Hierarchical routing and cross-layer mechanisms for improving video streaming quality of service over mobile wireless ad hoc networks

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HIERARCHICAL ROUTING AND CROSS-LAYER MECHANISMS FOR IMPROVING VIDEO STREAMING QUALITY OF SERVICE OVER MOBILE WIRELESS AD HOC NETWORKS

DOCTORAL THESIS

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Valencia, Spain

November 2013

Abstract

This thesis dissertation addresses the problem of providing video streaming services over mobile wireless ad hoc networks. This sort of network represents a hostile environment for this kind of real-time data transmission to the extent that obtaining a good quality of viewer experience is challenging and still under study. Besides the research point of view, providing high-quality multimedia services is decisive for the practical usability and feasibility of wireless ad hoc networks so that service providers can broaden the range of services offered. So far, mobile wireless ad hoc networks have been used to provide network connection among users who could not have connectivity otherwise. However, quality expectations and requirements have been increased notably, fostered by the advent of real-time multimedia applications over mobile devices. Due to the considerable processing and bandwidth constraints underlying these types of devices, coupled with their ability to move freely, it becomes a difficult task to achieve an acceptable quality of service throughout the entire video transmission.

Thus, the contribution of this thesis work is twofold. On the one hand, the main problems and limitations that may be encountered and should be faced when deploying real-time services over mobile wireless ad hoc networks are analyzed and discussed. Bandwidth constraints and node mobility are portrayed as the major causes that prevent good quality of service and smooth video playback. On the other hand, following then the aim of improving video streaming quality, this thesis proposes practical solutions that involve diverse routing and cross-layer techniques.

One of the proposed approaches focuses on hierarchical routing. Hierarchical arrangement of network nodes may reduce packet interference as well as offer a structured architecture that reduces control traffic overhead. Particularly, the proposed hierarchical routing protocol aims at providing scalability when the number of nodes grows, while maintaining complexity as low as possible. The resulting reduction in packet losses and video playback interruptions finally enhances the quality of received video streams.

Furthermore, on the basis that the nodes in an ad hoc network are willing to perform routing tasks, every node could become essential for the proper network operation and routing performance. In tune with this philosophy, a new cross-layer mechanism for recovering lost packets is proposed. By overhearing packets over the wireless shared

medium, any node in the surrounding area of the destination endpoint can altruistically retransmit those video packets that have not been correctly received at destination. Moreover, due to the video awareness and frame prioritization algorithm considered in this proposal, it becomes very convenient for real-time video streaming services. The results show that the presented mechanism succeeds in improving video quality and user experience, especially when packet losses are caused due to the mobility of the destination node.

Resumen

Esta tesis aborda la problemática que surge a la hora de proveer servicios de *streaming* de vídeo sobre redes móviles ad hoc inalámbricas. Este tipo de redes representa un entorno hostil para esta clase de transmisiones en tiempo real hasta el punto en que obtener una buena calidad de experiencia para el usuario se vuelve todo un reto. Además del punto de vista de la investigación, la posibilidad de proveer servicios multimedia de alta calidad es un factor decisivo para la usabilidad práctica y la viabilidad de las redes ad hoc de forma que los proveedores de servicios puedan ampliar su abanico de servicios ofertados. Hasta ahora, las redes móviles ad hoc inalámbricas han sido utilizadas para proporcionar conectividad de red entre usuarios que, de otro modo, no habrían podido tenerla. Sin embargo, los requerimientos y perspectivas de calidad se han ido incrementando notablemente, impulsados por la aparición de nuevas aplicaciones multimedia en tiempo real sobre dispositivos móviles. Debido a las considerables limitaciones en ancho de banda y capacidad de computación inherentes a este tipo de dispositivos, junto con la posibilidad de que puedan moverse libremente, se vuelve difícil obtener una calidad de servicio aceptable a lo largo de toda una transmisión de vídeo.

Así, la contribución de esta tesis tiene un doble objetivo. Por un lado, se analizan los principales problemas y limitaciones que pueden encontrarse y deben tenerse en cuenta a la hora de desplegar servicios en tiempo real sobre redes móviles ad hoc inalámbricas. Las restricciones de ancho de banda y la movilidad de los nodos aparecen como las causas principales que impiden obtener una buena calidad de servicio y una reproducción de vídeo sin interrupciones. Por otro lado, y siguiendo con el propósito de mejorar la calidad del *streaming* de vídeo, se proponen soluciones concretas que engloban diversos mecanismos relacionados con los protocolos de encaminamiento y técnicas *cross-layer*.

Una de las propuestas está centrada en encaminamiento jerárquico. La organización jerárquica de los nodos de la red puede reducir las interferencias entre paquetes así como ofrecer una arquitectura estructurada que ayude a reducir la sobrecarga de tráfico de paquetes de control. Concretamente, el protocolo de encaminamiento jerárquico propuesto tiene como objetivo incrementar la escalabilidad de la red a medida que el número de nodos aumenta, manteniendo una baja complejidad en el algoritmo. La

reducción de la pérdida de paquetes, así como de las interrupciones en la reproducción, hace que la calidad del vídeo recibido se vea notablemente mejorada.

Además, partiendo de la base de que los nodos de una red ad hoc están dispuestos a realizar tareas de encaminamiento, cada uno de estos nodos puede resultar esencial para el correcto funcionamiento de la red y el encaminamiento de paquetes. En armonía con esta filosofía, se propone un nuevo mecanismo *cross-layer* centrado en la recuperación de paquetes perdidos. Gracias a que el medio inalámbrico es compartido, cualquier nodo es capaz de sobreescuchar paquetes que no vayan dirigidos a él. Así, los nodos cercanos al nodo destino podrían guardar y retransmitir altruistamente aquellos paquetes que no hubieran sido recibidos correctamente en destino. Además, gracias a la capacidad de detectar y priorizar tramas de vídeo, esta propuesta resulta muy adecuada para servicios de *streaming* de vídeo en tiempo real. Los resultados obtenidos muestran que el mecanismo propuesto mejora la calidad de vídeo y la experiencia de usuario, especialmente cuando la pérdida de paquetes se produce debido a la movilidad del nodo destino.

Resum

Esta tesi aborda la problemàtica que sorgeix a l'hora de proveir servicis de *streaming* de vídeo sobre xarxes mòbils ad hoc sense fil. Este tipus de xarxes representa un entorn hostil per a esta classe de transmissions en temps real fins al punt en què obtindre una bona qualitat d'experiència per a l'usuari es torna tot un repte. A més del punt de vista de la investigació, la possibilitat de proveir servicis multimèdia d'alta qualitat és un factor decisiu per a la usabilitat pràctica i la viabilitat de les xarxes ad hoc de manera que els proveïdors de servicis puguen ampliar el seu catàleg de servicis oferits. Fins ara, les xarxes mòbils ad hoc sense fil han sigut utilitzades per a proporcionar connectivitat de xarxa entre usuaris que, d'una altra manera, no haurien pogut tindre. No obstant això, els requeriments i perspectives de qualitat s'han anat incrementant notablement, impulsats per l'aparició de noves aplicacions multimèdia en temps real sobre dispositius mòbils. A causa de les considerables limitacions en amplada de banda i capacitat de computació inherents a este tipus de dispositius, junt amb la possibilitat que puguen moure's lliurement, es torna difícil obtindre una qualitat de servici acceptable al llarg de tota una transmissió de vídeo.

Així, la contribució d'esta tesi té un doble objectiu. D'una banda, s'analitzen els principals problemes i limitacions que poden trobar-se i han de tindre's en compte a l'hora de desplegar servicis en temps real sobre xarxes mòbils ad hoc sense fil. Les restriccions d'amplada de banda i la mobilitat dels nodes apareixen com les causes principals que impedeixen obtindre una bona qualitat de servici i una reproducció de vídeo sense interrupcions. D'altra banda, i seguint amb el propòsit de millorar la qualitat del *streaming* de vídeo, es proposen solucions concretes que engloben diversos mecanismes relacionats amb els protocols d'acarrerament i tècniques *cross-layer*.

Una de les propostes està centrada en acarrerament jeràrquic. L'organització jeràrquica dels nodes de la xarxa pot reduir les interferències entre paquets així com oferir una arquitectura estructurada que ajude a reduir la sobrecàrrega de tràfic de paquets de control. Concretament, el protocol d'acarrerament jeràrquic proposat té com a objectiu incrementar l'escalabilitat de la xarxa a mesura que el nombre de nodes augmenta, mantenint una baixa complexitat en l'algoritme. La reducció de la pèrdua de paquets, així com de les interrupcions en la reproducció, fa que la qualitat del vídeo rebut es veja notablement millorada.

A més, partint de la base que els nodes d'una xarxa ad hoc estan disposats a realitzar tasques d'acarrerament, cada un d'estos nodes pot resultar essencial per al funcionament correcte de la xarxa i l'acarrerament de paquets. En harmonia amb esta filosofia, es proposa un nou mecanisme *cross-layer* centrat en la recuperació de paquets perduts. Gràcies a què el mig sense fil és compartit, qualsevol node és capaç de sobreescoltar paquets que no vagen dirigits a ell. Així, els nodes pròxims al node destí podrien guardar i retransmetre de forma altruista aquells paquets que no hagueren sigut rebuts correctament en destí. A més, gràcies a la capacitat de detectar i prioritzar trames de vídeo, esta proposta resulta molt adequada per a servicis de *streaming* de vídeo en temps real. Els resultats obtinguts mostren que el mecanisme proposat millora la qualitat de vídeo i l'experiència d'usuari, especialment quan la pèrdua de paquets es produeix a causa de la mobilitat del node destí.

Agradecimientos

Quiero dar las gracias a todas aquellas personas que de un modo u otro han estado presentes estos años y me han apoyado y animado, dejando de alguna forma su huella en este trabajo y en mí.

En especial quiero agradecer al Dr. Juan Carlos Guerri, director de esta investigación, toda la paciencia y el apoyo brindados, y todos los cafés que hemos compartido revisando algoritmos, artículos y resultados. Quiero también extender mi agradecimiento a todos mis compañeros del Grupo de Comunicaciones Multimedia por hacer tan gratas las horas de trabajo e investigación. Especialmente a Ismael de Fez, cuya actitud y filosofía son ejemplos a seguir. También a Román Belda, por compartir su pragmática visión de la vida, y al Dr. Francisco Fraile, por sus buenos consejos, entre los que incluyo sus recomendaciones musicales.

También me gustaría dar las gracias a mis padres, Andrés y María José, por su incansable apoyo y el cariño incondicional que me han dado en todas las etapas de mi vida. Y sobre todo, a Ana, fuente de inspiración y admiración, por contagiarme sus ganas de aprender y mejorar cada día, y compartir conmigo una fuente inagotable de ilusión.

A todos ellos, un gritón de gracias.

Pau Arce

Noviembre, 2013

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The most powerful wireless communication
does not travel on electromagnetic waves
but in the voice of the people

A mis padres

Amb Ana

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Acronyms

4G	4th Generation
ACK	Acknowledgement
AODV	Ad hoc On-demand Distance Vector
AR	Application Report
ARQ	Automatic Repeat Request
BER	Bit Error Rate
CBR	Constant Bit Rate
CH	Cluster Head
CIA	Cluster ID Announcement
CIF	Common Intermediate Format
COLSR	Clustered OLSR
CRC	Communications Research Centre
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DCCP	Datagram Congestion Control Protocol
DSCP	Differentiated Services Code Point
DSR	Dynamic Source Routing
DSSS	Direct-Sequence Spread Spectrum
ERP-OFDM	Extended Rate PHY Orthogonal Frequency-Division Multiplexing
FPS	Frames Per Second
GoP	Group of Pictures
GPS	Global Positioning System
HAODV	Heterogeneous AODV
HDSR	Hierarchical DSR
HNA	Host and Network Association
HOLSR	Hierarchical Optimized Link State Protocol
HR-DSSS	High Rate Direct-Sequence Spread Spectrum
HTC	Hierarchical Topology Control
HTTP	Hypertext Transfer Protocol
HVS	Human Visual System
IEEE	International Electrical and Electronic Engineers
IETF	Internet Engineering Task Force
IP	Internet Protocol
IR	Interference Range

ITU	International Telecommunication Union
MAC	Media Access Control
MANET	Mobile Ad hoc Network
MID	Multiple Interface Declaration
MOS	Mean Opinion Score
MPR	Multi-Point Relay
MTU	Maximum Transfer Unit
NS2	Network Simulator 2
NS3	Network Simulator 3
NTP	Network Time Protocol
OLSR	Optimized Link State Protocol
PAN	Personal Area Network
PoB	Play-out Buffer
PDR	Packet Delivery Ratio
PER	Packet Error Rate
PRR	Packet Reception Rate
PSNR	Peak Noise to Signal Ratio
QCIF	Quarter Common Intermediate Format
QoE	Quality of Experience
QoS	Quality of Service
RSSI	Received Signal Strength Indicator
RTP	Real-time Transport Protocol
RTS/CTS	Request to Send/Clear to Send
SNR	Signal to Noise Ratio
SVC	Scalable Video Coding
TC	Topology Control
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
VANET	Vehicular Ad hoc Network
VoD	Video on Demand
WBA	Wireless Broadcast Advantage
WMN	Wireless Mesh Networks
WSN	Wireless Sensor Networks

Chapter 1

Introduction

This chapter is intended to give an introduction to the background and scope of this thesis dissertation by providing an overview of the main related topics and some basic concepts of wireless ad hoc networks. Furthermore, the objectives and the structure of this thesis are described, as well as the contributions made towards the novel mechanisms for improving video streaming quality of service in mobile ad hoc networks.

1.1. Background

Wireless technology has experienced an important growth in the past decade. The main advances can be found in network infrastructure, mobile devices and wireless applications development. Nowadays, a great interest is focused on mobile ad hoc networks (MANETs). Unlike infrastructure-based network, a MANET is formed by a group of independent nodes, interconnected through wireless links without using network infrastructure or centralized administration. The theoretical advantages that ad hoc networks bring are well known. Among these advantages, it is worth highlighting the easy configuration and the ability to establish a communication path between any nodes of the network without using a central element. In many situations such as catastrophes or emergencies in which there are no infrastructures or they cannot be installed because of geographical or temporal reasons, this kind of network may be the ideal solution. Moreover, an ad hoc network can work in isolated mode or being connected to a larger network infrastructure like the Internet. In this sense, new scenarios can be conceived as applications of MANETs, such as extending Internet

coverage in rural areas or the popular concept of Smart Cities. They are also an essential element in the new 4G (4th Generation) networks.

Such network scenarios involve a set of independent wireless nodes that can communicate and move at the same time. Since no fixed infrastructure is required to allow such communications, nodes must cooperate in the task of routing packets to destination nodes. In order to communicate with nodes that are out of their transmission range, wireless nodes need to use intermediate nodes as routers. For this reason, MANETs are defined as multi-hop wireless networks. In this sense, routing protocols play an important role because they are in charge of discovering and maintaining routes for packets from the source node to the destination. In fact, routing in mobile environments is challenging due to the possible changes in network topology and the constraints existing on the resources (processing capacity, transmission bandwidth, battery power, etc.).

Moreover, applications and services are more and more bandwidth and resource demanding. For instance, video services are one of the most demanded (and demanding) services nowadays, whose bandwidth and delay requirements are very restrictive. Offering real-time video services in wireless ad hoc networks is not an easy task because of the difficulty of guaranteeing certain quality in a shared medium. Besides this fact, because of the dynamic topology of MANETs, routing protocols are more complex than traditional routing protocols used on the Internet. In any case, the main objective of these routing protocols is to achieve efficient routes between the nodes so that the information will be available in destination nodes reliably and within boundary time. A good performance of these protocols should have low overhead and bandwidth consumption, and a fast route convergence, even when there are changes in traffic load or the number of nodes (i.e. scalability). Likewise, a good design of these routing protocols should introduce new mechanisms and measurements with the aim of reducing packet jitter and maximizing connectivity and route recovery. Most of the proposed routing protocols consider ad hoc networks as homogeneous networks (flat protocols), which means that all nodes have the same capabilities. In contrast with flat routing protocols, hierarchical protocols consider that nodes with different capacities (bandwidth, transmission range, etc.) could exist in the same network. Therefore, every kind of node could perform different tasks (router and client, only router, only client) depending on its capabilities. Emerging Wireless Mesh Networks (WMNs) are a good example. WMNs are multi-hop ad hoc networks consisting of a mesh backbone and mesh client nodes. Additionally, WMNs have a hierarchical topology, i.e. a clustered structure and static backbone, which all help to improve the network stability. As in WMNs, hierarchical routing protocols could transform an ad hoc network in a more robust wireless network.

Besides routing protocols, video transmission can be improved by means of cross-layer techniques that take into account node mobility and coverage. Moreover, the broadcast nature of wireless transmissions could be exploited to take advantage from spatial diversity in order to route or retransmit packets according to the propagation conditions

and increase wireless throughput. Furthermore, for the proper operation of ad hoc networks, every node must act as router altruistically. Following this philosophy, router nodes could be aware of traffic going through them, or even packets simply heard because of the shared medium, and prioritize video flows, besides other techniques such as caching or automatic repeat request (ARQ).

Practical solutions should try to improve communications at (and gathering information from) several layers of the protocol stack. In such a cross-layer design, information about routing or network state should be useful for video applications to adapt video bitrates or even request recent lost packets. This kind of technique could be very versatile to deal with congestion situations or when node mobility causes important video degradation. However, packet loss occurs in both situations of traffic congestion and node mobility, but many solutions for the former are unlikely to be suitable for the latter, and vice versa. The way nodes realize of this kind of undesired situation is still an interesting research topic.

Therefore, despite the difficulty of providing hard Quality of Service (QoS) for real-time applications over MANETs, there are still many ways to improve video streaming quality, concerning routing, transport and application layers.

1.2. Mobile wireless ad hoc networks

Ad hoc networks may be formed by almost any kind of wireless device, as long as nodes maintain compatible radio interfaces (802.11 Wi-Fi, 802.15 Bluetooth, 802.15.4 ZigBee, 802.16 WiMAX, etc.). Since these nodes are wireless devices and may be using battery power, they are completely autonomous. Therefore, they might move anywhere while still communicating each other. Both node mobility and heterogeneity are common characteristics of MANETs. In this kind of network, every node must be able to forward and route packets that belong to other transmissions. This decentralized routing is the key for the proper operation of the network. Figure 1.1 depicts the usual appearance of an ad hoc network.
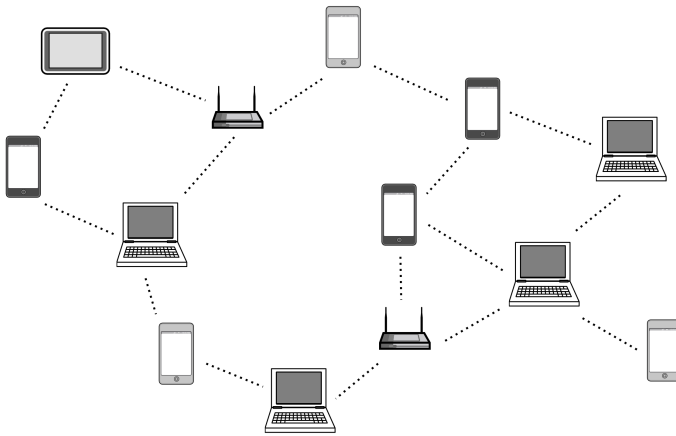
Figure 1.1 Example of mobile wireless ad hoc network

Despite the possible drawbacks derived from mobility and heterogeneity, the capacity of self-organization and self-configuration, besides other common features, confers this kind of network a great advantage in a number of situations and applications.

1.2.1. Main features

Wireless ad hoc networks share certain common features that make them different from regular wired networks. These structural differences might become a drawback to provide some kinds of services in a number of cases, but in other situations, this can confer a significant advantage on the creation and management of the whole network. These idiosyncratic features can be summarized as follows:

- **Dynamic network topology**

The network topology in a wireless ad hoc network is highly dynamic due to the mobility of nodes. Since nodes may move in and out of coverage of each other, topology may change rapidly and unpredictably, and connectivity among devices may vary with time. In addition to the mobility patterns of the mobile nodes, the network should adapt to the traffic and propagation conditions, which all difficult network management and establishment of packet routes. On the bright side, mobile nodes are able to form their own autonomous network on the fly, which entails a very powerful tool in many situations.

- **Resource-limited terminals**

Usually, MANET nodes are mobile devices such as smartphones and laptops, which often have low or moderate memory size, battery storage and CPU processing capabilities. Because of the size and cost constraints, most of the mobile devices are equipped with limited storage and low-performance processors. Although new cutting-edge mobile devices are emerging nowadays more powerful and efficient, battery

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limitations still prevent these devices from reaching their full potential. As new communicating and computing functions become more and more complex and computational expensive, power consumption also increases consequently. In this sense, transmission capabilities, such as bandwidth and coverage, are also reduced due to these limitations of mobile devices.

- **Transient connectivity and link capacity**

Wireless physical medium is shared among nodes and, unlike wired networks, every device within range can access the transmission channel. This fact may lead to high bit-error rates and may cause the channel over which terminals communicate to be subject to noise, fading and interference. Additionally, any node may not be reachable at some time, which could entail route breakages, since the path between any pair of users can traverse multiple wireless links. Taking also into account that wireless links might be heterogeneous and asymmetric, link capacity and connectivity can never be guaranteed.

- **Distributed operation**

One of the most distinctive features of MANETs is the lack of a central control of network operation, which provides this kind of network with the ability of being established everywhere and every time. Hence, nodes involved in a MANET should collaborate towards the common goal of management and connectivity, that is, each terminal may have to act as a relay as needed and to implement essential functions such as routing and security tasks. Each node, therefore, is an autonomous and independent terminal, which may function as both a host and a router, carrying out the basic processing tasks of hosts and endpoints and, at the same time, being able of performing routing and switching functions as routers.

- **Multi-hop routing**

Since delivering data packets from source to destination may involve multiple hops, packets should be forwarded via one or more intermediate nodes. This fact introduces the problem of discovering the proper route for a packet to reach the destination node. Thus, routing protocols come into play as mechanisms that allow nodes to draw a path to destination, or to the next hop at least.

To sum up, the principle behind ad hoc networking is multi-hop relaying, i.e. if the destination node is not directly reachable by the sender, packets are transmitted through the other nodes. Precisely, the absence of any central coordinator makes it difficult to manage this kind of network. Due to the lack of fixed infrastructure and limited resources, it is complex to develop protocols and algorithms that allow wireless services to be deployed with certain QoS. Nevertheless, despite these drawbacks, there are many practical applications of MANETs that have been implemented nowadays.

1.2.2. Applications

The importance of ad hoc networking is growing due to the increase of the number of mobile devices as well as the advances in wireless communications. Ad hoc networks

can be used in many situations, as demonstrates the increasing amount of applications, especially in those cases when deploying network infrastructure would be expensive or inconvenient. Ad hoc networking also allows mobile nodes to maintain connectivity to a fixed network by means of gateways, i.e. special nodes connected to both wired and wireless networks. In this sense, there are a significant number of practical applications, which range from large and highly dynamic networks to small and static networks, including mobile and power constrained networks.

In this regard, typical applications and some of the most illustrative use cases nowadays are described below:

- **Emergencies**

Ad hoc networks have traditionally been used in emergency situations after disasters or catastrophes, such as flood, earthquake or fire. This kind of network is particularly useful in such situations because communication infrastructures are often damaged and rapid deployment of a backup communication network is needed for rescue teams and security forces.

- **Military communications**

Modern military scenarios involve mobile vehicles, tanks, trucks and soldiers that should be continuously liaising with a wireless base station or directly connecting other communication devices within the radio range. By using multi-hop routing, soldiers can communicate with remote soldiers or teams via data forwarding from one radio device to another. However, due to the unpredictability of battlefields, nodes might be isolated or even destroyed, which makes network flexibility and dynamism necessary in this kind of military network.

- **Wireless Sensor Networks (WSNs)**

A wireless sensor network is a special ad hoc network usually deployed with the aim of monitoring physical or environmental conditions. The main difference between wireless sensor networks and common ad hoc networks is the fact that WSNs are designed with particular constraints, such as the node size, cost and power consumption, which all have to be low. Furthermore, WSNs are frequently deployed in unreliable environments and have to be ready for a massive and random deployment, which entails a high level of scalability.

- **Vehicular Ad hoc Networks (VANETs)**

A particular case of ad hoc networks can be applied when the nodes that form the wireless network are vehicles. Cars, trucks, motorbikes, etc. tend to move in an organized fashion, being constraint to follow paved roads. A vehicular ad hoc network allows vehicles to communicate and participate in the routing of other communications. Moreover, the interactions can be extended to the roadside equipment, obtaining information about road conditions, traffic congestion or accident warnings, and at the

same time, updating traffic lights in real time in order to optimize traffic flow in case of congestion.

- **Personal Area Networks (PANs)**

Wireless personal area networks are formed by multiple wireless devices centered on an individual's workspace. These ad hoc networks can be used to create autonomous home networks by means of interconnecting several devices with specific purposes, such as storage devices, connected televisions, printers, cameras, etc. Additionally, those devices may be connected to a wider network leading to a great concept: the Internet of Things. The notion of pervasive computing is also related to this kind of network, because they allow people and machines to closely and ubiquitously interact with other devices in their surroundings.

- **Body Area Networks (BANs)**

Body area networks are a special kind of sensor network applied to the body context and within a limited range. BANs are usually formed by wireless medical devices that provide continuous real-time health monitoring and can be used in a wide rage of applications, such as disease prevention, rehabilitation or simply for fitness purposes. This wereable technology is gaining ground due to the seamless integration between devices and clothes that is being achieved nowadays.

- **Smart Cities**

The intelligent management of the available resources in a city depends on the proper communication infrastructure. Therefore, following this philosophy based on efficiency, Smart Cities may require wireless ad hoc networks in order to connect every smart device and facilitate the cooperation between users. Environmental sensors and urban furniture actuators can provide cities with new services and applications, such as smart traffic lighting, traffic congestion control and smart signal roads.

1.3. Routing protocols for wireless ad hoc networks

Since wireless ad hoc networks consist of a set of mobile nodes that are connected by wireless links, it can be stated that this kind of network is designed for point-to-point connections. Hence, wireless nodes communicate directly with devices inside their radio range in a peer-to-peer nature. However, as aforementioned, if they wish to communicate with another device outside their range, intermediate nodes within their coverage area have to be used in order to forward packets to destination. In order to find a path from source to destination, traditional routing protocols cannot be directly applied in MANETs. The reason is simple: node mobility and link instability prevent routing protocols to find steady routes for long periods of time. Therefore, some requirements and considerations have to be taken into account when designing and deploying routing protocol for MANETS [1], which are discussed next.

1.3.1. Design of routing protocols

Given that this kind of network lacks a centralized management, routing protocols must be entirely distributed and route maintenance should involve the minimum possible number of nodes in order to minimize the overall computational cost and packet collision. In MANETs, moreover, topological changes are very frequent compared to those of wired networks, which force routing protocols to continuously adapt packet routes by sending and receiving routing information. In most cases, this path discovering and maintenance is calculated by means of a distributed algorithm running at network level. Besides the required fast reaction before topology changes, routing protocols should be able to mitigate the possible adverse effects caused by control packet losses, which might cause packets to be routed through a non-optimal path or even dropped due to a temporary inconsistency in routing tables.

In addition, despite the fact that routing protocols should use the limited resources carefully, e.g. bandwidth and battery power, they are expected to provide a certain level of QoS in order to be useful for the network operation. Some suitable metrics that are used to calculate route costs need to be defined attending to these limitations, i.e. the shortest path may not be the best. For example, the shortest path could have shorter lifetime or higher delay than others, which is not desirable in many situations. In this sense, the remaining battery lifetime of nodes can be taken into account when building the path, prioritizing nodes with higher remaining energy. Furthermore, routing protocols should be aware of the fact that links may be unidirectional and, consequently, a transmission that involves both request and response might fail, while broadcast transmissions may succeed. Finally, another concern in wireless networks is security. Since no centralized management is in charge of authentication, malicious nodes might use false information in order to corrupt the routing tables of neighbor devices.

1.3.2. Classification

In regard to how ad hoc routing protocols deal with these issues, they can be classified according to different criteria. First of all, the most common classification is based on the routing information update mechanism. Hence, routing protocols can be driven either by a routing table (proactive) or on demand (reactive). The main characteristic of proactive protocols is that each node in the network steadily keeps and updates a route to every other node in the network all the time, so that routes are always available when they are needed. As a consequence, there is a constant overhead due to routing traffic but there is no initial delay in data communications. Some examples of proactive routing protocols are Optimized Link State Routing (OLSR) [2], and Destination-Sequenced Distance Vector (DSDV) [3]. On the other hand, reactive protocols trigger the route discovering process only when nodes start a new transmission or a broken link is detected. This kind of routing protocol does not need extra control packets for maintenance, although high latency time can be generated when establishing the new route. The most significant examples of reactive routing protocols are Dynamic Source

Routing (DSR) [4], Ad hoc On-demand Distance Vector (AODV) [5], and its successor, Dynamic MANET On-demand (DYMO), which is still under standardization process (draft) as AODVv2 [6]. Additionally, there are hybrid proposals that combine the advantages of proactive and reactive mechanisms, such as the Zone Routing Protocol (ZRP) [7], and Zone-Based Hierarchical Link State (ZHLS) [8].

The aforementioned routing protocols make use of information about past and current status of the links to find the proper routes. However, since the topology of MANETs is highly unpredictable, there is another type of routing protocol that uses information about the expected future status of the wireless links in order to anticipate any topology change. Some routing protocols that fall into this category are Load Balancing Routing (LBAR) [9] and Route-lifetime Assessment Based Routing (RABR) [10], which try to predict the forthcoming state of the network to create more stable routes.

On the other hand, routing protocols can be also classified depending on the way nodes are organized throughout the network. Wireless networks formed by homogeneous nodes, i.e. devices with similar capabilities, are usually networks with flat topology. Hence, when the network size increases, route recovery time considerably increases as well as the control traffic overhead. This fact might lead to some scalability issues. However, in case networks contain heterogeneous nodes with different capabilities (bandwidth, transmission range, etc.) or the amount of nodes is extensive, hierarchical routing protocols may result appropriate to provide network scalability, such in Hierarchical State Routing (HSR) [11], Fisheye State Routing (FSR) [12], and Cluster-head Gateway Switch Routing (CGSR) [13].

Finally, routing protocols can be classified taking into account which metrics and specific resources they utilize in order to calculate the best routes. For example, hop count may not be the better choice if wireless links are prone to transmission errors, and link quality measurements, such as bandwidth and delay, could be used instead, like in [14]. Another sort of protocols prioritize energy consumption and remaining battery life in order to take routing decisions. Some examples of power-aware routing protocols are Power Aware Routing (PAR) [15] and Power-aware Source Routing (PSR) [16]. Furthermore, some proposals aim at improving the performance of routing by means of using geographical information. This way, the fact of using node location information to calculate packet routes helps in lowering routing overhead, like in Location-Aided Routing (LAR) [17].

Unfortunately, these routing protocols are designed to calculate routes that can only be used for unicast transmissions. Multicast communication needs a spanning tree to be dynamically build based on the current topology of the wireless network, which can change at any time due to the node mobility. In case any application or service needs multicast transmissions, the underlying routing protocol should be able to provide multicast routing and forwarding, like in Distance Vector Multicast Routing Protocol (DVMRP) [18] and On-Demand Multicast Routing Protocol (ODMRP) [19].

Moreover, another paradigm of routing can be used in wireless ad hoc networks, namely opportunistic routing [20], which is a routing technique that builds the routes dynamically, profiting from the broadcast nature of wireless communication and enabling promiscuous mode at nodes. This way, any node can overhear packets within their coverage area even though these packets are not addressed to them. In this context, packet forwarding is carried out by the node closest to the destination. This routing scheme results in the reduction in the amount of hops and provides dynamic backup routes as well. However, candidate selection and coordination functions are essential for the proper development of opportunistic routing protocols and differ from one algorithm to another, as in SOAR [21] or MIXIT [22].

Despite the great number of routing proposals, bandwidth-demanding and delay-constrained services such as video streaming cannot be provided with high QoS guarantees over mobile wireless ad hoc networks as long as specific mechanisms that consider this sensitive traffic are involved.

1.4. Problem definition and objectives

Traditionally, wireless ad hoc networks have been used in emergency situations and for military battlefield communications due the ability of this kind of network to be rapidly deployed without the need of any supporting infrastructure, considering that a fixed backbone could be unfeasible or even destroyed. Hence, basic connectivity and routing had been enough to support communications so far, but nowadays, the sort of service that is actually being deployed over wireless networks demands higher bandwidth and quality requirements. Compared to the transmission of non-real time data, streaming of video across wireless networks introduces many new challenges [23]. Basically, multimedia services must be deployed while providing an acceptable Quality of Experience (QoE) to the users, i.e. the perceptional quality experienced by the user has to be satisfactory and sustainable throughout the session. This can only be achieved by guaranteeing the sufficient bandwidth and maintaining packet delay and jitter below an upper bound. These requirements are more restrictive in the particular case of live or interactive streaming, which causes the task of providing and maintaining video quality to be yet more challenging.

When supplying multimedia services over MANETs, the limitations of the wireless medium become notably more restrictive. Due to the shared nature of the wireless medium, signal reception is exposed to adverse effects such as background noise, multipath fading and interference, which all cause high time variability and frequent link interruptions. Moreover, node mobility inevitably provokes network topology to change over time continuously, causing time-consuming route updates that can lead to packet burst losses for short periods of time, which degrade video quality noticeably [24].

Therefore, additional mechanisms and techniques have to be implemented to solve packet collision and mobility issues, which clearly limit the potential of MANETs when providing real-time bandwidth-consuming services.

In this context, the main objective of this thesis work is to:

> **Improve Quality of Service and Quality of Experience in video streaming services over mobile wireless ad hoc networks by means of new routing protocol improvements, which increase network scalability and route stability, including novel cross-layer techniques, which combine network, transport and application information to prevent video degradation.**

In order to achieve the main objective, the specific objectives or milestones considered are to:

O1. Analyze and evaluate the main causes of video quality degradation in video streaming services over mobile wireless ad hoc networks, attending to quantitative (QoS) and qualitative (QoE) parameters. Wireless ad hoc networks will be evaluated attending to wireless transmission capacity, channel interference, packet losses and mobility of nodes. Different kinds of scenario layouts and conditions will be assessed and detailed results will be obtained from both simulations and real testbeds.

O2. Propose and evaluate a scalable routing technique based on hierarchical routing, which improves the reliability of packet transmission and the maintenance of routes. This hierarchical routing protocol will be based on the well-known proactive protocol OLSR, which is commonly used in wireless ad hoc networks. Resulting hierarchical protocol will be evaluated as regards performance parameters and will be implemented on physical devices for testing purposes. Moreover, after analyzing the advantages and drawbacks of this approach, an additional load-balancing mechanism is proposed in order to improve the overall network performance and scalability.

O3. Propose and assess a cross-layer solution to directly improve transmission throughput despite node mobility and route breakages, which are two of the main reasons for packet losses in mobile wireless ad hoc networks. This will be carried out by designing a new routing improvement based on an opportunistic mechanism used to improve the reliability on video transmission exploiting the broadcast diversity and taking into account the time constraints of video flows. This algorithm consists of a cross-layer technique that uses routing information (e.g. neighbors, routes, link states) to cache and retransmit video packets to the destination within the maximum time the play-out buffer permits.

1.5. Structure of the document and contributions

This thesis work provides different contributions to the study of mobile wireless ad hoc networks' behavior regarding video quality assessment and routing improvements. Hence, the thesis is divided into the following chapters:

- Chapter 1 covers some basic concepts of ad hoc networks, giving background information about their applications and functionality. This chapter also briefly describes the main issues that can be encountered when providing video streaming services over MANETs, which motivated this work and laid the basis for establishing the objectives.

- Chapter 2 analyzes the main limitations that cause video quality degradation of video streaming services over mobile ad hoc networks. In this chapter, diverse scenarios are assessed in order to obtain concluding results that help in the design of specific algorithms and mechanisms for video quality improvement, which are covered in the next chapters. Regarding the video degradation assessment, this chapter evaluates, on the one hand, how the interference among nodes affects packet transmission and, on the other hand, the quality deterioration that video sessions suffer due to node mobility, which causes link breakages and route recalculations. Finally, some of the related approaches proposed in the literature are described and discussed. Chapter 2 is aligned with objective **O1**.

- Chapter 3 proposes Hierarchical OLSR (HOLSR), which is a hierarchical routing approach that aims at improving the scalability of large-scale wireless ad hoc networks without requiring too much additional complexity. In this chapter, HOLSR is evaluated as regards routing specific parameters, such as convergence time and overhead. Moreover, video quality is assessed in scenarios that experiment the mobility of nodes, comparing both hierarchical and flat protocol responses to delay-sensitive transmissions. Furthermore, after discussing some of the downsides of the hierarchical routing scheme, an additional proposal is described, which aims at improving the video quality by means of load balancing techniques and distributed access control mechanisms. Chapter 3 is aligned with objective **O2**.

- Chapter 4 presents Altruistic OLSR (ALTOLSR), a novel cross-layer proposal based on packet caching and retransmission, which improves video quality by means of recovering lost packets in the last hop. After describing ALTOLSR in detail, it is assessed and compared to other similar solutions. Besides video quality improvement, overhead and energy consumption are also considered in the evaluation. Chapter 4 is aligned with objective **O3**.

Furthermore, this thesis has led to the publication of scientific journal papers, conference presentations and book chapters. A detailed list of publications derived from this work is presented in Appendix A.

Chapter 2

Video Streaming Services over MANETs: Challenges and Prospects

Video services are much demanded nowadays but bandwidth and delay requirements of this kind of service are very restrictive. Offering real-time video services in wireless ad hoc networks is not an easy task because of the difficulty of guaranteeing certain quality in a shared medium. The influence of ad hoc routing and wireless capacity suggests that any evaluation of ad hoc networks requires an understanding of network capacity and node mobility. This chapter discusses about the main problems and limitations that can come across when video streaming services are going to be deployed over a wireless ad hoc network. Different scenarios and conditions are assessed to obtain results from both simulations and real testbeds. Finally, some of the most relevant and representative solutions in the literature are presented and classified.

2.1. Capacity of wireless ad hoc networks

The shared nature of the wireless channel in ad hoc networks may cause packet collisions within the carrier-sensing distance of the transmission node. Such situations can be avoided with proper mechanisms to access the wireless medium. The medium access control algorithm used in IEEE 802.11 (i.e. CSMA/CA) presents several basic mechanisms in order to avoid packet collisions, such as random back-off time or the RTS/CTS handshake mechanism. This kind of collision avoidance medium access entails some limitations in wireless ad hoc networks and, particularly, one of these limitations is the achievable transmission capacity. Specifically, the RTS/CTS

mechanism does avoid collisions that would decrease throughput due to retries, but on the other hand, this additional process adds a significant amount of protocol overhead that also results in a decrease in network throughput. All in all, the maximum bandwidth is reduced due to the fact that nodes cannot simultaneously access the shared medium. That is, when a node is transmitting a packet, neighbor nodes within its Interference Range (IR) must not transmit. As a result, an overall degradation in data rate is produced. This effect has been already studied in [25] and the channel capacity to be expected in an ad hoc network has been estimated according to analytical models. As a simplification of this study it can be stated that the theoretical per node capacity λ according to the number of competing nodes n is:

$$\lambda(n) = \Theta\left(\frac{1}{\sqrt{n}}\right) \tag{1}$$

Actually, nodes that are sufficiently distant can transmit concurrently because they do not interfere each other. However, when the network density grows (i.e. higher number of nodes per unit area), the packet collision probability also increases and the overall transmission capacity is altered as well. In order to illustrate this fact, Figure 2.1 shows the average throughput achieved per node as a function of the number of competing nodes in a simulated scenario where all nodes are within each others' radio ranges and are therefore causing interferences one another. The same scenario has been simulated using different transmission channel capacities in order to compare the behavior among 802.11b DSSS at 2Mbps, 802.11b HR-DSSS at 11Mbps and 802.11g ERP-OFDM at 54Mbps. Average results are presented with a 95% level of confidence. Analytical throughput expected is also depicted, which has been calculated from (1) by approximating coefficients for each mode.

a) 802.11b@2Mbps

b) 802.11b@11Mbps
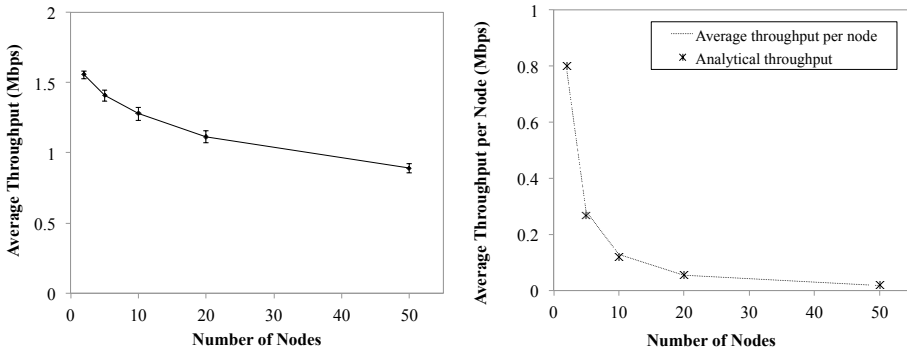
c) 802.11g@54Mbps
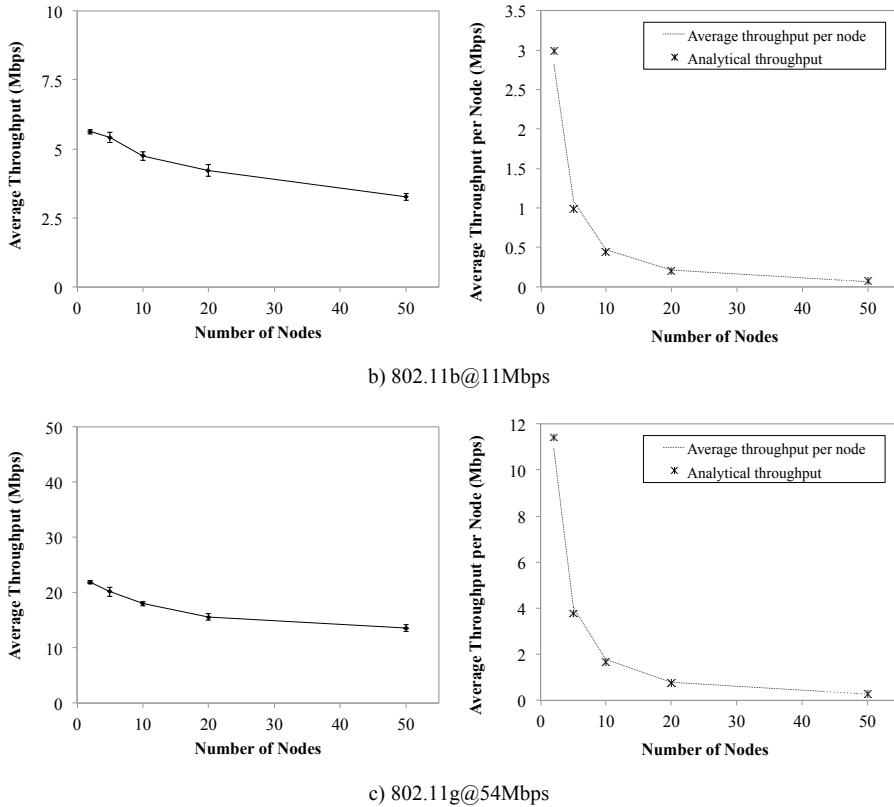
Figure 2.1 Average network throughput and average throughput per node depending on the number of competing nodes

Each node sends 1500-byte UDP packets to a random destination as fast as each 802.11 protocol allows. Although it is not a case of study in this thesis, it is worth noting that 802.11 MAC behavior is very dependent on the packet size given a certain BER, but in turn, the optimal packet length does not change with the number of competing nodes [26]. As shown, the 2-node scenario presents the highest capacity, since it has the minimum contention. However, as the number of competing nodes grows, the total amount of received data decreases. Not only throughput is divided among all the competing nodes but also the total amount of available capacity is also reduced as a result of the medium contention (e.g. from 1.54 Mbps for 2 nodes to 0.90 Mbps for 50 nodes at 2 Mbps).

Moreover, by comparing relative values from the figures above, it can be noted that there are significant differences in packet reception rate achieved for the different channel capacities mainly due to the radio link and the particularities of the different modulation schemes. For instance, in 802.11b@2Mbps when only two nodes are trying to access the channel, the maximum throughput per node is 0.77 Mbps, resulting a total

of 1.54 Mbps of effective network capacity, rather than the maximum capacity (2 Mbps), which is only the physical layer data rate. Indeed, effective throughput will never be as much as this upper limit due to several factors, such as the overhead of headers, ACK packets, additional inter-frame timings and, if it would be the case, RTS/CTS packets. Even in the best case, throughput would never overtake the Theoretical Maximum Throughput (TMT) [27]. Hence, this throughput represents the 77% compared with the standard maximum capacity (2 Mbps). In 802.11b@11Mbps and 802.11g@54Mbps, the throughput achieved when only two nodes are transmitting is 5.62 Mbps and 21.64 Mbps respectively, which comprises the 51% and the 40% in each case.

These results are not unexpected at all, but they have to be taken into account when analyzing wireless networks and specially when assessing services that consume an important amount of bandwidth, such video streaming services. Medium contention and transmission interferences do worsen the average network throughput when several data sources are competing for the medium access, but this contention exists even when only a single transmission is carried out through the network (or it is locally isolated in the network).

In multi-hop ad hoc networks, when a transmission is established, the nodes must cooperate to forward the packets through the network, which means that the available throughput on each host is limited not only by the access channel, but also by the forwarding load. As hop count increases, the maximum throughput of one flow decreases substantially and falls down because of the overhead of MAC layer and the mutual interference between packets of the same flow. This effect is called Intra-flow Contention [28] and represents the contention between packets from the same flow being forwarded at different hops along a multi-hop path, causing the actual bandwidth consumption. Figure 2.2 depicts this issue in a chain of nodes. Note that carrier-sensing range is usually higher than transmission range, so it may interfere with further nodes.
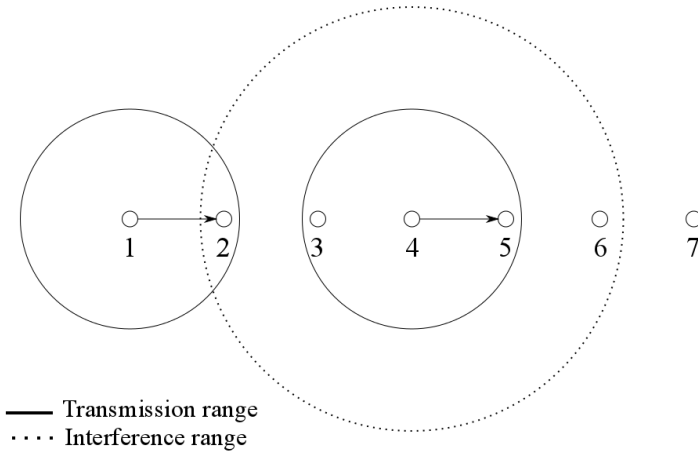
Figure 2.2 Intra-flow contention and MAC interference in a chain of nodes

In this example, transmission from node 4 to node 5 will interfere in other transmissions along the node chain. On the one hand, it will prevent any other transmission originated at nodes 2 to 6, and on the other hand, and more concerning, it might corrupt data transmission from node 1 to 2, since it interferes in the reception at node 2.

Usually, multiple-hop flows have to contend for the medium at each hop on its way to the destination node. Consequently, flows that extend over more hops will spend more time on competing with more nodes in the network. Then, packets forwarded on a longer path are more likely to be dropped than those on a shorter path. In order to show the effect of the path length caused by the intra-flow contention, a chain scenario with different chain lengths has been analyzed.

Simulated scenarios are comprised of stationary nodes located a certain distance away one another enough to have only next hop in range. This distance is intended to result in the maximum capacity possible, since with higher node density or more nodes in range, the capacity must be divided up among other nodes. Again, several 802.11 standards have been used in the evaluation, and in this case, transmission range is an important factor when designing the chain of nodes. In fact, the effective transmission range changes depending on the standard. To figure out which distance is appropriate to carry out the simulation for each standard, Packet Reception Rate (PRR) is depicted in Figure 2.3 attending to the distance between two nodes depending on the mode of the 802.11 standard used.

a) 802.11b@2Mbps

b) 802.11b@11Mbps

c) 802.11g@54Mbps
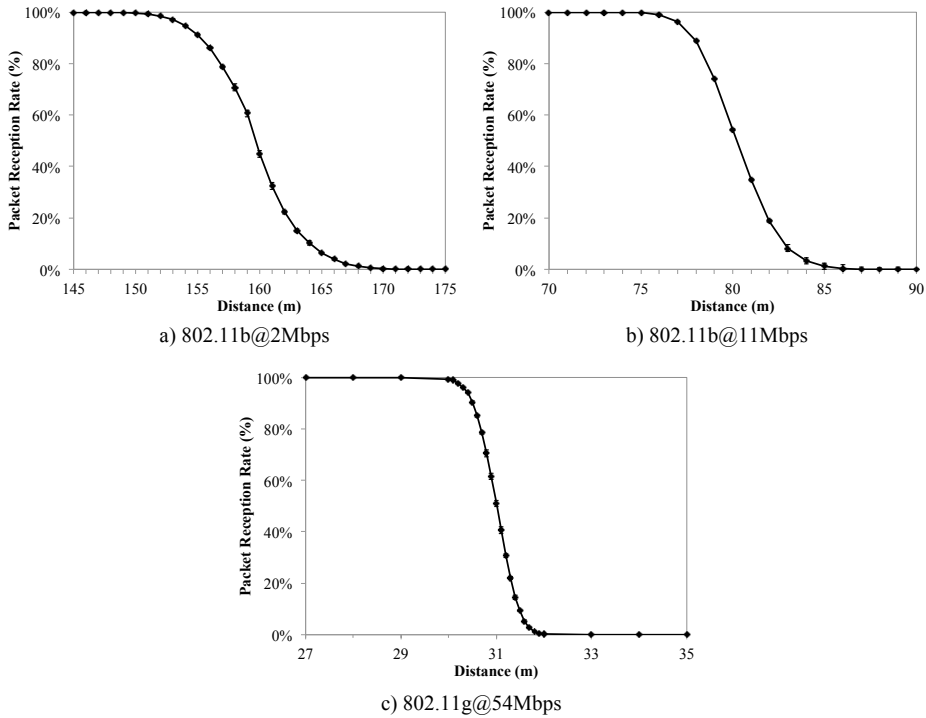
Figure 2.3 Packet Reception Rate according to distance

As observed, maximum transmission range varies from one transmission mode to another. Therefore, in order to maintain only one neighbor in range to forward packets, the distance between two adjacent nodes has been adjusted for each transmission mode in the simulation consequently (130 m in 802.11b@2Mbps, 70 m in 802.11b@11Mbps, and 25 m in 802.11g@54Mbps).

Once the chain scenario is designed, simulations can be carried out in order to assess the aforementioned decrease of throughput along a chain of nodes. Figure 2.4 depicts this decrease of the overall throughput depending on the total amount of nodes that are taking part in the path to destination.
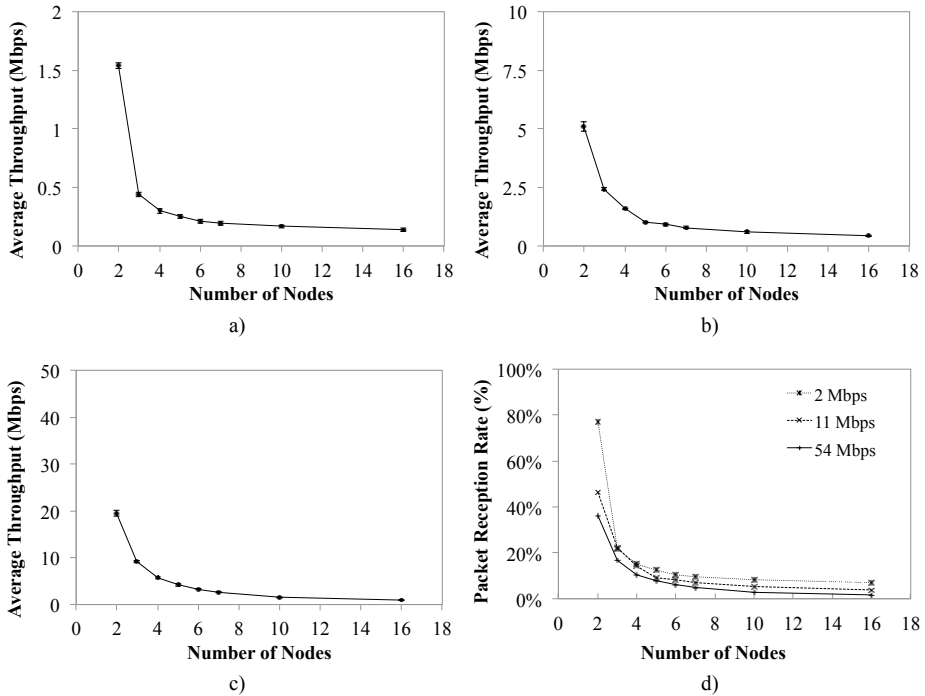
Figure 2.4 Average throughput vs. length of chain in wireless multi-hop networks for 802.11b@2Mbps (a), 802.11b@11Mbps (b), and 802.11g@54Mbps (c); Packet Reception Rate comparison between 802.11 modes (d)

Note that although there is only a single transmission, as the chain length grows the maximum throughput achieved at the receiving node decreases, as stated before, due to the contention of the packets of the same flow trying to access the shared medium.

These simulations have been carried out using a single transmitter in the chain head transmitting at the maximum channel rate. The fact of transmitting at this maximum channel rate may cause a situation of maximum intra-flow contention and, therefore, it could not be the optimal transmission rate. In order to evaluate the channel response for different transmission rates, a scenario consisting of a chain of 7 nodes has been simulated varying the source data rate. Figure 2.5 shows the network response while increasing the offered load.
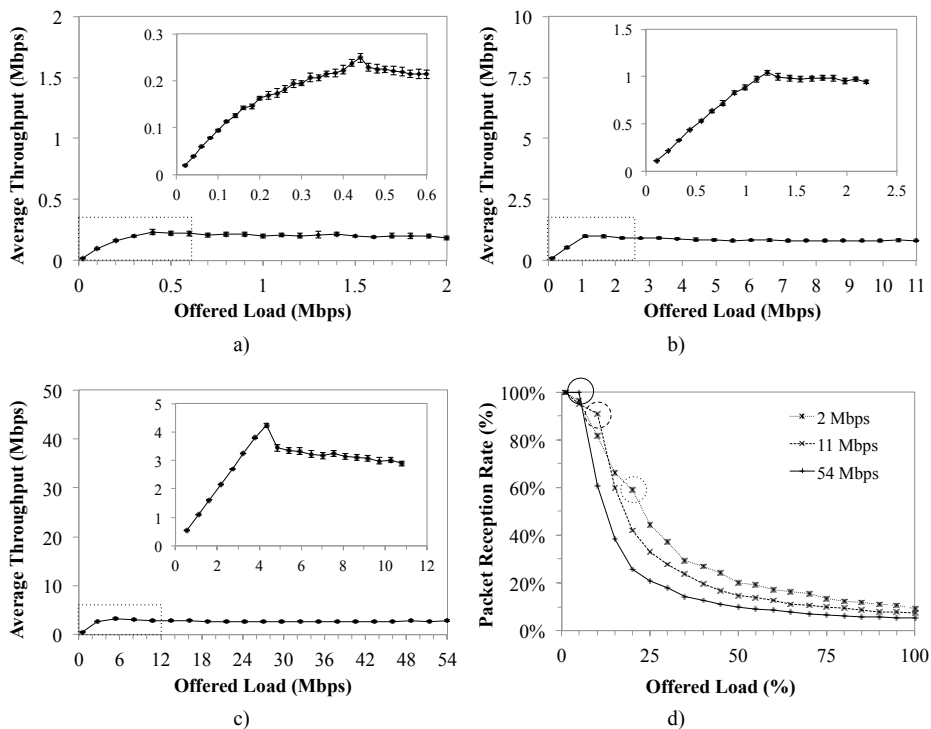
Figure 2.5 Average throughput vs. offered load in a 7-node chain network for
802.11b@2Mbps (a), 802.11b@11Mbps (b), and 802.11g@54Mbps (c); Packet Reception
Rate comparison between 802.11 modes (d)

Channel response is practically linear until a certain value. There is a maximum
throughput at this data rate value (0.44 Mbps in 802.11b@2Mbps, 1.21 Mbps in
802.11b@11Mbps, and 4.32 Mbps in 802.11g@54Mbps) and then, from this offered
load on, throughput decreases and is maintained steady, no matter how much the
offered load is augmented. Differences between 802.11 modes can be seen in Figure
2.5d and the point of maximum throughput is surrounded. In 802.11@54Mbps, the
throughput corresponds linearly to the data rate used until the drop. Percentage-wise,
the other modes reach their maximum throughput value with more offered load but the
fall is not so abrupt. Nevertheless, it can be observed that the offered load is not always
achieved even before the upper bound rate. Specifically, PRR value is 100% when
offered load is 5% in 802.11g@54Mbps, 91% for 10% of offered load in
802.11b@11Mbps, and 59% for 20% of offered load in 802.11b@2Mbps. This has to
be seen as an upper bound rate characteristic of wireless ad hoc networks, which are not
able to transmit at a higher rate due to physical limitations.

Although node interference and intra-flow contention are constraining factors that affect
the maximum throughput achieved in transmissions, there are still other issues that may

cause additional packet losses and may also difficult good quality transmissions in such distributed networks, such as, for instance, mobility of nodes.

2.2. Mobility of nodes

Ad hoc networks have the ability of self-organization and self-configuration but the topology of these networks is usually highly dynamic. Due to mobility and the multi-hop nature of ad hoc networks, any node can move out of the coverage area for a short time, losing the packet route to destination and even causing route breakages to other communications. Therefore, the nodes ability to move freely can become a problem because of these induced link breakages and the necessity to discover new routes towards destination for data transmission. These facts cause packet losses and delay while new routes are being configured, with the consequent loss of quality at the receiver.

In order to illustrate the catastrophic effect of mobility, some simulations have been carried out in scenarios that vary from low to high mobility. These scenarios consist of 50 nodes arbitrarily spread on a 1200 m x 600 m layout. Incidentally, this layout will be appropriately useful in Chapter 3 when clustered networks will be assessed. The mobility model used is the Random Waypoint Model (RWM). In RWM, each node chooses a destination point inside the assigned layout boundary. Nodes move then at a certain speed, selected between a minimum and a maximum value, and when they reach their destination, they wait for a certain pause time and finally the process is repeated again. It is worth saying that RWM has to be used with some considerations in order to obtain reliable results [29]. For instance, besides maximum speed, nodes must have a minimum speed other than zero. Moreover, results from the initial seconds of simulation have to be discarded because RWM needs some time to get past the warm-up period. Accordingly, NS3 is aware of these considerations and offers a steady version of RWM.

Therefore, the effects of mobility on throughput have been evaluated in NS3 by means of varying both speed and pause time of nodes. On the one hand, node speeds from 5 to 20 m/s have been used with a pause time of 0 s (nodes always moving). This will show the network behavior depending on the speed of nodes. On the other hand, pause times between 0 and 200 s have been used together with a node speed of 5 m/s. In both cases, 802.11b@11Mbps has been used and the flow data rate has been set to 100 kbps of Constant Bit Rate (CBR) traffic. Simulation duration has been set to 200 seconds so it is likely that with pause time of 200 s, most of nodes might change their position just once during the whole simulation. It is unlikely, but possible, that the destination node ends isolated from network, being impossible to find a route to it and consequently causing packet losses during almost the whole simulation. Average results are shown in Figure 2.6.

a) Pause Time   b) Node Speed
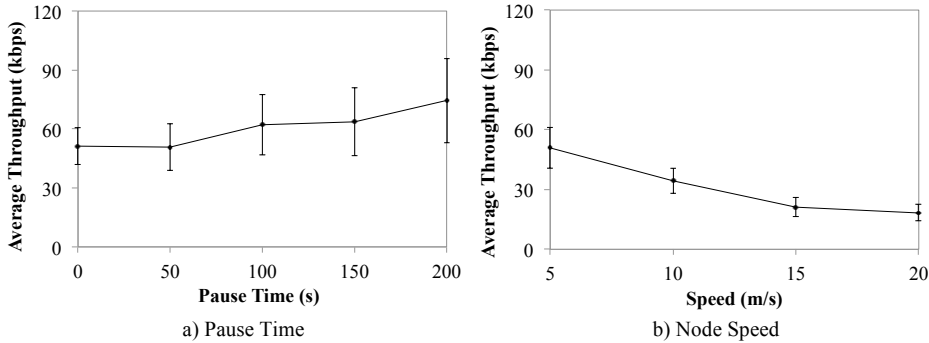
Figure 2.6 Average throughput depending on pause time (a) and node speed (b)

These results about speed of nodes clearly show how mobility affects end-to-end wireless transmissions. More significant than the absolute values themselves is the trend that shows a decreasing slope in throughput when speed increases. The same applies as regards pause time. The more static the nodes are (pause time higher), the higher the throughput achieved. It is also worth noting that scenarios with high mobility are very unpredictable, as can be inferred by the wide confidence intervals. Although both kinds of scenarios are quite aggressive regarding received throughput due to the randomness of the node movements, they are helpful to illustrate qualitatively the amount of packet losses caused by node mobility. In any case, throughput degradation, and consequently packet loss, is too high in such scenarios in order to carry out regular transmissions with certain data rates and specific quality.

Certainly, when video streaming comes into play, not only is throughput crucial but also packet delay could become critical, or more specifically, packet jitter. Similar experiments have been carried out using video sources instead of CBR and results are presented in following sections.

2.3. Video streaming over MANETS

Video streaming services, which are increasingly demanded nowadays, are bandwidth consuming and have high restrictive delay and loss constraints. Deploying such real-time services turns out difficult on wireless ad hoc networks due to the aforementioned issues. While video streaming requires a steady flow of information and delivery of packets by a deadline, wireless radio networks have difficulties to provide such a service reliably. Hence, the problem is challenging due to contention from other network nodes, as well as intermittent interference from external radio sources. Besides this, it is likely that any node might move away and therefore, the network topology may be altered causing link breakages and packet loss. Because of their nature, video streaming services are very sensitive to packet loss and delay. Figure 2.7 illustrates this video quality loss (PSNR degradation) when throughput is degraded because of node mobility, radio interferences or intra-flow contention.
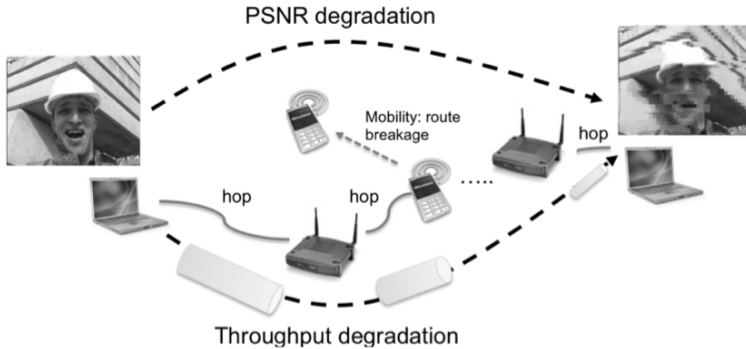
Figure 2.7 Video quality degradation in multi-hop wireless networks

Nowadays, most of video encoders are capable of reaching a quite low data rate and ensuring a rather good video quality. This is due to the use of a hierarchical coding, which causes many frames to be time dependent on others within the same video flow (e.g. MPEG-4, H.264, VP8). However, just because of this type of video encoding, the loss of a few packets can provoke the loss of one or several dependent video frames. Even a slight delay on some packets could result in deprecated frames, and therefore it would be better to skip it rather than play it back late. It is true that this time dependency is reduced to slice domain or even block domain within a frame in cutting-edge encoders, but the inter-frame dependency will be eventually unavoidable if a high compression rate is aimed to be achieved. This is why many video decoders have been developed with error concealment mechanisms in case of transmission failures.

2.3.1. Video quality measurement

In general, apart from the usual QoS measurements to evaluate a data transmission (e.g. throughput, delay, etc.), there are several specific ways to measure the quality of a multimedia transmission (rather related to QoE). Commonly, video quality models can be classified into three categories according to the availability of the reference video sequence: full-reference (FR) models, which compare the received sequence with the original sequence when the original sequence is entirely available to compare with; reduced-reference (RR) models, where the only access to the reference sequence is a partial information related to the original video; and no-reference (NR) models, where no information can be used as a reference.

Moreover, multimedia content assessment can be classified into objective, subjective and hybrid evaluation depending on the type of metrics used. Particularly, objective metrics are based on mathematical models that try to estimate the video quality perceived by the viewer. Currently, the most widely used objective video quality metric is the Peak Signal to Noise Ratio (PSNR) [30]. PSNR is a FR metric that represents the difference between the received frame and the reference frame. PSNR is widely used because it is mathematically simple to calculate as well as having clear physical

meanings. Nevertheless, other objective QoE metrics have been developed in order to achieve more accurate results such as the Structural Similarity Index (SSIM) [31] or the Video Quality Metric (VQM) [32]. SSIM is a FR metric designed to improve the traditional PSNR and is based on frame-to-frame measuring of three components (luminance similarity, contrast similarity and structural similarity) and combining them into a single value. On the other hand, VQM is an objective method to closely predict the subjective quality based on human eye perception and other subjectivity aspects, such as color distortion, blurring, etc.

On the other hand, there are different subjective methods used to assess the quality of video services. The subjective assessments are conducted with a set of viewers, which evaluate sequences of video depending on their perception. The test outputs can be obtained in terms of absolute scales or comparative scales. An example of an absolute qualitative scale is the Mean Opinion Score (MOS) scale, which was initially standardized by the ITU [33]. On the contrary, in comparative scales observers set mutual relations between sequences. Incidentally, there are some standard methods in the literature for conducting subjective video quality evaluations, such as the ITU-R BT.500 [34], which gives examples of assessment problems and recommended methods to be used. Nevertheless, although subjective evaluation is commonly used to assess simulated environments and protocols, it is neither practical for real-time video streaming (due to the need to compare with original sequence) nor scalable (because it would take many observers).

All in all, objective metrics are mainly used to compare how video streaming services perform over ad hoc networks. Packet delay and jitter are significant objective metrics, in addition to PSNR. Despite the fact that PSNR does not take into account some significant factors that can influence the video quality measurement, such as the Human Visual System (HVS) properties, it is useful enough to evaluate video transmissions that suffer degradation due to packet losses, which is the case mainly evaluated in this thesis. It is demonstrable by simple visual inspection that the effect of packet losses does not cause some specific kinds of distortions, such as blurring, color distortion or global noise, but spatial distortion, block displacement and temporal artifacts (e.g. video interruptions) may appear instead, which is measurable using PSNR. Moreover, it allows comparing and establishing connections with a greater number of results from other previous studies.

2.3.2. Video assessment

Although new video streaming solutions based on HTTP have appeared recently, real-time video traffic is still mainly based on UDP traffic. As has hitherto been the case in the previous simulations, traffic has been modeled as CBR UDP traffic, i.e. packets with the same size are sent at a constant bitrate. Due to the nature of video traffic patterns, this might result not as accurate as a real video transmission. Indeed, even though the average video bitrate is kept steady, some video frames are encoded with more bytes than others due to the spatial compression and the temporal dependency.

Moreover, in order to send these video frames through the network, they have to be packetized, that is, they need to be split in packets, which also contain transmission information such as timestamps, flow identifiers, and so on. The whole process ends with a set of packets of different sizes. It is true that for frames whose size exceeds the maximum packet size, several packets of the same size (the maximum size) will be created. However, video streaming usually is (and can be considered) a rather constant frame rate service, and taking into account that not every frame has the same amount of bytes, the resulting data flow is not likely to be a constant bitrate stream. That is the reason why video traffic must be treated separately and analyzed properly.

Moreover, video traffic performance can be studied from results obtained from additional parameters specifically related to video flows, such as PSNR or video interruptions, which give more information about what is happening to the video stream at destination. Therefore, similar scenarios, but now with video sources, have been simulated in order to observe the effect on video quality.

Firstly, the linear network formed by a chain of nodes has been simulated. Transmission channel uses IEEE 802.11b standard at 11Mbps, which characteristics are depicted in Figure 2.3b. Consequently, nodes are separated by a distance of 70 m. Source node transmits a video of 70 s of duration, 352x288 pixels (CIF), with a frame rate of 30 fps (the video is a loop of *mobile.yuv* [35], available on the Internet and commonly used for video assessment) encoded at different average bitrates (1000 kbps, 1500 kbps and 2000 kbps) with a tolerance of 10%. It has been encoded using H.264 with a GoP size of 30 frames, without B-frames (bidirectional). Then, it has been packetized to add RTP headers into packets of an MTU of 1400 bytes. So far, video is suitable to be streamed through the network.

Nevertheless, it is not advisable to use this video file directly in the simulations as a traffic source. This is mainly due to the great amount of data to be processed, redundancy checks and other optimizations that cannot be performed. Instead, it is usual to extract traces from the video file and use this information to generate traffic as though it were real video. This is carried out using Evalvid tools [36], which have been slightly modified to be used together with NS3. Packetized videos are then processed and video traces are extracted, which contain useful information, such as packet size, number id and timestamp about the packets to be transmitted. Video sources are simulated from these traces and then, new traces are obtained from the received video. Again, by means of Evalvid tools, resultant video is reconstructed from the original sequence taking into account the source and the received traces. Logically, at this point, lost packets, which do not appear in the received trace, cannot be used to reconstruct the video. Then, once both original and reconstructed videos are available for a full-reference analysis, PSNR can be calculated, besides the average packet delay, jitter, throughput and packet reception rate. These results are illustrated in Figure 2.8 for the different bitrates used.
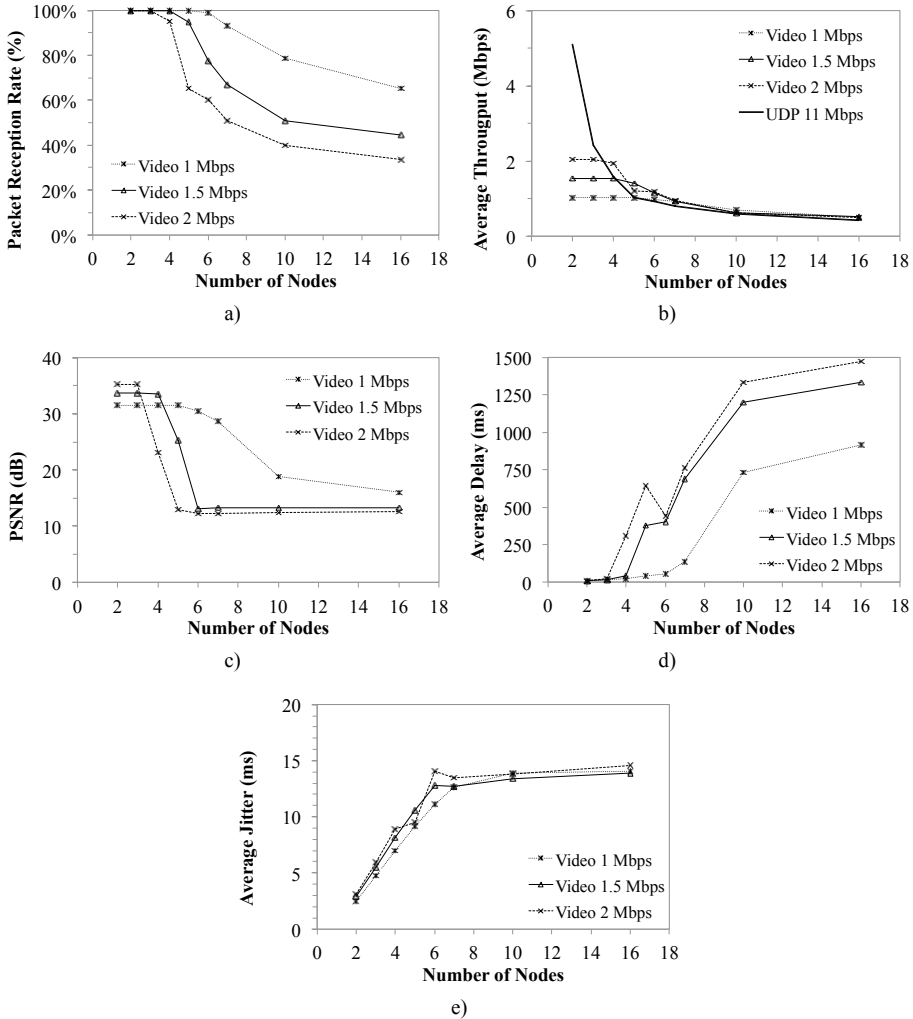
Figure 2.8 Average packet reception rate (a), throughput (b), PSNR (c), packet delay (d), and jitter (e) according to the length of network chain

In general, results show a clear trend; degradation is more noticeable as the number of nodes in the chain increases. As for PRR, Figure 2.8a shows that a video with a higher bitrate starts to lose packets before than another with lower bitrate when number of hops increases. For a video bitrate of 1Mbps, the PRR achieved is about 80% in a 10-node chain, 50% for 1.5Mbps and 40% for 2Mbps. Figure 2.8b depicts the throughput received at destination node as well as the maximum throughput achieved for a CBR UDP transmission of 11Mbps (recall that this is the maximum of the standard used) in order to compare with video results. Video transmissions adjust their bitrate slope to the maximum reachable due to interferences and the intra-flow congestion. Minimal

differences can be appreciated between UDP and video traffic when the maximum throughput is achieved that can be mainly due to the difference of packet sizes and therefore, differences in back-off times to access the medium. As aforementioned, although video bitrate is constant on average, video packet sizes differ due to the video encoding nature. Figure 2.8c shows the PSNR of the received sequences. As long as PSNR takes into account both encoding and transmission losses, the higher the bitrate, the better the PSNR, when transmission losses are negligible or zero. However, when packet losses occur, videos with higher bitrate are more affected because the percentage of received packets is decreased dramatically. Average packet delay is depicted in Figure 2.8d. Obviously, as the chain length increases, the packet delay should increase accordingly because the number of hops is higher. However, packet losses and interferences cause more delay than expected because packets are retained in node queues before they can be sent. In this particular case, the average packet delay in a large chain of nodes (16 nodes) can reach 913 ms, 1332 ms and 1471 ms for 1 Mbps, 1.5Mbps and 2Mbps of video bitrate respectively, which can be unaffordable in some kinds of real-time video transmissions. Hence, it would be logical to try to find a solution that could reduce the number of hops somehow without causing more interferences or contention, as addressed in Chapter 3. Packet jitter, which is shown in Figure 2.8e, is also aggravated as the hop count increases. Nonetheless, at a certain point, jitter scarcely grows even though hop count increases. Jitter is an important measure to take into account when designing video player buffers at reception in order to procure a fluent, seamless playback. All in all, from these figures it can be ascertained how the number of hops may affect the quality of a video transmission at a certain bitrate.

On the other hand, as shown before, mobility of nodes is also one of the main originators of packet losses in ad hoc scenarios due to link breakages that cause route rediscovering. In order to assess how mobility affects video transmissions in MANETs, similar scenarios to those used for CBR evaluation have been now used with video sources. In this case, the scenario consists of 50 nodes arbitrarily spread on a 600 m x 300 m layout. The mobility model used is the Random Waypoint Model (RWM). Again, node speeds from 5 to 20 m/s have been used with a pause time of 0 s (nodes always moving) and also pause times between 0 and 200 s have been used together with a node speed of 5 m/s. In both cases, 802.11b@11Mbps has been used. Source node transmits the same video as in the chain scenario. Simulation duration has been set to 100 seconds. This is an aggressive scenario where every node is moving (source and destination nodes included). The video used has been encoded at 100 kbps, 30 fps, and an encoding PSNR of 20.6 dB. Figure 2.9 shows the results regarding the average PRR, throughput, PSNR, packet delay and jitter, according to the pause time.

Figure 2.9 Average packet reception rate (a), throughput (b), PSNR (c), packet delay (d), and jitter (e) depending on pause time

As happened with CBR traffic, the throughput achieved is lower in environments with higher mobility (lower pause time). Incidentally, throughput remains consistent with PRR; for instance, for a PRR of 83% when pause time is 200 s, throughput reaches 81.1 kbps on average. Nevertheless, paying attention to PSNR, it can be seen something particular. Taking into account the fact that the average PSNR of the original sequence after encoding is 20.6 dB (reference measurement with no packet loss), received video in high mobility presents an average PSNR of 13.2 dB, which represents 64% for a

throughput of 35.8 kbps. Therefore, it would make sense if in low mobility simulations (200 s of pause time), where throughput achieves 81.1 Kbps (81% of the average bitrate), PSNR should reach approximately 16.7 dB, instead of 17.1 dB. This difference highlights the non-linearity of video coding, that is, the fact that after losing a few packets video quality may be further degraded than losing more but different packets, proving then that there are packets with more critical information, which are consequently worth protecting. Additionally, as nodes are more stationary, packet delay is decreased because of the fact that waiting time, likely due to rerouting events, is also diminished. Packet jitter, i.e. time difference between packet arrivals, is lower if node mobility is also lower and therefore, delay is also uniform, which is favorable to avoid video playback interruptions. Once node mobility has been evaluated, Figure 2.10 illustrates how node speed affects video transmissions regarding PRR, throughput, PSNR, delay and jitter.
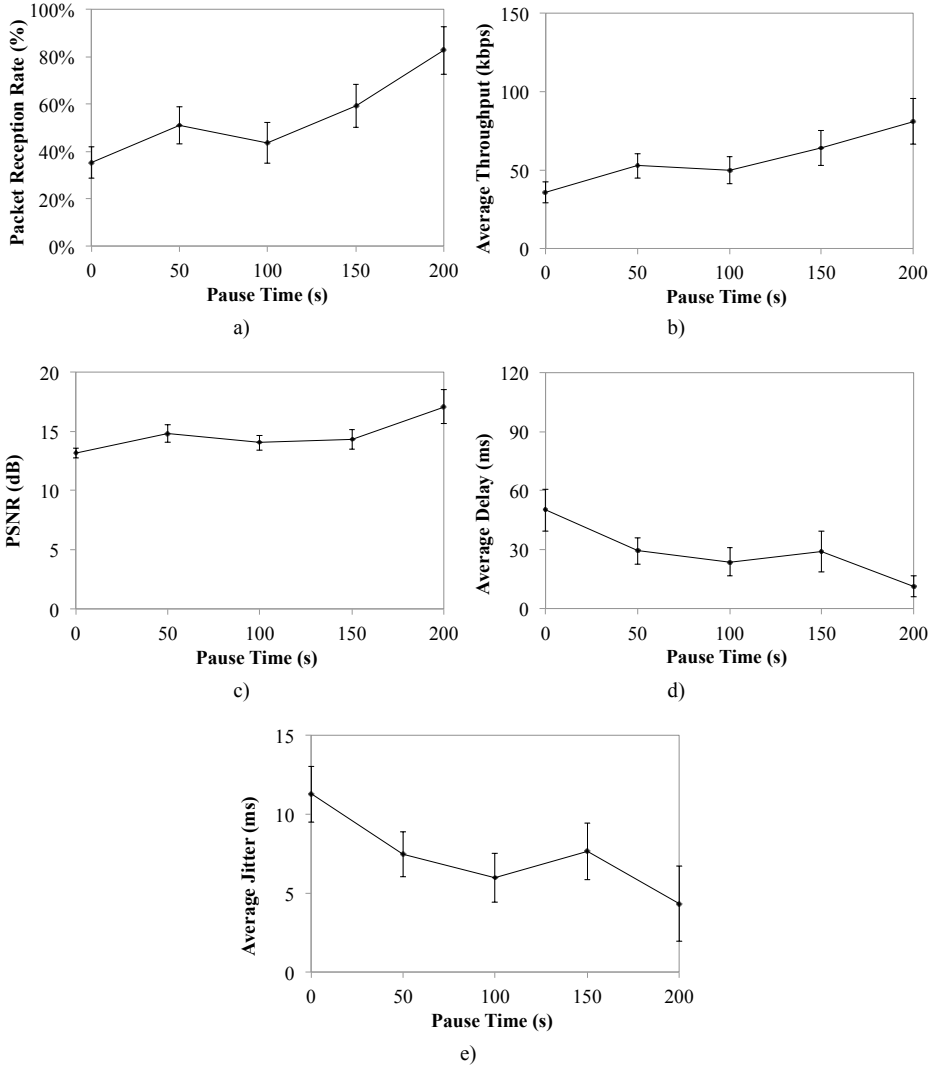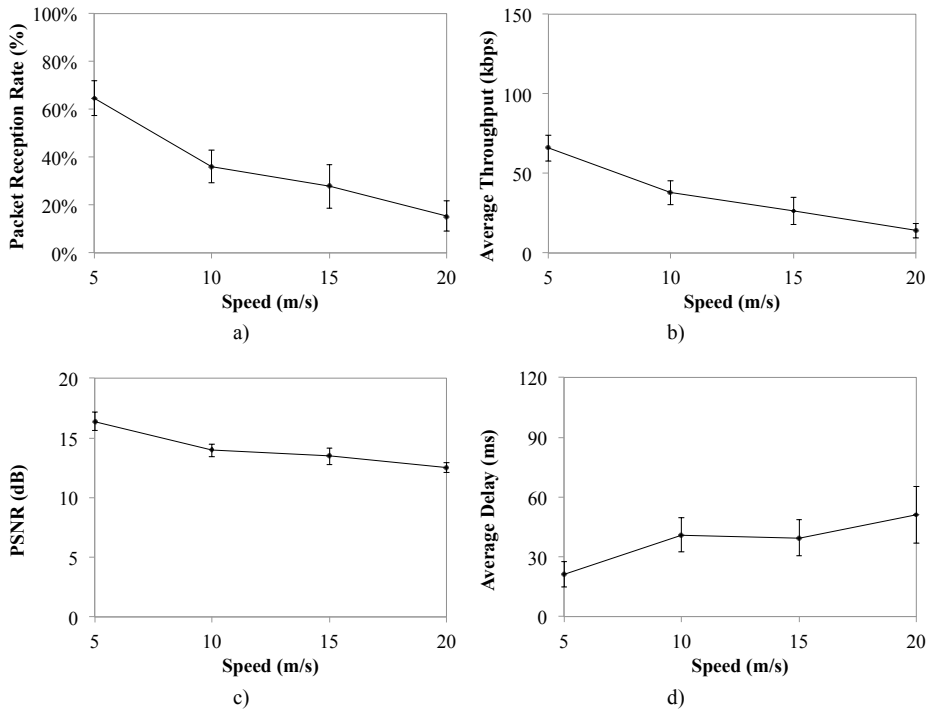

a)

b)

c)

d)
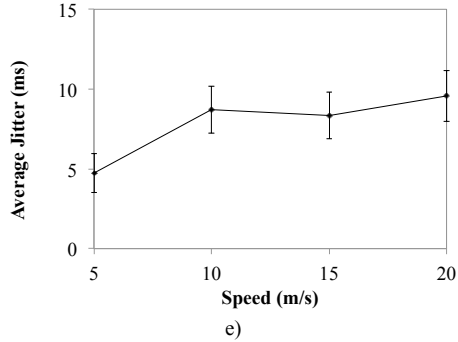
Figure 2.10   Average packet reception rate (a), throughput (b), PSNR (c), packet delay (d), and jitter (e) depending on node speed

As expected, when nodes move at higher speeds, the average PRR and throughput is dramatically decreased. Particularly, it is remarkable that at 20 m/s, throughput only reaches 14 kbps, which is obviously too low even for a mediocre video reception. As nodes move at a higher speed, packet delay increases because packets have to wait in node queues while broken routes are restored. Consequently, it is logical to think that ad hoc networks need faster rerouting protocols or network topologies that maintain routes steady for longer periods of time. Jitter also increases until a certain extent, but it does not grow indefinitely because packets with higher delays are likely to be lost and not taken into account.

2.4. Real testbeds

Network simulators are useful tools that allow building huge network topologies and testing new protocols and algorithms that could not be assessed otherwise. However, it would also be interesting to check some results whenever possible over real networks and devices. Hence, in this section video transmission has been assessed over a real testbed, which not only is useful for a better understanding of the real performance of wireless transmissions but also to have a real implementation available and ready to be improved with some of the achievable proposals. For scalability reasons, however, only a small-scale scenario has been assessed. Thus, real devices have been configured and arranged forming an ad hoc network.

2.4.1. Network setup

The testbed has been built with laptops and smartphones. Source and destination nodes are laptops with Linux and 802.11b/g wireless cards. For multi-hop transmission, Android Nexus ONE mobiles are used as intermediate nodes, which are in charge of routing video packets. These devices have been intentionally arranged so that the source node must always use any of the intermediate nodes to forward packets to the destination node. Therefore, transmission route is always forced to have two hops.

During the experiment, the destination node moves at approximately 1 m/s, following the itinerary depicted in Figure 2.11. Note that node 1 and node 2 do not see one another due to the thick walls. Hence, the experiment is carried out as follows. First, the destination is receiving the video transmission from source through node 1, which acts as a router (1). Then, destination moves away from the coverage of node 1, causing a route breakage and packet losses (2). Right away, destination node enters within the coverage of node 2. Video packets are then transmitted from source to destination through node 2. This route change does not occur immediately, but the routing protocol must first realize that the link has fallen and then recalculate the best route (3).
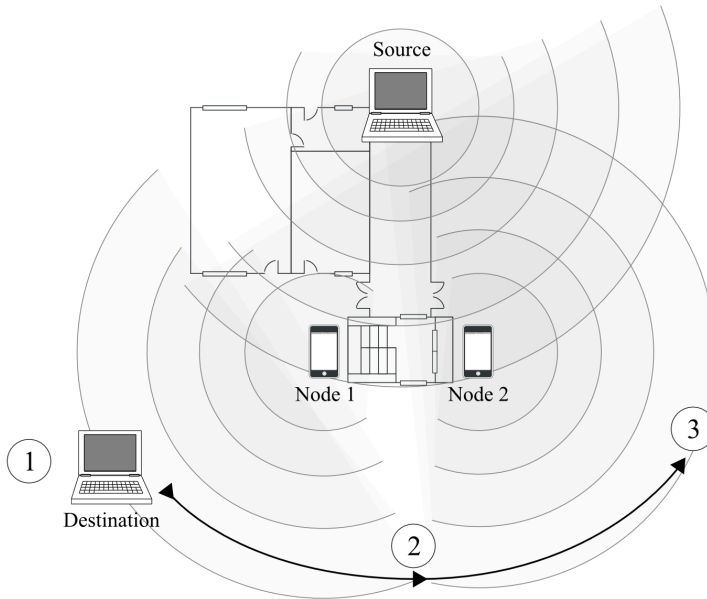
Figure 2.11   Network setup for testbed

The routing protocol used is an implementation of OLSR [37]. It has been built and configured from the source code for both laptops and mobile phones. The main parameters used to configure the testbed regarding wireless card and routing protocol are described in Table 2.1.

In the case of mobile phones, an Android widget has been developed as well in order to enable/disable the routing mechanism from the homescreen. Besides the installation of the *olsrd* daemon in mobile phones, it is worth saying that the process to configure and connect an Android smartphone to an ad hoc network is not straightforward and a thorough configuration is needed (Appendix B.1).

Table 2.1   Testbed wireless configuration parameters

Parameter	Value
Wireless Standard	802.11g
Data Rate	54 Mbps
Transmission Power	0 dBm
RTS/Fragmentation	Off
Power Management	Off
OLSR HELLO interval	2 seconds
OLSR TC interval	5 seconds

2.4.2. Video evaluation in a real testbed

Once the real network is set up, measurements can be carried out as though it was a simulation, but in this case, real video traffic is sent through the network. The video sequence used is the same as the one employed in Section 2.3.2. In short, the video is a CIF-sized sequence that lasts 70 s and has a frame rate of 30 fps. Here, it has been encoded at 500 kbps on average using H.264. During the experiment, Received Signal Strength Indicator (RSSI) has been measured at destination node to depict the signal quality received from node 1 and node 2. Figure 2.12 shows the RSSI variation caused by destination movement along the scenario layout, highlighting the three stages.
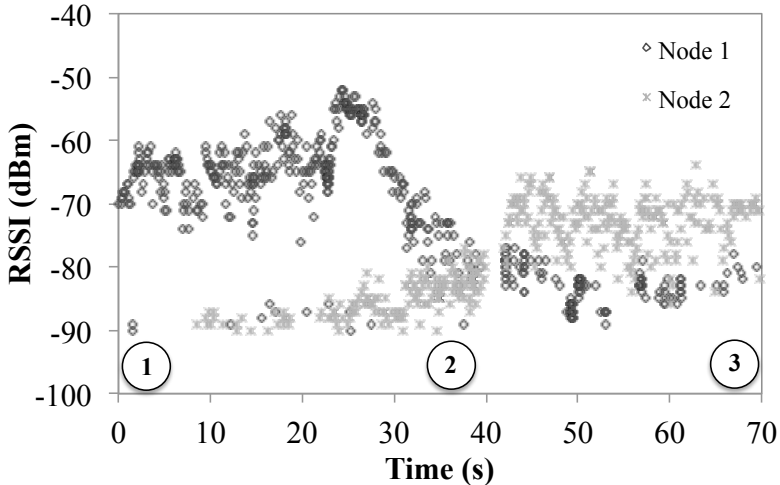
Figure 2.12   RSSI from node 1 and node 2 measured at destination

As long as destination remains within the coverage of node 1, RSSI values are high enough to guarantee the proper reception of video transmission. As destination moves out of range, depicted as stage 2, the signal received from node 1 decreases but signal strength from node 2 is progressively increasing. When destination node arrives at stage 3, RSSI values from node 2 indicate that destination falls within the coverage of node 2, and a new route can be established now. Finally, results regarding instant PSNR and packet delay are depicted in Figure 2.13.
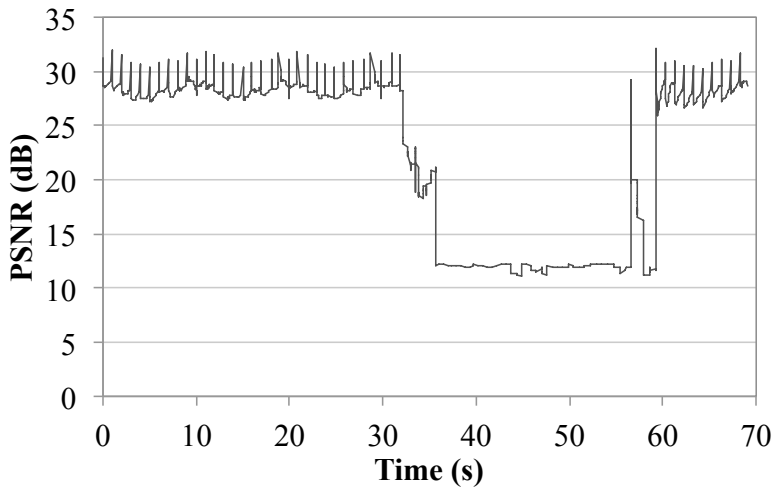
a)
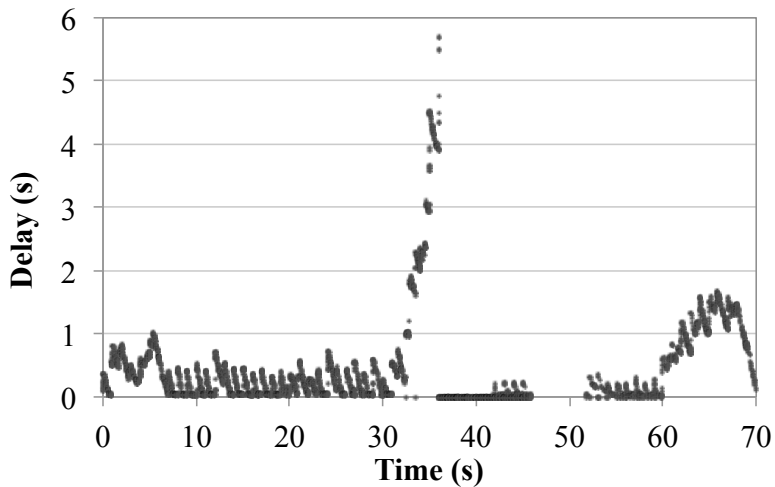
b)

Figure 2.13   Average PSNR (a) and packet delay (b) in the real testbed layout

Average PSNR of the encoded video used as a reference is 28.31 dB. However, average PSNR of the received video drops to 22.39 dB. This is due to the video playback interruption generated when OLSR is trying to discover the new route. Even in a rather simple scenario like this, the rerouting time is remarkable. OLSR takes about 20 seconds to realize that a link has fallen and recalculate the new route. It is true that this interval could be slightly shorter if OLSR is configured to keep routing tables faster updated (e.g. by reducing OLSR HELLO and TC intervals), but at the expense of increasing control traffic overhead. Regarding instant packet delay, it can be seen a noticeable increase when destination is arriving at stage 2. This fact coincides with the decrease in the signal strength received from node 1. A thorough analysis of packet delay and RSSI could be performed in order to anticipate link failures, as can be seen in other studies in the literature [38]. As a matter of fact, the difficulties and issues discussed in this chapter regarding mobile wireless ad hoc networks had inspired numerous research works that tried to deal with mechanisms to ensure transmission quality from different points of view.

2.5. Classification of solutions proposed in the literature

Video transmission with QoS over IP networks has been discussed for decades and has become the main topic in many papers and research works. Actually, it is yet challenging nowadays. In fact, it is extremely difficult to guarantee hard QoS in MANETs and it is common to consider adaptive quality of service proposals as the only viable solutions to achieve the technical problems that exist for QoS in wireless ad hoc networks. In this sense, there are multiple mechanisms designed to improve video quality over ad hoc networks. Some of the most relevant techniques are identified and classified below. A typical classification in the literature includes QoS Models, QoS Signaling and QoS Routing.

Firstly, QoS Models represent a sort of architecture to offer different types of services and the role of the rest of QoS components. Flexible QoS Model for Manets (FQMM) [39] is the first QoS Model proposed for MANETs. It considers the features from the solutions traditionally proposed in Internet (per-flow service granularity in IntServ and service differentiation in DiffServ) and applies them considering the particular characteristics of MANETs.

Among the other components, QoS Signaling is mainly used to reserve and release network resources. INSIGNIA [40] is the first signaling protocol designed for MANETs. It is an in-band signaling system at the IP layer that supports fast reservation, restoration, and adaptation algorithms. The signaling protocol is carried in the IP Option field of every IP data packet, but as a signaling protocol, INSIGNIA needs a routing protocol that considers changes in the topology. Their major drawback is the scalability problem as the number of flow states increases and consequently, so does the flow information kept in the mobile hosts. On the other hand, SWAN [41] is a stateless network protocol to deliver service differentiation support in MANETs. SWAN uses

rate control for UDP and TCP best-effort traffic, and source-based admission control for UDP real-time traffic. SWAN is designed to support real-time services over best effort MACs without the need to install and maintain costly QoS state at MANET nodes.

Finally, a lot of works have been done on routing protocols in ad hoc networks, taking into account different scenarios and traffic conditions [42] [43] [44]. It must not be forgotten that video streaming services are bandwidth-consuming services and may suffer from playback interruptions when packet losses occur. These interruptions can be annoying and may cause a significant decrease on the QoE of the viewers. Routing protocols that do not consider these constraint conditions regarding packet delay and losses will not be suitable for video streaming and it could therefore result in diminishing video quality and cause interruptions.

In this sense, as regards QoS Routing, several routing algorithms based on QoS parameters (such as packet delay or bandwidth estimation) have been proposed in order to improve the delay and the throughput of wireless transmissions [45]. Their functionality lies in searching for a path with enough resources to bear the expected transmission data rate. However, it is very important to balance the benefits of the QoS Routing with the cost of the overhead introduced by them [46]. In [47] is presented the Core-Extraction Distributed Ad hoc Routing (CEDAR) algorithm, which is designed to select routes with sufficient bandwidth resources. It uses only the core nodes for state management and route computation and it includes three main components: core extraction, link state propagation and route computation. In [48] the authors propose the QOLSR protocol, which includes quality parameters to the standard OLSR messages. It considers different scenarios taking into account the delay estimation together with the hop count metric.

Most of the routing protocols that have been proposed consider ad hoc networks as homogeneous, meaning that all nodes have the same capabilities. This kind of protocol is known as flat protocols, since ad hoc networks are usually networks with a flat topology. In such a flat topology, when the network size increases, both average path length and consequently packet loss probability increase as well. This scalability issue is also noticeable because routing traffic overhead grows. Nevertheless, many ad hoc networks might be considered heterogeneous because they contain mobile nodes with different capabilities (bandwidth, transmission range, etc.). To maintain scalability in these heterogeneous ad hoc networks, hierarchical routing protocols should be considered as a good option [49] [50] [51]. In this sense, emerging Wireless Mesh Networks (WMN) [52] are envisioned as hierarchical ad hoc networks that can rely on a static backbone that guarantees certain level of connectivity. Recently, the IEEE 802.11s amendment [53] for mesh networking has been released, which describes the architecture and propose some routing protocols that can make use of radio-aware metrics in order to enhance bandwidth and connectivity.

On the other hand, the fact that wireless transmissions can be heard within the coverage area of a node may lead to packet interferences with neighbor transmissions. However, nodes can take advantage of this effect. Even when overheard packets are not addressed to them, nodes can try to cooperate and forward those packets towards the actual destination. This is the basic operation of the opportunistic and cooperative routing protocols. For instance, ExOR [54] integrates routing and MAC techniques to choose the most appropriate forwarder for each packet in each hop among the set of nodes that actually received the packet. The downside is that the strict coordination that prevents spurious transmissions also hinders the spatial reuse from nodes farther away. In order to allow this spatial reuse, MORE [55] combines opportunistic routing with network coding without requiring node coordination, which improves the overall throughput by means of linearly combining sets of packets. Cached packets are encoded and forwarded only if they are innovative, i.e. independent from its previously received packets. Caching packets on certain nodes is another technique that is widely used in retransmission mechanisms, which are based on Automatic Repeat Request (ARQ) approach. Basically, when a packet or a batch of packets is lost and this loss is detected, destination node sends an ARQ to the source (or an intermediate node) so that it can retransmit lost packets [56].

When video traffic is transmitted, QoS constraints have to be taken into account [57] and new solutions involving several abstraction layers have been proposed in this sense [58] [59]. Hence, it is worth considering cross-layer routing solutions, which can extract useful information from other protocol layers. For instance, video awareness could offer new mechanisms to improve video transmissions, such as bandwidth adaptation, intra-frame prioritization or even algorithms that react to the play-out buffer state, obviously at the expense of adding complexity. This content-awareness can lead to other solutions based on enhanced video coding. More precisely, video compression systems have evolved and more versatile techniques have appeared, such as Scalable Video Coding (SVC) included in the norm H.264 (H.264/SVC) or Multidescription Coding (MDC), which is presented as one of the most suitable solutions in multi-hop networks due to the possibility to use disjoint paths towards destination [60]. Additionally, loss differentiation algorithms could provide enough information to upper layers in order to adapt video rate accordingly, since packet losses may occur due to multiple reasons and not every solution fits in any case [61].

2.6. Conclusion

This chapter has shown some of the main issues of MANETs through simulations and experimental results, exposing the problems to offer video streaming services. Intrinsic features of wireless channel and medium access in 802.11 standard have been proved to cause transmissions not to reach the maximum theoretical data rate. It has been determined that when the hop count of the packet path grows, not only contention is increased but also the packet loss probability. Moreover, if nodes are considered to be able to move freely causing network topology to change, more link breakages and

losses are induced, which consequently degrade video quality in reception. Routing protocols are in charge of reconstructing packet routes when this happens. Therefore, it is worth paying special attention to routing algorithms in order to improve network stability facing link failures and route breakages.

The results presented in this chapter suggest that ad hoc networks are practically non-scalable; however, some proposals and approaches in the literature have been gathered as well to show somehow the big effort that is being carried out to obtain an acceptable QoS from different points of view, and some of them convey interesting results. Far from being disappointing, this should encourage researchers to follow this path and persevere in their efforts. This review section has also described solutions and concepts related to this thesis, such as hierarchical routing, opportunistic routing and WBA, caching and ARQ procedure, and other cross-layer techniques in general. In this sense, this thesis presents novel proposals to address some of the most important open issues in mobile ad hoc networks, with the aim of improving transmission throughput and video streaming quality.

Chapter 3

Video Streaming over Ad Hoc Networks using Hierarchical Routing

Following the idea of improving QoS in video transmissions, this chapter is focused on hierarchical routing. By analyzing some of the hierarchical and clustered routing proposals in the literature, it can be stated that a clustered scheme may help improve scalability and performance of current flat routing protocols. However, these proposals are usually more complex as regards the routing algorithm and computation. In this sense, a hierarchical routing approach is proposed in order to improve the efficiency but trying to maintain complexity as low as possible. Hence, this chapter also focuses on the performance evaluation of the resultant hierarchical network from two different points of view. On the one hand, flat and hierarchical protocol behaviors are compared regarding convergence time and overhead. On the other hand, video transmissions are used in order to assess the resultant quality and compare both hierarchical and flat responses to delay-sensitive traffic. Moreover, some of the drawbacks of the hierarchical environment are also analyzed. Finally, in order to overcome these downsides, an additional approach for increasing QoS in video streaming over a hierarchical scheme is proposed.

3.1. Introduction

Because of the dynamic topology of MANETs, ad hoc routing protocols are more complex than traditional routing protocols used on the Internet. The main objective of these routing protocols is to achieve efficient routes between nodes so that the

information is available in destination nodes reliably and within boundary time. A good performance of these protocols should have low overhead and bandwidth consumption, and a fast route convergence, even when there are changes in traffic load or the number of nodes grows. These are desirable features in a scalable routing protocol. Moreover, since wireless networks usually consist of a wide variety of nodes, it is consequently convenient to consider these networks as heterogeneous networks, where not every node performs the same functions regarding routing operation. Figure 3.1 depicts a comparison between traditional flat routing and the equivalent routing in a hierarchical structure.
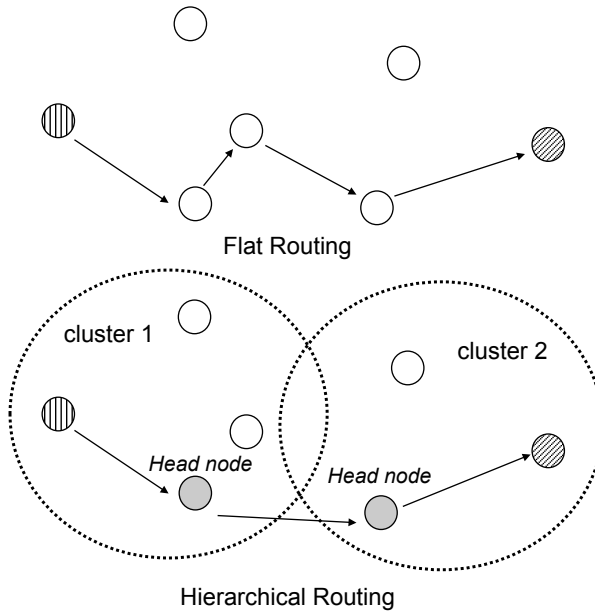
Figure 3.1 Conceptual comparison between Flat and Hierarchical routing protocols

In this sense, mobile nodes can be arranged into virtual groups or clusters, following certain preset rules and, most of the time, taking into account the geographical location and adjacency of them. In a clustering scheme, different tasks may be assigned (even dynamically) to the nodes depending on their characteristics (e.g. bandwidth, processing capacity, battery life, etc.). In each cluster, there is at least one head node or cluster head (CH), which usually serves as a local coordinator and is in charge of routing and forwarding packets from and towards other clusters. This communication between clusters is called inter-cluster transmission and it is commonly carried out by the CHs. In contrast, communication between nodes belonging to the same cluster is known as intra-cluster communication. Thus, both the cluster structure and this kind of tiered communication generate a hierarchical topology with some advantages over the flat topology [62].

Therefore, a cluster structure enables the opportunity to reuse wireless frequencies spatially as long as clusters were not overlapped. This fact can save resources and reduce transmission collisions, which are frequent in wireless ad hoc networks and one of the main problems to achieve high QoE. Moreover, a hierarchical routing protocol causes a network to be arranged as a hierarchy, consisting of certain number of clusters and a cluster leader elected within each cluster. This hierarchical network structure reduces the number of participating nodes and the communication overhead for routing discovery and maintenance. Additionally, cluster heads form a backbone themselves for inter-cluster routing and communication, so routing processes are hierarchized, i.e. local changes inside a cluster do not need to be spread along the whole network since routes between clusters remain unchanged. Hence, the amount of information processed and stored on each node is significantly reduced.

3.2. Related work

Some hierarchical routing protocols have been proposed in the literature in order to enhance network performance and transmission quality. The hierarchical concept is associated to the formation of physical or virtual groups of nodes, i.e. clusters, and the selection of one or more representative nodes in charge of the communications between clusters. These special nodes or cluster heads can be organized in multiple levels, resulting in a hierarchy of nodes. The way this hierarchy is arranged, maintained and employed differs from one approach to another.

Among these related proposals, [63] proposes a Weighted Clustering Algorithm (WCA) based on a non-periodic procedure for cluster heads selection, which is invoked on-demand. This way, this algorithm is aimed to reduce the computation and communication costs. It also remarks the existing trade-off between the uniformity of the traffic load handled by the cluster heads and the connectivity of the network, which is also related to the number of nodes that a cluster head can bear ideally. Incidentally, this issue is also addressed later in this chapter. Also related to clustering mechanisms, MobDHop [64] is a cluster formation algorithm that assumes that nodes are very likely to move in groups and, thus, it takes advantage of relative mobility of nodes to determine the formation of clusters. This circumstance allows enabling multi-hop clustering while minimizing the generated overhead. Furthermore, there are some hierarchical proposals that are also envisioned to support real-time services. This is the case of MMWN [65], which presents a set of adaptive cross-layer algorithms to support distributed, real-time multimedia applications in large ad hoc networks. This is achieved by using a hierarchical structure that combines autonomous clustering with an adaptive control of link quality and QoS route selection. However, it is not designed to operate effectively in a network with highly mobile nodes. The idea of using cross-layer mechanisms, especially to improve multimedia quality, is an interesting subject and it will be addressed in the proposal described in Chapter 4. Even the recent IEEE 802.11s standard [53] establishes a hierarchical structure and proposes the use of Hybrid

Wireless Mesh Protocol (HWMP) [66] for routing, which uses the MAC layer to find the right path to destination.

On the other hand, some other hierarchical protocols have been designed based on modifications of the existing flat routing protocols. This is the case of HAODV [67], which proposes some modifications to AODV in order to support and optimize routing in heterogeneous networks. This way, HAODV is able to find routes on demand through nodes that own interfaces with different radio technologies (e.g. Bluetooth, WiFi). In [68], a whole hierarchical structure is defined. This architecture is arranged autonomously in multiple levels of clusters, using HDSR as intra-cluster routing protocol whereas proactive routing is used for inter-cluster routing. Both HAODV and HDSR are based on reactive protocols, which generate routes on demand. In contrast, there are various hierarchical proactive alternatives. In this sense, in [69], two proposals of hierarchical protocols, concretely HLANMAR and HOLSR, are analyzed and compared. HLANMAR simply organizes nodes in hierarchical levels and uses backbone nodes to decrease the number of hops that packets would suffer using original LANMAR. Backbone nodes are supposed here to have long-range radio links. This is a common assumption when designing hierarchical routing protocols in heterogeneous networks. In case none of the nodes does fulfill the requirements to become a backbone node, special nodes can be intentionally deployed to guarantee network connectivity. Regarding HOLSR, there are currently several versions of this protocol due to the extended usage of the original OLSR. For instance, [49] additionally uses new kinds of messages in order to arrange the network in clusters and assign cluster heads autonomously. On the contrary, [70] uses a fisheye technique, which consists in maintaining accurate distance and link quality information regarding nearby nodes while progressively reducing accuracy as the distance increases. This technique is employed in order to limit the frequency update rate of route discovering in distant nodes and, therefore, forming a hierarchy implicitly. Another protocol based on OLSR is COLSR [71], which establishes a clustered scheme to limit routing messages within cluster bounds, reducing topology control overhead and the size of routing tables. It is interesting that inter-cluster communication can be carried out either through the cluster heads or by means of the border nodes, and even a hybrid approach is suggested. Nevertheless, new kinds of messages are employed for cluster formation and maintenance, which must be considered because they may cause high overhead in large ad hoc networks depending on the amount of clusters arranged.

All in all, although clustering may introduce overhead due to the cluster configuration and maintenance, cluster-based proposals have demonstrated that hierarchical protocols reveal better energy consumption and performance when compared to flat network topologies, especially for large-scale wireless networks [72].

3.3. Hierarchical routing proposal: Hierarchical OLSR

This section describes a hierarchical routing proposal that aims at improving QoE in video transmissions and minimizing overhead caused by the routing protocol when the number of wireless nodes grows. On the basis of a flat routing protocol, a clustered scheme may transform the wireless network in a scalable architecture, increasing performance.

Therefore, the hierarchical approach proposed in this chapter is based on the Optimized Link State Routing protocol (OLSR), which is described in RFC 3626 [2]. It is worth noting that the IETF is working on a new version of OLSR (OLSRv2), which aims to introduce some improvements, but it is still under standardization process (draft) [73]. OLSR is a variation of the traditional link state routing, modified to specifically improve operation in ad hoc networks. The main key of this optimization is based on a technique called Multi-Point Relay (MPR), which reduces the maximum number of retransmissions during the flooding operation of the routing protocol, typical of proactive routing protocols. Particularly, OLSR defines the basic types of control messages shown in Table 3.1.

Table 3.1   Basic types of OLSR messages

Name	Description
HELLO	Periodically transmitted to all neighbors with neighboring information
TC (Topology Control)	Contains network topology information. Spreading optimized using MPRs
HNA (Host and Network Association)	Used by a host to announce itself as a gateway to specific networks
MID (Multiple Interface Declaration)	Description of the multiple interface configuration of a node

The main operation of OLSR can be briefly explained as follows. Every node sends a HELLO message to identify itself and, additionally, it contains a list of neighboring mobile nodes. From a HELLO message, the mobile node receives information about its immediate neighbors and two-hop neighbors. In these messages, nodes also announce their own availability to act as MPR node. There are 8 levels of willingness, from the lowest (indicates that this node must never be chosen as MPR node), to the highest (indicates that this node should always be chosen as MPR node). The willingness must be considered when calculating MPR nodes. RFC 3626 proposes a simple method to optimize MPR calculation based on a heuristic algorithm:

MPR selection algorithm

INPUT: Neighbors set, two-hop neighbors set

OUTPUT: MPR set

1: First select as MPRs all the neighbors that are the only nodes to provide reachability to a two-hop neighbor

2: **while** (there exist uncovered two-hop neighbors)

3: Select as MPR node a neighbor that provides reachability to the maximum number of uncovered two-hop neighbors

4: **end**

5: Optionally discard any MPR node if all two-hop neighbors are still covered excluding it from the MPR set

Once the MPR set is built, information about the network topology is encapsulated inside TC messages and spread to every other node. TC messages are generated only by the MPR nodes, announcing which nodes have selected them as MPRs. Such messages are relayed by other MPR nodes throughout the whole network, enabling the remote nodes to discover the links between MPRs and their selectors. Based on such information, the routing table is calculated using the shortest-path algorithm. By using the MPR flooding mechanism, duplicated packets and routing overhead is reduced considerably. Figure 3.2 clearly shows this improvement graphically.
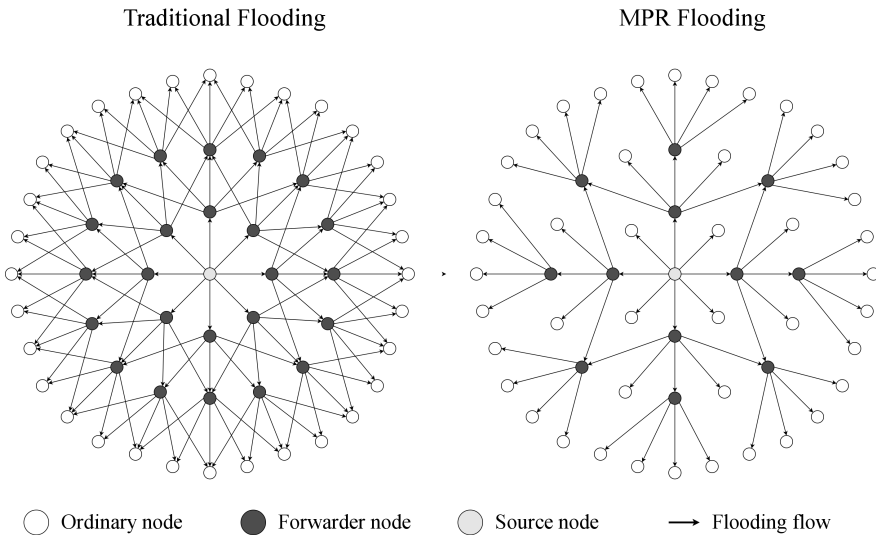
Traditional Flooding   MPR Flooding

◯ Ordinary node   ⬤ Forwarder node   ◯ Source node   ⟶ Flooding flow

Figure 3.2 Traditional vs. optimized flooding using MPRs

Regarding HNA messages, they are used to announce that a node is equipped with other non-OLSR interfaces. These non-OLSR interfaces may be point-to-point connections to other singular hosts or may connect to separate networks. In this case, this kind of node periodically generates HNA messages containing pairs of network address and netmask, corresponding to the connected hosts and networks in every non-OLSR interface. Additionally, the OLSR protocol does support nodes having multiple wireless interfaces participating in the MANET. This is achieved by means of using MID messages to announce the interfaces that are taking part of the routing process.

However, it could be said that OLSR employs a flat mechanism, whereby a node sends both HELLO and TC messages through all its interfaces participating in the MANET without regarding the link capabilities of the other nodes, i.e. all interfaces are considered equivalent. Thus, the flat OLSR mechanism might not scale well for large heterogeneous ad hoc networks. This is one of the main motivations to perform some improvements in order to allow OLSR to take advantage of the different interface capabilities when multiple interfaces are available in a host, leading to a hierarchical topology managed and maintained by a hierarchical version of OLSR.

As aforementioned, in large networks there are likely to be nodes with different and varied capabilities, even with multiple interfaces. Hierarchical OLSR (HOLSR) is introduced to increase scalability of OLSR in large ad hoc networks. Particularly in the literature, a layered version of OLSR with a hierarchical structure has been proposed, developed by the Communications Research Centre (CRC) of Canada, hereafter called CRC HOLSR [49]. This approach of HOLSR dynamically organizes nodes into cluster levels. At each level the cluster head declares its status and invites other nodes to join its cluster by means of Cluster ID Announcement (CIA) messages. Then, a Hierarchical TC (HTC) message is used to transmit the membership information of a cluster to the higher hierarchical level nodes. Cluster formation and topology dissemination are carried out with these new message types. The main improvements introduced by the CRC HOLSR protocol are the reduction in the amount of necessary topology control information, the efficient use of high capacity nodes, and a reduction in routing computational cost.

Maintaining the main advantages explained before for hierarchical routing, this chapter presents a new HOLSR approach. This HOLSR proposal is based on the ADHOCSYS project [74], which aims at providing broadband access in rural and mountain areas where other wired or one-hop wireless connections are not available or non-profitable. Some of the results obtained in this chapter have been developed and implemented within the ADHOCSYS framework.

The basic principle in the proposed hierarchical OLSR approach (hereafter ADHOCSYS HOLSR) is similar to the CRC HOLSR described above, but there are several differences. In this new proposal, it is considered that there are only two levels in the hierarchy, where *level-1* corresponds to the connection among *type-1* nodes (core network) and *level-2* corresponds to the connection among *type-2* nodes (access

network), as depicted in Figure 3.3. An access subnetwork, which is connected to other access subnetworks, is hereafter referred to as a cluster. A *type-1* node serves as the cluster head and advertises its reachability to other clusters. The cluster heads are predefined, so there is no need to develop an algorithm for cluster head selection. By limiting the number of tiers in the hierarchy, the complexity of cluster establishment and management is reduced drastically.
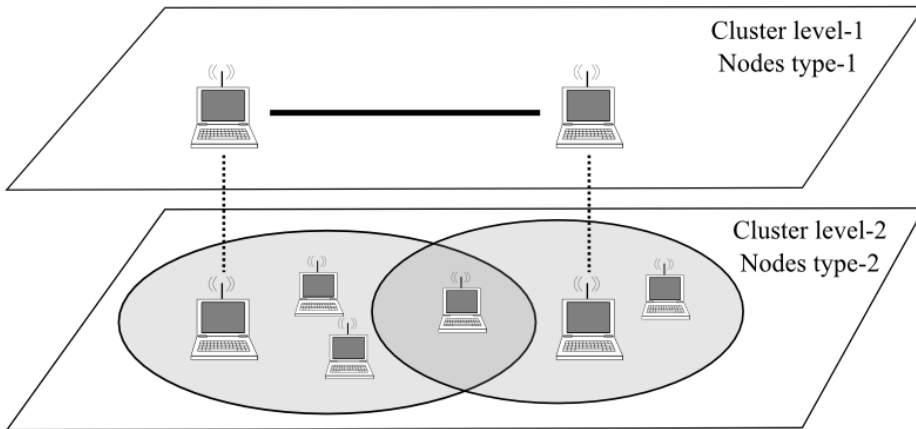
Figure 3.3 2-Tier hierarchical ad hoc network

Furthermore, the cluster heads are aware and connected to each other, either directly or via multi-hop relays. Communications between cluster heads can also be conducted using unicast traffic, as an alternative to subnet-directed-broadcast. As in CRC HOLSR, the cluster-head nodes should have at least two wireless interfaces, for inter- and intra-cluster communications respectively. Either a directional antenna with larger coverage area or higher transmitting power is supposed to be used for inter-cluster connection. Hence, distance between cluster heads may be longer, covering a wider area. The data rate for inter-cluster connection should be higher than the ones for intra-cluster communication. This would be very useful in rural areas as well as sparsely populated regions, where nodes might be concentrated in small localities geographically separated.

In order to establish routes between clusters, ADHOCSYS HOLSR uses only HNA messages, which are already considered in standard OLSR. According to the ideas described above, this HOLSR solution is implemented based only on the use of HNA messages. In this sense, it is the cluster head's responsibility to advertise its reachability to both internal nodes and other clusters. Nodes such as cluster heads, with associated hosts and/or networks, should periodically generate HNA messages. On the one hand, the CH informs other CHs about the nodes contained in the cluster. On the other hand, the CH is in charge of notifying the nodes inside the cluster about the route towards other nodes in other clusters. In this sense, when HNA messages are received from

other CHs, a CH should update its HNA Information Base and propagate new information to its cluster members via internal subnet-directed-broadcast HNA messages. This process is depicted in Figure 3.4.

HELLO$_X$	HELLO message generated by node X
MPR$_{XY}$	MPR node selected by nodes X and Y
HNA$_X$	HNA message generated by cluster head X
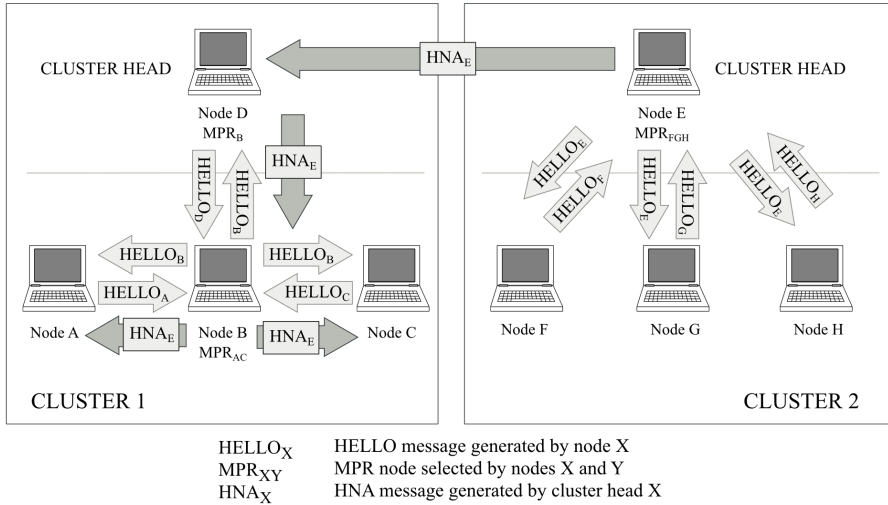
Figure 3.4 ADHOCSYS HOLSR control messages

As shown, node E, working as CH, sends an HNA message to other clusters in order to inform about the reachability of the nodes inside the Cluster 2. As CH of Cluster 1, node D spreads that HNA message to the other nodes. From that point, these nodes know that the path to reach every node in Cluster 2 involves going through the CH towards the other cluster. Furthermore, in order to keep HELLO and TC messages bounded within one cluster, address aggregation and private address allocation are used as simple mechanisms for this purpose.

The main difference between this approach and CRC HOLSR is that only HNA messages, which are already considered in standard OLSR, are used for both inter-cluster and intra-cluster topology dissemination, while new additional messages, such as HTC messages, are used for inter-cluster topology dissemination in CRC HOLSR. In other words, no modifications to HELLO and TC messages, or MPR selection, are initially foreseen in the proposed ADHOCSYS approach. Preliminary implementation details on real embedded devices are described in Appendix B.2.

With the aim of comparing the routing behavior of the proposed HOLSR with other previous proposals, a flat OLSR network and a hierarchical network using CRC HOLSR are set up and assessed as well, with the same number of nodes and traffic conditions. The NS-2 implementation should be able to demonstrate how the proposed solution performs in terms of connectivity, scalability and quality of real-time services.

3.4. Routing performance evaluation

Both OLSR and HOLSR are proactive routing protocols. The main characteristic of proactive protocols is that each node in the network steadily keeps and updates a route to every other node in the network all the time. Therefore, routes are always available when they are needed. As a consequence, although no initial delay exists in data communications due to route discovering, it is true that there is a constant overhead because of the periodic routing traffic. This constant overhead could become a disadvantage in large ad hoc networks or in ad hoc networks with high mobility of nodes.

3.4.1. Routing performance metrics and simulation scenario

Regarding the routing behavior, the performance of the OLSR, CRC HOLSR and ADHOCSYS HOLSR protocols is evaluated in terms of the following parameters:

- *Convergence Time*: time spent by the routing protocol to stabilize the routing information in all wireless nodes (in seconds).

- *Control Overhead*: amount of control packets transmitted by the routing protocols (in packets/s).

Both parameters are useful to evaluate the efficiency of the routing protocols, no matter the kind of traffic transmitted between nodes.

The scenario consists of a wireless ad hoc network, in which the amount of nodes forming the network is varied in order to evaluate the routing protocol behavior as the network grows. Hence, the time it takes for all nodes to know the route to any other node is measured and established as the convergence time. Moreover, the amount of routing packets generated using the different routing mechanisms under study is also measured and stated as the control overhead.

The radio model used for simulation is based on the Two-Ray Ground Propagation Model and the standard 802.11b. Node transmission and carrier-sensing ranges are approximately 170 m and 423 m respectively. The channel capacity was set to 11 Mbps. The traffic model used to gather the numerical results consists of constant bit rate (CBR) sources defined over 20 communication links among nodes randomly selected. Each communication session consists of two UDP packets, 512 bytes long, being transmitted every second, resulting in transmissions of approximately 8 kbps. The control overhead is measured in terms of the amount of control messages generated by the routing algorithm. In order to obtain these results, average measurements are presented. Every simulation takes 30 seconds and nodes are statically distributed, although they are randomly located along the simulation area in every different iteration. Nodes in the HOLSR simulation are distributed within two clusters of size 400 x 400 square meters with the CH nodes in the middle connected by a direct wireless link with a transmission range of 960 m. For the OLSR simulation, the scenario size is 800 x 400 square meters.

3.4.2. Routing simulation results

In this section, results show how the assessed routing protocols work regardless of the traffic sent. Firstly, the convergence time achieved depending on the network size is depicted in Figure 3.5. Not only should this time be considered as a startup time, but also it is meaningful to understand the behavior of the routing protocols before routing breakages. Hence, it is shown that the time used by the OLSR protocol until it converges, i.e. when every node from the network knows the route to reach every other node, varies deeply depending on the number of nodes forming that network. However, both HOLSR protocols keep this time nearly constant until the network converges. That is due to the fact that the stability of a cluster is achieved faster than the whole network and, at the same time, the cluster heads exchange information among them (through HNA or HTC messages) about the nodes that belong to their cluster. Even so, ADHOCSYS HOLSR is slightly faster than CRC HOLSR, as discussed later.
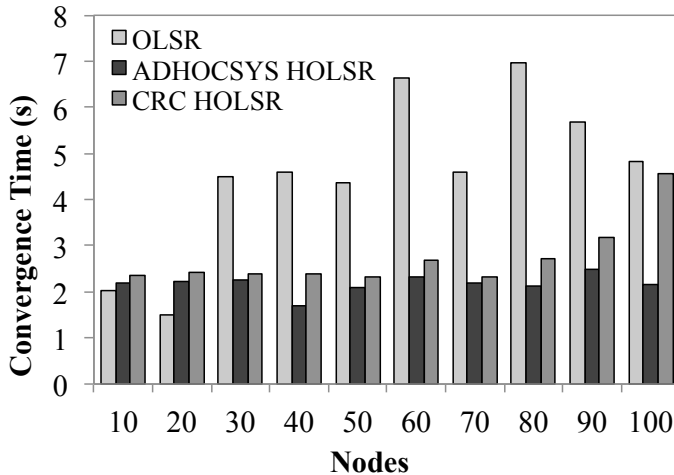
Figure 3.5 Convergence time in OLSR and HOLSR protocols

As regards routing overhead, Figure 3.6 shows that in networks with less than 40 nodes, flat routing protocols have a slightly smaller overhead of routing messages. From 40 nodes on, the overhead in OLSR protocol grows substantially (due to TC message generation), whereas in the hierarchical scenarios (using HOLSR protocols) it grows gradually. That is due to the fact that when the clusters have a more reduced size than the whole network, there is no need to generate so many TC packets.
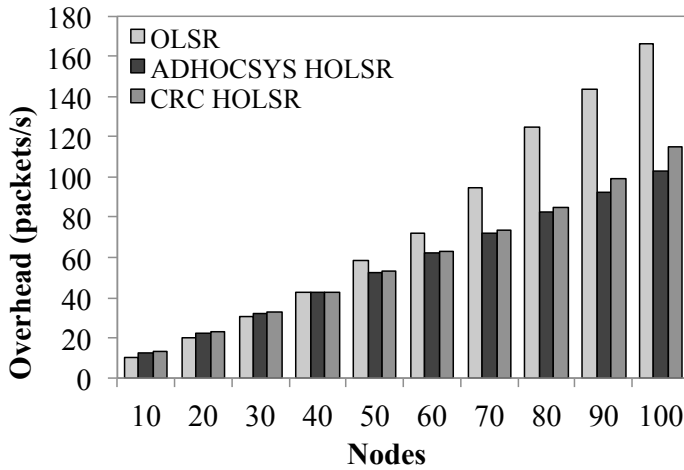
Figure 3.6 Routing overhead in OLSR and HOLSR protocols

Although the idea of using flat routing protocols could be considered in small networks (less than 50 nodes approximately), using hierarchical routing will produce almost the same performance as these results show. Moreover, when the network is bigger (more than 50 nodes), it can be found apparent scalability problems in OLSR protocol, whereas in the HOLSR protocols a lineal growth is maintained with regard to the overhead. Apart from that, this routing traffic is kept within each cluster because of the use of private address allocation and aggregation. Using subnet-directed-broadcast addresses bounded by addresses with a netmask, broadcast messages will be received and correctly interpreted only by nodes within the same cluster. Due to this fact and as Table 3.2 shows, the amount of TC packets in moderate or big scenarios is significantly smaller in HOLSR, reducing the total routing overhead.

Table 3.2   Average routing overhead for OLSR, ADHOCSYS HOLSR and CRC HOLSR (packets/s)

Algorithms	OLSR		ADHOCSYS HOLSR			CRC HOLSR		
Nodes	HELLO	TC	HELLO	TC	HNA	HELLO	TC	HTC
10	10,00	0	12,00	0	0,32	12,00	0	1
20	20,04	0	22,03	0	0,35	22,04	0	1
30	30,00	0,233	32,03	0	0,37	32,05	0	1
40	39,57	2,776	42,00	0	0,39	42,01	0	1
50	46,18	11,95	52,01	0	0,44	52,02	0,03	1
60	54,43	17,63	61,96	0,05	0,46	62,00	0,19	1
70	63,85	31,08	71,80	0,22	0,52	72,05	0,78	1
80	77,06	47,84	80,38	1,89	0,64	82,21	2,22	1
90	89,83	53,62	86,84	5,32	0,75	92,00	6,56	1
100	95,00	71,69	93,43	9,24	0,84	102,10	12,16	1

Taking into account the previous results, it can be stated that both CRC HOLSR and ADHOCSYS HOLSR have similar performance as could be expected. However, ADHOCSYS HOLSR presents shorter convergence time. This is due to the fact that the cluster head takes out the subnet configuration of its interfaces from the beginning, and therefore, the nodes can establish the routes towards other clusters since the first HNA received. As a drawback, cluster heads have to be statically configured and cannot be selected dynamically among the available nodes. On the other hand, HTC messages in CRC HOLSR do not contain all the routes to the nodes belonging to the same cluster until the cluster has been entirely formed. As for the number of messages used, CRC HOLSR uses a slightly bigger amount of packets to obtain similar performance regarding the convergence time.

3.5. Video performance evaluation

For the reasons explained before and once the scalability of hierarchical routing protocols has been proved, from now on only the proposed ADHOCSYS HOLSR is compared to the flat OLSR. Despite the similarity of both hierarchical protocols, ADHOCSYS HOLSR keeps message compatibility with the standard OLSR and has slightly better performance than CRC HOLSR. This procedure will be enough to assess and compare video performance in both flat and hierarchical scenarios.

3.5.1. Video simulation scenario

In order to evaluate and compare the performance of OLSR and ADHOCSYS HOLSR regarding video transmissions, a simulation scenario has been set up using NS-2 and Evalvid tools for trace generation and video assessment. Simulation environment consists of 50 wireless nodes (moderate-scale network size) forming an ad hoc network

using OLSR as the routing protocol in an area of 1200 x 600 square meters. With regard to the HOLSR protocol, the network architecture is defined using two clusters connected by a point-to-point link. Radio model, medium access and coverage range are the same as those used in Section 3.4.1. Each of these clusters is defined as an area of 600 x 600 square meters, containing the same amount of nodes. The duration of every simulation is 200 seconds.

Every node in the simulation scenario, including source and destination, moves according to the RWM. As in the previous chapter, different values are assigned to the pause time parameter, from 0 to 200 s, while nodes are moving at a maximum speed of 5 m/s. Also, a mobile scenario has been assessed by varying node maximum speed from 5 to 20 m/s with a pause time of 0 s (nodes continuously moving). In the clustered scenario, nodes move freely according to the RWM but constrained to the geographical area of the cluster they belong to.

The video trace file used in the simulation is again *mobile.yuv* [35] with a size of 176x144 (QCIF) and 30 fps of frame rate. The video loop is generated with duration of 170 s, encoded into an MPEG-4 video file using the common GoP pattern IBBPBBPBBPBB. The traffic load used consists of 20 UDP CBR sessions established between nodes that are randomly selected. Again, each source sends two packets of 512 bytes every second, nearly 8 kbps. This can be considered as moderate background traffic.

3.5.2. Video performance metrics

With the aim of comparing both protocols, PSNR, packet delivery ratio (PDR) and end-to-end packet delay are chosen to measure the quality of the video transmission sequence. These parameters are tightly related to QoS. Firstly, PSNR shows the difference between the received sequence and the original one pixel by pixel. Incidentally, the reference value for the video file used as regards PSNR is 24.37 dB on average. Secondly, PDR metric is defined as the percentage of video packets successfully delivered to the destination against total packets sent. Finally, it is worth stating that end-to-end packet delay is measured at application level, so it takes into account all the delay suffered by a packet that does reach the destination, including queuing, propagation and transfer time.

Additionally, another performance metric is defined, namely *interruption*. An interruption is observed when one or more consecutive frames cannot be decoded due to losses of some video packets. The nature of the Human Visual System (HVS) makes it very difficult for a viewer to notice distortion if only a small amount of consecutive frames are lost. However, when the number of lost packets increases beyond a limit, the distortion can be noticed. Therefore, the seriousness of an interruption depends on how long the interruption occurs.

Interruptions can be classified according to their seriousness as *minor* and *major interruptions*. Depending on coding parameters and the GoP size of the encoded video,

interruptions could vary in seriousness. In this case, it is established that an interruption must be considered minor if it lasts shorter than 1 GoP, which, according to the GoP size (12 frames) and the frame rate (30 fps) of the encoded video, it is equivalent to 0.4 s. Also, taking into account the video encoding parameters used in this evaluation, minor interruptions do not cause a distortion greater than 0.76 s at worst. That is due to the fact that a minor interruption could lose only one intra frame at the most, as can be observed in Figure 3.7, so the distortion effects are perceived just until the next intra frame is received. On the other hand, then, a major interruption is defined when the video interruption lasts 0.8 s or more. Long interruptions distort the received video or even might stop it momentarily. It is worth mentioning that the frequency the interruptions occur is another parameter to be considered as well. Interruptions may be considered as a parameter rather related to the QoE experienced by the user.
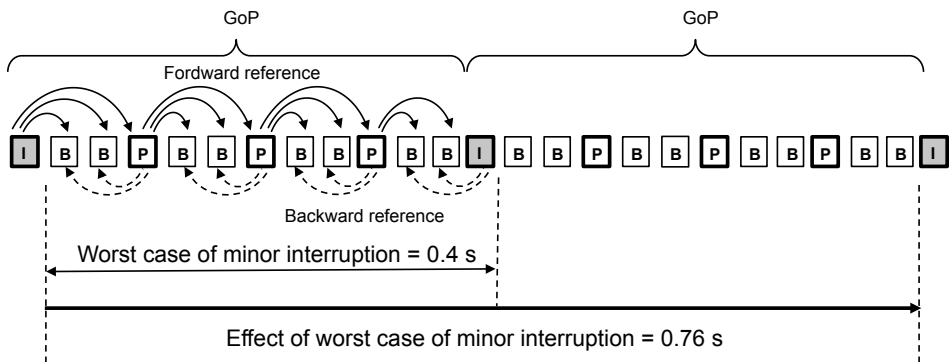
Figure 3.7 Graphical relationship between video GoP structure and worst case of minor interruption

3.5.3. Video simulation results

As mentioned in previous sections, the quality of video transmissions is highly affected by node mobility. Both lower pause times and higher node speeds correspond to the worst scenario because wireless nodes are likely to change packet routes quite often. The hierarchical structure of HOLSR may help reduce the effect of mobility in the network.

Concerning pause time, results are presented in Figure 3.8 for average PSNR, PDR and end-to-end delay. Paying attention to the PSNR metric in Figure 3.8a, it can be observed that the average PSNR of both protocols increases when the pause time grows. However, HOLSR improves the average PSNR between 1 dB (for a pause time 200) and more than 3 dB (precisely, for a pause time of 150 s, the average PSNR is 20.32 dB in OLSR and 23.52 in HOLSR). Provided that the same parameters and conditions are used in every simulated scenario for both protocols, the results obtained permit to evaluate the improvement when the ad hoc network is configured by means of clusters and a head node is in charge of the communication among the different clusters.
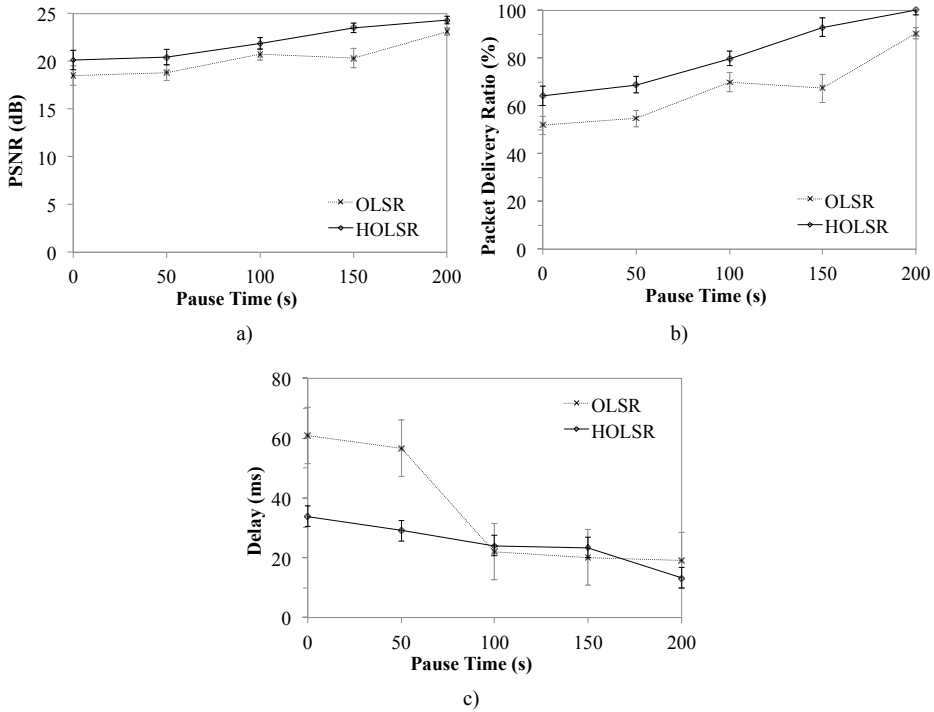
Figure 3.8 Average PSNR (a), Packet Delivery Ratio (b), and end-to-end delay (c) vs. pause time

By definition, PSNR results are close related to packet losses. In this sense, Figure 3.8b shows the results about the delivery ratio measured during the simulations. The main reason for packet losses is the route breakages and the resulting time spent on rerouting. Therefore, it can be stated that the bigger the pause time, the bigger the percentage of packets delivered, since node mobility is reduced. Also, it can be pointed out that as the mobility diminishes, HOLSR quickly increases the delivery ratio. For instance, for a pause time greater than 100 s, the delivery ratio is over 80%. Furthermore, Figure 3.8c depicts the end-to-end delay for the video transmissions. It is shown that when there is a high degree of mobility (from 0 s to 100 s of pause time), HOLSR delivers data packets quicker than OLSR. The main causes are the low convergence time and low overhead generated by HOLSR, which make that route recalculation could be achieved faster. Finally, under a low degree of mobility (from 100 s to 200 s of pause time) both protocols have similar results.

Another way to see the effect of mobility in video transmission is varying the speed of wireless nodes. As Figure 3.9a shows, both protocols follow similar trend to decrement the PSNR with the speed. However, OLSR seems to be much more sensitive to the effects of the nodes' mobility, showing worse results. Figure 3.9b highlights the effect of the speed concerning PDR. In this sense, OLSR suffers a very high percentage of

video packets loss. From the results, it is clear that the HOLSR protocol delivers at least 20% more packets than the flat OLSR protocol for a maximum speed of 5 m/s and more than 40% for 20 m/s. As regards packet delay, the difference between both protocols can be seen in Figure 3.9c. Note that the average packet delay is also depicted for the static scenario (node speed of 0 m/s). This can help compare other values of packet delay when nodes are in movement. In this sense, retransmissions at MAC level due to packet loss cause delay to increase as node speed increases. The time the packets remain in queues waiting for the routes to be recalculated also contributes to enlarge this end-to-end packet delay. Taking into account the speed of mobile nodes, simulation results show that HOLSR has always better performance than OLSR, i.e. HOLSR has the shortest delay (no more than 50 ms). This is due to the fact that in a hierarchical environment routes between clusters are recalculated faster due to the less variable links between cluster heads. Moreover, the overhead reduction helps to avoid bigger packet delivery delay.
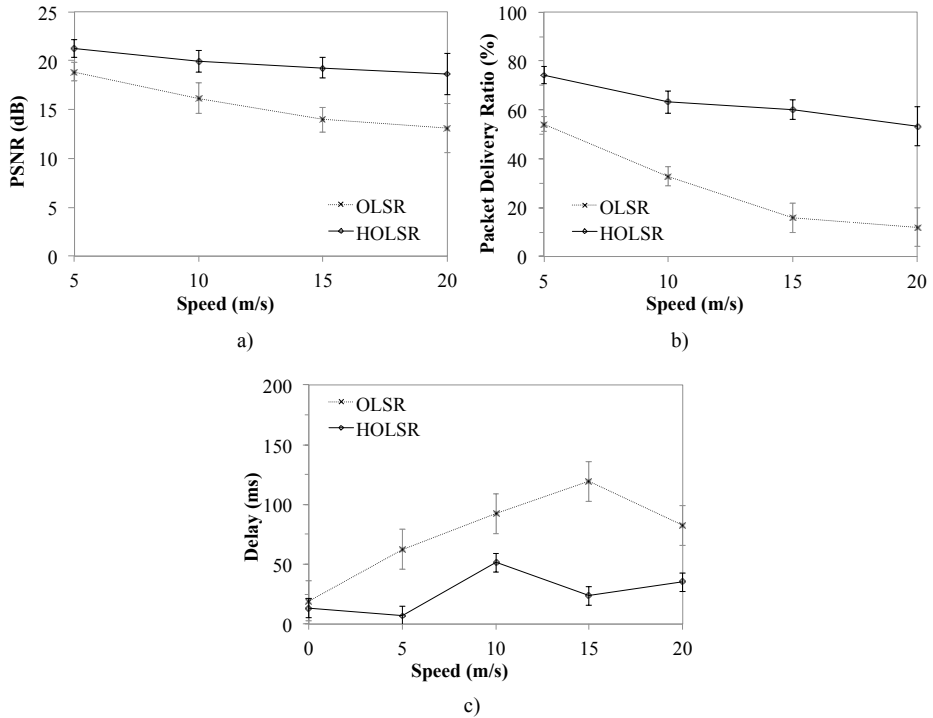
Figure 3.9 Average PSNR (a), Packet Delivery Ratio (b), and end-to-end delay (c) vs. speed

This essential improvement of HOLSR with regard to flat OLSR is mainly due to the cluster formation. When a route is lost or a link falls in flat OLSR, the recently found route could be totally different and could use different nodes so the MPR set has to be recalculated. In HOLSR, the hierarchical architecture forces to pass through the cluster

heads and hence, there is a part of the route that remains static, allowing a faster recovery of the broken route.

Finally, the occurrence of interruptions is examined in order to have a closer look on the video quality. As aforementioned, minor interruptions cause small distortion effects on video stream. Figure 3.10 draws the amount and cumulative length of minor and major interruptions measured in the simulations varying the pause time. It can be seen from Figure 3.10a and Figure 3.10b that even if the number of minor interruptions is close to 60, it hardly means 2.5 seconds in all, against 200 seconds which is the total time simulation. It can be also observed that HOLSR has better performance than flat OLSR in the measured range, and practically has no minor interruptions in scenarios with low mobility. Figure 3.10c and Figure 3.10d illustrate the results for major interruptions, which cause more noticeable distortions. The number of interruptions and the total length decrease when pause time increases, as can be expected. Comparing both protocols, it can be observed that there are less interruptions and a shorter duration in HOLSR, so that means that there will be fewer gaps on the received video. This is important because by reducing major interruptions, users do not perceive that video freezes frequently.

a)   b)

c)   d)
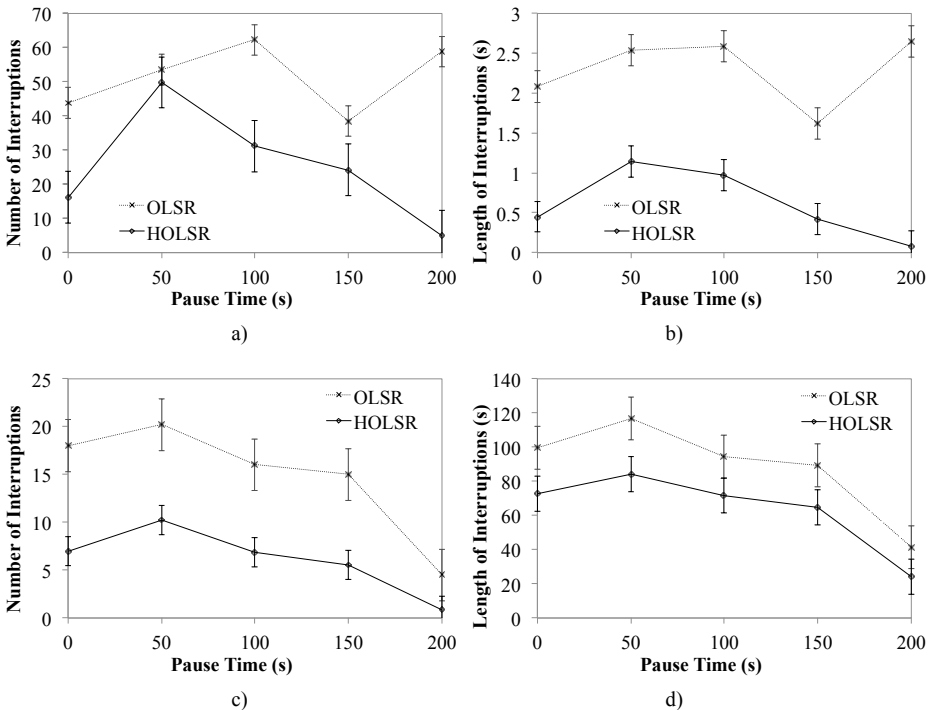
Figure 3.10   Video interruptions vs. pause time: number (a) and cumulative length (b) of minor interruptions; number (c) and cumulative length (d) of major interruptions

Moreover, Figure 3.11 shows how minor and major interruptions occur according to node speed. Although HOLSR works better with low average speeds, both protocols have similar behavior regarding minor interruption length in high node speeds. Curiously, duration of minor interruptions decreases as node speed grows. This is due to the fact that node mobility causes larger interruptions, so in this case, most of the interruptions will be considered as major. Therefore, it is worth paying more attention to the behavior of major interruptions. In this regard, HOLSR has better performance than flat OLSR due to its hierarchical structure. Although HOLSR has more interruptions for high speeds, the total duration, as well as the distortion effect caused, is smaller.
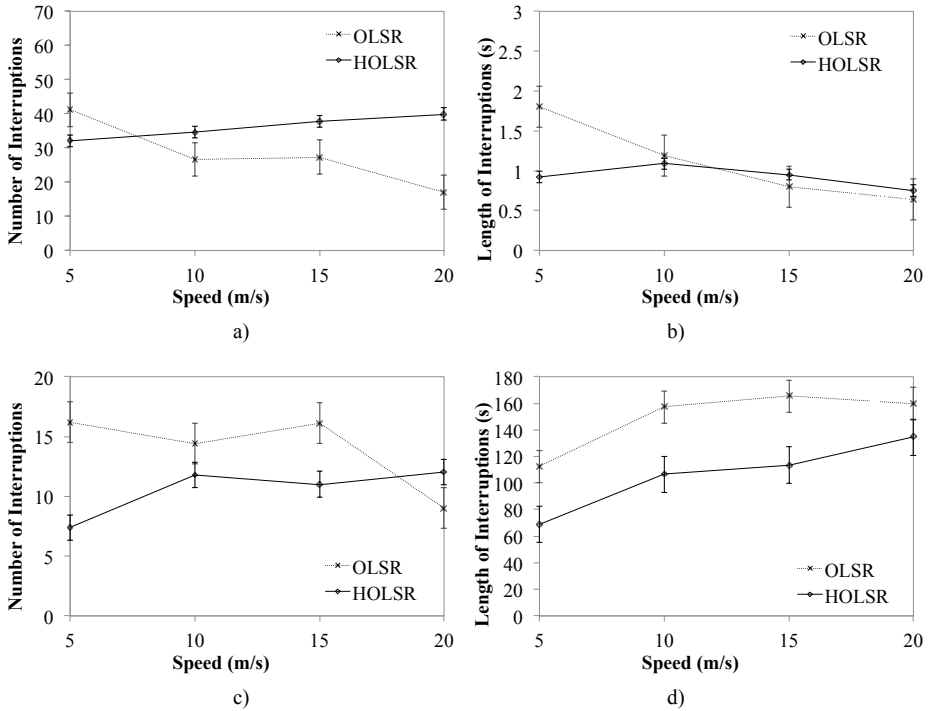
Figure 3.11 Video interruptions vs. speed: number (a) and cumulative length (b) of minor interruptions; number (c) and cumulative length (d) of major interruptions

3.6. Improving QoS over HOLSR

Results have shown that not only does HOLSR overtake flat routing in terms of convergence time and packet overhead, but also it performs better for video transmissions regarding PSNR, packet delay and video interruptions in scenarios from low to high mobility. Nevertheless, even though HOLSR improves video quality at a certain extent, packet losses in both protocols could be unacceptable in some situations

due to the effect in the received video that they involve. Therefore, some QoS improvements can be proposed from this point in order to reduce losses and consequently, enhance video transmissions.

3.6.1. Drawbacks for QoS guarantees

First, some considerations have to be taken into account to draw a balanced picture of the scenario. On the one hand, it is true that in order to take advantage of a hierarchical environment, nodes with cluster-head capabilities are needed. These nodes should have better performance on processing capability, bandwidth, transmission range and power consumptions, besides multiple interface connectivity. Given the heterogeneous nature of the present networks, where devices with different characteristics (mobile phones, laptops, PCs) coexist, it is possible to find the appropriate devices to perform cluster-head tasks. This could be a problem in other kinds of networks where all devices have lower characteristics and none of them has two interfaces or wide transmission range. In these cases, the ad hoc network hardly supports real-time services (e.g. video streaming). Therefore, in these scenarios it could be necessary to have some kind of wireless ad hoc infrastructure, i.e. preconfigured MPR nodes in OLSR and cluster heads in HOLSR.

On the other hand, in a hierarchical architecture all outgoing traffic to other clusters must go through the cluster head, increasing the overload between cluster heads and even causing packet losses due to congestion. In this sense, an evaluation of the traffic load supported by the cluster heads in these cases is carried out in this section. The simulation scenario is formed by two clusters with 5 nodes each one. The background traffic model used consists of 12 CBR sources counting both clusters. Each communication session consists of UDP packets, 1000 bytes long, being transmitted every second. By changing the sending interval, we can achieve link loads from 10% to 100% of the theoretical maximum. The radio model is the same as used in previous sections. The average results regarding the transmission of a video flow from one cluster to another have been presented.
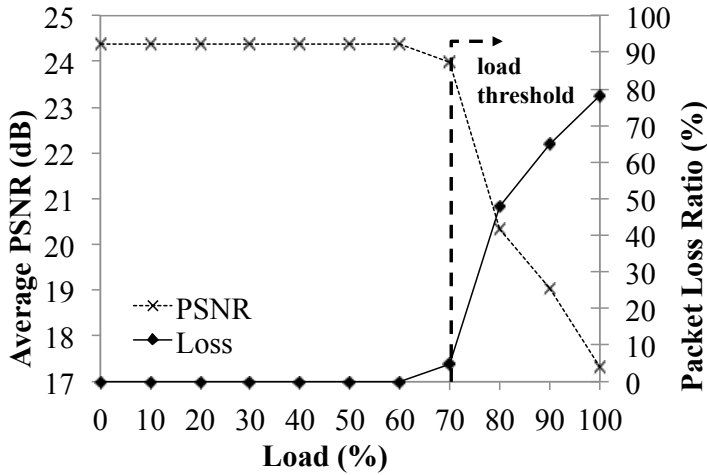
Figure 3.12   Average PSNR and packet loss ratio vs. cluster heads link load

Figure 3.12 shows the average PSNR and packet loss ratio of the received video depending on the link load between cluster heads. When load reaches 70% of traffic capacity, PSNR drastically falls and the packet delivery loss increases considerably. For instance, PSNR descends almost 4 dB from the reference value when the traffic load is 80% because of the transmission degradation. This practically corresponds to 50% of packet losses. In such situations, it would be interesting to predict a congestion event and do not let video quality be degraded excessively. Therefore, a threshold can be established before packet losses start to be unconcealable. For example, a threshold when the load reaches 70% can be defined, even though it is a conservative threshold. For traffic load exceeding the defined threshold, it will be interesting to take any kinds of measures in order to reduce this overload. This can be achieved either with adaptive algorithms that reduce the sending rate, which implies cross-layer mechanisms, or by balancing the traffic load using new alternative routes, as proposed in the following section.

3.6.2. Load balancing and distributed admission control for QoS

In a hierarchical environment, QoS can be achieved at two levels: intra-cluster and inter-cluster solutions. Intra-cluster solutions refer to mechanisms used within the same cluster as though it was a whole network. For this purpose, this kind of algorithm should acquire some measures about the network behavior, as occurs in QOLSR [45]. QOLSR proposes a modification of OLSR, adding a new heuristic method that considers QoS parameters when selecting MPRs. In QOLSR, then, a modification in HELLO and TC messages is needed in order to include information about the delay metric of every node, and bandwidth consumption can be added as well. In addition, for the successful measurement of packet delay, a single global time axis is required, and it

is achieved by means of synchronizing nodes with GPS, NTP or another efficient synchronization protocol.

Additionally, intra-cluster solutions can be used together with other inter-cluster approaches. By studying the proposed hierarchical scheme and simulation results, it can be concluded that packet losses are mainly produced by collisions in the radio channel of the cluster head, which is not capable of receiving all packets directed to other clusters. Increasing inter-cluster link bandwidth will have no effects since collisions occur at cluster channel level. An interesting method to avoid this problem could be the discovery of new routes to other clusters through new cluster heads.

The basic idea of the proposed inter-cluster solution is depicted in Figure 3.13. Each cluster head obtains an estimation of the output channel losses towards other clusters. Then, a cluster will be able to include a new route to other cluster in order to balance the traffic load when these losses exceed a certain threshold.
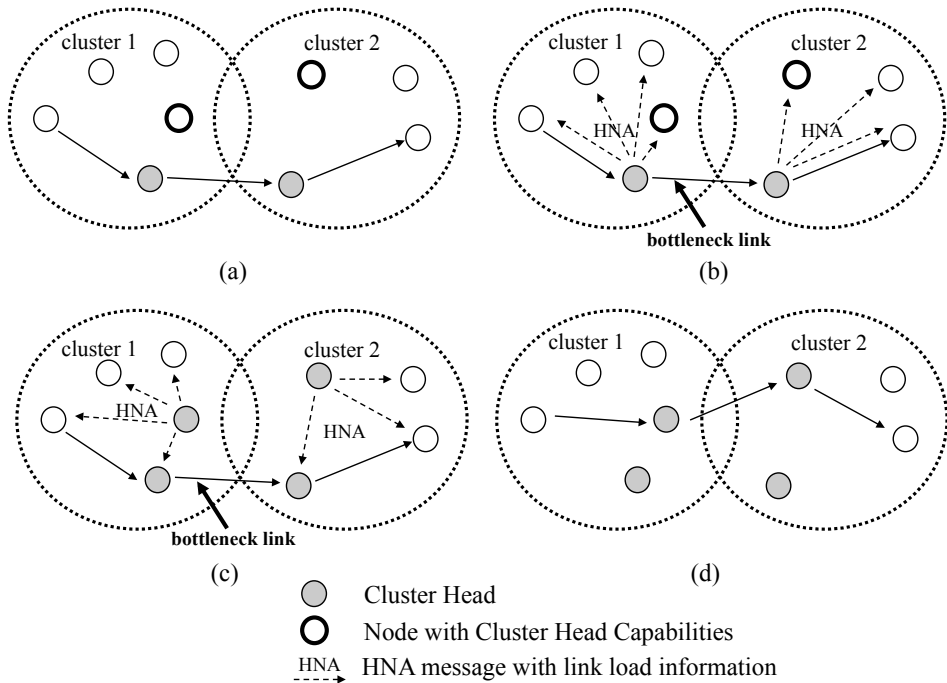
Figure 3.13   Selection of new routes based on HNA message information

Essentially, the proposed method consists in including on HNA messages generated by the cluster head, information about the link load so it can be spread to other nodes in the cluster (Figure 3.13b). When any two-interfaced node receives an HNA message with a high load ratio meaning that the cluster head is overloaded, it might be possible that this node becomes a cluster head itself and starts sending HNA messages to neighbor nodes

(Figure 3.13c). This will depend on whether this node has cluster-head capabilities, i.e. when besides two wireless interfaces, it has also enough battery life and computing performance. The nodes receiving HNA messages from both cluster heads may select one of them, depending on their traffic load or the link losses of each cluster head (Figure 3.13d).

Moreover, when a cluster head is overloaded, it has to be capable of carrying out control access and rejecting new packet flows so the current connection quality does not result deteriorated. In [75], a Distributed Admission Control for MANET Environments (DACME) is described. The authors propose to send end-to-end messages in order to interchange QoS-related parameters, such as the available bandwidth. Using this parameter, the source node decides whether an incoming connection can be established. Intermediate nodes just forward these messages so they participate on admission control tasks without being aware of it. In the same manner, cluster-head nodes in the presented hierarchical architecture inform by means of HNA messages of the link load towards other clusters. If the cluster heads receive new streams but the threshold is exceeded, they could drop the new connections until the link load between cluster heads decreases.

In order to assess the performance of this proposal, new simulations have been carried out. The proposed Balanced HOLSR (BHOLSR) has been compared with previous HOLSR and flat OLSR. The simulated scenario comprises 40 static nodes randomly spread over an area of 600 x 300 square meters (two clusters of 20 nodes each in an area of 300 x 300 square meters for the hierarchical protocols). The radio model used is 802.11b at 11 Mbps for OLSR and intra-cluster communication in HOLSR and BHOLSR. Additionally, 802.11g at 54 Mbps is used for inter-cluster communication in both hierarchical protocols. However, transmitting power has been increased in order to achieve an inter-cluster coverage range of approximately 540 m, ensuring the communication between cluster heads. Intentionally, traffic flows are sent from arbitrary nodes from one cluster to nodes from the other. The same source and destination nodes are used when assessing OLSR, which obviously does not discern any hierarchy or cluster formation. In order to observe the effect of traffic overload, offered load is gradually increased in steps of 400 kbps on average every 10 seconds, until a maximum of 4 Mbps. This way, the behavior of the studied routing protocols can be assessed as traffic data rate increases and also when offered load overtakes the maximum sustainable capacity. As estimated from Figure 3.12, a threshold of 70% is set in BHOLSR to trigger the balancing mechanism and try to find new routes through other nodes that may become cluster heads. Simulations last 200 s and traffic flows start at 50 s after the beginning of the simulation in order to let routing protocols converge. Average throughput according to the offered load is depicted in Figure 3.14, comparing OLSR, HOLSR and BHOLSR.
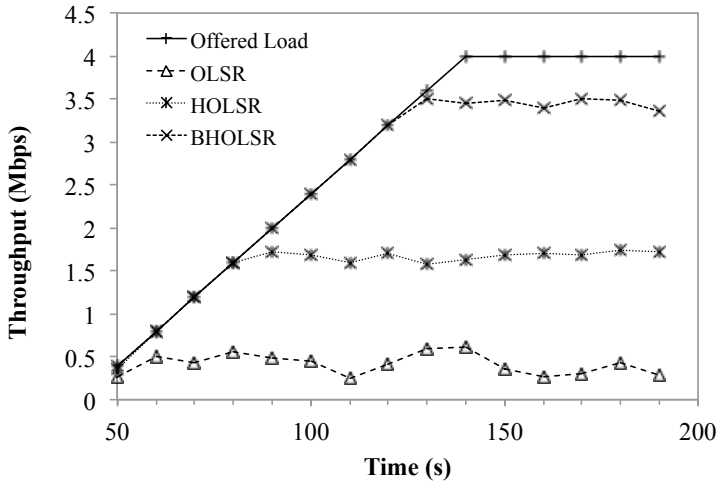
Figure 3.14   Throughput comparison between OLSR, HOLSR and BHOLSR vs. offered load

As observed, OLSR is very sensitive to interferences and, therefore, throughput never reaches the offered load due to the large length of transmission paths (between 7 and 12 hops) and packet collisions, which may even cause route recalculation if OLSR control packets are lost. On the contrary, HOLSR achieves higher throughput due to the fact that the number of hops is reduced by using inter-cluster dedicated links. However, when cluster heads become overloaded, packet losses occur and throughput is negatively affected. Even when the offered load is high and saturates cluster heads, throughput is improved by approximately 280% compared with flat OLSR. In contrast, BHOLSR achieves greater throughput because of the load balancing mechanism. Moreover, it is worth noting that BHOLSR will work properly provided that secondary cluster heads are available in order to alleviate traffic congestion near the main cluster head link. In the performed simulations both main cluster head and secondary cluster head become overloaded just before the end of the simulation, and as long as no other secondary cluster head is available, packet losses unavoidably occur. Even so, when the offered traffic overtakes the maximum network capacity, average throughput using BHOLSR is 200% higher than using HOLSR, and almost 570% higher than using flat OLSR. This is due to the fact that the new cluster heads provide alternative routes to other clusters, reducing traffic congestion near the main cluster heads and shortening the path length, that is, the number of hops.

Finally, Figure 3.15 shows the load ratio of main cluster head and secondary cluster head during the simulation. These cluster heads belong to the cluster that contains the source nodes.
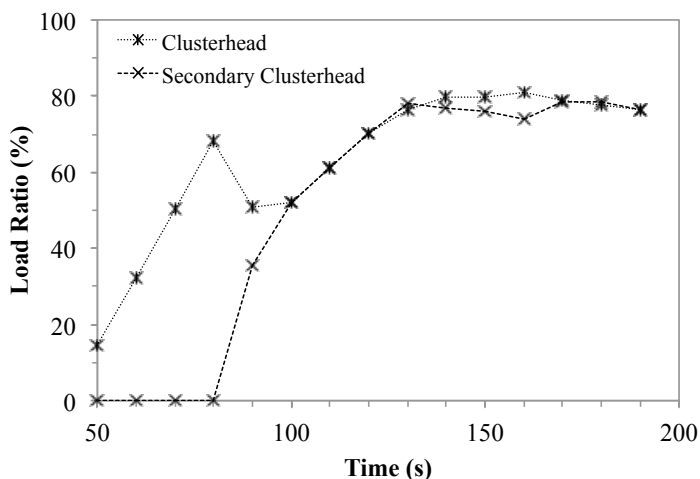
Figure 3.15 Load Ratio of main cluster head and secondary cluster head

As aforementioned, when load ratio reaches the threshold (70%), the balancing mechanism is triggered and another node starts announcing itself as a secondary cluster head. Since then, traffic is balanced avoiding packet interference and congestion around the main cluster head. Obviously, if there is not any other secondary cluster head available when offered load increases, load ratio of both cluster heads may pass the threshold because there is no possibility of redirecting incoming traffic through other routes.

Since the proposed QoS solution works together with hierarchical routing protocols, the presented proposal can be used itself as a multipath routing protocol, where source nodes can send packets through multiple routes if there are multiple cluster heads available. This increases the range of possibilities regarding video transmission as far as new multipath and Multidescription video encoding techniques could be employed [76].

3.7. Conclusion

Hierarchical routing has been presented as a way of arranging wide ad hoc networks in clusters to improve network efficiency. Although the clustering mechanism may lead to an increase in control traffic and complexity, routing protocols can benefit from hierarchical structures so that routing flooding, especially in proactive protocols, can be confined within clusters and nodes can be arranged in virtual groups to optimize communications and reduce interferences. Hence, the resulting network may scale well when the number of nodes grows. These facts have been proved in this chapter, where a thorough study has been carried out, considering a well-known flat protocol (OLSR) and two algorithms based on a hierarchical protocol (HOLSR). The proposed ADHOCSYS HOLSR has demonstrated to have better results on performance

evaluation regarding scalability and packet losses. Particularly, this protocol gets better PSNR (differences from 1 dB to 6 dB in certain cases); reduces packet delay (by almost 100 ms) due to the low convergence time and by reducing the total amount of hops in the path; and causes less control overhead than flat OLSR, so the packet delivery ratio becomes higher (differences from 10% to 50%).

Nevertheless, the main drawback of a hierarchical framework is the necessity of a minimal infrastructure to act as cluster heads when no other nodes are available. This could happen even in heterogeneous networks when devices only have a single wireless interface. Moreover, another issue that has to be taken into account is the overload that the link between cluster heads could bear. The studies conducted in this chapter point out that packet loss is mainly caused due to congestion around the cluster head when neighboring nodes are trying to send data through this cluster head towards other clusters. In this sense, a new approach is proposed in order to improve QoS for inter-cluster communications. The balancing proposal BHOLSR is presented as an enhancement of HOLSR that uses the traffic load information in cluster heads in order to take advantage from the hierarchical structure and let other qualified nodes become cluster heads and alleviate inter-cluster link congestion. Results have shown that BHOLSR remarkably improves throughput due to the fact that new routes are dynamically discovered and established between clusters (about 200% better than HOLSR and 570% better than flat OLSR).

Finally, it is worth highlighting that the proposals presented in this chapter, as well as the QoS enhancements, could be perfectly merged with other approaches in other layers and communication levels and, moreover, are completely suitable in the concept of wireless mesh networks (WMNs) due to the hierarchical structure of the supporting backbone.

Chapter 4

Altruistic OLSR: A Cross-layer Recovering Mechanism for MANETs

Video streaming services have restrictive delay and bandwidth constraints. Ad hoc networks represent a hostile environment for this kind of real-time data transmission. Emerging mesh networks, where a backbone provides more topological stability, do not even assure a high Quality of Experience. In such scenario, mobility of terminal nodes causes link breakages until a new route is calculated. In the meanwhile, lost packets cause annoying video interruptions to the receiver. This chapter proposes a new mechanism for recovering lost packets by means of caching overheard packets in neighbor nodes and retransmit them to destination. Moreover, this cross-layer technique can be improved using video aware cache, which would be able to recover full frames and prioritize more significant frames. Results show the improvement in reception, increasing the throughput as well as video quality, whereas larger video interruptions are considerably reduced. Overhead and energy consumption are also taken into consideration.

4.1. Introduction

Mobile ad hoc networks (MANETs) are infrastructureless wireless networks where nodes act as relays in order to forward packets from source to destination when they are not directly within the same wireless transmission range. Consequently, every node should be able to forward packets addressed to other nodes. In this kind of network, routing protocols are in charge of establishing routes towards destination. When the

number of hops increases in a route, the throughput is negatively affected. This is due to the fact that the packet loss probability and the interferences caused by the intraflow contention are increased in every additional link [25]. Moreover, mobility of nodes makes it difficult to create and maintain these routes. When any node moves out of range of its neighbor, the entire route (or partially) has to be recalculated. Within this rerouting time, packets cannot be delivered, causing packet losses and non-negligible delays.

New wireless technologies and enhancements (e.g. 802.11n, 802.11ac, etc.) are being developed with the aim of increasing transmission rate and capacity, but in contrast, new services appear, which have higher bandwidth requirements. On the other hand, current technologies are wide spread and have more and more users. For this reason, it is worth taking advantage of these existing technologies and proposing new improvements that allow current infrastructures and standards to be used, always without losing sight of the upcoming technologies. This will be helpful in order to provide these new services with Quality of Service (QoS) attending to the new requirements that they entail.

MANETs can be set up at very low cost compared with those networks based on access points that need wired infrastructure support. However, due to the difficulty of maintaining minimum QoS conditions, ad hoc networks tend to be designed with a static wireless backbone, which provide them with the minimum structure to assure connectivity and stability to a certain extent. This is the case of the upcoming wireless mesh networks (WMNs) [77], which could become a trade-off between cost effort and the transmission quality offered [78].

A typical wireless mesh scenario is depicted in Figure 4.1, where a hierarchical structure can help in stabilizing routes despite the mobility of some terminals. In case a destination node is moving around in such environment, packet losses are likely to be concentrated on the last hop, when such node moves out of the forwarding neighbor range. When this occurs, next packets cannot be sent and could be discarded as long as the new route is not established. In the event that these packets have arrived correctly at the node preceding the destination, it makes sense to make an effort to finally reach those packets to their destination without having to be discarded or resent again through a new route consuming time and resources. Since any neighbor of the destination node may have overheard those packets, it can become an altruistic node and forward those packets, although it does not take part of the original packet path.
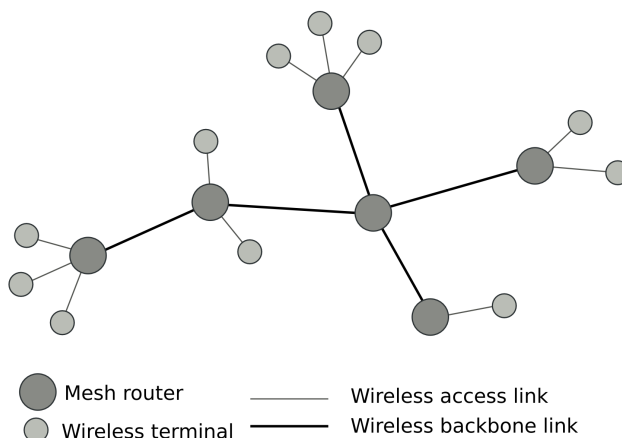
Figure 4.1 Typical mesh network topology

Video streaming services, which are increasingly demanded nowadays, are bandwidth-consuming services and may suffer from playback interruptions when packet losses occur. These interruptions can be annoying and may cause a significant decrease on the Quality of Experience (QoE) of the viewers. Routing protocols that do not consider these constraint conditions regarding packet delay and losses will not be suitable for video streaming and it could therefore result in diminishing video quality and cause interruptions. Hence, it is worth considering cross-layer routing solutions, which can extract useful information from other protocol layers. Furthermore, wireless networks have a particularity inherent to the wireless channel nature that is exploited by opportunistic [79] and cooperative routing protocols [80]. Neighbor nodes can overhear the packets that are being sent within their coverage area, even though these packets are not addressed to them, which is called Wireless Broadcast Advantage (WBA) [81]. This feature from the link layer can also aid the routing protocol in order to improve network performance and connectivity.

Following this idea, this chapter proposes a cross-layer packet recovering mechanism that benefits from the inherent broadcast nature of wireless medium in such a way that neighboring nodes of the destination node may help in recovering lost or undelivered packets within the last hop. This proposal increases the throughput and the mean quality experienced by the user in video transmissions, as it considerably reduces interruptions caused by link breakages and node mobility. In this sense, this proposal seeks to improve network connectivity and QoE of video streaming services. By definition, nodes belonging to an ad hoc network could become routers and forward traffic even if they are not part of these conversations. Following this philosophy, nodes can become cooperative nodes just because of the fact that they belong to the network. However, it is true that either being an ad hoc router or a cooperative node will consume battery and device resources. In situations when users do not want to waste device resources in helping foreign communications to be carried out, it would be necessary some

additional incentive, such as higher priority, or a penalty otherwise. Governmental or emergency networks are the typical examples where nodes cooperate for a common goal, but it is not limited to them as long as a proper motivation is offered. The proposed technique has been implemented as an improvement of the Optimized Link State Routing (OLSR) protocol [2], which is one of the proactive protocols most used in MANETs and mesh networks.

4.2. Related work

Ad hoc networks usually present a mesh topology, where every node may have one or more neighbors and any of them may act as a router. In order to benefit from this feature, multipath routing protocols store several routes for the same destination in order to be able to choose among the possible routes if the current one results broken [82] [83]. Moreover, an Automatic Repeat Request (ARQ) mechanism can be implemented to retransmit lost packets from the source through one of the alternative routes, increasing the overall throughput and even providing the possibility of changing to a new route seamlessly without video interruption [84]. Usually, routes are established taking into account the number of hops, but there are also other routing protocols that take into account information from other protocol layers so that the best route can be selected depending on various factors: path loss, delay, available bandwidth or link quality [85] [86]. Some of them can even control video quality parameters to adapt the transmission rate to the current network conditions and path bandwidth [87].

The ARQ method negatively affects real-time video streaming when packets are retransmitted frequently, because a higher end-to-end delay is introduced for each retransmitted packet, which can become deprecated and discarded, leading to video playback interruptions. In this sense, [59] proposes a cross-layer framework for video streaming, which incorporates special intermediate nodes through the path. These nodes act as video assistants, which are in charge of buffering video packets and retransmit them when destination node sends an ARQ. The requested frame is then sent back to the destination in a shorter time than the source could do. For this purpose, routes are built dynamically and the shortest path is selected in which a suitable video assistant is located. Compared to the end-to-end ARQ method, this mechanism reduces the delay of packets that have to be retransmitted at the cost of introducing some complexity when routes are created.

As stated before, WBA allows nodes not taking part in the communication to hear packets sent by a neighbor. Therefore, retransmitter nodes in the ARQ scheme should not be limited to nodes belonging to the transmission path. Reference [88] proposes a method that cooperatively uses neighboring terminals of the nodes along the route to forward packets, not only the nodes that are currently part of the route. Therefore, lost packets have more chances to be retransmitted, improving effectiveness of retransmission. Also, reference [89] proposes a cooperative relaying algorithm for

interference reduction, where idle nodes can be used as potential video relays. Video rate and transmission power are distributedly controlled in order to maximize the sum video quality. Nevertheless, cooperative routing may cause additional energy consumption since more nodes than in deterministic routing are participating in the transmission path. Hence, reference [90] takes into account this power consumption and proposes a cooperative routing mechanism that uses variable transmission power in order to balance achievable throughput and battery life.

Actual implementations of wireless mesh networks [91] rely on an ad hoc backbone with a stable topology, and consequently, link losses are usually low. This can be the case of real practical scenarios, such as smart cities or campus universities. For this reason, most of packet losses will occur on the last hop due to possible movements of the destination node or some of its neighbors. Therefore, it is certainly reasonable to limit retransmission mechanisms to last hop neighboring in such scenarios, causing less interference to other nodes and reducing the overall packet delay and energy consumption, which is desirable in real-time video transmissions. In a similar wireless scenario, reference [92] proposes a buffering scheme during handoff between access points in order to avoid packet losses. In this case, signal strength is measured in these access points to foresee when client nodes are moving.

4.3. Altruistic recovery

In wireless mesh networks, due to the long-term stability of the backbone, packet routes rely on these static nodes, which hardly suffer modifications. Logically, nodes that are likely to move around are devices that make use of these ad hoc networks to communicate, which usually are the transmission source, the destination or any of their nearest neighbors, which could affect the current packet route. Thus, it makes sense to apply recovery mechanisms at network edges, more precisely at the destination surroundings.

With this in mind, the main objective of this proposal is to provide throughput gains in wireless communications and improve the QoS of video transmissions, providing the user with a higher QoE. To this end, this chapter proposes a cross-layer technique that uses information drawn from MAC, routing and application layers in order to increase the overall packet delivery ratio and, in case of video transmissions, reduce packet delay so as to avoid playback interruptions. Furthermore, in order to maintain compatibility with existent wireless devices and network standards, no modifications to MAC layer are performed and only slight changes in the routing protocol are needed.

On traditional routing, e.g. OLSR, when a route is broken due to the movement of nodes, packets are likely to be discarded on the queue of any intermediate node during the rerouting time, causing a negative effect on the throughput. Figure 4.2 depicts this situation in a reduced scenario with 5 nodes. Node 4 is the destination and has two neighbors (node 2 and node 3). The packet route calculated by the routing protocol (OLSR in this case) is 0->1->2->4. Suppose now that node 4 moves and gets out the

transmission range of node 2. The transmission route results broken and then, by means of the routing protocol signaling, a new route towards node 4 is established through the node 3. Therefore, the new route will be 0->1->3->4 (Figure 4.2a).
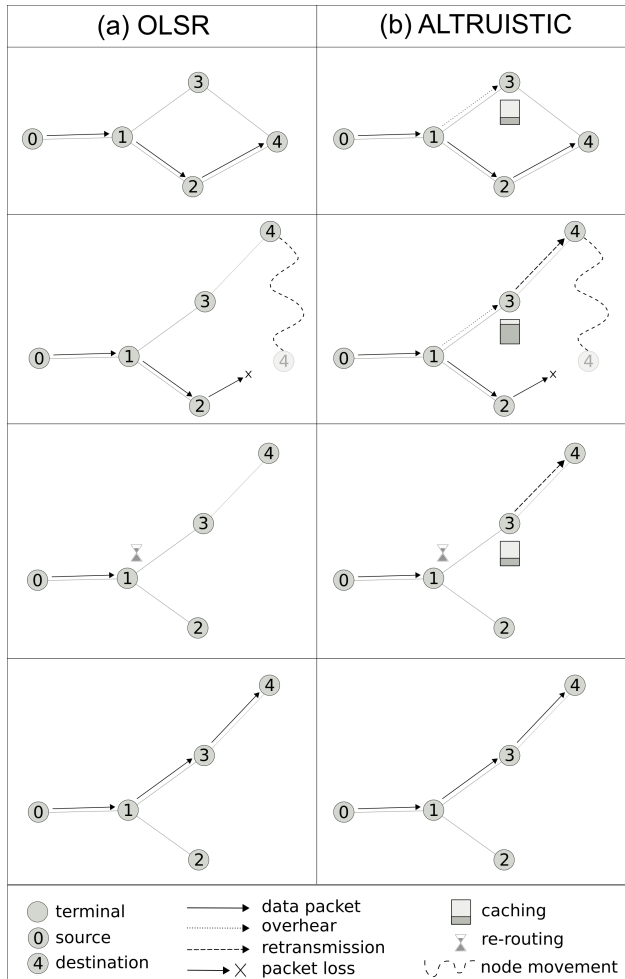
Figure 4.2 Comparison between OLSR (a) and Altruistic OLSR (b)

As a feature common to wireless ad hoc networks, all nodes within the radio range of a sender terminal can take advantage of WBA and overhear packets even if they are not the genuine receivers. In general data-link layer protocols, the overheard packets are discarded if the destination address is not the terminal's address. For the improvement proposed in this chapter, the neighbors of the destination node (i.e. node 3) may cache packets that they overhear in promiscuous mode and are addressed to their neighbors (Figure 4.2b). In this example, node 3 can keep sending previously overheard packets

that retains in the cache, until the new route is completely established. The ideal case is given when every packet that was not received at destination, has been overheard by a neighbor node and in addition, this neighbor node is able to retransmit it to destination. In practice, when the routing algorithm detects a link failure, source node queues outgoing packets (i.e. stops transmitting) and waits until a new route has been found. Packets that remain in the outgoing queue during a long time should be discarded.

In this approach, not every node forming the path has to buffer packets for retransmission, in contrast to other cooperative caching techniques, which make use of every possible node near the transmission route as a retransmitter candidate [93]. Usually, most of ad hoc mobile nodes are resource-limited devices so it would be worth limiting the amount of nodes that should perform packet caching and retransmission. In this scheme, a node caches most recently received packets only if they are addressed to a neighbor. If destination is no longer in the neighborhood (one-hop nodes), the cache is emptied for this node and no more packets addressed to it are cached. In order to avoid an excessive memory usage, this cache has a maximum size for each neighbor and packets are cached only for a short time. In addition, every cache entry stores both the packet and the arrival time so that packets that are older than a certain validity time (VT) are discarded, avoiding deprecated packets to be retransmitted.

For a better understanding, Figure 4.3 draws the main events that are taking place in this scenario. During the initial steady state, video transmission is being received correctly. When the destination node starts to move, there comes a time when packets cannot reach the destination and finally, the routing protocol notices that there has been a route breakage. Then, when the destination node comes into coverage again, transmission can be resumed after the new route discovering time. Note that destination can benefit from cached packets of altruistic neighbor nodes if they are still in range.
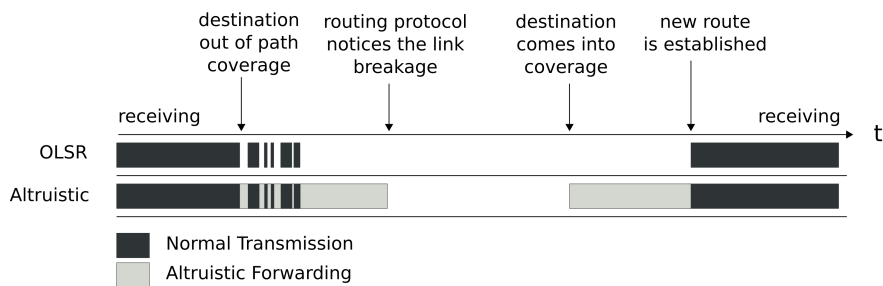

Figure 4.3 Timeline comparing the rerouting behavior between OLSR and Altruistic OLSR

4.3.1. Candidate selection

When relaying on extra nodes to retransmit lost packets, candidate selection becomes an important process to ensure the best performance. Reference [59] chooses the candidate before the route has been established, assuring a good position for the

retransmitter throughout the path. Instead, opportunistic routing protocols [54] track all possible routes for each packet (or batch of packets [55]) and mark the priority of each route.

Actually, among the nodes that have cached packets for retransmission, there will be some of them holding more packets and fresher ones, which turn those nodes into more effective retransmitters. Therefore, the way the retransmitter node is selected has to be considered. In the scheme presented in this proposal, candidate selection is carried out by the destination node so that no coordination function is needed among all possible retransmitters, reducing complexity and overhead. In order to select the best retransmitter candidate, destination node chooses one of its neighbors attending to a measurement value. This value, which can be estimated according to several methods, will help the destination node choose the most suitable neighbor to retransmit lost packets. Each node periodically informs its neighbors about this measurement value by means of a new field in OLSR HELLO message. As occurs in other proactive routing protocols, OLSR periodically broadcasts HELLO messages in order to discover and update neighboring information, which is very convenient for the aim of this proposal. When HELLO messages are generated to inform about neighbors' connectivity, each neighbor entry will also contain a value representing the goodness of the cache content for this neighbor. It is worth noting that the frequency of this update is closely related to the frequency configured for HELLO messages. As the interval of HELLO messages are configured shorter, cache information is updated more frequently, but the overhead is also higher. When destination node receives HELLO messages from its neighbors, it is able to compare and finally decide which one has the most valuable set of packets to be retransmitted. This decision is made from the values that neighbors have sent inside the modified HELLO messages and it will be explained in detail later. When cache is empty for all of its neighbors, no additional fields are inserted into the traditional HELLO, reducing message size and overhead. Otherwise, it is indicated using the reserved field of the HELLO message header. Figure 4.4 depicts an example, where node D is the destination, and nodes A, B and C inform periodically about their suitability to be retransmitters. In this example, node C will be chosen because it has a higher value.
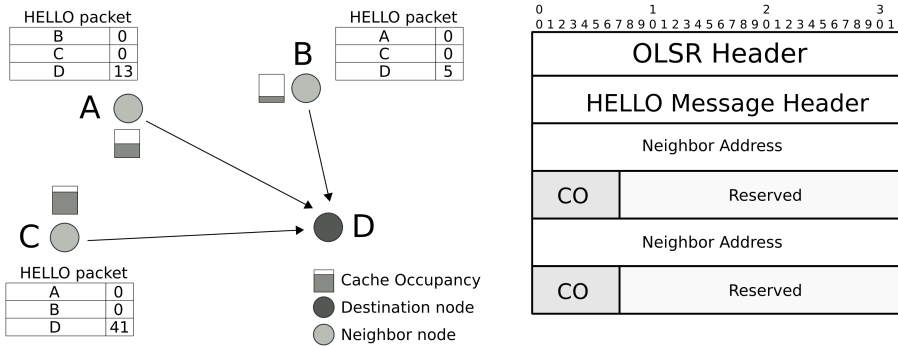
Figure 4.4 Modification to HELLO packets for the candidate selection mechanism

The aforementioned measurement value can be calculated in several ways, attending to: 1) geoposition, where nearest neighbors would achieve greater values; 2) Expected Transmission Count (ETX), i.e. nodes with greater delivery probability would be more suitable; or 3) Cache Occupancy (CO), that is, attending to the total amount of packets cached for a specific destination. Other methods could also be used as long as they provide a measurement value to be set in HELLO messages, or even a combination of them. For instance, by knowing the position of the neighboring nodes and the cache occupancy in each of them, destination node could choose a candidate more accurately taking into account also the direction in case it is moving. Diverse local positioning methods could be used for this purpose [94]. In this evaluation, CO has been used as the measurement value so that caches that contain more packets are given higher values. Packets older than a certain validity time are discarded and therefore are not taken into account. Hence, as long as destination chooses a retransmitter neighbor that maximizes CO value, the amount of useful video packets for destination will also be maximized. Reserved bytes could be used to send further information about each neighbor node (ETX, geoposition, remaining battery, etc.), which could be employed jointly to select the best retransmitter.

Then, the proposed scheme acts as follows. When the destination node detects any packet loss (examining sequence numbers in video packet headers or more generally, in Real-time Transport Protocol (RTP) headers), it generates and sends a report by means of a new kind of OLSR message: the Application Report (AR) packet. This AR packet contains the identifier (sequence number) of the last correctly received packet (*Last Packet ID*) and an *ACK Vector*, which gives a run-length encoded history of previous data packets received at destination, as carried out in other standards such as Datagram Congestion Control Protocol (DCCP) [95]. Moreover, original OLSR packets contain a header field indicating how long after a reception of this packet, the information is still valid (*Vtime*). In AR packets this field is used to inform neighbors about the maximum time a retransmitted packet will still be valid for video playback, i.e. the play-out buffer (*PoB*) size. As explained before, destination node holds information about which neighbor has been estimated the most suitable for retransmitting lost packets (*Altruistic*

Neighbor Address). All these parameters are encapsulated in a new AR message according to Figure 4.5. The ACK Vector itself consists of two fields: State, which informs about reception or loss; and Run Length, which specifies how many consecutive packets have the given State.
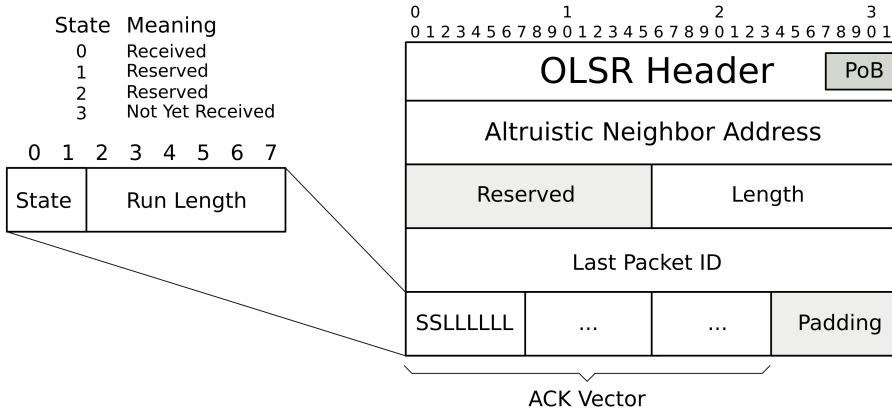
Figure 4.5 AR packet format

Nevertheless, during a long link failure it may well be the case that no packets were received and therefore, packet loss cannot be detected from sequence numbers. For this reason, the destination node (and only this node) periodically informs about the last received packets through AR messages. This is also carried out in order to update neighbors' cache regularly, so that both deprecated as well as correctly received packets could be deleted. The network overload increase owing to AR packets is later assessed in Section 4.4.

4.3.2. Cache

Network nodes are configured with a certain maximum cache size and timeout in order to limit the total amount of packets stored and avoid retaining stale packets, respectively. When a node receives an AR message from one of its neighbors, it checks every packet in the cache addressed to this node and compare the packet arrival timestamp with the validity timestamp set in the AR message. Deprecated packets are immediately deleted. The rest of packets are checked against the ACK Vector, and those that are not set as received by destination are then retransmitted. Packets remaining in the cache are deleted after a preconfigured validity time. Optimal timeout period for caching packets closely depends on the size and state of the play-out buffer at destination node. If this buffer eventually underruns, QoE will be seriously degraded. Hence, by means of AR messages, destination node can inform other nodes about which is the maximum PoB time allowed for the current video transmission. Neighbors can now configure the cache validity time more accurately according to this. This way not only is the amount of packets the altruistic node caches optimized but also the

amount of video packets that are retransmitted, with the concomitant bandwidth and energy saving.

4.3.3. Video awareness

As explained, this proposal could be appropriate for managing time-constraint transmissions because it takes into account temporal considerations and restrictions. Nevertheless, the relative importance of video frames (I, P or B) and the policy taken for which frames to cache and forward are other considerable parameters, at the expense of adding some complexity to the algorithm. It is worth noting that this could be done below frame level with video codecs that support slicing. This sort of video awareness is carried out in altruistic neighbors that are able to discern and inspect video packets, and classify them according to the kind of frame they belong to (i.e. packets from I-frames are more critical than those from P- or B-frames). Moreover, intra-frame packets can be prioritized so that other packets will be discarded instead if node cache fills up. From a practical point of view, although deep packet inspection could consume extra time and computation, it could be feasible to check only the Differentiated Services Code Point (DSCP) field from IP headers or a Header Extension in RTP. In this case, video source must use this field to mark packets belonging to higher priority frames before sending them. In any case, this enhancement could be feasible for static power-supplied nodes with higher processing capabilities (e.g. backbone nodes).

Another interesting consideration can also be taken into account. Outdated packets that belong to a frame from which some packets are not deprecated yet, are not discarded until all packets from that frame are completely obsolete (Figure 4.6). This way, the algorithm tries to not split I-frames especially, because they are usually formed by a considerable number of packets.
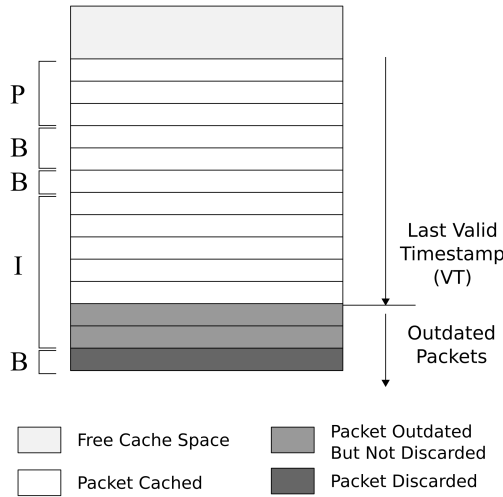
Figure 4.6 Cached video packets and discarding policy

This scheme is not only valid for making decisions according to the type of frame, but also it is useful when using other sort of video coding that could be arranged into layers, such as Scalable Video Coding (SVC) [96]. By using this coding scheme, video packets from base layer can be prioritized over other improvement layers in order to reduce interruptions considerably.

In order to offer a general overview of some of the solutions mentioned in Section 4.2, Table 4.1 compares them with the mechanism proposed in this chapter in order to show the main differences attending to some distinctive qualitative parameters. It is worth noting that, unlike other cooperative routing protocols, this proposal is not a routing algorithm itself but take advantage of OLSR information to implement an ARQ mechanism that also exploits WBA and performs caching in order to retransmit lost packets when needed. Moreover, the presented cross-layer solution is video-aware, which allows discerning video traffic and improving QoE by reducing video interruptions when node mobility causes route breakages.

Table 4.1   Qualitative comparison among recovery solutions

Mechanisms	ARQ	Video Awareness	WBA	Caching	Adaptive	Multipath
[84]	Yes	No	No	No	No	Yes
[87]	Yes	Yes	No	No	Yes	No
[59]	Yes	Yes	No	Yes	Yes	No
[88]	No	No	Yes	No	No	Yes
This proposal	Yes	Yes	Yes	Yes	No	No

4.4. Evaluation

4.4.1. Sample network

Firstly, the scenario depicted in Figure 4.2 is assessed regarding throughput, PSNR, packet delay and packet losses, using a video streaming source. All PSNR values cover both encoding distortion as well as channel-induced distortion. This first scenario consists of 5 nodes, where destination node moves causing a route change.

This scenario has been simulated in NS-3 and the most relevant simulation parameters and video properties are shown in Table 4.2. RTS/CTS mechanism does avoid collisions that would decrease throughput due to retries, but on the other hand, this additional process adds a significant amount of protocol overhead that also results in a decrease in network throughput, so it is not used in the simulations. Additionally, wireless channel and transmission conditions are depicted in Figure 4.7, which also shows the Packet Reception Rate (PRR) according to the distance between two nodes (i.e. the probability of receiving a packet correctly), with a 95% level of confidence.
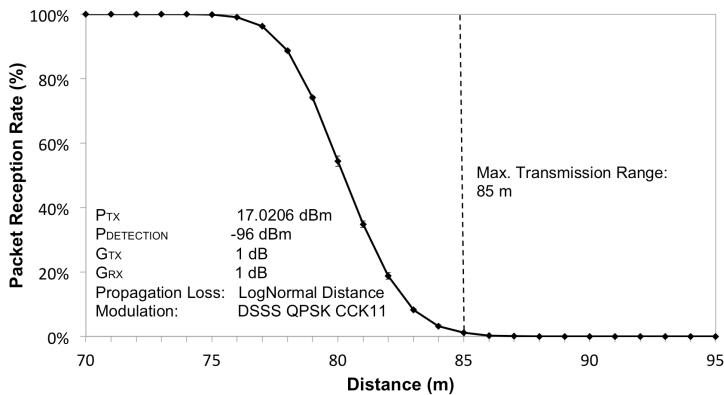

Figure 4.7 Channel parameters and PRR at 11Mbps according to distance

Table 4.2   List of relevant simulation parameters

Parameter	Value
Wireless Standard	802.11b
Data Rate	11 Mbps
RTS/CTS	Off
Video resolution	352x288 (CIF)
Video duration	80 seconds
Average video rate	500 kbps
Max. queue delay	1 second
Cache validity time	1 second

Figure 4.8 shows the results comparing the scheme proposed with the standard OLSR. Figure 4.8a illustrates the instantaneous throughput received in the destination node. It can be observed that packet reception is interrupted during a gap of time in traditional OLSR, due to the movement of the receiving node. A considerable decrease is stated in the altruistic scheme, but even though some glitches or slight interruptions may appear, it manages to recover a number of packets that allow video to keep playing almost seamlessly. This effect can be corroborated in Figure 4.8b, where PSNR is represented. There can be seen the effect of the interruption in the quality of the received video. Comparing with OLSR, the altruistic scheme manages to recover some additional video frames, thus improving the overall quality of video.

Besides PSNR, time instants of early AR packets are also depicted in the same figure, so it can be clearly shown the temporal relevance between the changes suffered in PSNR and the moment an AR packet is early transmitted. These are AR packets that are not sent periodically from destination, but only when a packet loss is detected. By sending these packets instantaneously, destination node may recover some useful packets in time, being able to recover video frames that would be lost otherwise. After the rerouting, altruistic neighbor become part of the actual route of packets and stops caching video packets (in case there would be more neighbors, they could become altruistic nodes).

Figure 4.8c illustrates end-to-end packet delay. As long as the maximum queue delay is set to 1 second, packets that stay longer than this delay in the queue are dropped. In this particular scenario, only one node is likely to suffer packet losses. Consequently, maximum packet delay reaches just over 1 second and below in OLSR. On the other hand, the altruistic recovering mechanism may present some packets with a higher

delay due to retransmissions, even beyond 1 second, and there can also be distinguished some packet bursts retransmitted by the altruistic neighbor.

Figure 4.8d shows the cumulative number of interruptions or burst losses regarding their length in packets. It can be stated that there is a higher number of interruptions in traditional OLSR, especially burst losses that last few packets. In this case, altruistic retransmission recovers most of the small burst losses. Moreover, the maximum burst loss length is reduced considerably, as well as the number of bigger interruptions, compared with standard OLSR.
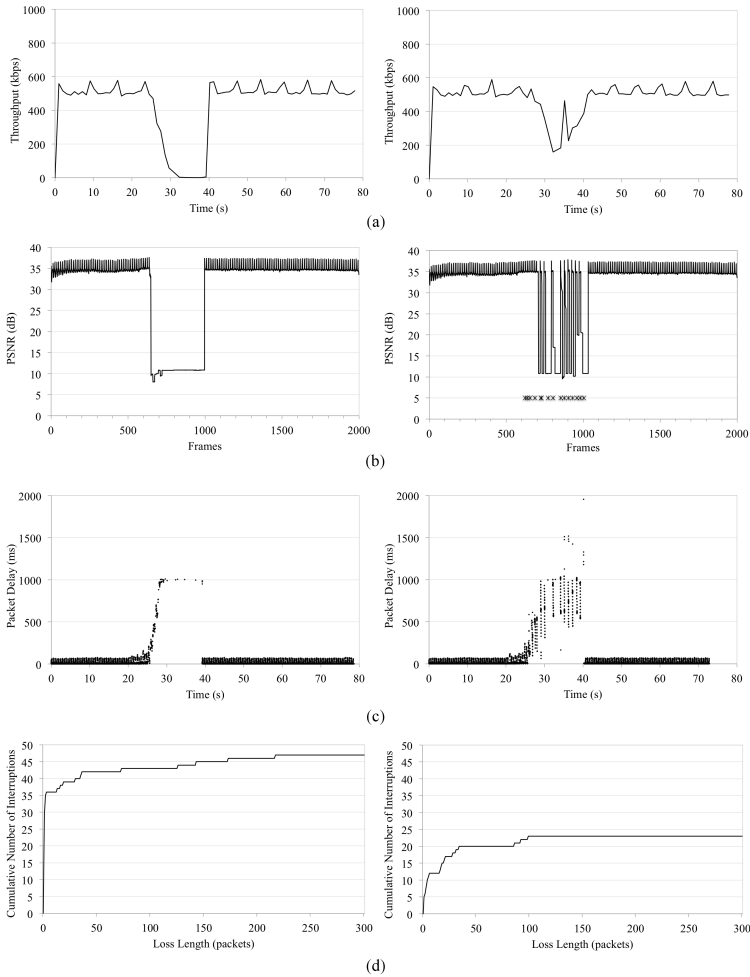

Figure 4.8 Comparison between OLSR (left) and Altruistic OLSR (right) regarding throughput (a), PSNR (b), end-to-end packet delay (c), and cumulative number of interruptions (d)

Finally, it is worth mentioning that even though the average PSNR along the whole simulation increases from 30.59 dB in OLSR to 32.34 dB in the altruistic scheme, the improvement is even more noticeable if only the frames within the zone of interest (from second 20 to second 44, i.e. approximately the rerouting time) would be taken into account (from 17.99 dB in OLSR to 25.02 dB in the altruistic scheme). PSNR reference value is 34.89 dB, which is the average PSNR obtained from comparing the original video sequence with the encoded one, not taking into account any transmission loss. It is also worth mentioning that the goal is to show the relative improvement that this proposal offers over traditional OLSR routing and the exact absolute values are not to be necessarily concerned, since they strongly depend on the current video enconding parameters and network conditions. The fact of prioritizing I-frames has also slightly helped improve PSNR, since more interdependent frames could be decoded. However, such particularized analysis cannot be carried out in random scenarios where destination node moves freely, resulting in one or several (or none) rerouting occasions and link breakages. Nevertheless, average values can be measured, which shows the effectiveness of the proposed scheme, as described below.

4.4.2. Random scenario

Therefore, in order to carry out more thorough assessments of the proposed scheme, it has been evaluated in random scenarios with 20 nodes uniformly distributed along a simulation area of 300 m x 300 m. Only the destination node is moving during the simulation time, specifically at 1 m/s (walking speed) according to the Random Waypoint Model. In order to obtain more realistic scenarios, background traffic is sent during the simulations. It consists of 20 UDP sessions with constant bit rate (CBR) of 1 kbps each, established between nodes that are randomly selected. The rest of the simulation parameters are similar to the previous simulated scenario (Table 2 and Figure 7). These parameters entail certain Bit Error Rate (BER) depending on the packet Signal to Noise Ratio (SNR), which is calculated including propagation losses due to distance between nodes. Therefore, there can be some cases where destination or altruistic nodes fall out of coverage. In the particular case of the backbone, where nodes are static, nodes may still be subject to packet losses due to radio interferences and medium access collisions. Hence, packet losses could be caused because of either node mobility or congestion in the backbone nodes.

Since the proposed algorithm can be summarized as a video-aware ARQ mechanism based on packet caching, it is interesting to compare it with other ARQ mechanisms that perform caching of video packets, such as that described in [59]. It makes use of a special video assistant node in the route that is in charge of caching the video packets that it has forwarded previously. As the best results are achieved when the video assistant is located in the middle of the path, the simulated algorithm makes use of the node located as close as possible to the middle of the packet route to perform caching and retransmission. This node is selected dynamically so it will change if the route changes. Hereafter, this algorithm is referred as VAARQ. Figure 4.9 shows a comparison between traditional OLSR, VAARQ and the altruistic scheme proposed

(ALTOLSR) regarding PSNR, frame loss, packet delay, overhead and cumulative number of interruptions, with a 95% level of confidence. Average results are presented.
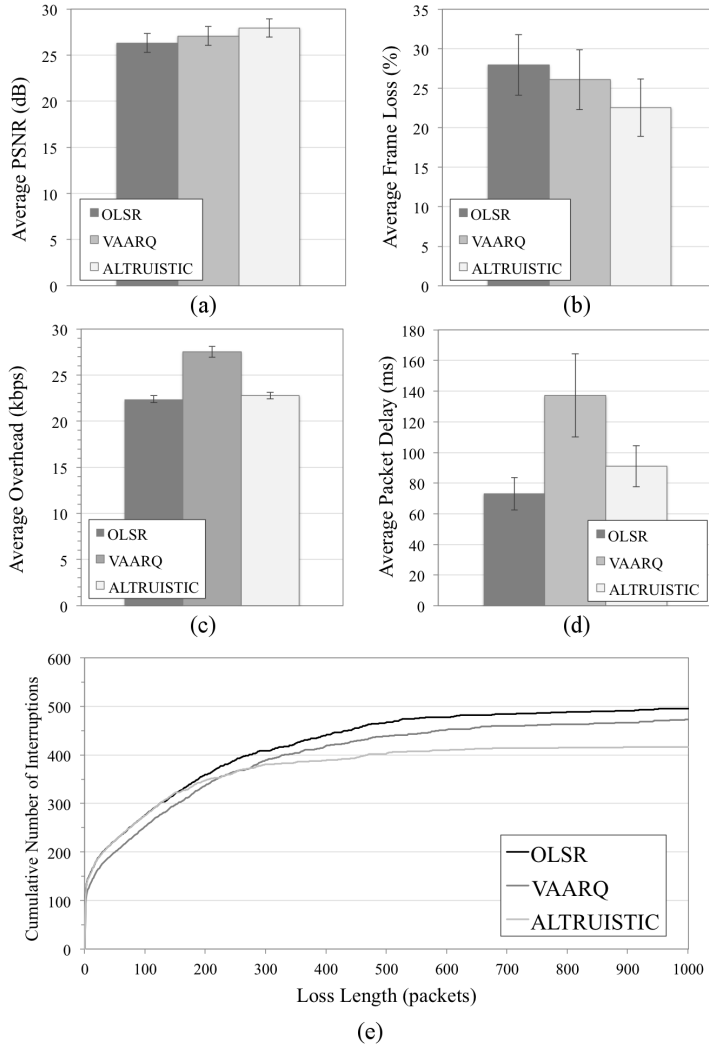
Figure 4.9 Comparison between OLSR, VAARQ and Altruistic OLSR regarding average PSNR (a), frame loss (b), overhead (c), packet delay (d), and cumulative number of interruptions (e)

Attending to Figure 4.9a and Figure 4.9b, both PSNR and video frame loss are improved by using the altruistic recovering mechanism (about 6% and 5% on average, respectively). VAARQ algorithm obtains better results than traditional OLSR but fails to recover some video packets due to the destination mobility, which causes that ARQ

requests do not reach the video assistant. Figure 4.9c shows the total OLSR overhead introduced by all the 20 nodes in the simulation (including AR messages for ALTOLSR) and the overhead introduced by the ARQ packets in VAARQ (the difference is about 2% in the altruistic algorithm and almost 20% in VAARQ). The number of routing protocol packets in the altruistic scheme is increased due to the additional signaling (AR packets) between destination node and its neighbors and the extra information in HELLO messages. However, in this case VAARQ introduces a higher amount of overhead because ARQ packets are sent for every packet loss detected, even if there are several contiguous lost packets. Average packet end-to-end delay is also increased using the altruistic scheme (20%), according to Figure 4.9d. This is due to the fact that packet delay is measured only with correctly received packets. Packet retransmission obviously increases packet delay compared with no retransmission, but this delay would be greater if this retransmission is performed from the video source instead of retransmitting from a node close to destination. Even when retransmittion is carried out from an intermediate node (as in VAARQ), packet delay is dramatically increased (47%). As long as jitter is maintained rather steady and does not increase (as observed from the error bars in Figure 4.9d for the altruistic mechanism), it could be concealed at the receiver buffer, not affecting the video playback. Finally, Figure 4.9e shows the cumulative number of interruptions depending on their length in packets. Firstly, it can be stated that the background traffic coursed through the backbone causes losses along the path due to congestion and interferences. These packet losses could be recoverable using VAARQ if the retransmitter node has managed to cache the lost packets. On the contrary, ALTOLSR is only able to recover losses that are produced in the last hop, which are sometimes caused due to congestion but mainly produced due to the mobility of the destination node. Secondly, even though some kinds of losses cannot be concealed using ALTOLSR, this algorithm is able to obtain better PSNR. This is achieved because most of the packet losses are still caused near the last hop and there are some neighbors close to destination that are capable of becoming altruistic nodes. Since source node transmits approximately 75 packets per second on average (value obtained from the video trace files), it can be inferred that largest burst losses (greater than 150 packets, i.e. larger than 2 seconds) are reduced with the altruistic mechanism. Moreover, VAARQ manages to recover short interruptions (shorter than 5 packets), which are likely produced in the backbone, but eventually, it follows a similar trend as OLSR. Despite the fact that VAARQ also reduces video interruptions, the amount of recovered packets is higher in the altruistic approach, especially in scenarios with mobile destination nodes.

All in all, by reducing the amount of lost packets, more frames can be recovered and, therefore, PSNR is notably increased. Additionally, some of the video playback interruptions are also prevented, which all provide a significant improvement in video quality.

As aforementioned, ALTOLSR does not increase the amount of control packets notably, but as long as frame losses increase, more control overhead is generated in

order to recover lost packets. Therefore, in order to analyze how frame losses affect the amount of overhead generated, ALTOLSR and VAARQ are compared regarding the number of retransmission requests (AR messages in ALTOLSR and ARQ packets in VAARQ) and the total control overhead generated. Hence, Figure 4.10 depicts the number of ARQ requests needed to obtain certain values of PSNR. It can be seen that in order to obtain similar PSNR, the amount of ARQ requests is definitely lower using ALTOLSR than using VAARQ (note the logarithmic scale in the x-axis).
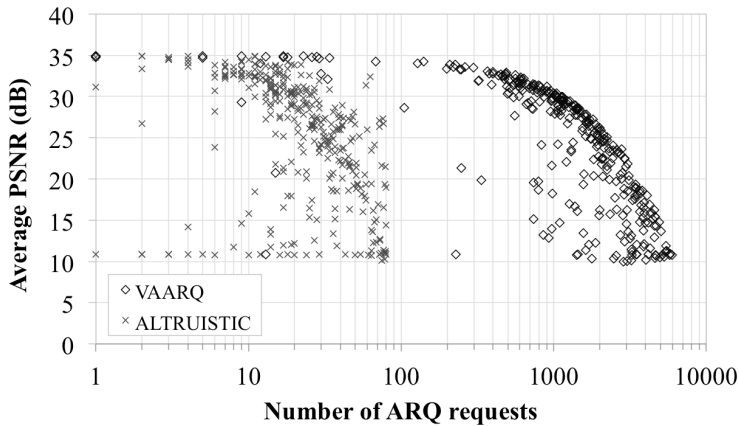
Figure 4.10   Average PSNR vs. number of ARQ requests

By using ACK Vectors in ALTOLSR, several video packets can be requested using only one AR message. Even if some AR messages or the recently retransmitted video packets are lost, next AR messages may contain the request for those video packets that are still missing, as long as they have not been deprecated yet. Additionally, Figure 4.11 depicts the overhead caused by both protocols according to the amount of lost frames compared to traditional OLSR.
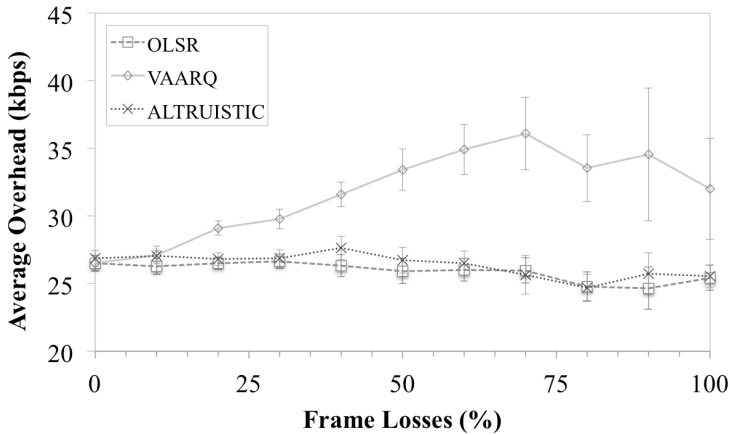
Figure 4.11 Control overhead according to frame losses

Although high lossy environments may cause a rise in this kind of traffic for ALTOLSR, it is not really meaningful in comparison with all the routing traffic (under 5%). As depicted, other ARQ solutions such as VAARQ may introduce a higher amount of routing traffic when losses increase (28%). In ALTOLSR, it is worth noting that this traffic increase is only produced in the last hop and does not affect the rest of the network unlike in VAARQ. Unfortunately, although ALTOLSR can recover a great amount of lost packets, it would be useful only if losses are caused in the last hop or in the surrounding area of the destination node.

4.4.3. Resource consumption considerations

In general, wireless ad hoc networks are resource-demanding networks, especially because nodes that belong to a transmission route are consuming their own resources (e.g. processing time, memory and battery) although they are neither the source nor the destination of the communication. This tradeoff between connectivity and energy consumption has been analyzed in [97] and the feasibility and convenience of implementing ad hoc networks have been demonstrated, despite the fact that incentives to the users could be necessary to persuade them to share the capabilities of their devices with other users. In addition, if any of these router nodes has to become an altruistic node and it also has to cache packets to retransmit, this resource consumption increases inevitably.

In the mechanism proposed in this chapter, altruistic nodes must allocate sufficient storage to perform caching properly. The amount of available storage in an altruistic node for caching packets from a specific destination node, as well as the interval of time packets are cached, may influence the quality of the received video. Also, play-out buffer (PoB) size is important to assess video quality because retransmitted packets could become deprecated depending on the kind of service. In these sense, new

scenarios have been simulated varying the cache validity time. Furthermore, by using different valid PoB sizes, three typical situations have been defined in order to simulate scenarios close to real situations: a PoB of 150 ms, which represents an interactive videoconference; a PoB of 1 s, which represents a real-time video streaming service; and finally a PoB of 5 s, which works as a Video on Demand (VoD) situation with a buffer slightly larger. Validity time of cached packets has been varied from 0 s (no packets are cached) to 5 s for each different situation in order to assess how PSNR is affected. Hence, Figure 4.12 depicts the average PSNR according to the cache validity time configured in the altruistic nodes.
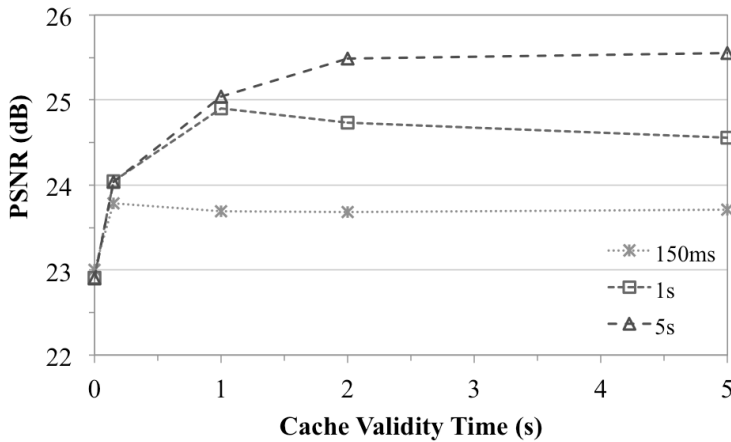
Figure 4.12   Average PSNR vs. cache validity time for different PoB sizes

As shown, a cache validity time of 150 ms is enough to improve PSNR in about 1 dB. For a PoB of 150 ms, however, values greater than 150 ms do not improve video quality because most of recovered packets are already obsolete for the receiver. Similarly, cache validity time of 1 second is optimal for a PoB of 1 second in reception. In the case of using a PoB size of 5 seconds, either storing video packets during 2 seconds or 5 seconds in cache means no evident difference. This fact is tightly related to the AR interval, which was set to 1 second in the simulations. This means that, at least every second, the destination node is going to inform altruistic nodes about the packets that need to be retransmitted. In the case that cache validity time is 1 second, some of the cache packets might be dropped before retransmission request reaches the altruistic node. However, by caching packets during more than 1 second, e.g. a cache validity time of 2 seconds, the altruistic node is able to retransmit a slight higher number of packets as long as they are not deprecated yet. Therefore, higher cache validity times do not really improve PSNR provided that PoB size is big enough because lost packets are recovered continuously due to the periodical transmission of AR messages.

Additionally, Figure 4.13 shows the maximum cache occupancy according to the cache validity time. It represents the maximum amount of memory storage in Kilobytes (KB)

that an altruistic node would need to cache video packets for each flow. Since a cache validity time of 5 s implies a greater amount of available storage but PSNR improvement is not remarkable compared with a validity time of 2 s, it can be concluded that a value of 2 s is more efficient in this analyzed scenario, although the optimal value will be determined by the actual destination PoB size and the AR interval. As aforementioned, destination node can inform altruistic nodes about the PoB size using AR messages, allowing altruistic nodes to adapt the cache validity time.
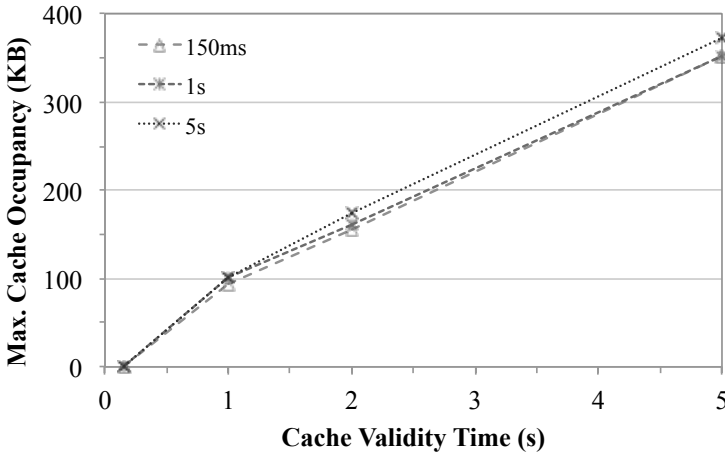
Figure 4.13   Maximum cache occupancy regarding the cache validity time for different PoB sizes

Regarding energy consumption, the fact of adding further mechanisms that use packet retransmission necessarily entails an increase in battery consumption. Taking into account that in ad hoc networks most of the nodes are mobile nodes or battery-dependent devices, new proposed techniques should not be very energy demanding in general.

In order to understand how the mechanism proposed affects the battery life of participant nodes, additional simulations have been carried out and energy consumption has been measured. Figure 4.14 depicts the basic scenario under test, which consist of 7 nodes. The route is established between source node (node 0) and destination node (node 6), using node 1 and 2 as routers. Destination node is moving during the simulation, so that an alternative route has to be found through node 3. Node 4 and node 5 are only listeners, although node 4 becomes an altruistic node when simulating ALTOLSR, and node 1 is in charge of video retransmissions (VA) when simulating VAARQ. Simulation parameters regarding transmission power, propagation loss, etc. are similar to previous simulations.
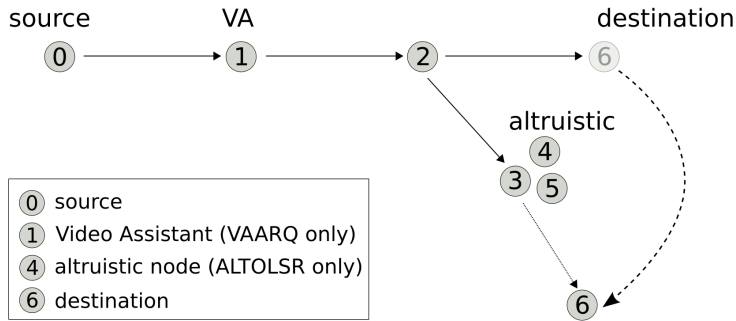
Figure 4.14   Scenario for energy consumption assessment

Usually, wireless radio interfaces consume different amount of energy depending on the state they are working in, which can be transmission (TX), reception (RX), idle and sleep. A node in TX or RX state is likely to consume more power than in sleep or idle state. Nodes that are not taking part of the actual path, such as node 5 in this case, are also receiving packets and dismissing them, which mean non-negligible consumption. Power consumption parameters are described in Table 4.3. Finally, Figure 4.15 shows the maximum energy consumption for every node in the scenario under analysis.

Table 4.3   Power consumption parameters of Intel PRO/Wireless 3945ABG card

Parameter	Value
Transmission (max.)	1.8 W
Reception (max.)	1.4 W
Idle mode (nominal)	150 mW
Sleep mode (max.)	30 mW
Operating voltage	3.3 V
Standard	802.11 a/b/g
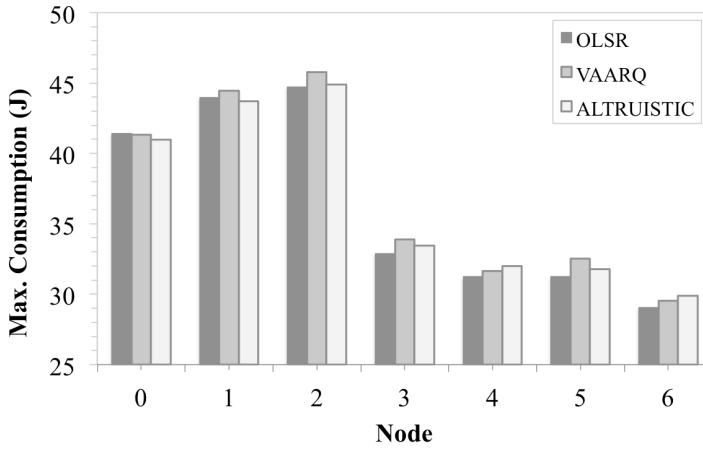
Figure 4.15   Maximum energy consumption per node

Particularly, it can be seen that the altruistic scheme causes an increase in consumption only in the last hop (nodes 3-6) compared to OLSR, unlike VAARQ, which produces higher energy consumption from the retransmitter node until destination (nodes 1-6). Due to the intra-flow contention, which appears in multi-hop networks even for a single transmission, a forwarder node consumes energy because of both the reception of packets sent by the neighbors and the retransmission of packets. Using ARQ mechanisms that use caching nodes near the source will ensure that video packets have been cached, but at the same time, retransmitting packets through a high number of hops would entail higher energy consumption, not only in the nodes that take part in the path but also in neighboring nodes, which are actually receiving these packets as well (RX state). Moreover, altruistic node (node 4) has higher consumption due to retransmissions (2%) but this increase is not meaningful compared with a node that is carrying out packet forwarding (below 28%). Nevertheless, VAARQ mechanism increases the average consumption only in 1.6%, but this increase occurs in every node in the retransmission path and neighboring nodes, which eventually contributes to the faster network performance deterioration. Finally, taking into account that the reference value is 34.89 dB, PSNR is increased from an average of 25.7 dB and 26.7 dB in OLSR and VAARQ, respectively, to 28.7 dB in ALTOLSR. Thus, it is worth mentioning that by using the altruistic scheme, PSNR is notably improved and only the surrounding area of destination node is affected by retransmissions.

4.5. Conclusion

Mobility of nodes makes it difficult to create and maintain transmission routes in wireless ad hoc networks. Thus, providing loss and delay sensitive services such as video streaming in these kinds of networks and guaranteeing a certain QoE is still

challenging. When any node moves out of range, routes have to be recalculated and in the meanwhile, packets could be lost.

The main objective of the proposal presented in this chapter is to provide throughput gains in wireless communications and improve the QoS of video transmissions, providing the user with a higher QoE. To this end, it is proposed a cross-layer technique that uses information drawn from MAC, routing and application layers in order to increase the overall packet delivery ratio and, in case of video transmissions, reduce frame losses so as to avoid playback interruptions. This scheme proposes that neighboring nodes of the destination node help in recovering lost packets when a route breakage occurs.

Simulation results show that the proposed algorithm reduces video frame loss considerably (5%) and thus improves average PSNR in approximately 2 dB (6%), even achieving about 7 dB (39%) of improvement when considering only the rerouting time window. Packet delay is affected by retransmissions, but due to the proximity of the retransmitter, the average packet delay is kept lower than in other mechanisms based on source ARQ. The number and length of burst losses is also reduced with the altruistic mechanisms, leading to a higher video quality and better user experience. Moreover, unlike other ARQ solutions, the proposed approach maintains lower overhead even though the amount of losses grows (5%), and energy consumption is only increased in nodes close to the destination node, which benefits the overall network performance.

Although an initial assumption has been taken about the stationarity of backbone nodes, this hypothesis is nowadays perfectly plausible considering how wireless mesh networks are evolving. Due to the nature of this proposal, it makes more sense in environments that concentrate packet losses in the last hop.

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Appendix A. List of Publications

Following there is a list of publications that provide most of the content of this thesis dissertation. The following notation is used: B refers to book chapters, C to conference papers and J to journal papers.

Chapter 2

[J.1] P. Acelas, P. Arce, J. C. Guerri, and W. Castellanos, "Evaluation of the MDC and FEC over the quality of service and quality of experience for video distribution in ad hoc networks," Multimedia Tools and Applications, vol. 68, no. 3, pp. 969-989, 2014.

[J.2] J. C. Guerri, P. Arce, and P. Acelas, "Mechanisms for improving video streaming in mobile ad hoc networks," Waves 2009 (iTEAM UPV Journal), vol. 1, pp. 24-34, 2009.

[C.1] W. Castellanos, P. Arce, P. Acelas, and J. C. Guerri, "Route recovery algorithm for QoS-aware routing in MANETs," in Proc. of the ICST Conference on Mobile Lightweight Wireless Systems (MOBILIGHT '11), Bilbao, Spain, pp. 81-93, May 2011.

[C.2] T. R. Vargas, P. Arce, I. de Fez, V. Murcia, F. Fraile, R. Belda, P. Acelas, and J. C. Guerri, "Solutions to improve the video streaming service over heterogeneous networks," presented at the 1st Workshop on Future Internet: Efficiency in High-Speed Networks (W-FIERRO), Cartagena, Spain, Jul. 2011.

[C.3] P. Acelas, P. Arce, W. Castellanos, and J. C. Guerri, "Estudio sobre el Efecto de la Codificación de Vídeo por Multidescripción en Redes MANET," presented at XV Simposium Nacional de la Unión Científica Internacional de Radio (URSI '10), Bilbao, Spain, Sep. 2010.

[C.4] W. Castellanos, P. Acelas, P. Arce, and J. C. Guerri, "AQA-AODV: QoS-aware AODV protocol with adaptive feedback scheme," presented at the ICST Conference on Heterogeneous Networking for Quality, Reliability, Security and Robustness (QSHINE '09), Las Palmas, Spain, Nov. 2009.

[C.5] P. Acelas, P. Arce, and J. C. Guerri, "Effect of the multiple description coding over a Hybrid Fixed-AdHoc Video Distribution Network," in Proc. of the 2nd International Workshop on Future Multimedia Networking (FMN '09), Coimbra, Portugal, pp. 176-187, Jun. 2009.

Chapter 3

[B.1] J. C. Guerri, P. Arce, P. Acelas, W. E. Castellanos, and F. Fraile, "Routing and Coding Enhancements to Improve QoS of Video Transmissions in Future Ad Hoc Networks", Multimedia Services and Streaming for Mobile Devices: Challenges and Innovations, IGI Global, pp. 244-261, 2012.

[J.3] P. Arce, J. C. Guerri, A. Pajares, and O. Lázaro, "Performance Evaluation of Video Streaming over Ad Hoc Networks using Flat and Hierarchical Routing Protocols," Mobile Networks and Applications – Special Issue on Multimedia over Ad Hoc and Sensor Networks, vol. 13, no. 3-4, pp. 324-336, 2008.

[C.6] P. Arce, J. C. Guerri, A. Pajares, and O. Lázaro, "Performance Evaluation of Video Streaming over Ad Hoc Networks using Flat and Hierarchical Routing Protocols," in Proc. of the 3rd International Mobile Multimedia Communications Conference (MOBIMEDIA '07), Nafpaktos, Greece, Aug. 2007.

[C.7] P. Arce, J. C. Guerri, A. Pajares, and O. Lázaro, "Evaluación de Prestaciones del Servicio de Video Streaming sobre Redes AdHoc utilizando OLSR y HOLSR," presented at the VII Jornadas de Ingeniería Telemática (JITEL '08), Alcalá de Henares, Madrid, Spain, Sep. 2008.

Chapter 4

[B.2] P. Arce, S. González, and J. C. Guerri, "Altruistic networks: Where every node matters", invited by the Editor for publication in Recent Advances in Ad Hoc Networks Research, Ed. Nova, publishing in 2014.

[J.4] P. Arce, and J. C. Guerri, "An Altruistic Cross-Layer Recovering Mechanism for Ad Hoc Wireless Networks," Wireless Communications and Mobile Computing, online: http://onlinelibrary.wiley.com/doi/10.1002/wcm.2459/abstract, 2014.

[J.5] S. González, P. Arce, and J. C. Guerri, "Buffering Technique for Optimizing Energy Consumption in the Transmission of Multimedia Traffic in Ad-Hoc Network", submitted to IEEE Latin America Transactions, 2013.

Additionally, the author has participated in the following publications:

[B.3] F. Fraile, P. Arce, R. Belda, I. de Fez, J. C. Guerri, and A. Pajares, "Social Aware TV Content Delivery over intelligent networks," Social Media Retrieval, Computer Communications and Networks, Ed. Springer, pp. 373-391, 2013.

[J.6] R. Belda, I. de Fez, F. Fraile, P. Arce, and J. C. Guerri, "Hybrid FLUTE/DASH video delivery over mobile wireless networks," Transactions on Emerging Telecommunications Technologies, doi: 10.1002/ett.2804, 2014.

[J.7] A. Miquel, R. Belda, I. de Fez, P. Arce, F. Fraile, J. C. Guerri, F. Martinez, and S. Gallardo, "A power consumption monitoring, displaying and evaluation system for home devices," Waves 2013 (iTEAM UPV Journal), vol. 5, pp. 5-13, 2013.

[J.8] R. Belda, P. Arce, I. de Fez, F. Fraile, and J. C. Guerri, "Android real-time audio communications over local wireless," Waves 2012 (iTEAM UPV Journal), vol. 4, pp. 35-42, 2012.

[J.9] V. Murcia, M. Delgado, P. Arce, and J. C. Guerri, "IPTV-Oriented network architecture," Waves 2011 (iTEAM UPV Journal), vol. 3, pp. 32-39, 2011.

[J.10] P. Acelas, P. Arce, W. Castellanos, R. Belda, I. de Fez, F. Fraile, V. Murcia, T. R. Vargas, M. Monfort, and J. C. Guerri, "An Interactive Wireless-based Telemedicine System for Back Care Applications," Waves 2010 (iTEAM UPV Journal), vol. 2, pp. 56-65, 2010.

[C.8] I. de Fez, J. Arambarri, P. Arce, F. Arribas, S. Barrera, I. Bilbao, E. Burgoa, J. C. Guerri, P. Ortiz, E. Vaz, and D. Zaragoza, "GrafiTV: Interactive and Personalized Information System over Audiovisual Content," in Proc. of NEM Summit, Istanbul (Turkey), pp. 41-46, Oct. 2012.

[C.9] P. Guzmán, P. Acelas, T. Vargas, P. Arce, J. C. Guerri, E. M. Macias, and A. Suarez, "QoE evaluation and adaptive transport for 3D mobile services," Reunión Red Temática W-FIERRO, Cartagena, Spain, Jul. 2012.

[C.10] J. V. Llácer, D. Díaz, F. Pinyol, P. Arce, A. Campo, M. Rovira, J. C. Guerri, and E. Burgoa, "RAUDOS 2: Interactive multiplatform network for distribution of audiovisual content," presented at the IV Congreso de Televisión Digital Interactiva (CTVDI '11), Palma de Mallorca, Spain, Nov. 2011.

[C.11] P. Arce, F. Fraile, M. Monfort, and J. C. Guerri, "Interactive TV-centric Health Care Services in Smart Homes," in Proc. of the 8th European Conference on Interactive TV and Video (EuroITV '10), Tampere, Finland, Jun. 2010.

[C.12] E. Burgoa, M. Rovira, F. García, P. Arce, J. M. Quinteiro, E. Loizaga, J. Martínez, J. Tejada, M. Zorrilla, J. López, C. Galicia, F. Pinyol, J. C. Guerri, J.

V. Llácer, N. Martínez, J. Ágreda, A. Arrieta, D. González, E. Martel, and V. Beviá, "Raudos: Interactive Multiplatform Audiovisual Delivery," in Proc. of the 8th European Conference on Interactive TV and Video (EuroITV '10), Tampere, Finland, Jun. 2010.

[C.13] T. R. Vargas, K. Ramantas, P. Arce, J. C. Guerri, K. Vlachos, and S. Sales, "A preemptive scheduling scheme for flexible QoS provisioning in OBS networks – A review," 2nd Workshop en Redes Multinivel. Red Temática Española: "Redes Multinivel: IP Sobre redes de transporte," Universitat Politècnica de Catalunya, Vilanova i la Geltrú, Spain, Jun. 2010.

[C.14] J. C. Guerri, A. Pajares, P. Arce, and R. Santamaría, "Evaluación del protocolo DCCP y el algoritmo TCP-Friendly para la adaptación del tráfico," presented at the XIV Simposium Nacional de la Unión Científica Internacional de Radio (URSI '09), Santander, Spain, Sep. 2009.

[C.15] R. Belda, V. Murcia, F. Fraile, P. Arce, and J. C. Guerri, "Video On Demand Services for Emergency Scenarios Over Heterogeneous TETRA-DVBT Networks," in Proc. of the Wireless Personal Multimedia Communications Symposium (WPMC '08), Lapland, Finland, Sep. 2008.

[C.16] R. Belda, I. de Fez, F. Fraile, V. Murcia, P. Arce, and J. C. Guerri, "Multimedia System for Emergency Services over TETRA-DVBT Networks," in Proc. of the 34th EUROMICRO Conference on Software Engineering and Advanced Applications (SEAA '08), Parma, Italy, Sep. 2008.

Also, during the elaboration of their thesis, the author has participated in the following projects:

- ICARE: Innovative Cloud Architecture for Real Entertainment (2012-2015). 11012, ITEA 2 Call 6.

- REMEDISS: Red médica sensorizada (2012-2014). IPT-2012-0882-430000.

- HAUS: Hogar digital y contenidos audiovisuales adaptados a los usuarios (2011-2013). IPT-2011-1049-4300000-AR.

- GRAFI-TV: Sistema de información interactiva y personalizada sobre contenidos audiovisuales (2011-2012). TSI-090100-2011-173.

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- INNOVA: Proyectos de prueba de concepto (2012). Universitat Politècnica de València.

- MULTIDISCIPLINAR: Proyectos de investigación multidisciplinares (2012). Universitat Politècnica de València. PAID-05-12.

- RRHH: Redes híbridas para la provisión de servicios turísticos (2010-2011). TSI-020302-2010-165.

- AV-MOV: Contenidos multimedia para el transporte multimodal (2009-2011). TSI-020301-2009-11.

- MIQUEL: Sistema multimedia sobre entornos inalámbricos aplicado a los trastornos del sistema músculo-esquelético (2008-2010). TEC-2007-68119-C02-01/TCM.

- RAUDOS: Red interactiva multiplataforma de distribución de contenidos audiovisuals (2008-2009). TSI-020302-2008-115.

- MODELATV: Personalización de servicios y gestor de modelos de negocio en TV móvil (2007-2009). FIT-330300-2007-15.

- EVENT-TUR: Sistema integral de distribución de contenidos y comunicación heterogénea como soporte a una gestión centrada en el usuario de eventos y centros de congreso (2007-2008). FIT-350100-2007-56.

- RURALTUR: Plataforma de movilidad inalámbrica para el despliegue de servicios y contenidos multimedia en el sector del turismo rural (2005-2007). FIT-350301-2005-5.

- ADHOCSYS: Wireless Ad Hoc Broadband Monitoring System (2004-2007). FP6 IST STREP Project, IST-2004-026548.

Appendix B. Implementation details

B.1. Ad hoc mode and OLSR installation on Android devices

In order to configure a multi-hop wireless network, participant nodes should be working in ad hoc mode. Unfortunately, since Android officially does not support ad hoc mode, devices must be rooted (superuser access) for such configuration, and this process may differ among devices. This section is intended to serve as a guideline to configure a multi-hop ad hoc network on Android devices.

Firstly, once superuser access is granted, edit **/data/misc/wifi/wpa_supplicant.conf** and copy the lines below (delete any other line). Note that your previous configured networks will be removed.

```
ap_scan=2
ctrl_interface=eth0
update_config=1

network={
    ssid="AdhocNetwork"
    scan_ssid=1
    key_mgmt=NONE
    mode=1
}
```

To configure network parameters, you can use the GUI to enter in Wireless Networks configuration. Use Advanced Options to set Static IP and provide both valid IP and netmask (e.g. 10.0.0.1, 255.255.255.0).

Otherwise, you can use the command prompt. Plug the phone and start the command line:

```
$ adb shell
```

And configure the wireless network interface:

```
# busybox ifconfig eth0 10.0.0.1 netmask 255.255.255.0 broadcast
10.0.0.255 up

# wpa_supplicant -i eth0 -c /data/misc/wifi/wpa_supplicant.conf -d
```

Restart the wireless networking (may be you also need to reboot the device). The smartphone should be now connected to the configured ad hoc network.

In order to install OLSR so that devices can route packets along multiple hops, download source files from [37]. Android NDK is needed for compilation.

```
$ make NDK=/path/to/android-ndk OS=android DEBUG=0 build_all

$ make NDK=/path/to/android-ndk OS=android DEBUG=0 install_all
```

After compiling, OLSR files are placed in **data/local**.

```
data/local/
          /bin/
              olsrd
          /etc/
              olsrd.conf
          /lib/
              <plugin libraries>
```

Configuration file **data/local/etc/olsrd.conf** should be configured according to the network requirements. Interface name must be changed to fit the phone's wireless interface name (e.g. eth0).

The final step is to actually install OLSR files in the device.

```
$ adb push data/local/ /data/local/
```

Then, OLSRd can be launched from the adb shell or directly from a terminal application on the smartphone. Note that absolute paths may be omitted if the global variable $PATH is properly set.

```
# /data/local/bin/olsrd -f /data/local/etc/olsrd.conf
```

Recently, as part of the Commotion project, an Android app is being developed to make it easy to install and run OLSR mesh networking on Android devices. It can be followed here:

```
https://code.commotionwireless.net/projects/commotion-android
```

B.2. HOLSR configuration on Routerboard 500 series

Hierarchical OLSR has been implemented on Routerboards 532 using OpenWrt, which is a Linux distribution for embedded devices, available at:

```
https://openwrt.org
```

Hierarchical routing can be achieved by using the *olsrd* daemon from OpenWrt. The Routerboards are considered cluster heads and, consequently, they must have two wireless interfaces available and correctly configured. By running the *holsrd* script, two instances of *olsrd* for both intra-cluster and inter-cluster interfaces are launched. The main lines of *holsrd* are shown below:

```
#!/bin/sh /etc/rc.common

OLSRD=/usr/sbin/olsrd

# ...

$OLSRD -f /usr/share/olsr/intra.conf < /dev/null > /dev/null &
rm /var/run/olsrd-ipv4.lock
$OLSRD -f /usr/share/olsr/inter.conf < /dev/null > /dev/null &
```

For simplicity, Host and Network Associations (HNA) are statically configured. The configuration files *intra.conf* and *inter.conf* are used to configure intra- and inter-cluster communication, respectively. The IP assignment for access networks follows the rule 10.0.X.0/24. Note that OLSR UDP ports must not overlap with one another. Incidentally, inter-cluster communication may use another prearranged port number.

```
# intra.conf
# ...
OlsrPort 698

Hna4
{
    # Associated networks to other cluster heads
    10.0.0.0 255.255.0.0
}
```

```
# inter.conf
# ...
OlsrPort 1698

Hna4
{
    # Associated network to this cluster head
    10.0.1.0 255.255.255.0
}
```