement for multi-hop communications in IEEE 802.11 DCF-based wireless systems, combined with the CS-AOMDV solutions;

3. to analyze the behaviour of the proposed MAC and routing solutions as the basis for both TCP and UDP transport layer communications.

The main parameters used in the simulations are reported in Table 7.1. More specific assumptions and parameters for the analyzed scenarios are reported in subsections 7.3.1, 7.3.2, 7.3.3, 7.3.4 and 7.3.5 respectively.

More in detail, the simulation analysis focuses on the analysis of performance indexes under variable factors, separately, to provide useful insights of the system behaviour. Five different tests are considered:

- the *mobility test* is planned to analyze the ability of protocols to cope with dynamic route changes and link failures;

- the *connection test* analyzes the impact of the variable number of concurrent active connections;
- the *workload test* is defined to show the impact of variable network-load and traffic source conditions on the system performance;
- the *mesh connection test* shows the impact of regular static network topology;
- the *tcp test* analyzes the impact of the TCP protocol on the multipath routing scheme performance.

7.3.1 Mobility Test

This section shows some results obtained with the scenario parameters defined in Table 7.1, and with 20 active sources (each one connected to a randomly selected destination) and a packet generation rate (CBR) of 4 packets/s for each source. Each node follows a Random Waypoint (RWP) mobility model with node speed uniformly distributed in a range [0..MAX Speed] (no pause times). The widely adopted RWP mobility model is based on the cyclic selection of pseudo-random, uniformly distributed coordinates for a node destination (in the simulated area) and a constant speed value (in the speed range) to reach the destination. This mobility model is quite unrealistic, but it is widely used in worst case analysis of wireless scenarios, that is, when the system is analyzed under stressing and unpredictable mobility conditions. The mobility test is controlled by varying the Max Speed factor in a range from 5 m/s to 25 m/s.

As shown in Figure 7.3, the average end-to-end goodput (that is, the source-destination throughput at the application level, without overheads) is influenced by node mobility: great mobility translates in link failures and low route persistence. This fact requires additional overheads for route creation. As expected, the AODV protocol has a slightly worst performance than multi-path protocols. AOMDV reduces the overhead being able to quickly recover route failures by adopting one

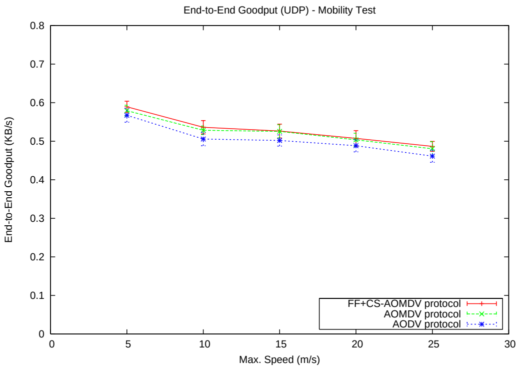


Figure 7.3: Mobility Test, End-to-end goodput

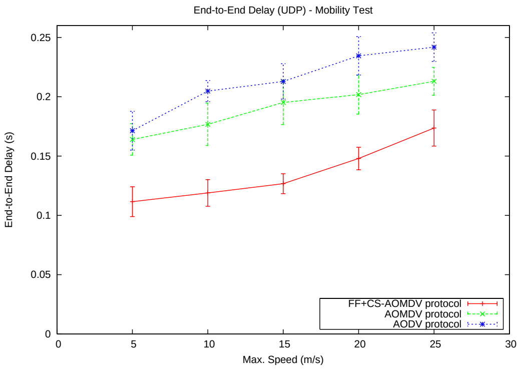


Figure 7.4: Mobility Test, End-to-end delay

alternate existing route, if any. The effect of FF and CS-AOMDV introduces a generalized marginal advantage under the goodput viewpoint, which means that the concurrent exploitation of multiple paths does not introduce significant advantages under the goodput viewpoint, for this scenario. With light communication load, the reason is that one route path is able to satisfy the application needs. In overload, the reason is given by the contention effect which is obtained near the source and destination nodes. Despite multiple disjoint paths can be found, on the average, their respective flows have to cope with the bottleneck contention effect in the proximity of source and destination nodes, which nullifies the advantage of concurrent paths. As confirmed in [YKT04], when the source-destination are close to each other only one link can be active, thus the presence of multiple paths does not lead to an increase in goodput. This fact strongly depends on the assumption to have a single shared channel for communication in the system.

In Figure 7.4, we show the average end-to-end delay for received packets. The average delay increases as a function of the mobility due to the frequent route failures. In this case, the significant advantage of CS-AOMDV (which outperforms other schemes) is given by the reduction of collision overheads (thanks to FF) and by the increased queue-emptying behaviour of intermediate nodes obtained with the implicit channel reservation inherited by a node upon packet reception. Multi-path

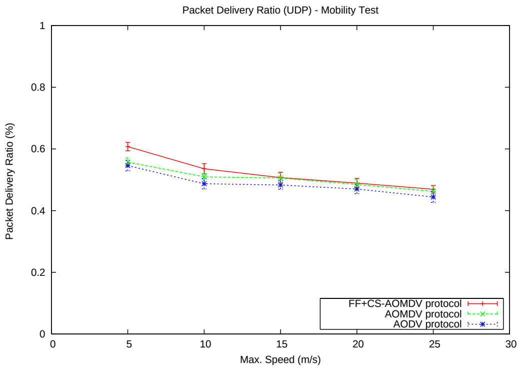


Figure 7.5: Mobility Test, Packet Delivery Ratio

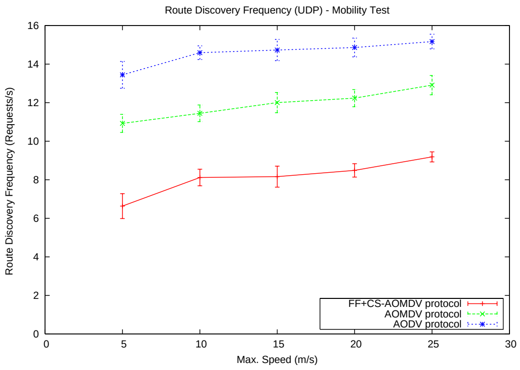


Figure 7.6: Mobility Test, Route Discovery Frequency

schemes outperform AODV basically because they are more efficient in recovering route failures, on the average.

Figure 7.5 shows the end-to-end data packet delivery ratio as a function of the MAX speed. The percentage gain is marginal (+4%) with multi-path schemes, compared with single-path AODV. The index decreases when the mobility increases, as expected. In other words, the route reliability and the capacity to eventually deliver data packets to the final destination is marginally influenced by the proposed framework. This result is relatively surprising, but analysis of results has shown that the effect of homogeneous node mobility is dominating this performance index, when the number of route hops is greater than two, and this may reduce the transmission of data packets. Figure 7.6 shows the average frequency of route discovery messages per second in the whole system. Route discovery messages are sent by sources when a new route is needed. As expected this index increases when the mobility increases. On the other hand, the cross-layered framework shows better results than AOMDV, which outperforms AODV, respectively.

Another overhead index is shown in Figure 7.7: the normalized routing load indicates the number of routing messages transmitted in the system normalized with

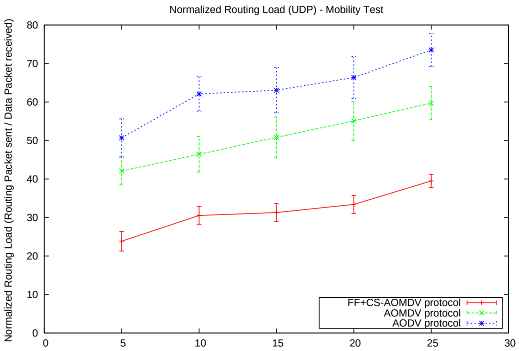


Figure 7.7: Mobility Test, Normalized Routing Load

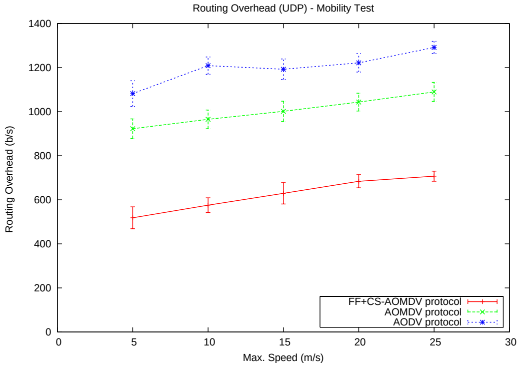


Figure 7.8: Mobility Test, Routing Overhead (b/s)

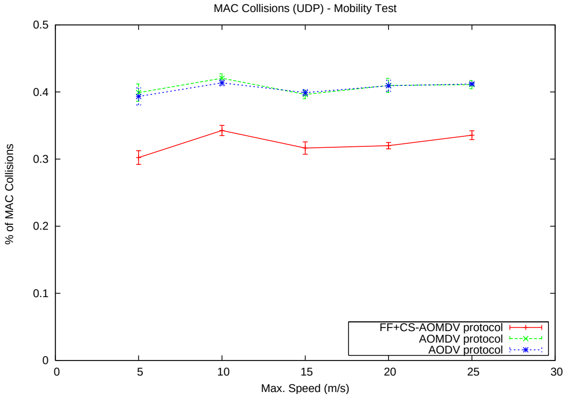


Figure 7.9: Mobility Test, MAC Collisions (%)

respect to the number of delivered data messages (as a function of the Max Speed of nodes). This index is indicative of the reduction of MAC contention determined by the reduction of routing messages in the system. The FF composed with CS-AOMDV outperforms AOMDV and AODV respectively. Since this index is not fully indicative of the channel utilization wasted due to routing functions, in Figure 7.8 we show another similar index: the total load of routing messages expressed in bit/s. Since the routing messages are quite similar in size, this figure is qualitatively very similar to previous one.

The last performance index shown in Figure 7.9 for this test is the MAC layer percentage of collisions resulting in the transmission of data packets, by assuming the adoption of RTS/CTS messages. RTS/CTS have the advantage of reducing the cost of collisions, and they contrast the hidden terminal problem. Figure 7.9 shows that proposed framework significantly reduces the insurgence of MAC collisions, mainly due to the contribution of the FF mechanism. By increasing the node mobility, the collision risk increases due to the higher number of route requests originated by more frequent route failures.

7.3.2 Connection Test

In this section we repeat the same simulation tests shown in section 7.3.1 by varying the number of active sources, that is, the number of end-to-end connections. Each source produces a CBR flow of 4 data packets/s to be routed towards a randomly selected destination. The destination node is never changed by one source, and all nodes follow a Random Waypoint mobility model with speed randomly distributed in [0..Max Speed= 5 m/s] (average speed = 2,5 m/s). This means that the route path length is varying dynamically between each source and destination.

In Figure 7.10, the average end-to-end goodput (per source) is influenced by the number of active connections: more connections translates in more congestion and route failures. Some false link failures caused by nodes which have experimented more than 7 collisions (the default value of the Short Retry Limit in MAC DCF 802.11) [dcf] can be observed in the system. The AODV protocol has a slightly worst performance than multi-path protocols. The effect of FF and CS-AOMDV introduces a generalized marginal advantage under the goodput viewpoint, mainly due to the reduction of MAC contention of the FF mechanism. The concurrent exploitation of multiple paths has a marginal effect for the reasons illustrated in section 7.3.1

In Figure 7.11, we show the average end-to-end delay for received packets. The average delay increases as a function of the number of active connections due to the network congestion and shared channel contention effects. CS-AOMDV outperforms other schemes under a scalability viewpoint. This is given by the reduction of collision overheads (thanks to FF) and by the increased queue-emptying behaviour

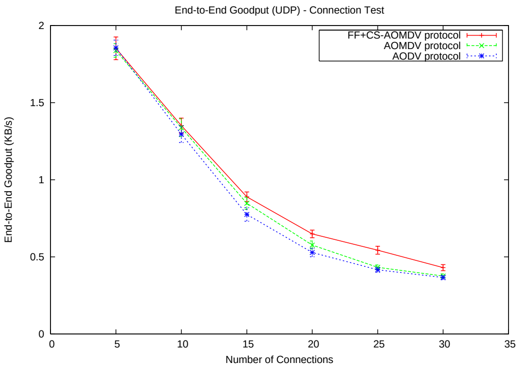


Figure 7.10: Connection Test, End-to-end goodput

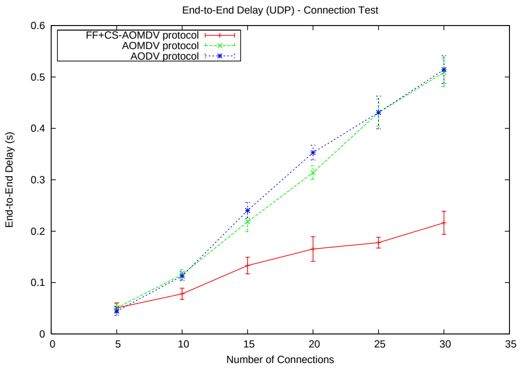


Figure 7.11: Connection Test, End-to-end delay

of intermediate nodes obtained with the implicit channel reservation inherited by a node upon packet reception. More specifically, the CS-AOMDV and the FF mechanism contribute to reduce the tail of the end-to-end delay distribution, with respect to other schemes.

Figure 7.13 shows the normalized routing load (as a function of the number of active connections). This index is very similar to previous one, under a qualitative viewpoint. The FF composed with CS-AOMDV outperforms AOMDV and AODV respectively. It is also interesting to note that when the number of connections is high, the AODV and AOMDV systems achieve a good general routing knowledge, which contributes to reduce the routing overheads in case of route failure. The total load of routing messages expressed in bit/s is not shown since this figure is qualitatively very similar to Figure 7.13.

7.3.3 Workload Test

In this section we repeat the same simulation tests shown in section 7.3.1 and 7.3.2 by varying the packet generation rate of 20 active sources, that is, the offered load of the system. Sources produce a CBR flow of [2..10] data packets/s, to be routed towards a randomly selected destination. The Random Waypoint mobility speed is

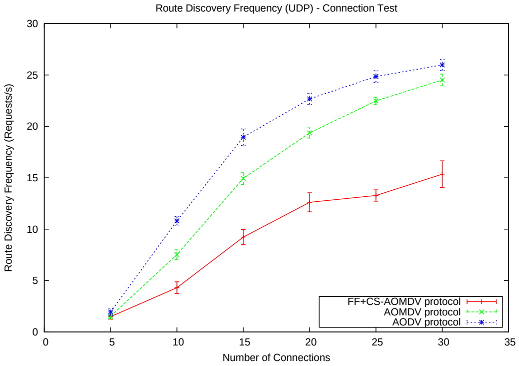


Figure 7.12: Connection Test, Route Discovery Frequency

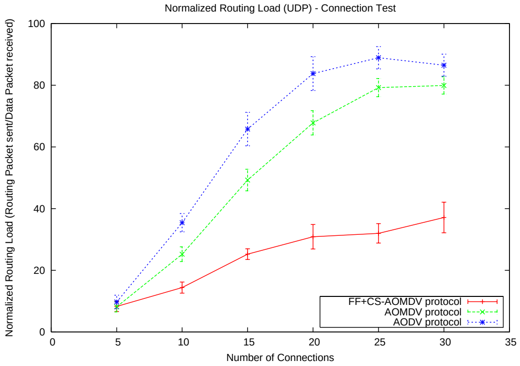


Figure 7.13: Connection Test, Normalized Routing Load

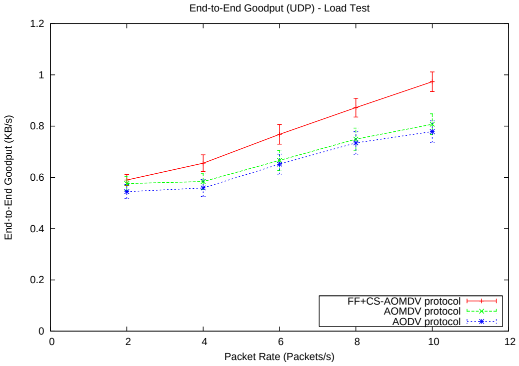


Figure 7.14: Workload Test, End-to-End Goodput

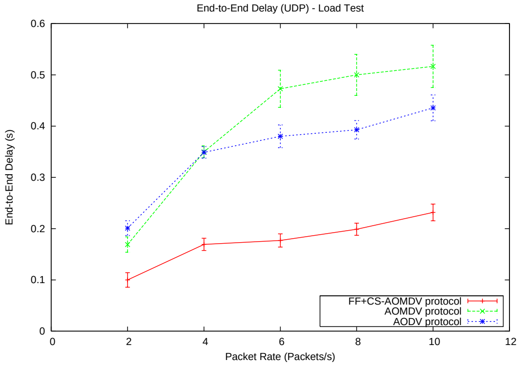


Figure 7.15: Workload Test, End-to-end Delay

randomly distributed in [0..Max Speed= 5 m/s] (average speed = 2,5 m/s).

Figure 7.14 shows the average system goodput. It is worth noting that the increased offered load produces an increased goodput. The FF + CS-AOMDV outperforms other schemes by demonstrating that a good scalability can be obtained when the system load increases, with the proposed protocol framework. Figure 7.15 shows the end-to-end delay performance: the FF + CS-AOMDV framework outperforms other schemes in this scenario, under the system scalability viewpoint. It is worth noting that AOMDV introduces additional overheads with respect to

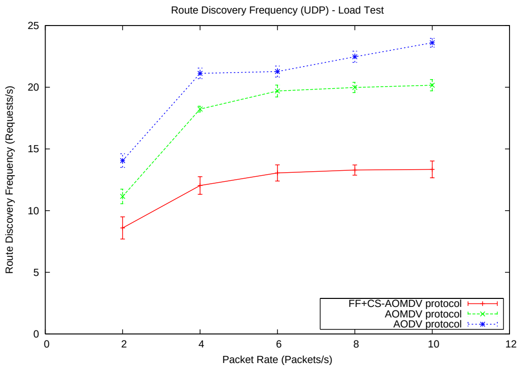


Figure 7.16: Workload Test, Route Discovery Frequency

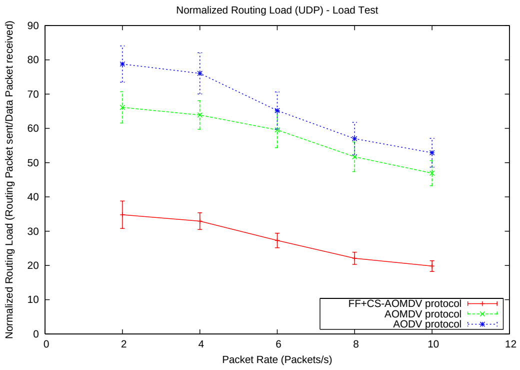


Figure 7.17: Workload Test, Normalized Routing Load

AODV when the load increases: this behaviour can be explained by considering that AOMDV could use previously discovered paths (still valid) that have become sub-optimal, while AODV could have recently discovered a new shortest path between source and destination. In other words, under dynamic topologies, the refresh effect of more frequent route discovery processes has a potential for delay reduction, even if this would imply an overhead as shown in Figure 7.17.

Figure 7.16 shows the average number of route discovery messages per second: as expected, the AODV protocol has the maximum overhead, followed by AOMDV and FF + CS-AOMDV, respectively. If the offered load increases, the route discovery overhead marginally increases, as expected, due to the insurgence of collisions which could introduce additional route failures. Figure 7.17 shows the normalized routing overhead: this demonstrates that the scalability of FF + CS-AOMDV outperforms other schemes. In addition, the figure shows that the overhead effect of routing functions is reduced when the established routes duration can be successfully exploited to deliver more packets, generated with high packet rate.

7.3.4 Mesh Connection Test

In this section we show the wireless mesh connection test similar to the test in section 7.3.2, to show the impact of regular static network topology (a mesh-like regular

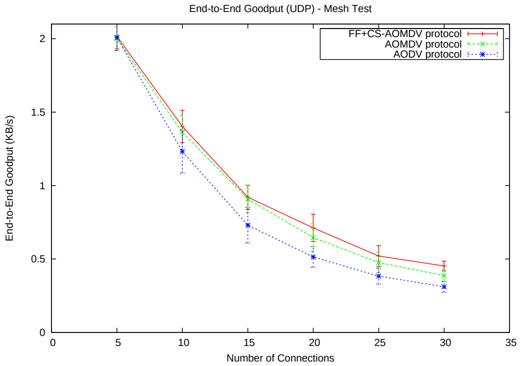


Figure 7.18: Mesh Test, End-to-End Goodput

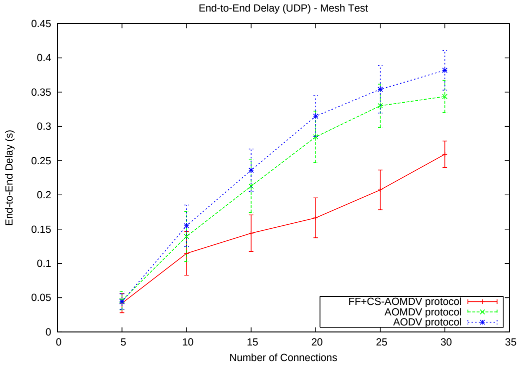


Figure 7.19: Mesh Test, End-to-End Delay

structure of 100 static nodes, see figure 3b) on the system performance. Figure 7.18 shows the end-to-end goodput index of a source, as a function of the number of connections: the difference with respect to the mobile ad hoc scenario is given by a small increase of the goodput with the FF + CS-AOMDV framework, and a small reduction of goodput obtained by AODV when the congestion grows. In other words, the static regular topology provides little differences with respect to mobile ad hoc scenario considered for the same tests in section 7.3.2. This confirms that the number of stable available paths of the mesh topology is not providing significant aggregate throughput for the existing connections, due to the self-contention and single channel bottleneck effects in proximity of the sources and destinations. Figure 7.19 shows the effect of static regular topology on the end-to-end delay, as a function of the number of connections. In this scenario, a generalized reduction of delay is introduced. This is due to the reduction of route failures due to lack of node mobility.

In Figure 7.20, the route discovery frequency shows very similar results compared with the same figure obtained in the mobile ad hoc scenario. Quite surprisingly, this demonstrates that the reactive routing functions under the mobile ad hoc scenario are not heavily influenced by the mobility failures, provided that routing protocols can recover such failures with efficient route recovery functions (like in AODV),

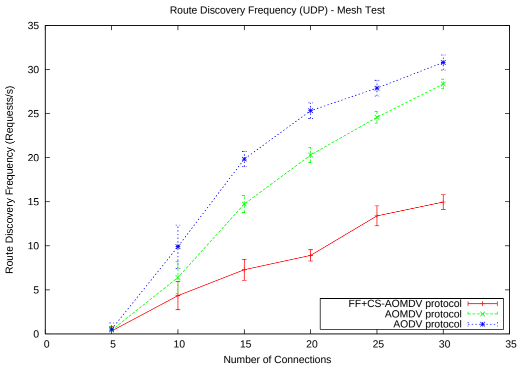


Figure 7.20: Mesh Test, Route Discovery Frequency

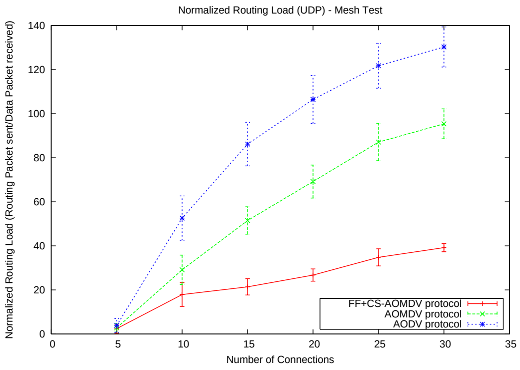


Figure 7.21: Mesh Test, Normalized Routing Load

and/or existing alternative route paths (like in AOMDV and CS-AOMDV). Figure 7.21 shows the normalized routing overhead: the mesh scenario introduces an increase in the number of transmitted routing messages with respect to the mobile ad hoc scenario. This can be explained by considering that the mesh topology provides a high number of alternate paths, on the average, and multiple route paths may incur in a multiplication factor of additional management overheads (e.g. multiple propagation of RREQ broadcast messages, and one RREP messages from destination to the source, for each different path).

7.3.5 TCP Test

So far, we have considered only mobile scenarios with UDP transport protocol, and with CBR traffic generators. Simulations under saturated TCP traffic has revealed drawbacks and limits of multipath routing and multi-hop fast-forwarding when supporting TCP data flows, as described in [YB04, YKT04]. Although CS-AOMDV has been defined in order to implement weighted traffic allocation on multiple routes by sending consecutive packets on each path, aiming to reduce in this way out-of-order reception, quite hard-to-predict interactions with the TCP protocol can be obtained depending on the TCP version used (TCP Reno, in our tests). Figures 7.22 and 7.23 show the goodput and delay performance metrics under a mobility

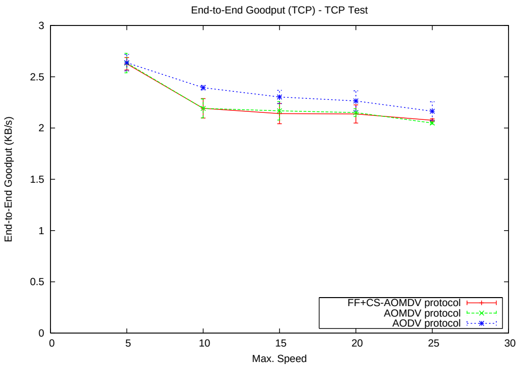


Figure 7.22: TCP Test, End-to-End Goodput

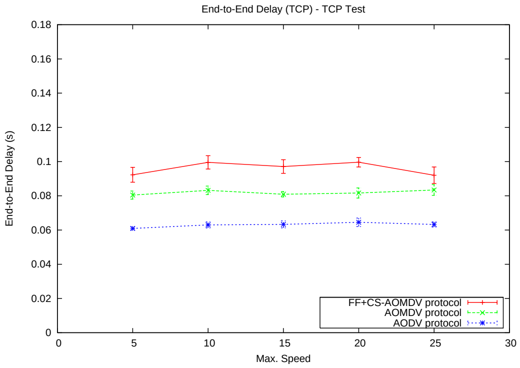


Figure 7.23: TCP Test, End-to-end Delay

analysis scenario for mobile ad hoc networks (Max Speed in the range [5..25 m/s]) and a fixed number of 20 end-to-end FTP-like connections (that is, saturated buffers on the sources). Despite some common parameters, this scenario cannot be easily compared with previous ones, due to significant variations in the sources and protocols behaviour. In this analysis, as reported in Figure 7.22, all multi-path routing schemes produce similar end-to-end goodput results. Quite surprisingly, the AODV protocol has goodput results better than multi-path protocols. In general, as expected, the goodput is generally reduced when the mobility increases. By looking at Figure 7.23, differences are shown in the end-to-end delay: in general, the concurrent FF+CS-AOMDV scheme shows worst delay performance than AOMDV and AODV in saturated TCP scenarios. In other words, complex correlated effects exists in all the layers, ranging from the space and time contention of multiple flows, up to route failures and management functions, congestion, buffer management and end-to-end reliable (re)-transmission schemes.

Basically, when the FF+CS-AOMDV framework is used, in case of a single managed TCP flow split over multiple concurrent paths, each path may experience significantly different RTTs, which may be determined by many factors including: i) the hop count of the path, ii) the congestion level of each path, and iii) the number of FF MAC transmissions in the intermediate nodes. The increased variance of the RTT estimate could cause TCP to reduce the sending rate of data. This contributes to explain the reduced performance of FF+CSAOMDV in terms of end-to-end goodput, and the increasing end-to-end delay in delivering data in Figures 7.22 and 7.23.

In conclusion, the concurrent exploitation of multiple paths and FF MAC mechanism should be based on a well designed cross layered solution, by possibly splitting TCP connections into multiple virtual TCP flows, each one managed with a separate congestion window whose size is based on RTT estimation on respective paths. In addition, the effect of multi-channel multiradio technologies should be considered as a potential for enhancing the throughput in multi-hop communication scenarios.

Chapter 8

Conclusions

In this thesis, we have investigated some cross-layer optimizations for Mobile Ad Hoc Networks (MANETs). Firstly, we have explored motivations, benefits and drawbacks of a cross-layer methodology for protocol design in MANETs. We have analyzed the interactions between MAC, routing and clustering protocols, and we have demonstrated that these protocols should be considered mutually cooperative, in order to support multi-hop communication in MANETs. Secondly, we have proposed some novel solutions for the integration of MAC, clustering and routing protocols.

The AC clustering scheme has been defined to exploit node and system heterogeneity and to cope with system dynamics. The different node roles identified by the clustering scheme are adaptively mapped over a differentiated priority mechanism at MAC Layer. The simulation results have confirmed the effectiveness of our cross-layer solution in (i) supporting nodes' heterogeneity and mobility, by reducing the clustering overhead (see Figure 4.5, 4.6) and in (ii) providing differentiated channel access at MAC Layer, by reflecting the node roles assigned by the AC scheme (see Figure 4.13, 4.14). The cross-layered Clustering+MAC framework provides effective enhancement in inter-cluster routing as well as in efficient broadcasting of alert messages in vehicular networks (see Chapter 4).

Moreover, we have also investigated and analyzed some novel solutions for the joint design of MAC and routing protocols in MANETs. We have proposed to enhance multi-hop communications by (*i*) favouring the spatial reuse of the channel at routing layer by using multiple node-disjoint routes in a concurrent way and (*ii*) by alleviating the effect of self-contention at MAC Layer with a multi-hop reservation scheme (Fast Forward). The simulation results have shown that our cross-layered framework may reduce the packet latency and routing overheads, and may enhance the end-to-end performance of UDP flows when compared with traditional solutions (single-path AODV and AOMDV routing protocol, and IEEE 802.11 DCF at the MAC layer). Also, the results have investigated some drawbacks that limit the advantages of concurrent path exploitation under the TCP transport protocol.

Finally, our results have provided a set of guidelines for supporting efficient multi-hop communication, by exploiting cross-layered MAC, routing and clustering layer solutions.

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