Routing in Wireless Multimedia Sensor Networks

Houda Zeghilet

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Ecole Doctorale : IAEM Lorraine
Département de Formation Doctorale : Automatique
Laboratoire de rattachement : Centre de Recherche en Automatique de Nancy

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par **Houda ZEGHILET**

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Membres du jury :

Rapporteurs:
Pr. Congduc Pham, Université de Pau et des Pays de l'Adour, LIUPPA
Dr. Benchaiba Mahfoud (Maître de Conférences/A), USTHB, LSI

Examinateurs:
Pr. Francis Lepage, Université de Lorraine, CRAN (directeur de thèse)
Pr. Nadjib Badache, USTHB, LSI (directeur de thèse)
Pr. Samira Moussaoui, USTHB, LSI
Dr. Moufida Maimour, Université de Lorraine, CRAN (co-directeur de thèse)

Abstract

Nowadays, the proliferation of inexpensive hardware such as CMOS cameras and microphones that are able to ubiquitously capture multimedia content has led to the emergence of wireless multimedia/video sensor networks (WMSN/WVSN). As a consequence, a wide spectrum of applications can be projected in many areas and everyday life. Compared to traditional WSNs, WVSNs introduce unique challenges due mainly to the big amount of data to be captured and transmitted over a constrained network. A WVSN may require a certain level of quality of service in terms of delay, bandwidth, jitter, reliability, quality of video perception, etc.

In this work, we aim to deal with the problem of routing video content in a wireless sensor network. Many routing protocols targeted to WSNs have been proposed in the literature and can be qualified from a network organization perspective either as flat or hierarchical. In a flat topology, nodes have same functionalities and each of them can take part in the routing process. However, in a hierarchical architecture, the sensors are organized in clusters allowing for more scalability, less consumed energy and thus longer lifetime for the whole network.

Few of the existing routing protocols considered specifically the transmission of intensive data such as video. In this work, we first propose a cluster-based (hierarchical) routing protocol called ELPC (Energy Level Passive Clustering) where the main objective is to enhance the network lifetime while handling video applications. This is achieved thanks to a load balancing feature where the role of clusterheads is alternated among candidate nodes depending on their energy level.

The second contribution consists in a multipath routing protocol with interference awareness. In fact, by allowing concurrent multiple flows, the end-to-end delay gets reduced and the application needs in terms of bandwidth can be satisfied. Instead of completely suppressing interferences, our multipath routing protocol tries to minimize them through a simple algorithm without extra overhead. Multiple paths are built at once while minimizing their inter-path interferences thanks to some additional information on neighboring nodes piggybacked on the route request messages. In addition to interference awareness, we propose a multiqueue multipriority scheme where the influence of data type in a video is considered. Simulation results show that using less interfering paths combined to a multiqueue multipriority scheme allows for better video quality.

Résumé

Aujourd'hui, la prolifération de matériel peu coûteux tels que les caméras et les microphones capables de capturer du contenu multimédia de façon ubiquitaire a conduit á l'émergence des réseaux de capteurs sans fil multimédia/vidéo (RCSFM /RCSFV). En conséquence, un grand éventail d'applications peuvent être projetées dans de nombreux domaines de la vie de tous les jours. Par rapport aux réseaux de capteurs traditionnels (RCSF), les RCSFVs présentent des défis uniques principalement en raison de la grande quantité de données à capturer et à transmettre au-dessus d'un réseau contraint en ressources. Un certain niveau de qualité de service peut être exigé en termes de délai, bande passante, gigue, fiabilité, qualité de perception de la vidéo, etc.

Dans ce travail, nous visons le problème du routage de données vidéo dans un RCSF. De nombreux protocoles de routage ont été proposés dans la littrature. Ils peuvent être qualifiés de *plat* ou *hiérarchique* en vue de l'organisation du réseau. Dans une topologie plate, tous les noeuds ont les mêmes fonctionnalités où chacun peut participer au processus de routage. Cependant, dans une architecture hiérarchique, les capteurs sont organisés en groupes (clusters) permettant une plus grande évolutivité, moins d'énergie consommée et donc une plus longue vie pour l'ensemble du réseau.

Parmi les protocoles de routage existants, peu considérent spécifiquement la transmission de données intensives comme la vidéo. Dans ce travail, nous avons d'abord proposé un protocole de routage hiérarchique appelé ELPC (Energy Level Passive Clustering) dont l'objectif principal est d'améliorer la durée de vie du réseau en prśence de flux vidéo. Ceci est obtenu grâce à l'équilibrage des charges au moment de la construction de la topologie où le rôle de tte de groupe est alterné entre les nœuds candidats en fonction de leur niveau d'énergie.

La deuxième contribution consiste en un protocole de routage multichemin qui prend les interférences inter-chemin en considération. En effet, en permettant la transmission de plusieurs flux concurrents, le délai de bout en bout se trouve réduit et les besoins de l'application en termes de bande passante peuvent être satisfaits. Au lieu de supprimer complètement les interférences, notre protocole de routage multichemin tente de les minimiser en se basant sur l'ajout d'informations supplémentaires sur les noeuds voisins dans les messages de construction de la topologie. De plus, nous proposons un schéma de files d'attente priorités multiples où l'influence des types de données dans une vidéo est considérée. Les résultats des simulations montrent que l'utilisation de chemins moins interférents combinée à un rgime de multipriorité permet une meilleure qualité vidéo.

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Contents

Chapter 1

Introduction

Recent technological advances have led to the emergence of small low-power devices that integrate sensors with on-board processing and wireless communication capabilities. Pervasive networks of such sensors, called Wireless Sensor Networks (WSNs), open new vistas for a wide spectrum of applications [14]. Recently, the integration of low-power wireless networking technologies with inexpensive hardware such as CMOS (Complementary Metal-Oxide Semiconductor) cameras and microphones is fostering the development of a particular instance of WSNs referred to in the literature as wireless multimedia sensor networks (WMSNs)[13]. In addition to scalar sensor data, the *multimedia sensor* devices allow retrieving and communicating a multimedia data content. From this perspective, significant benefit to many sensor networking applications are provided in domains like surveillance, target tracking, health care, industrial process control, traffic management, etc.

Wireless Video-based Sensor Network (WVSN) is a particular instance of a WMSN where the scalar WSN is strengthened by introducing the ability of retrieving richer information content through image/video sensors [94, 39]. A WVSN can operate in an ad-hoc manner and hence does not require a network infrastructure adding a much higher level of flexibility and allowing a wider range of applications. In a WVSN's application, video sensors are deployed at strategic positions with other non visual sensors. A central controller or a base station commonly referred to as the *sink* is responsible for requesting/analyzing sensed data.

WVSNs generate unique challenging problems and should be designed to satisfy limited resources while providing a good video quality. From a communication point of view, supporting multimedia content in WSNs is very demanding. Many types of traffic can flow in the network having different characteristics and quality of service (QoS) requirements. Additionally, multimedia applications dealing with audio/video streams have specific requirements that are difficult to fulfill. In this case, the network should sustain transmission of large burst of data at a high bit-rate. These characteristics need to be addressed efficiently taking into account the severe hardware, bandwidth and power limitations of the sensor nodes.

Designing an efficient routing protocol for WVSNs' applications is a challenging task. Although, there are many routing solutions proposed in WSNs, these protocols should be rethought to suit the multimedia case [46]. The objective of this thesis is to develop efficient communication protocols in WMSNs (WVSNs). In general, routing protocols proposed in sensor networks can be classified from a network organization perspective into hierarchical and flat routing protocols. Hierarchical topology is achieved through clustering techniques and allows more scalability, less consumed energy and thus longer lifetime for the whole network. In fact, most of the sensing, data processing and communication activities can be restricted within clusters. Moreover, clustering allows data aggregation which reduces congestion and energy consumption and can provide load balancing if appropriately configured. In WVSNs they can be of a great benefit to support the delivery of high volumes of data in these networks. This is why, we propose in this thesis a cluster-based routing protocol called ELPC (Energy Level Passive Clustering) where the main objective is to enhance the network lifetime while handling video applications. This is achieved thanks to a load balancing feature where the role of clusterheads is alternated among candidate nodes depending on their energy level.

When flat routing protocols are considered, multipath routing appears to be an essential solution for supporting the quality of service requirements of WVSNs' applications by providing load balancing. However, the multiple paths may be highly interfering if their respective links are too close. Consequently, the overall achieved throughput is far from being the summation of the bandwidth offered independently by the different paths. To deal with the problem of inter-path interferences, we propose a multipath routing protocol where instead of completely suppressing interferences, it tries to minimize them through a simple algorithm without extra overhead. We also suggest the use of a multiqueue multipriority scheme where the influence of data type in a video flow is considered.

This thesis is organized as follows. In chapters 2, we review routing protocols proposed in WSNs. In chapter 2, routing solutions are broadly grouped into two different classes : flat and hierarchical-based routing protocols. Flat routing solutions are further grouped into data-centric, location-based, multipath and QoS protocols [11, 15]. Hierarchical-based routing algorithms are classified into pre-established and on-demand cluster-based routing algorithms. In the former, the routing functionality is performed on already formed hierarchical topology whereas in the latter, the clustered topology is built using the routing packets (and data packets) flowing in the network.

In chapter 3, we review routing techniques in WMSNs. We begin by introducing Wireless Multimedia Sensor Networks (WMSNs) by giving a general architecture and the characteristics of these networks. Then, routing techniques to ensure a given QoS are presented. In this chapter, we present routing solutions that were initially proposed in WSNs which, we believe, suit the multimedia case. Also, routing solutions proposed specifically in WMSNs are presented.

Chapter 4 presents our first contribution namely, Energy Level Passive Clustering (ELPC) algorithm. In this protocol, the network topology is built based on the energy level of nodes. Thus, nodes with more energy elect themselves as clusterheads. This results in higher lifetime for the whole network as a load-balancing among nodes is achieved. We apply the resulting algorithm with a flooding based routing algorithm as a combination to ensure routing in

WSNs. This combination shows good performances in terms of network lifetime and delivery ratio. Also, we studied the performances of video transmission over WSNs using our approach and show how the video quality can be enhanced using our clustering protocol.

In chapter 5, we propose a multipath routing protocol in WMSNs with interference awareness and study the effect of inter-path interference on video data transmission over WSNs. Our protocol permits interferences between paths but tries to minimize them through a simple algorithm without extra overhead. We propose to implicitly block the neighboring nodes of the nodes belonging to a path already constructed by piggybacking additional information in the route request messages. The sink node is responsible of blocking the nodes using the piggybacked data when it receives route request messages for other paths. Several transmission strategies using the built paths are evaluated through simulation. The impact of interference on video data quality is then considered for these different strategies. Finally, we propose a multiqueue multipriority scheme to improve the performances of the network in case of congestion when high data rates are used.

Finally, chapter 6 concludes this thesis, summarizes the main contributions of this work and discusses potential future work directions.

Chapter 2

Routing in Wireless Sensor Networks

2.1 Introduction

The network layer is responsible for implementing an addressing scheme in the network in order to deliver data packets. It mainly establishes paths for data transfer through the network. Compared to traditional ad-hoc networks, routing is more challenging in wireless sensor networks due to their limited resources in terms of available energy, processing capability and communication, which are major constraints to all sensor networks applications. These constraints yield frequent topology changes making route maintenance to be a non-easy task. Additionally, the typical mode of communication is many-to-one from multiple sources to a particular sink rather than from one entity to another. Finally, since data related to one phenomena may be collected by multiple sensors, a significant redundancy is likely to be present and has to be considered. This is why routing protocols proposed for ad-hoc networks in recent years are not suitable for wireless sensor networks. Alternative approaches that take the above limitations into account with energy-awareness are required. Due to that, multiple routing protocols for wireless sensor networks have been proposed [11, 15].

From network organization perspective, routing protocols can coarsely be classified in two main classes : flat and hierarchical routing. In a flat topology, each node plays the same role and has the same functionality as the other nodes in the network. As opposed to a flat organization, clustering allows a hierarchical architecture with more scalability, less consumed energy and thus longer lifetime for the whole network. This is due mainly to the fact that most of the sensing, data processing and communication activities can be performed within clusters.

In this chapter, we review routing protocols proposed in WSNs. The routing solutions are broadly grouped into two different classes: flat routing solutions and hierarchical-based protocols. Flat routing solutions are further grouped into data-centric, location-based, multipath and QoS protocols [11, 15]. Hierarchical-based routing algorithms are classified into pre-established and on-demand cluster-based routing algorithms. In the former, the routing functionality is performed on already formed hierarchical topology whereas in the latter, the clustered topology is built using the routing packets (and data packets) flowing in the network.

2.2 Flat Routing

Flat routing protocols are designed for networks with homogeneous nodes where all the network nodes have the same processing and data transmission capabilities, moreover their packet forwarding role is also similar. Flat routing protocols can be further classified into various classes depending on different criterion like protocol functionality, route construction metrics, design aims, etc.

Data-centric approach appears as a new routing class in WSNs where data is gathered or routed based on the attribute of the data rather than using routes based on the unique identities (ID) of nodes [6, 55]. In order to limit energy consumption due to unnecessary flooded messages, some routing protocols, mainly geographic ones [114, 97, 62, 72] with location awareness, restrict flooding to localized regions. Quality of Service routing protocols constitute another class of routing aiming to minimize a cost function as a metric of optimization which may capture features such as node residual energy, link latency, hop count, and bandwidth usage. Also, multipath routing has also been proposed as an efficient routing solution in WSNs [108, 33, 28]. In this paradigm, many routes are constructed between the source and the destination and are used to route data with more reliability, efficiency and resiliency. It is worth noting that a given protocol may include features from more than one of the cited classes.

2.2.1 Data-centric Routing

Due to the large number of sensor nodes in the network, it is not feasible to assign a global identifier to each node. This consideration has led to data centric routing, where the sink node sends queries to certain regions and waits for data from the sensors located in the selected regions. Since data is being requested through queries, attribute-based naming is necessary to specify the properties of data. Early works on data centric routing, e.g., SPIN and Directed Diffusion [6, 55] were shown to save energy through data negotiation and elimination of redundant data. These two protocols motivated the design of many other protocols which follow a similar concept.

Sensor Protocols for Information via Negotiation (SPIN)

SPIN [6] is a data-centric negotiation-based information dissemination protocol designed for WSNs. The sensor nodes generate meta-data descriptions in order to represent their data about an event. These data are advertised by the sensors using ADV messages. Nodes interested in the advertised data send a request message (REQ) to the nodes holding the data. The same procedure is being repeated in the neighboring region until data has been received by the sink node. SPIN considers the fact that nodes in close proximity have similar data, and hence it is required to only distribute data that other nodes do not possess. This is mainly employed to reduce redundancy in the sensor network. The meta-data naming is application-specific and can be used for many types of applications. Also, the meta-data negotiation mechanism proposed by SPIN provides much energy saving than flooding by reducing the dissemination of redundant data. However, the adopted advertisement mechanism cannot guarantee the delivery of data.

Directed Diffusion and its Variants

Directed Diffusion as a data-centric dissemination scheme was proposed in [55]. It deals with several elements. An interest message is a query which specifies what a user is interested in. Each interest contains a description of a sensing task using attribute-value pairs. This scheme is also used to name data generated by nodes. In order to receive data, the interest message is flooded by the sink. When this interest is received by an intermediate node, it sets up a gradient to the neighbor from which it heard the interest. Upon receiving interest messages, nodes start to sense their environment for events (matching data). Once these latter are observed, the nodes become sources and send data to all neighbors to which they have gradients towards the originators of interest. First data messages are flagged as *exploratory* and are forwarded down multiple paths using a small data rate. Later, when receiving first data messages, the sink reinforces only one or a small set of paths. When these latter are reinforced, the sources start to send data at a higher rate.

Directed Diffusion can be considered as an energy-efficient scheme [28]. It involves application in sensor-network communications to complement the basic dissemination algorithms. This greatly reduces communication cost by replacing communications by computations. Data caching and aggregation are other sources of energy-efficiency since they permit reducing the number of messages to be forwarded in the network. Moreover, the on-demand nature of paths construction enables robustness and especially saves energy. However, the scheme still presents some drawbacks, with respect to energy-efficiency. Directed Diffusion relies heavily on flooding to both building and maintaining paths which is very expensive depending on the number of nodes in the network and especially the number of the gradients at each node. Moreover, paths selection using energy aware metrics was not proposed in the original version of the paradigm.

In order to improve Directed Diffusion in terms of energy efficiency (mainly through minimizing flooding), many variants have been proposed. An extension of Directed Diffusion called Rumor Routing is presented in [7] where the queries generated by the sink are delivered to the nodes that have observed an event related to these queries. This is done through the propagation of agents on behalf of the nodes that have detected the events. On reception of agents, nodes can acquire updated information about the events in the network. This knowledge is reflected in the node's event caches. By using the event cache, a node can conveniently send a query message. Under these circumstances, the query is sequentially propagated to one of the neighbors selected randomly. Once the query arrives at a node with an entry related to the demanded event in its event cache, the query is then forwarded through the learned path. This procedure allows for reducing the unnecessary flooding in the network. Rumor Routing is intended for situations where geographic routing criteria are not applicable because a coordinate system is not available or the phenomenon of interest is not geographically correlated.

Gradient Based routing (GBR) [102] is another extension of Directed Diffusion where the number of hops when the interest is diffused through the whole network is memorized and used in query propagation. As such, each node can calculate a parameter called the height of the node, which is the minimum number of hops to reach the sink. The difference between a node's height and that of its neighbor is considered the gradient on that link. A packet is forwarded on a link with the largest gradient. GBR uses some auxiliary techniques such as data aggregation and traffic spreading in order to uniformly divide the traffic over the network. In GBR, three different data dissemination techniques have been proposed to obtain a balanced distribution of the traffic in the network, thus increasing the network lifetime.

Sensor Network as a Database System

Some data-centric Routing protocols consider the sensor network as a database system. COUGAR [117] is a routing solution that views the network as a huge distributed database system. The key idea is to use declarative queries in order to abstract query processing from the network layer functions such as selection of relevant sensors. The abstraction is supported through an additional query layer that lies between the network and application layers. COUGAR incorporates an architecture for the sensor database system where sensor nodes select a leader node to perform aggregation and transmit the data to the Base station. This later is responsible for generating a query plan, which specifies the necessary information about the data flow and in-network computation for the incoming query and send it to the relevant nodes. The query plan also describes how to select a leader for the query. COUGAR provides energy savings especially when the generated data is huge. However, the addition of query layer on each sensor node may add an extra overhead in terms of energy consumption and memory storage. Also, synchronization among nodes is required to achieve successful in-network processing as the leader nodes should wait for data from all the incoming sources.

ACQUIRE (Active Query Forwarding in Sensor Networks) [100] is another routing technique that considers the wireless sensor network as a distributed database. In this scheme, a node injects an active query packet into the network. Neighboring nodes that detects that the packet contains obsolete information, emits an update message to the node. Then, the node randomly selects a neighbor to propagate the query which needs to resolve it. As the active query progresses through network, it is progressively resolved into smaller and smaller components until it is completely solved. Then, the query is returned back to the querying node as a completed response.

2.2.2 Location-based Routing

The idea of location-based Routing or geographic routing is to use location information available to a node locally for routing. The location of nodes may be available directly by communicating with a satellite, if nodes are equipped with a small low power GPS (Global Positioning System) receiver. Also, relative coordinates of neighboring nodes can be obtained by exchanging such information between neighbors [110]. Moreover, the distance between neighboring nodes can be estimated based on incoming signals strength. This location information is then used to limit the route discovery flooding to a geographic area around the destination [62] [19]. For instance, the sink may request an information from the nodes located in a specific zone. Then, the request is delivered by the neighboring nodes to this zone. Thus, enabling an efficient routing in terms of energy consumption by restricting flooding. Moreover, the location information can be used to guide packet forwarding through a simple greedy forwarding. In this latter, each node forwards the packet to a neighbor closer to the destination than itself, until ultimately the packet reaches the destination. This technique can guarantee the delivery of data if nodes have consistent location information [114] [59]. Moreover, with consistent location information, the latency of data delivery can also be reduced.

GPSR: Greedy Perimeter Stateless Routing

GPSR [59], is one of the most famous geographic routing protocols in WSNs. It assumes bidirectional radio reachability, that all nodes know their own position and that sources can determine the locations of their destinations. Packets are marked with their destinations location. GPSR adopts *greedy forwarding* wherever possible and *perimeter forwarding* otherwise. In the former, a node can make a locally optimal greedy choice of a packet's next hop which is the neighbor geographically closest to this packets destination. This scheme is repeated successively until the destination is reached. In the latter (i.e. perimeter forwarding), the *right hand rule* is used to avoid voids in the network (absence of communicating nodes). The sequence of edges traversed by the *right-hand rule* is called a perimeter. GPSR works better in a free open space scenario with evenly distributed nodes but suffers from several problems. For example, in city scenarios, greedy forwarding is often restricted because direct communications between nodes may not exist due to obstacles such as buildings and trees.

Geographic and Energy Aware Routing

Yu et al. [114] discussed the use of geographic information when disseminating queries to appropriate regions since data queries often include geographic attributes. The protocol is an extension of Directed Diffusion paradigm that uses energy aware and neighbor selection heuristics to route a packet towards the destination region instead of blindly flooding it in the whole network. Each node in GEAR keeps an estimated cost and a learning cost of reaching the destination through its neighbors. The estimated cost is a combination of residual energy and distance to destination. The learned cost is a refinement of the estimated cost that accounts for routing around holes in the network.

There are two phases in the algorithm: First, forwarding packets towards the target region and then forwarding the packets within the region. In the first step, a node, upon receiving a packet, checks its neighbors to see if there is one neighbor, which is closer to the target region than itself. If there is more than one, the nearest neighbor to the target region is selected as the next hop. If they are all further than the node itself, this means there is a hole. In this case, one of the neighbors is picked to forward the packet based on the learning cost function. This choice can then be updated according to the convergence of the learned cost during the delivery of packets. When the packet reaches the target region it can be diffused within the region by either recursive geographic forwarding or restricted flooding.

Energy Aware Greedy Routing (EAGR)

Razia et. al. [48] suggest a location-based protocol that works on geographical information as well as the energy level available in the sensor node. In most of the greedy routing algorithms, only shortest-path is calculated, keeping aside the fact that in this case the node presents in most of the shortest path will loose its energy very quickly. Therefore, it creates a hole in that area and results in dropping packets. In EAGR, all nodes have the same energy level and a threshold energy level is set. Nodes having less than that energy level are considered dead. Then, the algorithm finds out the location of each node. All the nodes having energy level greater than their threshold value get information about their neighbor and create a table of their locations. Based on this table, average distances to its neighbors are calculated. For forwarding data, EAGR selects the node having distance equal to or less to this average distance value and having maximum energy level amongst all the neighbors. By considering energy level in selection, whenever needed, a new node is selected, and no single node gets its energy depleted more quickly, resulting in longer life for the network. In EAGR, packets only get dropped when the destination is dead or there is no further neighbor alive to forward data.

2.2.3 Multipath Routing

Multipath routing protocols enable a source node to discover several paths towards the destination. Traditionally, one of the constructed paths is considered as primary and used for data transmission and the other ones are used when this path fails. Another approach consists in concurrently transmitting data over the discovered paths to allow for better reliability, adequate network resources or load balancing [108].

Resiliency Support through Alternate multipath Routing

In wireless sensor networks, routes can break at any time due to node or link failures. Multipath routing is used in this case to recover from failure of the data transmission path. Thereby, a sensor node can use an alternative path to forward its packets towards the sink [28]. A multipath extension of Directed Diffusion [55] is proposed in [33]. In Directed Diffusion, many paths are discovered, but only one path is reinforced and used for data transmission whereas the other paths are maintained using periodic low-rate flooding. The work in [33] aimed to restore paths from the source to the sink without periodic flooding by setting up and maintaining alternate paths in advance. A braided multipath routing is proposed and have shown to be more energy efficient compared to the disjoint multipath approach both for independant and geographically correlated failures.

Concurrent Multipath Data Routing

In this class of multipath routing, multiple routes are simultaneously used to transmit data packets. This scheme can be motivated by improving packet reliability, traffic distribution to ensure some QoS requirements and network lifetime enhancement [108]. Achieving packet reliability is a challenging task in wireless sensor networks mainly due to wireless links, nodes and network caracteristics. A simple and intuitive way to improve data reliability is to send the same data over multiple paths. The work in [37] proposes an aggressive and costly fault tolerant technique where data packets are allowed to simultaneously follow multiple paths to a destination. In ReInForm [22], data packets are assigned different priority levels that map to a desired level of reliability. This information (along with other network conditions parameters) is added to the message to deduce the number of copies to be sent. The intermediate nodes use this information to send the required copies along multiple paths until the sink is reached. Accordingly, the reliability of this protocol is achieved at the high cost of energy consumption and bandwidth utilization. Another approach to enhance data transmission reliability is to salvage the lost packets. A distibuted N-to-1 multipath is proposed in [74] that permits to construct multiple disjoint paths from the source to the sink in one route discovery process. A multipath traffic dispersion and per-hop alternate path salvaging of lost packets is also proposed.

Using multiple paths concurrently to send data packets permits to share the communication load between the nodes. In REER [115], a robust and energy efficient multipath routing protocol is proposed. REER proposed the use of the residual energy, node available buffer size, and Signal-to-Noise Ratio (SNR) to predict the best next hop through the paths construction phase. In data transmission phase, messages are split up into a number of segments of equal size, coded using a XOR-based error correction scheme, and then transmitted across multiple paths simultaneously. This is mainly done to minimize the end-to-end delay. This method is shown to outperform the one using a single path for data transmission.

Load balancing using disjoint multipath routing is explored in [83]. After constructing paths using a cost metric, the source node transmits data packets with the assigned rates on each path. A traffic allocation algorithm is formulated as an optimization problem to find the appropriate allocated data rate on each path. More energy saving and better delays are noticed compared to Directed Diffusion[55]. Load balancing to control congestion caused by high traffic rates using geographical mutipath routing is addressed in [92]. Repartition mechanisms are proposed to deal with congestion by splitting the traffic up before the congestion area. An End-to-End Packet Scatter (EPS) is also proposed to split the flow at the source and perform rate control to cope with profound congestion.

Expending network lifetime can also be achieved through using multiple paths for data transmission. In fact, multipath routing permits to homogeneously distribute the energy among the nodes [84]. This aspect is addressed in the majority of the solutions presented in this section.

2.2.4 Quality of Service Routing

One of the major design goals of WSNs routing protocols is to ensure reliable data communication under minimum energy depletion to extend the lifetime of the network. In QoS-based routing protocols, the network needs to ensure some QoS metrics besides energy efficiency. The QoS issue in WSNs is introduced in [105] where multiple paths with multiple QoS levels are used to route data in the network. In maximum lifetime routing [25] a cost function is defined as a combination of communication energy and residual energy levels of the two end nodes. A shortest cost path routing algorithm is proposed which uses these link costs to route data between the two end nodes. Other examples of protocols include SPEED [51], Energy Aware QoS Routing Protocol [12] and Minimum cost forwarding [118]. Some of these protocols are discussed further in the next chapter of this thesis.

2.3 Hierarchical Routing

Flat routing protocols are quite effective in relatively small networks. However, they scale very bad to large and dense networks since, typically, all nodes are alive and generate more processing and bandwidth usage. On the other hand, hierarchical routing protocols have shown to be more scalable and energy-aware in the context of WSNs. In hierarchical-based routing, nodes play different roles in the network and typically are organized into clusters. Clustering (Figure 2.1) is the method by which sensor nodes in a network organize themselves into groups according to specific requirements or metrics. Each group or cluster has a leader referred to as *clusterhead* (CH) and other ordinary member nodes (MNs). The clusterheads can be organized into further hierarchical levels.

2.3.1 Clustering and Routing

From a routing perspective, clustering allows to split data transmission into *intra-cluster* (within a cluster) and *inter-cluster* (between clusterheads and every clusterhead and the sink) communication. This separation leads to significant energy saving since the radio unit is the major energy consumer in a sensor node. In fact, member nodes are only allowed to communicate with their respective clusterhead, which is responsible for relaying the data to the sink with possible aggregation and fusion operations. Moreover, this separation allows to

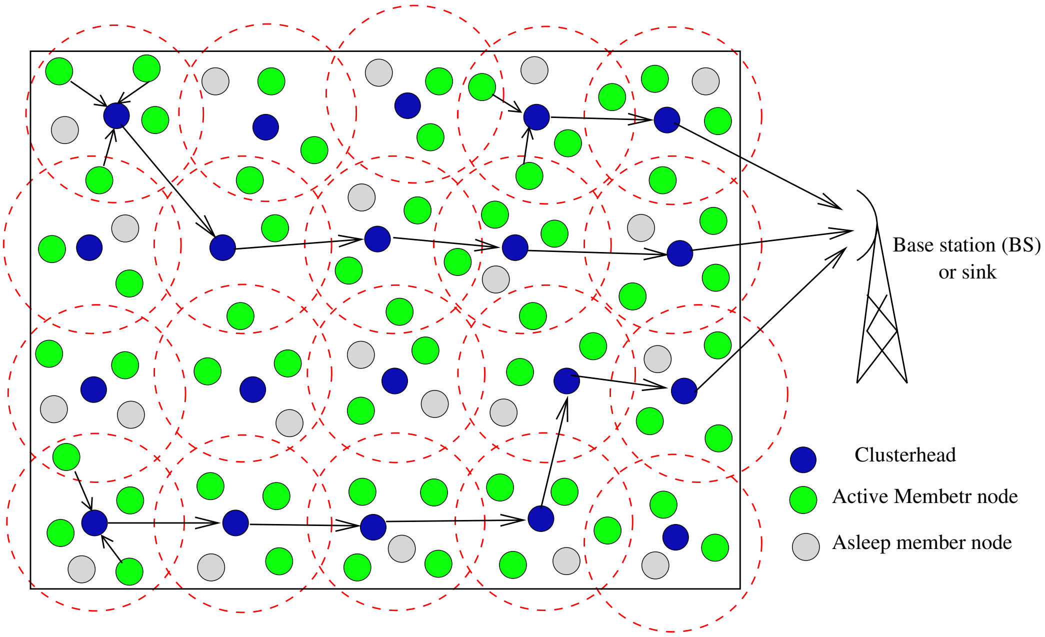
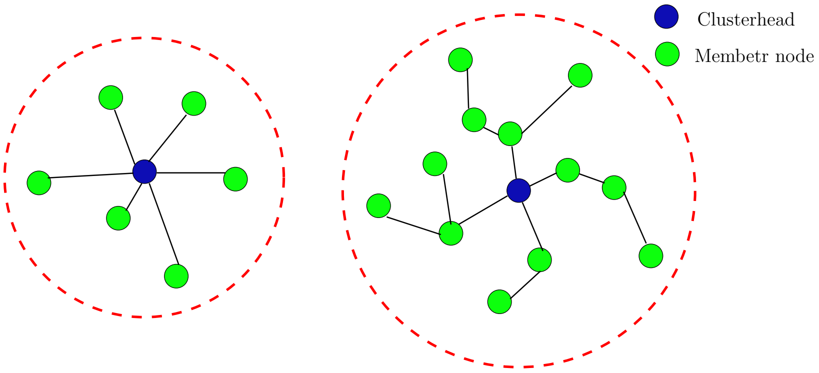


Figure 2.1: Cluster-based topology



(a) One-hop intra-cluster connectivity (b) multi-hop intra-cluster connectivity

Figure 2.2: One-hop toward the sink

reduce routing tables at both member nodes and clusterheads in addition to possible spatial reuse of communication bandwidth.

Intra-cluster communications

Most of the earlier work on clustering assume direct (one-hop) communication between member nodes and their respective clusterheads [52, 119]. All the member nodes are at most two hops away from each other (Figure 2.2(a)). One-hop clusters makes selection and propagation of clusterheads easy, however, multi-hop intra-cluster connectivity is sometimes required, in particular for limited radio ranges and large networks with limited clusterhead count. Multi-hop routing within a cluster (Figure 2.2(b)) has already been proposed in wireless ad-hoc networks [70]. More recent WSNs clustering algorithms allow multi-hop intra-cluster routing [16, 34].

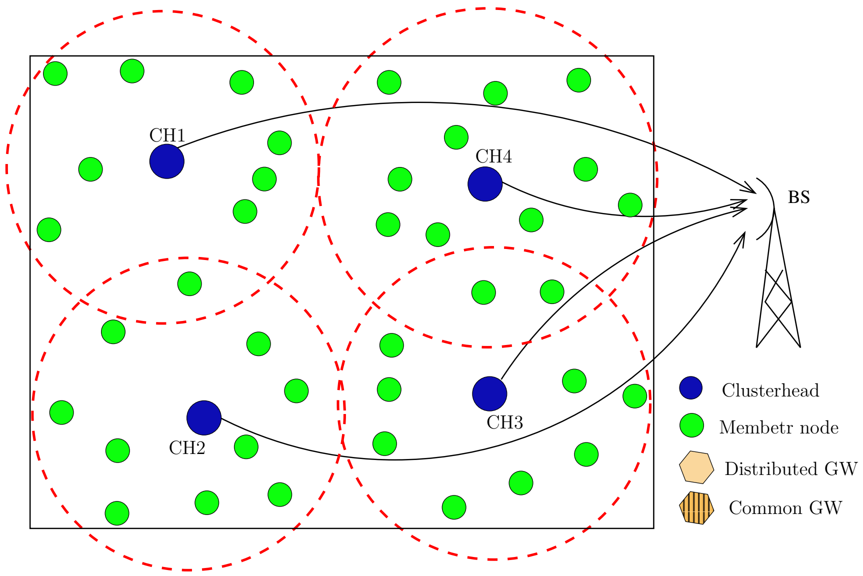


Figure 2.3: One-hop toward the sink

Inter-cluster Routing

Earlier cluster-based routing protocols such as LEACH [52] assume that the clusterheads have long communication ranges allowing direct connection between every clusterhead and the sink (Figure 2.3). Although simple, this approach is not only inefficient in terms of energy consumption, it is based on irrealistic assumption. The sink is usually located far away from the sensing area and is often not directly reachable to all nodes due to signal propagation problems. A more realistic approach is multihop inter-cluster routing that had shown to be more energy efficient [81]. Sensed data are relayed from one clusterhead to another until reaching the sink (Figure 2.1).

Direct communication between clusterheads is not always possible especially for large clusters (multihop clusters for instance). In this case, ordinary nodes located between two clusterheads could act as *gateways* (GW) allowing the clusterheads to reach each other (Figure 2.4). A gateway node is either *common* or *distributed*. A common (ordinary) gateway is located within the transmission range of two clusterheads and thus, allows 2-hop communication between these clusterheads. When two clusterheads do not have a common gateway, they can reach each other in at least 3 hops via two distributed gateways located in their respective clusters. A distributed gateway is only reachable by one clusterhead and by another distributed gateway of the second clusterhead cluster.

Inter-cluster communication in several proposals is achieved through organizing the clusterheads in a hierarchy (Figure 2.5) as done in [16] and [79]. Multiple level hierarchy allows better energy distribution and overall energy consumption. However, maintaining the hierarchy could be costly in large and dynamic networks where nodes die as soon as their energy supply is completely discharged.

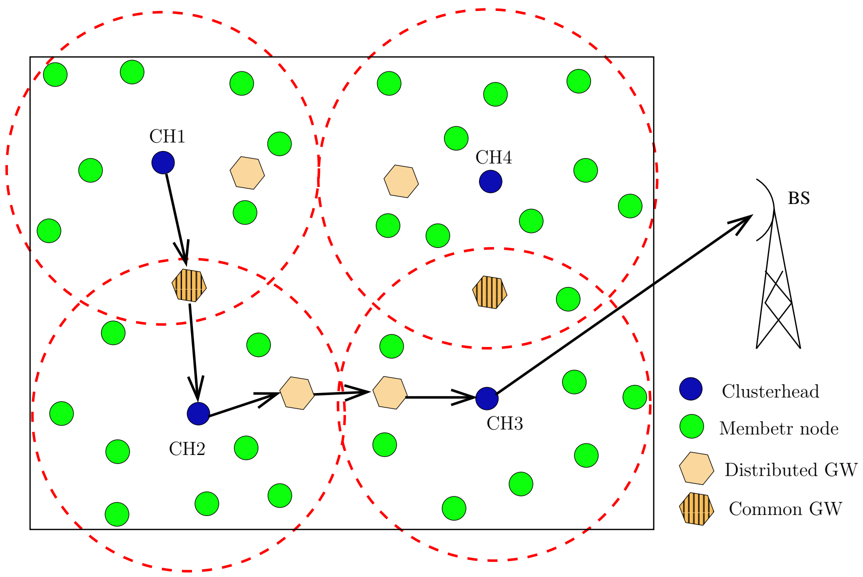


Figure 2.4: Multi-hop inter-cluster communication

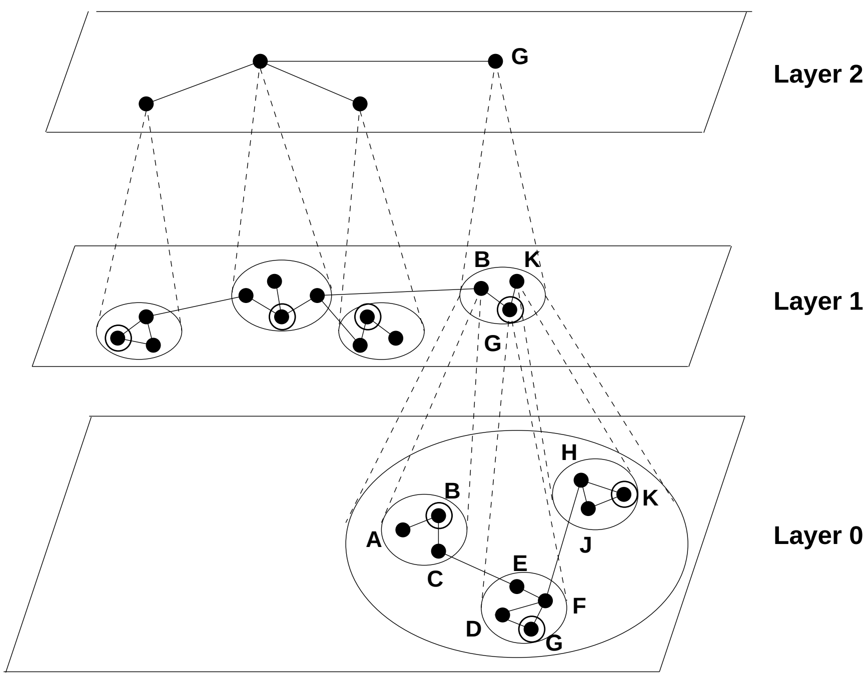


Figure 2.5: 3-level hierarchy (redrawn from [18])

2.3.2 Clustering Algorithms Taxonomy

In the literature, there have been several different ways to classify Clustering algorithms for WSNs. In [120], the classification is performed based on parameter(s) used for electing clusterheads and the execution nature of a clustering algorithm which can be either probabilistic or iterative. In iterative clustering techniques, a node waits for a specific event to occur or certain nodes to decide their role (e.g., become clusterheads) before making a decision. Probabilistic Clustering Techniques enables every node to independently decide on its role in the clustered network while keeping the message overhead low. Considering how the cluster formation is carried out, a clustering algorithm is either executed at a central point or in a distributed fashion at local nodes. Centralized approaches are used by few earlier proposals like LEACH-C [24]. They require global knowledge of the network topology and are inefficient in large-scale topologies. A distributed approach, however, is more scalable since a node is able to take the initiative to become a clusterhead or to join an already formed cluster without global topology knowledge.

Authors of [9] classify clustering algorithms according to their convergence rate into two classes : variable and constant convergence time algorithms. The former algorithms have a convergence time that depends on the number of nodes in the network and thus are more suitable to relatively small networks. Constant convergence time algorithms converge in a fixed number of iterations, regardless of the size of the nodes population.

Clustering algorithms can also be classified into homogeneous or heterogeneous [82] depending on the nature of the deployed sensor network. In heterogeneous environments, the clusterhead roles can be preassigned to nodes with more energy, computation and communication resources. In a homogeneous environment, the clusterheads can be designated in a random way or based on one or more criteria. It is worth mentioning, that even in a homogeneous network, heterogeneity can occur simply in terms of available energy at nodes. As time goes on, some nodes depending on their role and environmental factors, will discharge more quickly their batteries. This is why energy and clusterhead rotation have to be considered in the process of clustering.

In this chapter, we adopt a different classification to present clustering protocols in WSNs. Most proposed cluster-based routing protocols rely on already formed clusters. Afterwards, the inter-cluster communication is generally ensured using traditional flooding among only clusterheads or by recursively executing the clustering algorithm to obtain a hierarchy of clusterheads routed at the sink. We qualify these protocols as *pre-established* cluster-based routing algorithms. Protocols that build clusters based on packets flowing in the network without a priori construction are qualified as *on-demand* cluster-based algorithms. It is worth mentioning that the second class had always been omitted in surveys like [120] [9] and [78]. On-demand clustering by exploiting existing traffic to piggyback cluster-related information, eliminates major control overhead of traditional clustering protocols. Besides, there is no startup latency even if there is a transient period before getting maximum performances.

2.3.3 Pre-established Cluster-based Routing Algorithms

In this section, we review most important clustering algorithms. Even if they are limited only to the clusters formation and do not address explicitly inter-cluster routing. It is generally straightforward to apply on top of the clustered topology a routing protocol taking into account only the clusterheads in the route discovery phase.

Low Energy Adaptive Clustering Hierarchy (LEACH) and its variants

Low-Energy Adaptive Clustering Hierarchy (LEACH) [52] is one of the most popular hierarchical routing algorithms for sensor networks. LEACH is a cluster-based protocol with distributed cluster formation with random clusterhead election. A sensor node chooses a random number between 0 and 1. If this random number is less than a threshold value the node becomes a clusterhead for the current round. Based on the received signal strength of the advertisement, a non-clusterhead node decides to which cluster it will belong for this round and sends a membership message to its clusterhead. Based on the number of nodes in the cluster, a clusterhead creates a TDMA schedule and assigns each node a time slot in which it can transmit. This schedule is broadcast to all the cluster nodes. This is the end of the so-called *advertisement* or *setup phase* of LEACH. Then begins the *steady state* where different nodes can transmit their sensed data.

LEACH is completely distributed and requires no global knowledge of network. However, it forms one-hop intra and inter cluster topology, which is not applicable to large region networks. Clusterheads are assumed to have a long communication range so they can reach the sink directly. This is not always a realistic assumption since the clusterheads are regular sensors and the sink is often located far away. Furthermore, dynamic clustering brings extra overhead due to the advertisements phase at the beginning of each round, which may diminish the gain in energy. Since the decision to elect a clusterhead is probabilistic without energy considerations, LEACH clusterhead rotation assume a homogeneous network and can not ensure real load-balancing in case of nodes initially with different amount of energy. A node with very low energy becomes a clusterhead for the same number of rounds as other nodes with higher energy and will die prematurely. This could affect a zone coverage and network connectivity.

LEACH-C [24] is a centralized version of LEACH where only the advertisement phase differs. At this phase, each node sends information about its current location and residual energy level to the sink. Based on nodes location, the sink builds clusters using the simulated annealing algorithm [87] so the amount of energy required by member nodes to transmit their data to their respective clusterhead is minimized. Collected information about nodes energies allows the sink to discard those with energy below the average network energy. Consequently, energy load is evenly distributed among all the nodes.

Energy Efficient Hierarchical Clustering (EEHC)

Energy Efficient Hierarchical Clustering (EEHC) [17] can be seen as an extension of LEACH with multi-hop intra clusters and a hierarchy of clusterheads to route data to the sink. In the single-level clustering of EEHC, each sensor in the network becomes a *Volunteer* clusterhead with probability p. It announces this to the sensors within k hops radio range. Any sensor that receives such advertisements and is not itself a clusterhead joins the closest cluster. If a sensor does not receive a clusterhead advertisement within a certain time duration it can infer that it is not within k hops of any volunteer clusterhead and hence becomes a *forced* clusterhead. Data transmission to the sink can be performed using multi-hop routing through clusterheads organization in a multi-level hierarchy rooted at the sink. To do so, the single-level clustering is repeated recursively at the level of clusterheads. This distributed process allows EEHC to have a time complexity of $O(k_1 + k_2 + ... + k_h)$ where h is the number of levels and k_i is the maximum number of hops between a member node and its clusterhead in the ith level of hierarchy. Since spent energy in the network depends on p and k, the authors provide methods to compute the optimal values of these parameters that ensure minimum consumed energy. Simulation results showed significant energy saving when using the optimal parameter values.

Hybrid Energy-Efficient Distributed Clustering (HEED)

Both EEHC and LEACH do not consider energy in selecting clusterheads. HEED [119] brings one more step toward energy-efficient cluster-based routing with explicit consideration of energy. Selected cluster heads in HEED have relatively high average residual energy compared to member nodes. Additionally, HEED aims to get a well-distributed clusterheads set over the sensor field. Indeed, in HEED, the probability that two nodes within the transmission range of each other to be clusterheads is small. It is worth mentioning that the main drawback of LEACH is that the random election of clusterheads does not ensure their even distribution in the sensing field. It is quite possible to get multiple clusterheads concentrated in a small area. In this case, this area sensors are likely to exhaust their energy more quickly which may lead to insufficient coverage and network disconnection. Distributing clusterheads evenly in the sensing area is one important goal to be met in order to ensure load balancing and hence longer network lifetime.

HEED periodically selects clusterheads according to a hybrid of their residual energy and intra-cluster communication cost. Initially, to limit the initial clusterhead announcements, HEED sets an initial percentage C_{prob} of clusterheads among all sensors. The probability that a sensor becomes a clusterhead is $CH_{prob} = C_{prob}\ E_{residual}/E_{max}$ where $E_{residual}$ is the current energy in the sensor, and E_{max} is its maximum energy. Afterwards, every sensor goes through several iterations until it finds the clusterhead that it can transmit to with the least transmission power. If it hears from no clusterhead, the sensor elects itself to be a clusterhead and sends an announcement message to its neighbors. Each sensor doubles its CH_{prob} value and goes to the next iteration until its CH_{prob} reaches 1. Therefore, there are two types of status that a sensor could announce to its neighbors: Tentative status and Final status. In the first state, the sensor becomes a tentative clusterhead if its CH_{prob} is less than 1. It can change its status to a regular node at a later iteration if it finds a lower cost clusterhead. In the final state, the sensor permanently becomes a clusterhead if its CH_{prob} has reached 1.

At the final phase, each sensor makes a final decision on its status. It either picks the least cost clusterhead or pronounces itself as clusterhead. Simulation results showed that HEED outperforms LEACH with respect to the network lifetime and energy consumption distribution. However, HEED suffers from a consequent overhead since it needs several iterations to form clusters. In each iteration, a lot of packets are broadcast.

2.3.4 On-demand Cluster-based Routing Algorithms

In this class of cluster-based routing algorithms, the clustering topology is built along with the routing discovery phase. We report here on the most imporatnt protocols belonging to this class of hierarchical routing. Further in this thesis (in chapter 4), we present our contribution that falls into this class.

Passive Clustering (PC)

Passive clustering (PC) [63] is an *on demand* clustering algorithm. It provides scalability and practicality for choosing the minimal number of forwarding nodes in the presence of dynamic topology changes. PC constructs and maintains the cluster architecture based on outgoing data packets piggybacking *cluster related information.* Passive clustering eliminates setup latency and major control overhead of traditional clustering protocols by introducing two innovative mechanisms for the cluster formation: *"first Declaration wins"* rule and *"gateway selection heuristic"*. With the *"first Declaration wins"* rule, a node that first claims to be a clusterhead *rules* the rest of nodes in its clustered area. The *"gateway selection heuristic"* provides a procedure to elect the minimal number of gateways.

The algorithm defines several states in which a node can be. At cold start, all nodes are in the initial state. Nodes can keep internal states such as *clusterhead-ready* or *gateway-ready* to express their readiness to be respectively a clusterhead or gateway. A candidate node finalizes its role as a clusterhead, a gateway (Full-GW or Dist-GW) or an ordinary node. Additional fields suggested by PC in the message header of each packet are :

- *id* : the identity of the originator of this message,
- *state* : this packer sender status in the network,
- $CH1$ and $CH2$: these two fields are only used by a gateway to announce its two clusterhead addresses,

The reactive nature of PC motivated its combination with on demand routing protocols. Originally, PC was applied to reactive routing protocols like AODV [23] and DSR [57]. The major overhead in these routing protocols is caused by the flooding of route queries. It was suggested to allow only non-ordinary nodes to rebroadcast query messages.

The PC algorithm presents some shortcomings that have been targeted by several works. In [95], the authors proposed to add alive packets to keep the cluster stability as it depends highly on the data packet traffic. Also, a sequence numbering to synchronize packets arriving from a source node is proposed. In fact, if packets containing different states arrive out-of-order at the destination (i.e., the sending node changed its state between transmission of multiple packets) then the destination node will be misled about the true state of the source node. In addition, unnecessary rebroadcasts are eliminated when the final destination of the message is a cluster member.

In WSNs, the PC algorithm was proposed in combination with Directed Diffusion (DD) in [50] to mainly achieve energy efficiency. The main idea of the combination is to save energy in the flooding phases by allowing only clusterheads and gateways to participate in them. member nodes are only allowed to send data messages in the data sending phase. Under different network size and load, the combination showed best performances in terms of delivery ratio and average dissipated energy.

Motivated by the results shown in [50] when applying the original PC along with Directed Diffusion paradigm other works have been proposed in order to achieve better performance of the combination. In [88], the selection of clusterheads and gateways are done using a heuristic of residual energy and distance. By using residual energy the flooding nodes are chosen in an energy efficient manner. Distances are used to reduce overlapping region and so the number of gateways. The solution proposes to apply a periodic sleep and awake among cluster members. This technique is similar to the one proposed in LEACH and requires a synchronization process between nodes.

CLIQUE

The work in [40] presents CLIQUE, an approach for cluster head selection based on machine learning (Q-learning). The authors observed that a clusterhead may require less energy than its direct neighbors in a multi-hop intra-cluster topology. They conclude that clusterhead role assignment must take into account not only the current state of the selected clusterheads, but also those of its neighbors and nodes on the paths to the clusterhead. in CLIQUE, clusterhead roles are neither explicitly assigned nor do the nodes need to agree on a clusterhead. Instead, each node decides on a per-packet basis whether to act as clusterhead (aggregating some packets then sending the result to the sinks) or to forward the packet to a better suited neighbor. Authors claimed that this role-free scheme makes the algorithm flexible and robust and eliminates the need for multiple clusterhead selection rounds.

Authors of [40] focused on the clusterheads selection process and assumed that clusters are predefined (rectangular grids) and that each node knows the identity of the cluster to which it belongs. They targeted a traditional, periodic data reporting application and a multiple sinks network. The sinks flood the network with DATA REQUEST packets announcing their data interest. These packets can carry some routing information that is further used by nodes to estimate the routing cost to the sinks. The routing cost is calculated using a combination of hop counts to reach the sinks and battery status of the nodes on the routes to the sinks. Each sensor node is an independent learning agent, and actions are routing options using different neighbors as the next hop toward the clusterhead. The clusterhead is defined as the cluster node with the best (lowest) routing cost to all sinks.

Even if CLIQUE may incur more energy consumption due to possible coexistence of multiple clusterheads in one cluster, the authors showed through simulations that CLIQUE saves up to 25% of consumed energy thanks to its lower overhead. However, CLIQUE is more suitable for regular data reporting and its performances are to be proved for other types of applications such as event driven ones.

2.4 Conclusion

Routing in WSNs has been an active area of research in the last years. Most of the work have been motivated by the need to design an efficient routing protocol to provide reliability, load sharing and QoS guarantees while extending the network lifetime. Many routing classifications are proposed in the literature. In this chapter, we reviewed the major flat as well as hierarchical routing solutions proposed in WSNs. Every routing class can be divided into many sub-classes according to different criteria. In flat routing, data-centric approach appears as the most important *new* routing class that has been proposed in WSNs. Hierarchical routing solutions have been classified into pre-established and on-demand solutions. In the first sub-class, the routing topology is built prior to the data dissemination phase. In the second one, the routing topology is built *passively* along with the routing discovery phase.

The emerging multimedia applications of WSNs impose new challenges in design of algorithms and communication protocols for such networks. In the view of these challenges, new routing solutions should be proposed to cope with the limitations of such networks. In the next chapter, wireless multimedia sensor networks are introduced and routing solutions that have been proposed especially for them are presented.

Chapter 3

Routing Multimedia in Wireless Sensor Networks

3.1 Introduction

The proliferation of inexpensive hardware such as CMOS cameras and microphones that are able to ubiquitously capture multimedia content from the environment has led to the definition of wireless multimedia sensor networks (WMSNs) [13]. In addition to scalar sensor data, in WMSNs, video sensor nodes allow retrieving and communicating a rich data content such as video/audio streams and still images. From this perspective, several new applications can be envisaged in many domains such as video surveillance, health care, industrial process control, traffic management, etc.

From a communication point of view, supporting multimedia content in WSNs is very demanding. Many types of traffic can flow in the network having different characteristics and quality of service (QoS) requirements. Additionally, multimedia applications dealing with audio/video streams have specific requirements that are difficult to fulfill. In this case, the network should sustain transmission of large burst of data at a high bit-rate. These characteristics need to be addressed efficiently taking into account the severe hardware, bandwidth and power limitations of the sensor nodes.

Designing an efficient routing protocol for WMSNs is a challenging task. Although, there are many routing solutions proposed for WSNs, these protocols should be rethought to suit the multimedia case [46]. In fact, the efficiency of employing data-centric approaches to route multimedia data in WSNs depends on the protocol design and characteristics. In some cases, describing and addressing multimedia content is a difficult task. For example, generating meta-data descriptions, like in SPIN [6], for multimedia data is not a realistic task on power constrained sensors.

Location-based protocols constitute a good solution to multimedia data routing in WSNs. In fact, greedy forwarding in location-aware routing protocols can guarantee the delivery of data if nodes have consistent location information [114] [59]. Moreover, with consistent location information, the latency of data delivery can also be reduced as the shortest paths can easily be discovered. This is extremely important for multimedia data communication with QoS requirements.

Hierarchical network architectures are proposed in [13] as reference architectures to support multimedia communication in WSNs. However, the hierarchical routing solutions proposed initially for WSNs have to be rethought to suit the multimedia case if certain conditions are assumed like the in-network processing. Also, the concentration of data traffic towards a small number of nodes (clusterheads) remains a major threat to the network lifetime for these solutions.

This chapter reviews routing thechniques that are suitable to multimedia applications over WSNs. We begin by introducing Wireless Multimedia Sensor Networks (WMSNs) in Section 3.2 by giving a general architecture and the charateristics of these networks. Then, routing thechniques to ensure a given QoS are presented in Section 3.3. Hierarchical routing organization of a WSN with the aim of handling multimedia is considered in Section 3.4 before concluding.

3.2 Wireless Multimedia Sensor Networks

Wireless Multimedia Sensor Networks (WMSNs) are particular instances of WSNs where the scalar WSNs is strengthened by introducing the ability of retrieving richer information content through image/video sensors [94, 39]. A WMSN can operate in an ad-hoc manner and hence does not require a network infrastructure adding a much higher level of flexibility and allowing a wider range of applications. Figure 3.1 depicts a typical WMSN architecture where video sensors are deployed at strategic positions with other non visual sensors. A central controller or a base station commonly referred to as the *sink* is responsible for requesting/analysing sensed data. All nodes collaborate to ensure a given application requirements. For instance, low-power scalar sensors only take part in relaying in addition to sensing environmental data. Sensors with higher capabilities could do more such as taking part in a distributed compression task in order to not overwhelm video sensors by all the tasks (capture, compression and transmission).

Multimedia data communication in WSNs has specific characteristics and needs. Generally, multimedia content should be received with a certain level of quality of service (QoS) while optimizing resources utilization. There are many factors and needs influencing the development of communication protocols in wireless multimedia sensor networks :

Energy Requirements

Sensor nodes are power-constrained as they run on small batteries that have limited power. This makes power consumption a fundamental concern in WSNs. In WMSNs, high volumes of data are produced which require, in addition to high data transmission rates, extensive processing. In fact, capturing and/or compression of rich multimedia content (video and audio) require a lot of energy. The power consumption of these tasks may easily dominate the one of communication functionalities [65]. Therefore, protocols and algorithms to maximize

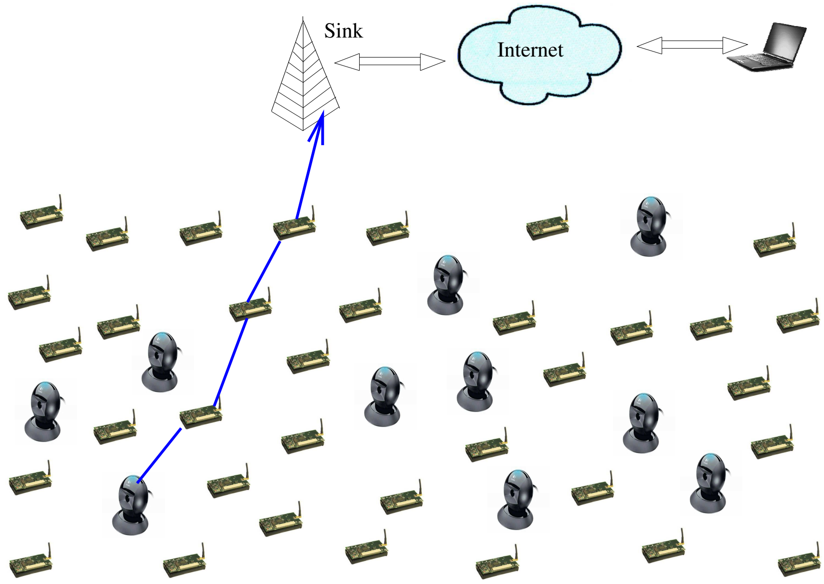


Figure 3.1: Typical Wireless Multimedia Sensor Network

the system lifetime are a critical issue.

High Bandwidth

Video and audio content require transmission bandwidth that is orders of magnitude higher than that supported by currently available sensors. In fact, the nominal transmission rates for sensor nodes may reach a maximum of 250 kbit/s (TelosB [4] using IEEE 802.15.4 compliant). Therfore, hardware and software solutions are necessary to provide sufficient bandwidth for supporting multimedia content in WSNs. Furthermore, the sensor nodes may also relay the packets from the other nodes due to multihop communication paradigm in WSNs which makes managing the available bandwidth more stressful.

Encoding Techniques

Efficient processing techniques for lossy compression are necessary for WMSNs for two reasons [46]. First the limitations of sensor nodes that capture and compress multimedia signals and second the communication efficiency of these techniques is of great importance in optimizing the limited bandwidth utilization. Predictive coding has been widely used in communication networks in the last years [43]. While it can provide many possibities in compression levels and quality, the computational complexity of predictive encoders is unacceptably high for power constrained sensor nodes. Furthermore, predictive coding is error sensitive and should be properly handled in wireless channel lossy environments. The power consumption of solutions (such as redundancy, unequal error correction, MDC [42], etc.) addressing this problem remain an important design issue. On the other hand, it has recently been shown [93] that the traditional balance of complex encoder and simple decoder can be reversed within the framework of the so-called distributed source coding (DSC). This latter is based on Slepian and Wolfs and Wyner and Zivs [8] theoretical results. DSC exploits the source statistics at the decoder, and by shifting the complexity at this end, allows the use of simple encoders. Such algorithms are very promising for WMSNs and especially for networks of video sensors.

Cross Layer Design

Addressing QoS requirements of multi-priority traffic (consisting of video and audio along with the standard sensed data traffic) in one communication layer is difficult to achieve. Cross-layer optimization of multimedia coding, routing, transport, link and physical layer algorithms must be investigated. In fact, these layers can operate in a cooperative way to achieve reliability and efficiency. An interesting example of multimedia-based cross-layer design is just congestion mitigation by transport layer [30]. If the classical layer organization is respected, a typical transport protocol will reduce the current transmission rate to resolve congestion issues, potentially impacting the quality of the received media by the sink (loss of video frames, higher delay, etc.). However, a cross-layer design may benefit from a multimedia coding technique that prioritizes the transmitted packets. In such case, the transport protocol would only reduce the transmission rate of the less-relevant packets, satisfactorily addressing congestion and potentially resulting in better end-to-end quality of the application. Despite notable research efforts, the mapping of the QoS parameters across different layers for the purpose of cross-layer optimization still remains elusive and needs to be addressed.

These design characteristics and needs are difficult to fulfill taking into account the limitations of WMSNs. These networks are much constrained in resources than WSNs. Actually, they must deal with large size of data having different QoS requirements using the same devices equipped with image/video capturing sensors. As they are small sized, these devices present many limitations in terms of memory, processing and power supply. The wireless medium in use is shared and characterized by limited capacity, high path loss, channel fading, interference, noise disturbances, and bit error rate (BER). Also, the topology of the network can change at any time due to node and link failures caused by the hostility of the environment, the energy shortage, etc.

3.3 QoS Routing Techniques

Quality of service (QoS) depends strongly on the applications. Thereby, heterogeneous QoS requirements should be supported by communication protocols in a WMSNs as a wide variety of applications can be envisaged in such networks. Data traffic is generally unbalanced ranging from simple scalar data to rich video content. Also, reporting models of this traffic may be different according to the application definition. Hence, many QoS parameters may be required :

- Bandwidth requirements for streaming (especially for audio and video data).

- Reliability and distortion.
- Real-time and latency requirements.
- Energy consumption and network lifetime.
- Robustness and fault tolerance.

Clearly, QoS routing techniques proposed for WSNs take the first step in addressing the concerns of data routing in WMSNs [13]. In general, this class of protocols are well suited for multimedia data delivery in WSNs. However, it should be taken into consideration that ensuring some QoS garantees for scalar data is completely different when audio/video streams are considered. For example, a QoS based routing protocol can ensure a good reliability and a small packet loss. But when used in WMSNs, even if a small packet loss is achieved the quality of a prioritized stream (video) can still be affected. In fact, in a video application if important data is lost, the video becomes undecodable.

In this section, we consider QoS routing protocols (i) aiming at providing the necessary bandwidth for multimedia applications, (ii) supporting real-time and latency constrained data, and (iii) those maximizing reliability and data quality (especially for image and video). As many mechanisms are proposed to support reliability, the protocols of this class are further grouped into subclasses. Protocols supporting many QoS metrics are also presented.

3.3.1 Sufficient Bandwidth Provision

Streaming (real-time) applications in WMSNs primarily aim at sustaining the transmission of high quality data at a high bit-rate. Therefore, they require sufficient resources especially in terms of bandwidth [85]. In general, routing protocols aiming at providing sufficient bandwidth for multimedia applications use multipath transmission. In fact, this technique appears to be an essential solution for supporting this parameter by spreading multimedia traffic over multiple paths. We report here on two protocols MR2 [76] and TPGF [104]. The latter makes uses of location information as opposed to MR2 that implements an incremental multipath approach. The two protocols aim at providing the necessary bandwidth to support multimedia traffic in the network.

TPGF and MPMPS

Two-Phase geographic Greedy Forwarding (TPGF) [104] is a multipath protocol that proposes to adopt geographical information to facilitate the on-demand disjoint multipath routing. For that, it makes use of the location information of the neighboring nodes and the base station. The protocol explores one (or multiple) shortest hole-bypassing paths in WMSNs. When a source node wants to explore one transmission path, it generates a route request message and forwards it to its chosen neighbor based on the greedy forwarding rule. The chosen neighbor node appends its digressive node number together with its node ID to the list of identifiers in the request packet and greedily forwards the request to next hop. If the chosen node finds that it has no next node available for transmission, it will step back (send a block node message) to its previous-hop node and mark itself as a block node to forbid the loop. The previous-hop node will attempt to find another available neighbor node as the next-hop node. This procedure is repeated until the request reaches the base station. Whenever a routing path reaches the base station, the base station generates an Acknowledgment by copying the recorded list of identifiers from the route request into the Acknowledgement message. The Acknowledgement is then unicasted back to the source node. When this latter receives the successful Acknowledgment, it starts to send out multimedia streaming data to the successful path with the pre-assigned path number. By mean of simulation, TPGF was compared with GPSR in terms of number of hops and number of built paths. The simulation results have shown that TPGF permits to construct more paths than GPSR and that unlike GPSR, is not not affected by the changing of transmission radius.

The cross layer multimedia-based optimization scheme proposed in [121] exploits TPGF routing for video data transport in WMSNs. Video data are split in two streams namely image and audio sub-treams. Each stream is given a priority depending on the monitoring context. For that, the authors cite a communication scenario of a fire monitoring application where visual information is more relevant for the application. In this case, the image data should be delivered with minimum transmission delay. Thus, the paths with lower delay are assigned to the higher priority sub-streams, leaving the remaining paths to the lower priority substreams. In the simulation experiments, the original data (72 kbps) is split into an image stream (48 kbps) and an audio stream (24 kbps). Simulation results have shown that MPMPS can effectively choose the maximum number of paths for video transmission.

MR2

A disjoint multipath routing algorithm is proposed in [76]. In this paper, the problem of interfering paths in the context of wireless multimedia sensor networks is studied. The main objective is to provide necessary bandwidth to multimedia applications through non-interfering paths while increasing the network lifetime. The paper proposes an on-demand incremental approach where, for a given session, only one routing path is built at once. Additional paths are built when required, typically in case of congestion or bandwidth shortage. These paths are chosen to be non-interfering with the used ones. In order to solve the problem of interference between close paths, the proposed solution forces the multipath routing to build paths that are not interfering with each other from the beginning by putting all the interfering nodes of a given path in a passive state. Passive nodes do not further participate in building any other path in future and consequently will not interfere with previously built paths. The process starts at the sink when it floods the network with requests until they reach the source nodes. The source node starts immediately sending data on the selected paths and all the intermediate nodes between the source and the sink will inform their neighbors to switch to the passive state. The proposed work argues that putting some nodes in a passive or sleep mode increases the overall throughput and reduces the consumed amount of energy in the network. Results obtained through simulation show that the proposed protocol achieves better throughput with less energy consumption by using fewer non-interfering paths when compared to multipath schemes without interference awareness.

3.3.2 Reliability Support

Achieving reliability is a challenging task in wireless sensor networks due to many reasons such as wireless links, nodes and network characteristics. When dealing with multimedia data another layer of complexity is added. In fact, packet losses may have different impact on data quality as their content presents different levels of priority. In this case, routing protocols may interact and use information from other layers to leverage this complexity. Different mechanisms have been proposed to achieve reliability in WMSNs :

Multipath Routing and Congestion Control

Congestion in WMSNs degrades the performance of traffic flows present in the network. When providing adequate bandwidth for multimedia applications, multipath routing can achieve fairness from a congestion point of view.

The work proposed in [77] adresses the problem of congestion control in WMSNs. It aims at providing the necessary bandwidth to support video streaming in WMSNs by applying load repartition mechanisms over a simple multipath routing protocol called SLiM. This later follows main ideas behind existing routing protocols in ad hoc and sensor networks. It adopts a sink-initiated approach where the sink floods the network with a request until the source is reached. With one flooding, multiple paths are built and maintained at intermediate nodes towards the sink. In SLiM, paths are built with respect to a quality metric specified by the application. This metric can be the path length, its available energy, an estimation of its lifetime or any other metric depending on the application requirements. The protocols define three load repartition strategies for congestion control from mode 1 to mode 3 in addition to the no load repartition scenario in which a source uses the same path without any congestion control concerns. In mode 1 the source uses all the available paths to the sink from the beginning of the transmission. In modes 2 and 3, explicit congestion notifications are used using a congestion notification messages (CN). In Mode 2, the source starts initially with one path. For each CN message received, the source adds a new path until all available paths are marked as active. In Mode 3, the source starts initially with one path. Upon reception of a CN message the source will uniformly balance the traffic of the path on all available paths. Therefore depending on the number of CNs received for each path, the transmission rate is not the same on all the active paths. Through simulation using TOSSIM, it has been shown that load repartition does improve congestion control by reducing the packet drop probability. Regarding fairness, which is a key factor in congestion control, the preliminary results show that even simple load repartition strategies can have a very high impact on performances.

Another work dealing with congestion control and reliability in WMSNs is proposed in [107]. It follows the same ideas proposed in [77]. The authors propose the construction of many disjoint paths from the video sources to the destination. Paths between a single source sink pair are totally disjoint but may share some nodes when they are originating from different sources. The common nodes, called major joint node, are identified by the sink and used to monitor the congestion state of the network. To handle congestion, the major node sends a congestion notification message CN, to a source through the path according to its queue state. After CN message is received by the source, it transmits data on this path and switch to another path after a period of time. The authors have shown through simulations that their proposition achieves higher data rate and longer network life time, which is more reliable than normal multipath without congestion control. But under higher transmission rates from source, both the reception rate and the network life time will drop fast. These problems affect the reliability of the proposed algorithm.

Reliability Through Retransmissions

One way to achieve reliability is the recovery of lost packets through retransmissions. In a multi-hop WSNs, retransmission-based reliability can be achieved using acknowledgement mechanisms. In [53], a Group of Pictures (GOP) based geographic multipath routing scheme with selective retransmission is proposed. An intermediate node can selectively retransmit frames by considering the effect of the drop of each frame to the video quality. It calculates the video quality of a specific GOP based on the already received frames and then request retransmission of certain frames if the current calculated video quality is less than the associated acceptable threshold value. Simulation results have shown that this scheme can more evenly distribute the loads to different sensor nodes in the network without sacrificing the video quality.

Reliabilty Using FEC

Forward Error Correction (FEC) techniques are used for controlling errors caused by the data transmission over unreliable or noisy communication channels [29]. Using FEC techniques consists in encoding (at the sender) and transmitting redundant packets (based on error correction codes) in addition to the original data packets. At the receiver side, lost packets are ignored, and original data packets can be reconstructed after enough number of encoded packets are successfully received [96]

In [27], the authors propose a multipath transmission strategy for H.26L [3] real-time video communications in video sensor networks. The multipath scheme is used to support the delivery of multiple flows in the network while the required level of reliability is achieved by using forward error correction (FEC) as an error control technique. The proposed routing protocol, DGR, uses a deviation angle adjustment method to construct multiple disjoint paths between the video source VN and the sink. Thus, encountering the route coupling problem caused by interference between packets transmitted over different paths between a same source destination pair. The deviation angle is defined as the angle that specifies how much the path is expected to deviate from the reference line defined as a straight line between the source and the sink. The probe (PROB) message is broadcast initially by the source for route discovery. A selected next hop will continue to broadcast PROB message to find its next hop, and so forth. A node receiving a PROB will calculate its mapping coordinates based on the deviation angle, the positions of the node itself, the upstream node and the sink. Then, DGR will select as the next hop node the neighbor whose mapping coordinates is closest to the Strategic Mapping Location, instead of the neighbor closest to the sink as in traditional geographical routing protocols. After this step, hybrid video stream broadcasting and sub-streams unicasting schemes are implemented based on the pre-established multipaths. In this scheme, an active VN first broadcasts a RTS (request-to-send) message to its one-hop neighbors where delayed broadcast of CTS (clear-to-send) is used to solve the hidden terminal problem. Then, the VN will broadcast to its one-hop neighbors a packet concatenating all the data and FEC packets of a video frame. Those neighboring nodes that are the first intermediate nodes of individual paths to the sink are referred as CooperativeNodes. Upon receiving the concatenated packet broadcast by the VN, each Cooperative Node selects its own payload according to the CooperativeNodeList in the concatenated packet. CooperativeNodeList contains the identifiers of the CooperativeNodes and the sequence numbers of the corresponding packets assigned to these nodes. Then these CooperativeNodes unicast the assigned packets to the sink via the respective individual paths. DGR was evaluated using OPNET simulator. A Forman video encode by the H.26L video coding standard was used in QCIF format (176 144 pixels/frame). The authors evalute their solution in terms of lifetime, number of successful frames received by sink before lifetime, average End-to-end packet delay, energy consumption per successful data delivery and PSNR.

The work in [10], proposes an error resilient image multipath transport based on a clustered topology. This work proposes to organize the nodes into one-hop clusters. A cluster head is selected in each cluster and maintains a membership list of its cluster nodes. Every node knows its cluster head. Every cluster head knows the path(s) to its neighboring clusters as well as the path(s) to the sink. When a node becomes the source, it asks its cluster head for the relaying nodes. An in-network combining scheme is used where multiple copies of the coded image from different relaying nodes are combined along the path by cluster heads. The image packets are processed to correct bit/symbol errors using RS codes [106] and multiple copies of image coefficients are generated using a RS decoding algorithm. These copies are sent using a path diversity algorithm where the cluster head randomly selects different forwarding nodes. The same data is sent to these nodes to provide resiliency against node failures. In addition, forward error correction coding is applied on packets to further improve reliability and by that the image quality. The function of FEC coding [106] is placed at each node instead of only at the source and the destination. Noticeable image quality improvement are achieved at low energy consumption especially in case of higher node failure and larger number of hops.

Dropping Policies based on Priority Mechanisms

When dealing with large data sizes (video or images), the data rate is likely to surpass the capacity of the network (aggregate bandwidth). This can cause congestion in the network. Adapting the data rate by means of dropping policies to meet the available bandwidth can be a solution to ensure packets delivery. However, indiscriminate dropping of data, i.e. data of high importance might be dropped while others not, can be inefficient. In fact, the packets discarding policy should be set according to their relative importance.

Politis et al. propose in [91] a packet scheduling scheme over a multipath routing algorithm for minimizing perceived video distortion and energy consumption in wireless multimedia sensor networks. The packet scheduling algorithm is based on a video distortion model where the loss model considers the predictive nature of the H.264/AVC encoding scheme. Therefore, the proposed distortion scheme is a recursive formula that takes into account the correlation among video frames and the impact of frames losses on the distortion. A simple error concealment mechanism is applied which replaces a lost frame with its previous. Two packet scheduling algorithms are proposed : the baseline packet scheduling and power aware packet scheduling. In the first scheme, the transmitted packets are distributed among the available paths according to their impact in the video distortion. Also, if the required rate for error free transmission is higher than the available aggregate transmission rate then the sender decides which video packet to be dropped. In the second scheme, the distortion model is also used to assign priorities to packets. In addition to the aggregated bandwidth of the multiples routes, the energy of the node is also considered in the packet dropping mechanism. The algorithm estimates the power that will be consumed by every node in all the multiple paths and predict whether the node will be able to receive and transmit data. Through simulations, the power aware packet scheduling along with the multipath transport have shown to be more efficient in terms of video quality and energy consumption.

In [75], a simple multipath routing protocol as well as a priority-based video transport are proposed. The proposed routing algorithm follows main ideas behind existing routing protocols in ad hoc and sensor networks. The paths are selected according to their lifetime. The video is coded using a Layer coding techniques and a priority is assigned to every layer (the highest priority to the basic layer and so on). Three strategies are defined to send video data from the video source to the sink. In the first, the source chooses the best path in terms of lifetime and only uses this one to transmit all the frames independently of their corresponding layer. The second is an iterative version of the first strategy where the source transmits the video frames independently of their corresponding layers on the best path. When this path is dead, i.e. broken due to lack of energy at one of its nodes, the best path among the remaining paths is used and so on until no path is available. In the third strategy, multiple paths are simultaneously used and a priority mechanism is applied. Based on the lifetime of paths built in the routing process, the source assigns a path to each layer. The best path in terms of lifetime is assigned to the basic layer and the enhanced layers are transmitted each on a different path with lower lifetime. If there is not enough paths, then available ones

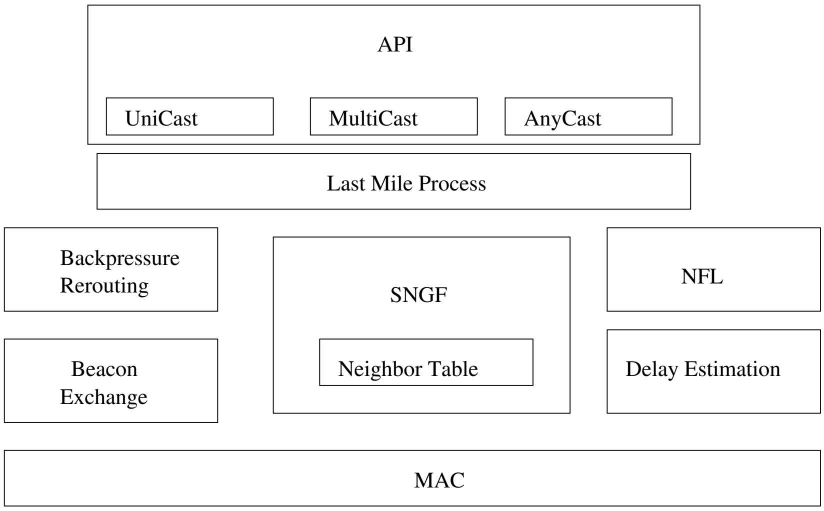


Figure 3.2: Speed Protocol

are assigned to the most priority layers with one layer per path. When one of the assigned paths fails, the source tries to assign another path from those not already in use. If such a path is not available, then it decides to drop the lowest priority layer among those currently transmitted. This allows for increasing the video streaming time even with less quality. The three strategies were compared through simulation. The third strategy permitted to receive a larger number of frames compared to the second one.

3.3.3 Latency Constrained/Real-time Routing

The delay constraint is a very important concern in the design of time critical WMSNs applications. A deadline within which the data must be reported to the central processing entity is imposed. Video streaming (real-time) applications primarily aim at sustaining transmission of high quality data at a high bit-rate. They require strict end-to-end delay, bandwidth, and jitter guarantees [85]. In this subsection, we survey protocols designed to guarantee delay constraints and real time streaming in WMSNs.

SPEED and its extensions

Supporting real-time traffic in wireless sensor networks is proposed in SPEED [51]. SPEED protocol requires each node to maintain information about its neighbors and uses geographic forwarding to find the paths. In addition, SPEED strives to ensure a certain speed for each packet in the network so that each application can estimate the end-to-end delay for the packets by dividing the distance to the sink by the speed of the packet before making the admission decision. The routing module in SPEED is called stateless geographic non-deterministic forwarding (SNFG) and works with four other modules at the network layer, as shown in 3.2 , redrawn from [51]. The beacon exchange mechanism collects information about the nodes and their location. Delay estimation at each node is basically made by calculating the elapsed time when an ACK is received from a neighbor as a response to a transmitted data packet. By looking at the delay values, SNGF selects the node, which meets the speed requirement. If such a node cannot be found, the relay ratio of the node is checked. The neighborhood feedback loop module is responsible for providing the relay ratio which is calculated by looking at the miss ratios of the neighbors of a node and is fed to the SNGF module. If the relay ratio is less than a randomly generated number between 0 and 1, the packet is dropped. And finally, the back-pressure rerouting module is used to prevent voids, when a node fails to find a next hop node, and to eliminate congestion by sending messages back to the source nodes so that they will pursue new routes. According to simulation results, SPEED performs better than DSR [57] and [23] in terms of end-to-end delay and miss ratio.

SPEED is proposed for WSNs but took a first step in addressing the concerns of real-time routing in WMSNs as it considers scarce resource conditions and can provide service differentiation [13]. However, SPEED does not consider any reliability metric in the routing process. MMSPEED [38] is a multipath version of SPPED that tries to improve this limitation. MMSPEED can differentiate between flows with different delay and reliability requirements. The timeliness of the packets is guaranteed by using multiple packet delivery speed options. In the reliability domain, various reliability requirements are supported by probabilistic multipath forwarding. The protocol has significant potential in video transmission applications [31]. Multimedia-aware Multipath Multi-Speed (Multimedia-aware MMSPEED) routing protocol is another extension of SPEED proposed in [31] to support high video frame rate and packet dependency. In Multimedia-aware MMSPEED near optimum path is reserved for I-packets and marginal paths are used for P-frames.

Delay-Constrained Routing

A Directed Diffusion-based multipath routing protocol is proposed in [67] to support multimedia data transport. The authors define a combination of expected transmission count (ETX) and delay as a path selection metric instead of pure delay that is used in Directed Diffusion[55]. Using (ETX) permits to choose non interfering paths which leads to increase throughput. The reinforced paths are used for transmitting video traces generated using Multiple Description Coding scheme [42]. The different descriptions are transmitted over the different paths. Results show that the presented protocol for multipath video streaming over WSNs obtains higher throughput than its single path counterpart (EDGE [66]) through the use of multiple disjoint paths.

3.3.4 Multiple QoS Metrics Routing

In order for the routing algorithm to be effective, it should support different and multiple QoS requirements. Therefore, routing protocols need to characterize the network with multiple metrics such as energy, delay, and data loss probability. The basic problem, therefore, is to find a path that satisfies the multiple constraints for QoS routing in an energy-efficient way. Compared with routing decision using single-objective or single-link constraint, the multiobjective or multiconstraint routing decision is very different, and the problem of determining a QoS route that satisfies the multiple constraints has been proven to be NP-complete [71]. Heuristic algorithms are then proposed as solutions to support this problem.

Design of a QoS-aware Routing Mechanism for Wireless Multimedia Sensor Networks

A multi-path multi-channel QoS aware routing protocol for WMSNs is presented in [49]. The protocol aims to support, in a distributed manner, high data rate for WMSNs by ensuring bandwidth and end-to-end delay requirements of real time data and maximized throughput of non-real time data. The authors propose a slight changed version of Directed Diffusion [55] combined with a channel assignment technique in the route construction phase. Thus, each node is assigned with the knowledge of available path and channels to transmit/receive data packets. The sensor data is then classified according to its level of importance using a classifier that checks the type of the incoming packets and sends it to appropriate queues. Different priorities for real time packets and non-real time packets are assigned to data packets. For real time packets, the authors propose a QoS packet scheduling based on the dynamic bandwidth adjustment and path-length-based proportional delay differentiation (PPDD). The PPDD model is used to determine the delay encountered by each packet in a particular queue along the the path. The waiting Time Priority (WTP) algorithm [35] is then exploited to dequeue packets from the queues according to service class and waiting time. Data is then routed through the nodes along the path from source to the destination in which nodes choose paths/channels that meet the bandwidth and the delay requirements. Bandwidth and delay tuning is performed at the sink and broadcast in the network. Data packets that do not respect the deadline are discarded. The proposed protocol has shown, through simulation, better performances in terms of average delay per real-time packet, average lifetime of a node, and throughput of non-real-time data when compared with single-r and multi-r mechanisms proposed in [12].

Multipath Video Delivery Based on Packet and Path Priority Scheduling

The work in [64] provides a transmission mechanism to improve the video quality perceived at the receiver while considering energy, bandwidth and delay constraints of the network. The proposed approach is based on packet and path priority scheduling while employing multipath video transmission over WMSNs. For routing, the authors adopt a multipath routing solution AOMDV [26] and use methods proposed in [54] to score paths according to their properties and QoS requirements of the multimedia application. Scoring mechanism is based on free buffer size, residual energy, hop count and packet loss rate for each path. Paths that have better conditions get higher scores. The protocol periodically updates the score of the paths as these latter change over time. The video packets are classified in the source according to their types (I, P or B frames). Initially, AOMDV multipath routing is executed for exploring all possible node-disjoint paths from video source node to the receiver. If the aggregate transmission rate of multiple paths becomes lower than the required transmission rate, video sender will select and drop some packets that have lower distortion on video quality (i.e. B-frame packets) to adapt its transmission rate to multipath bandwidth. For paths satisfying delay constraint of video frames, video source node will send control packets to each path for collecting information about paths. Also, a weighted round robin scheduling is performed to distribute classified packets on scored paths. In this step, paths are ordered sequentially according to their scores and for each transmission, packets that are in higher priority queues will be sent to paths with higher scores. This leads to more important packets being transmitted using more reliable paths which could increase video quality at the receiver.

MCRA : Multi-Constrained Routing in Wireless Multimedia Sensor Networks

A novel routing model dealing with multiple service requirements in multimedia sensor networks is proposed in [116]. In this model, a WSN is represented as a weighted, connected graph and a set of equations modelling the residual energy, the end to end delay, the packet loss and the hop count are derived. Using this model, the authors propose the design of a multi-constrained routing algorithm (MCRA) based on query-flooding and query-driven delivery models. Starting from the sink node, interests are sent to all its neighbours. When certain intermediate node in the network receives an interest, it begins to measure its residual energy and packet drop ratio, as well as the current system time. Afterwards, this node uses the detected information to calculate and rewrite the end to end delay and the packet loss ratio. It also checks the QoS constraints according to some formulas and floods the interest to its neighbours. These steps are repeated until the source node is reached. When the source node receives multiple interests that have same query event type but travelled along different paths, it selects the interest with the minimum value of hop count. And then, it begins to send data towards the sink node by using the node list value as the travel path of the data packet. In addition, the authors propose to apply the differentiation service in MAC layer to MCRA, so that real-time data and best-effort data in networks are classified into different priority levels to forward. Theoretical analysis and extensive simulations show that the protocol has a good overall performance, thanks to the low end-to-end delay and loss ratio of data delivery, the low average energy consumption, the high packet delivery ratio, and the moderate control message overhead.

Cross-Layer Design for QoS Support in WMSN

The work in [103] proposes a cross-layer design architecture to maximize the number of video sources admitted without affecting the quality of existing sources in WMSNs. In this architecture, application layer, routing layer and data link layer interact adaptively with each other to achieve this objective. In this work, the authors propose, a Source Directed Multipath Routing (SDMR) to find geographically disjoint paths based on local state information. In the proposed routing algorithm, a source i determines three possible paths directed towards the destination sink. The shortest path between the source and destination is the primary one. The next hop in the path are chosen within the transmission range of a sensor from the origin line, called path origin line (PoL). The two secondary paths, are also determined on the location basis and restricted above and below r unit of distance from PoL, respectively. A relaying node i computes the displacement for the forwarding node j from the (PoL) and uses it in the next hop selection. To select the forwarding node, the node i computes the resistance for each of the potential nodes that belong to the set of forwarding nodes compliance with the per hop and the delay constraints. The resistance of a node with smaller displacement is lower and higher if it is far from PoL. On the other hand, a node will have lower resistance if its residual energy is higher than the other forwarding candidates and vice versa. A node j is selected as a forwarding node if it has the lowest resistance. To support QoS in the MAC layer, the prioritized scheduling of the enhanced distributed coordination function (EDCF) provided by IEEE 802.11e wireless LAN standard is exploited. The framework is evaluated through simulation using NS2 and the performance metric is the quality of video measured as the signal to noise ratio (SNR) and packet delay. The adaptivity of the framework is also studied by considering the number of admitted sources.

3.4 Clustering and Routing in WMSNs

In WMSNs, cluster-based network architectures have more advantages than flat network architectures especially for multimedia data processing and transmission. In the homogeneous flat network, all the nodes should have the same hardware capabilities and functionalities for multimedia processing and transmission, and this leads to increase the energy consumption and the cost of the deployed network. Also, a single-tier flat architecture can cause the sink to be overloaded with the increase in sensors density, which can affect the performance of the network and cause latency in communication and tracking events. Moreover, in cluster-based network, clusterheads can perform data aggregation and filtering to reduce the amount of transmitted data and do better scheduling among the nodes within clusters.

From this perspective, different solutions for hierarchical data communication and routing are proposed in WMSNs. These solutions can be classified according to the nature of deployed nodes (capabilities) in the network into heterogeneous and homogeneous clustered architectures. In these latter, distributed processing can be performed by nodes having similar capabilities (apart from being able to retrieve multimedia content).

3.4.1 Heterogeneous Organization

Three reference communication architectures for WMSNs are introduced in [13]. In addition to a simple flat network architecture, a single-tiered clustered and a multi-tiered network architectures are proposed. In the first architecture, heterogeneous video, audio, and scalar sensors relay data to a central clusterhead, which is also in charge of performing intensive multimedia processing on the data (processing hub). The clusterhead relays the gathered content to the wireless gateway and to the storage hub. Heterogeneous sensor nodes are also used in the second architecture in which each tier is in charge of a subset of the functionalities.

Resource-constrained, low-power scalar sensors are in charge of performing simpler tasks, such as detecting scalar physical measurements, while resource-rich, high-power devices are responsible for more complex tasks. Data processing and storage can be performed in a distributed fashion at each different tier.

Routing Protocol for Heterogeneous Hierarchical WMSNs

A routing protocol for heterogeneous WMSNs is proposed in [60]. The authors propose to classify the network nodes into a monitoring class, a delivery class and an aggregation class. The monitoring class consists of multimedia sensing nodes (MSNs) responsible for gathering multimedia data such as audio, video and still images. The delivery class consists of resources constrained relay nodes (RNs). In this class, relay nodes deliver data from MSNs to cluster heads. The aggregation class consists of cluster heads (CH) which have more powerful resource and computing abilities than relay node. Also, cluster heads can directly communicate with BS to manage a routing path and gather data from surveillance field. There are two kinds of the routing path between BS to MSNs. One is used to send a command message from BS to MSNs. The other is used to send a report message that includes a sensed multimedia data from MSNs to BS and named the delivery path. The routing paths are established by flooding with control messages broadcasted by the CH. A control message includes a sender ID and the number of hops from BS. After receiving the control message, each CH broadcasts the control message to their cluster members. In the cluster, each RN stores the hop count from the control message.

For ensuring WMSNs delivery requirements, each delivery path should be independently established without overlap of relay nodes which are involved in other delivery path. To establish a delivery path, relay nodes are elected by an evaluation function that decides the qualification according to the distance, remaining energy of a relay node, and bandwidth. After establishing delivery path, CH forwards a control message to relay nodes in order to establish command paths. Command paths do not need to avoid an overlap of the relay nodes. Since the proposed method manages two kinds of routing paths, the method consumes more energy than existing method in the phase of the routing path establishment.

LANMAR

The work in [41] suggests to use landmark ad hoc routing protocol (LANMAR) in WMSNs with deploying limited number of mobile swarms, in which the network is divided into groups (LANMAR groups) and each group has a landmark node which is dynamically elected. A swarm is a group of nodes physically close to each other and usually share the same mobility pattern. Comparing to other sensor nodes, the swarm nodes have better capabilities in terms of hardware functionalities and networking capabilities (such as high quality video camera, multiple long radio range, large channel bandwidth, and maybe ability to communicate with satellites) and they can move with relatively high speed. An example of mobile swarm can be a group of tanks or unmanned aerial vehicles (UAV) moving together. The mobile swarms can communicate and exchange information between each other by using satellite communication or mobile backbone network (MBN). With the help of the limited number of mobile swarms, high quality of multimedia streams can be supported in large-scale sensor network. Once there is a hot or interested spot, a swarm can be directed to that area to help forwarding high quality multimedia streams. Results presented in this work show that the delivery rate and average end-to-end delay of the proposed protocol (Swarm-based LANMAR) outperforms LANMAR and AODV.

A Hierarchical Multi-hop Multimedia Routing Protocol for WMSNs

The work in [98], presents a hierarchical multihop routing protocol for video communication in WMSNs called MEVI. MEVI adopts an heterogeneous network whith different node capabilities : scalar and camera nodes. These later are supposed to be equipped with a richer energy source, video camera as well as larger memory and processing capabilities. MEVI assumes that camera nodes act as CHs that are used for routing, slot allocation, synchronizing non-CH transmissions, multimedia retrieval and data aggregation. Non-CHs are used for simple tasks, such as detecting scalar physical measurements (scalar sensor node). Data transmission consists of two phases : intra-cluster communication and inter-cluster communication. During the intra-cluster communication phase, the nodes create clusters and the non-CHs send the sensed values to their CH during their time-slot.

MEVI relies on the Link Quality Indicator (LQI) as the metric to select a reliable CH. Join messages are included in the data packets. They are sent by non-CHs nodes. The inter-cluster communication is the period when CHs and the BS are communicating with each other. This period is used by the CHs to send the aggregate and multimedia data packets to the BS, and the BS can request multimedia content for a CH if necessary. A route discovery phase consists of pairs of route request (RREQ) and reply (RREP) messages sent initially by the CHs nodes. Once the CHs have routes, they are able to transmit their aggregate packet to the BS during the Send Aggregate packets (SA) period. As soon as the BS receives the aggregate packets, it will analyze the data. If the recent history of the non-CHs sensed scalar data is higher than a soft threshold, this can be a possibility of an event occurrence, and multimedia data is used to verify event occurrence and visually identify the real impact of the incident. In this case, the BS has to request multimedia content from a CH and to trigger route discovery if it does not have a route to the CH, during the Multimedia Request (MR) period. When the CH receives the multimedia request message, it will turn the FoV to the location of the non-CH where there is the possibility of an event occurrence. Then, it retrieves and transmits video content to the BS using multiple hops, which have been found previously in normal mode. MEVI was compared through simulation with LEACH in terms of both QoS and QoE metrics. The simulation results have shown that MEVI increases network lifetime by at least 60 percent for small and large scale scenarios compared with LEACH and simple versions of MEVI. The video quality for MEVI transmissions is increased by at least 20 percent for small field sizes. Nevertheless, for large field sizes, MEVI is still able to deliver video, unlike LEACH which is not able to send video content on a large scale.

3.4.2 Distributed Processing

In this class of hierarchical protocols, the sensor nodes are supposed to be equivalent in terms of processing capabilities. The video sensor are equipped with cameras to capture the multimedia content. Distributed processing is performed in the network to ensure the compression and the communication tasks. The work in [123] proposes a clustered architecture to distribute the image compression and transmission loads in WMSNs. Motivated by LEACH, the operation of the proposed clustering protocol is also controlled through rounds. The first round begins with a camera cluster set-up phase, which sets up all the camera clusters; and then is a normal cluster set-up phase, which elects the normal cluster heads by LEACHs clusterhead selection algorithm; and last is a steady-state phase.

In the camera set-up phase, the camera-equipped node broadcasts a message to declare its existence. A normal sensor node, which receives this message, determines which camera cluster to join based on the received signal strength of the messages from the camera nodes. It transmits a join-request message back to the closest camera-equipped node. The camera-equipped node adjusts the transmission radius to set up the camera cluster based on the receiving join request messages and finds an allocation of the image compression tasks onto the nodes in the camera cluster based on their residual energy. Then it sets up a TDMA schedule and transmits this schedule out. In the normal set up phase, except the camera-equipped nodes, all the normal sensor nodes are organized into clusters by LEACHs clusterhead selection algorithm firstly. Then the camera-equipped node joins in the closest normal cluster. In the steady phase, the camera-equipped node sends the images to the nodes according to the TDMA schedule in the camera cluster. Then the node which receives the image compresses the image and sends the compressed data to the normal cluster head according to the TDMA schedule in the normal cluster. Data is sent from the normal cluster head node to the base station using a fixed spreading code and CSMA. According to the simulation results, this two-hop scheme permits to prolong the network life time when nodes are densely deployed. However, this scheme is only applicable when the sensor nodes are two hops away from the sink.

3.5 Conclusion

We discussed in this chapter routing techniques in WMSNs. In general, these protocols should support one or multiple QoS constraints. When QoS routing protocols are considered, multipath routing appears to be an essential technique to support QoS constraints of multimedia data. Hierarchical solutions constitute good solutions to routing multimedia over WSNs as these networks are composed of heterogeneous nodes that can be grouped in different levels. Hierarchical architectures permit to distribute processing and communications loads in the network. This can lead to significant gain in terms of energy consumption and network lifetime. In the next chapter, a cluster-based routing protocol is proposed and used for routing both scalar and video data in WSNs.

Chapter 4

Energy Level-based Passive Clustering

4.1 Introduction

Hierarchical routing protocols based on clustering techniques have been proposed to achieve scalability and reduce the need for global coordination. Clustering is the method by which sensor nodes, in a network, organise themselves into groups according to specific requirements or metrics. Each group or cluster has a leader referred to as *clusterhead* (CH) with possible one or more nodes belonging to at least two clusters called *gateways* (GW) in addition to other ordinary member nodes. As opposed to a flat organisation, clustering techniques allow more scalability, less consumed energy and thus longer lifetime for the whole network. In fact, most of the sensing, data processing and communication activities can be restricted within clusters. Moreover, clustering allows data aggregation which reduces congestion and energy consumption and can provide load balancing if appropriately configured. Furthermore, they can be naturally combined with data-centric routing to make use of data aggregation techniques.

Passive clustering (PC) [63] is a way to perform on-demand clustering to eliminate control messages overhead. It does not use any explicit control messages to maintain clusters. Instead, it relies on control information piggybacked on outgoing data packets. In WSN, PC was combined with Directed Diffusion (DD) [55] in [50, 95, 88] mainly to achieve energy efficiency. However, when used with routing protocols, Passive Clustering concentrates traffic on a set of nodes (clusterheads and gateways) performing flooding. We argue that this concentration can lead to a variance in energy consumption among sensor nodes and is able to cause rapid partition of the network.

In this chapter, we propose Energy Level Passive Clustering (ELPC) where the flooding task is alternated among nodes depending on their energy level. A node with more energy is more likely to become and keep the role of a clusterhead or gateway. In this way, a load-balancing among nodes for data dissemination is achieved with higher lifetime for the whole network. This is even more interesting in the context of WVSNs where a big amount of data is to be handled. We apply the resulting algorithm with DD as a combination to

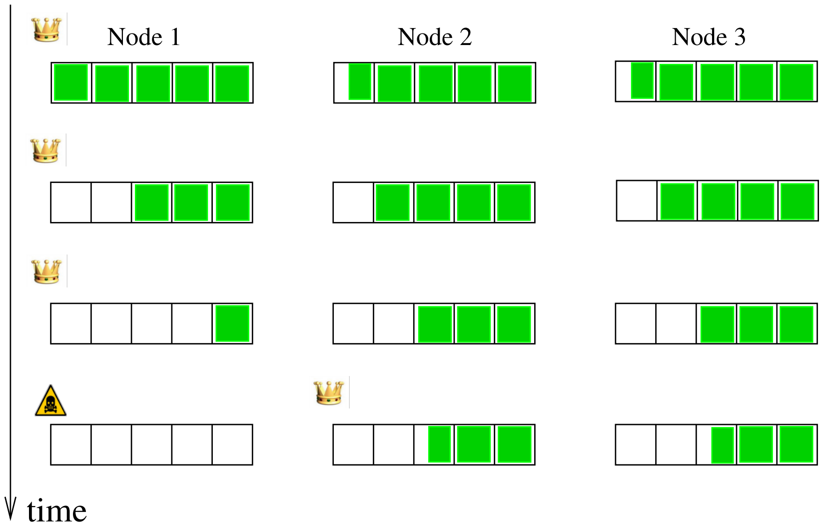


Figure 4.1: Network Lifetime with PC

ensure routing in WSN. This combination shows that our mechanism outperforms DD and its PC combination proposed in [50] in terms of network lifetime and delivery ratio. Finally, we studied the performances of video transmission over WSN using our approach and show how the video quality can be enhanced using a clustering algorithm along with DD. In the literature, there are some few research work trying to enhance DD to be more suitable to video transmission but, to the best of our knowledge, none made use of passive clustering.

The rest of this chapter is organised as follows. Section 4.2 gives the details of our proposal, the Energy Level-based Passive Clustering (ELPC). Section 4.3 is dedicated to simulation results where the performances of ELPC are assessed for both scalar and video transport data. Section 4.4 concludes the chapter.

4.2 Energy Level-based Passive Clustering (ELPC)

The main idea in combining PC to flooding-based routing protocols in WSN is to reduce energy consumption by minimising flooding. As this process is known to be very costly, the energy expenditure of the flooding nodes (clusterheads and gateways) will be much higher than those of ordinary nodes. This will cause a variance in the power amounts of the nodes in the network and by that a fast partitioning of the network. This is the case of [50, 95, 88] where there is no load-balancing feature when combining PC to flooding-based routing protocols. In fact, topology construction in PC is done according to the lowest ID rule. The drawback of doing so is its bias towards nodes with smaller IDs leading to their battery drainage. Assume that three nodes 1, 2 and 3 (with same initial amount of energy) are contending to be a flooding node as shown in Figure 4.1. If we use PC algorithm, node 1 will be selected to be a CH since it has the smallest ID. Even if we consider energy as done in [88], a CH will keep its role until it exhausts its whole energy.

4.2.1 ELPC Description

Our objective is to achieve energy efficiency in terms of network lifetime, not only in terms of energy consumption. This is done through alternating flooding role (clusterheads and gateways) among nodes depending on their energy. The aim of doing so is to have the same amount of energy at all the nodes at a given time which increases substantially the whole network lifetime.

In ELPC, each node's battery is split into levels. One can make a correspondence between different energy levels of a node and virtual sub-batteries it consumes sequentially. The energy level (l) of a node can be computed using :

$$l = \left\lceil L \quad \frac{E_r}{E_i} \right\rceil \tag{4.1}$$

where E_r is the remaining energy, E_i is the initial one and L is the suggested number of levels. For instance, if the number of levels is equal to 5, a node with only the half of its battery will have an energy level of 3. We introduce the notion of *candidature* to be a flooding node by defining the *network energy level (nel)* parameter. A node is not allowed to declare itself as a clusterhead (or a gateway) if its energy level is lower than this parameter. A flooding node can keep its role as long as its energy level is higher than the *nel*. Otherwise, it gives up its role and passes to the *initial* or *ordinary* state according to whether it knows or not a clusterhead in its vicinity.

Finding a meaningful value for the network energy level is non-trivial. It depends on the energy level of the network nodes and can be viewed as the minimum level of energy necessary for a node to be a flooding node. We suggest to take an initial value that corresponds to the half of the battery charge. This value is decreased locally each time the condition to be a clusterhead is not satisfied. The local network energy level is then propagated within outgoing packets header. The local *nel* value is updated each time a node receives a smaller *nel* value.

In addition to the PC related fields, we add the following ones to the packet headers (Figure 4.2) :

- l, the energy level of the node that sends the packet
- *nel*, the network energy level
- *give-up*, as in [50] is set when the node is a CH that gives-up its role. It is used to replace the *give-up* message proposed in PC. In ELPC, this field is set when the energy level of a CH drops bellow the *nel*.

We use the same states as suggested in [63] (section 2.3.4 in chapter 2) where at startup, a node is at the *initial* state. Nodes form and maintain the clustering topology by changing their internal and external states based on incoming and outgoing messages. When sending the next message, a node announces its external state which becomes visible in the network.

l	nel	id	state	CH1	CH2	give–up

Figure 4.2: ELPC Packet header

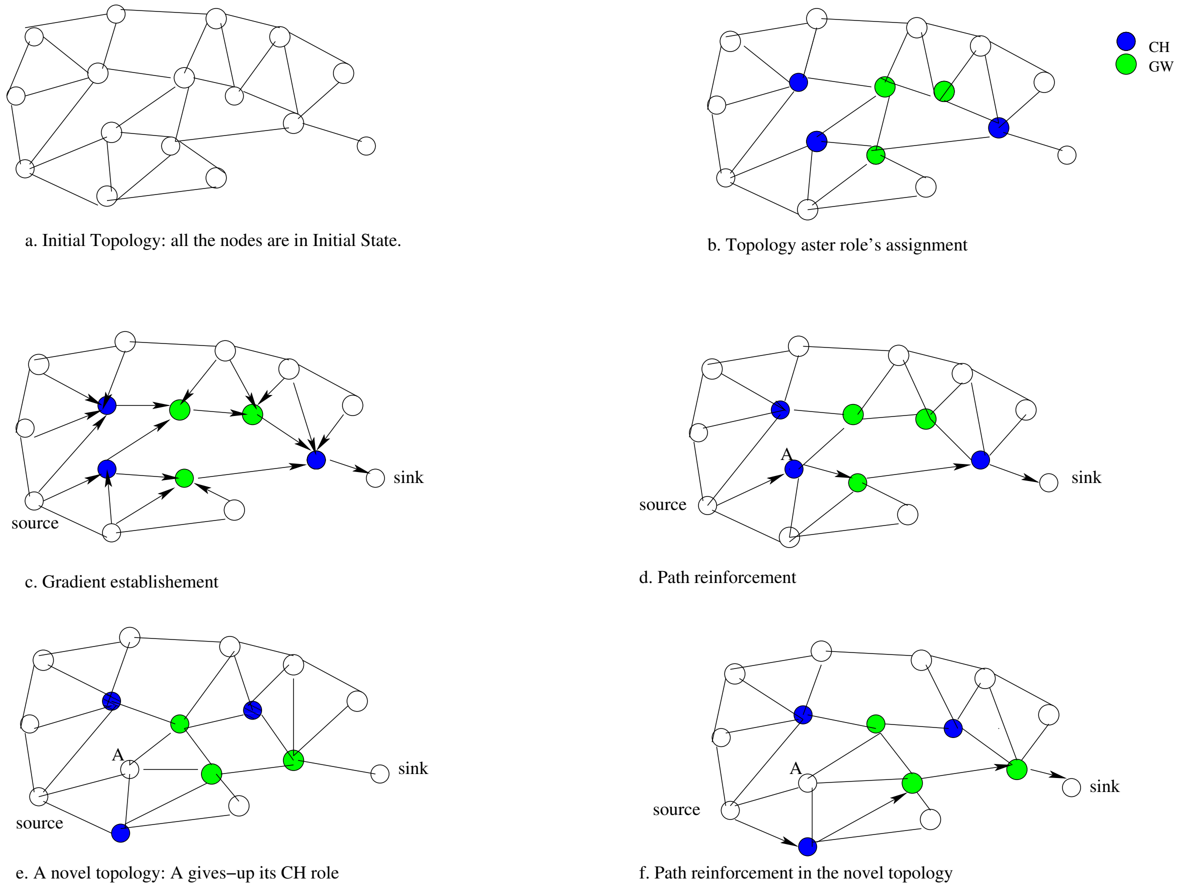


Figure 4.3: ELPC illustrated

Algorithms 1 and 2 summarise how PC is modified to allow load-balancing feature depending on nodes energy levels.

Figure 4.3 shows the establishment of routing structures of directed diffusion when this latter is used in combination with ELPC. Initially, all nodes in the network are in the *initial* state. Nodes will use the first interest messages to establish the new topology as described in the algorithms. A possible topology is illustrated in Figure 4.3(a-b). After establishing the gradient (Figure 4.3(c)) and path reinforcement (Figure 4.3(d)), the source begins sending the sensed data. When the energy level falls under the network energy level at node A, it gives-up its role of clusterhead (Figure 4.3(d)) and a new topology is established (Figure 4.3(e)). This is done using next circulating messages in the network (data messages, interests, exploratory data). The resulting passive clustering can be applied to any routing protocol in sensor networks as they mostly rely on flooding and particularly with DD. This not only reduces energy consumption as in [50], it also increases the whole network survivability as it will be shown in the following section.

1 ELPC : initialisation and incoming message processing

- *CH_ list* is the list of known clusterheads to this node,
- *GW_ list* is the list of known gateways to this node,
- *ORD_ list* is the list of known ordinary nodes to this node,
- *INIT_ list* is the list of known nodes to this node that are in initial state,
- *give_ up* if set, it indicates that this node wants to give-up its role,

Initialisation phase

```
state ← initial
loop
    wait for receiving/sending a message
end loop
```

Incoming message processing

```
give_up ← false
if msg.nel < nel then
    nel ←msg.nel;
end if
if msg.give − up then
    delete the node from lists and updates its state;
    return; {example: if the clusterhead has given-up its role,the node passes to the initial state}
end if
if msg.state == CH then
    if state == CH then
        if l < msg.level then
            give_up ← true;
            add CH to the CH_list;
        else if l == msg.level then
            Use nodes' identities to solve conflict (if any)
        else
            add the CH to the CH_list; check lists;
            return
        end if
    end if
else
    add the CH to the CH_list; check lists; recalculate my state;
end if
if (msg.state == GW) then
    add the gateway to the corresponding list and update its state {the same principle is applied. Here the conflict takes place when the states are the same and the related CH are also the same. The energy level is then used to solve it.}
end if
if (state == initial) AND (msg.state! = CH) then
    state ← CH_Ready;
end if
```

2 ELPC : outgoing message processing

```
if give_up == true then
    give_up ← false;
    if CH_list is not empty then
        state ← Ordinary;
    else
        state ← initial;
    end if
end if
if state == CH_Ready then
    if l > nel then
        state ← CH;
    else
        decrease nel;
        if CH_list is empty then
            state ← CH;
        end if
    end if
end if
if state == GW_Ready then
    if l > nel then
        state ← GW;
    else
        decrease nel;
        if GW_list is empty then
            state ← GW;
        end if
    end if
end if
if (state == CH) OR (state == GW) then
    if l < nel then
        give_up ← true;
        if CH_list is not empty then
            state ← Ordinary;
        else
            state ← Initial;
        end if{the same principle is applied if the node is a gateway. If the first condition
        is not satisfied the node declares itself as an ordinary node: state ← Ordinary}
    end if
end if
Update msg fields; send msg;
```

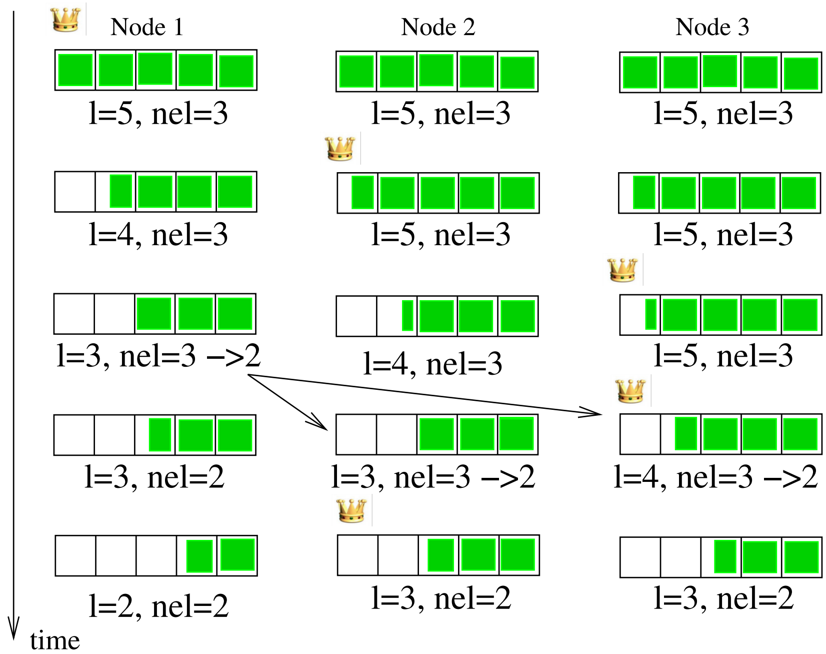


Figure 4.4: ELPC and load-balancing feature

4.2.2 ELPC and Network Lifetime

Figure 4.4 illustrates the same example of Figure 4.1 with ELPC applied. The number of levels is chosen to be five for all the three nodes and the *nel* is initially set to 3 corresponding to the half of battery charge. We can see that the clusterhead role is alternated between the three nodes depending on their energy levels. When two nodes have the same energy level, then the nodes' identities are used to solve conflict in declaring roles. At step 3, we can note that node 1 decreases its *nel* to 2 (since $l = nel$) and propagates this new value to its neighbours so all nodes can have same estimation of the network energy level. It is straightforward that by using ELPC compared to PCDD (Figure 4.1), we enhance the network lifetime by allowing fair energy distribution among nodes.

We can also show using a simple formal method how ELPC allows longer lifetime than PC combined with a flooding-based routing protocol (let's say DD). Consider a network region with one cluster and say $k, k \geq 1$ potential candidates to be a clusterhead. Let E_L be the amount of energy per level which we consider to be the same for all the region sensors. Let E_i be the available energy at a sensor i at the beginning of the session where $E_1 \leq E_2 \leq ... \leq E_{k-1} \leq E_k$. We call a *round* the time interval in which a given candidate is a clusterhead. Let P be the power dissipation of a sensor when it is a clusterhead.

In PCDD, the number of rounds is k since each candidate becomes a clusterhead once. Each round lasts E_i/P when sensor i is the clusterhead in this round. Given that a region lifetime is defined as the time until the first candidate dies, the PCDD lifetime corresponds to the duration of the first round. Since, it is the candidate with largest amount of energy (E_k) who is elected for the first round, then this region lifetime in PCDD can be given by :

$$\Lambda^{PCDD} = \frac{E_k}{P} \tag{4.2}$$

In ELPC, the number of rounds is $\sum_{i=1}^{k} E_i/E_L$ and each candidate (i) becomes a clusterhead E_i/E_L times. This is because each round consists in exhausting a level (E_L) of energy. It comes that each round lasts E_L/P. When the first clusterhead is died (the kth one with the largest amount of energy at the beginning of the session), it remains one level of energy for the $(k-1)$ other candidates and this region lifetime can be computed as follows :

$$\Lambda^{ELPC} = \frac{E_L}{P}\left(\sum_{i=1}^{k-1}(E_i/E_L - 1) + E_k/E_L\right)$$

Equivalently :

$$\Lambda^{ELPC} = \frac{1}{P}\sum_{i=1}^{k}(E_i - (k-1)E_L) \tag{4.3}$$

Note that $E_i = E_L$ when $L = 1$ and that :

$$\forall i \in [1, k-1] : E_i \geq E_L$$

Then we can write the following :

$$\sum_{i=1}^{k-1} E_i \geq (k-1)E_l$$

$$\sum_{i=1}^{k} E_i \geq E_k + (k-1)E_l$$

Dividing by P, it follows that $\Lambda^{ELPC} \geq \Lambda^{PCDD}$ and that $\Lambda^{ELPC} > \Lambda^{PCDD}$ when $L > 1$ and $k > 1$. This means that if we have only one level of energy ($L = 1$) or just one potential candidate to be a clusterhead ($k = 1$), ELPC behaves exactly like PCDD. To get better performances in ELPC, we need naturally to have more than one level of energy and more than one potential candidate so the network connectivity is ensured for longer durations.

4.3 Simulation Results

We implemented our Energy Level Passive Clustering (ELPC) using NS-2 [5] and compared it to the original directed diffusion (DD) and PCDD (DD combined to passive clustering with energy considerations but without load balancing feature as done in [88]). We generated flooding traffic in the network using the Two Phase Pull DD algorithm with its two flooding phases. The interest flooding is initiated by the sink and the data flooding is performed by the sources when events are detected in the network. Additional fields in the message header are added as attributes to exchange the node's and the network's energy level for instance.

We adopted the IEEE 802.11 and the two-ray propagation model. The radio propagation of each sensor node reaches up to 40 meters. Results are averaged over 20 randomly generated

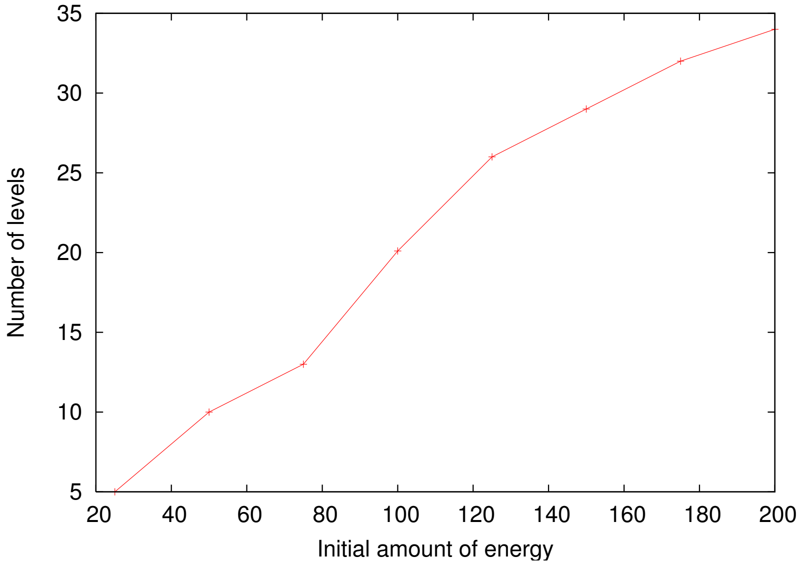


Figure 4.5: Levels number allowing the best average dissipated energy when varying initial energy

topologies. We performed both sufficient and insufficient energy scenarios. In the first set, nodes have sufficient amount of energy to terminate the simulation. This allows us to mainly assess the average dissipated energy per correctly received information. In the second set of simulations the amount of energy at nodes is chosen so it is smaller than the minimum required energy in the different protocols. This allows us to assess the network lifetime.

The Number of Energy Levels. The number of energy levels is one important parameter to be defined. As ELPC virtually divides each node's battery, we believe that the initial amount of energy has a great effect on this parameter. To evaluate this, we performed simulations for 100 sensor nodes where the initial energy is varied. For each amount of energy, we also varied the number of levels and recorded the average dissipated energy in each simulation. Figure 4.5 plots the number of levels corresponding to the smallest value of the average dissipated energy as a function of the initial one. It shows that the number of energy levels depends on the initial amount of energy. The average amount of energy per level can be given by $E_m = E_i/N_l$, then according to Figure 4.5, it is almost 5 J. This value is used in all the simulation experiments.

Convergence Time and Number of Clusterheads. In this set of experiments, we evaluate ELPC and compare it with Passive Clustering without energy considerations. This is done in terms of convergence time, the number of elected clusterheads, the achieved delivery ratio and the amount of consumed energy. The convergence time is defined as the time at which all nodes are declared for the first time in one of the following states : CH, GW or Ordinary. Fixed area networks are considered for this experiments where a network area size of 160×160 m^2 is used. We used random and grid topologies to best track the characteristics

Sufficient amount of energy

Number of nodes	25		49		64		100	
Protocol	PC	ELPC	PC	ELPC	PC	ELPC	PC	ELPC
Convergence time	102.6	101.6	141.8	142.1	198.5	198.2	215.5	214.9
Number of CH	7	10	12	17	16	21	21	32
Energy consumption	18.5	16.5	31.7	31.8	49.2	48.8	65.2	62.8
Delivery ratio	0.92	0.94	0.90	0.90	0.89	0.88	0.86	0.87

Insufficient amount of energy

Number of nodes	25		49		64		100	
Protocol	PC	ELPC	PC	ELPC	PC	ELPC	PC	ELPC
Convergence time	100.9	101.3	142.8	142.1	196.5	193.2	209.2	210.8
Number of CH	7	17	12	29	16	39	22	55
Delivery ratio	0.59	0.88	0.56	0.83	0.57	0.84	0.53	0.82

Table 4.1: PC and ELPC with sufficient and insufficient amount of energy

of our proposition.

Table 4.1 summarises the simulation results of our experiments with random topologies for sufficient and insufficient energy settings. In the former, the number of selected clusterhead nodes in ELPC is bigger which is the consequence of alternating the clusterhead roles. The two protocols gave same performances in terms of the convergence time, the number of delivered events and the energy consumption in the construction phase. The simulation results are more significant when insufficient amounts of energy are used. In this case, the number of clusterheads using ELPC is much bigger. This can be explained by the difference in the energy states of the nodes which lead to the selection of several nodes as clusterheads. Moreover, ELPC allows for higher network delivery ratio. This is mainly due to network lifetime enhancement. To sum up, ELPC allows for good alternation in clusterhead roles and prolong by that the network lifetime.

4.3.1 Scalar Data Transport

In this section, we are interested in the evaluation of ELPC compared with DD and ELPC in a scalar WSN before considering the case of video transport in Section 4.3.2. We consider five sources and five sinks unless stated otherwise. To examine the effect of network topology on the different solutions, we vary the number of nodes and consider either a fixed area of 160×160 m^2 with variable nodes density or fixed average density network with variable area dimensions.

First, we performed simulations with nodes having sufficient amount of energy to terminate the simulation. Figure 4.6 shows, as a function of the number of nodes, the delivery ratio of the different solutions in fixed area (a) and fixed density (b) scenarios. Passive clustering (in both PCDD and ELPC) allows for better performances in terms of delivery ratio which, reaches higher values and even 100% in some cases. In fact, when increasing the nodes number or the network density, more flooded messages are observed in the network. Passive clustering allows to reduce the resulting overhead and keeps the performances of DD as it was executed for small densities and networks.

Prolonging the network lifetime is our primary goal when using energy level-based PC. We conducted other experiments with nodes assigned insufficient energy to capture network partition. We use the time to first node to die in order to see if energy consumption is fairly distributed in the network. An other metric is also used, the number of events before partition, to show the delivery capacity of the network before giving up.

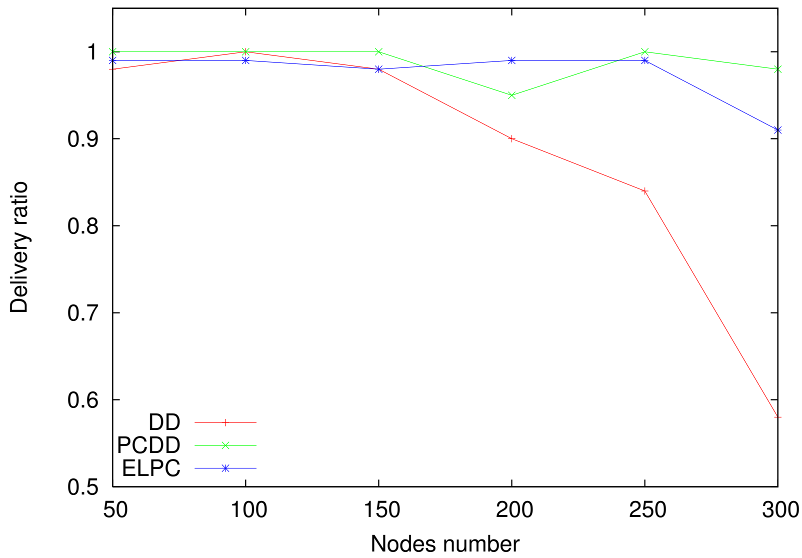
Network topology effects.

Figure 4.7 plots the time to network partition as the network size increases. This time decreases with the number of nodes increasing. This was to be expected, as a larger number of nodes results in a higher number of floods and hence bigger amount of energy is consumed in the network. Our solution (ELPC), however, achieves better performances compared to the two others. In case of fixed area scenario (figure 4.7(a)), the improvement is up to 41.15% and at least 23.35% compared to PCDD and between 56.28% and 78.5% compared to the original DD. In case of fixed density (figure 4.7(b)), it is between 7.21% and 50% compared to PCDD and between 55.1% and 76.17% compared DD.

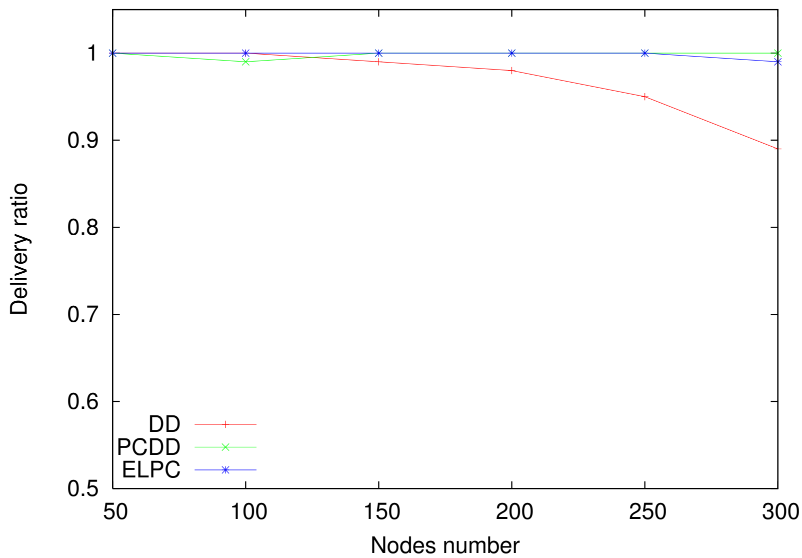
The improvement is mainly due to the fact that clustering reduces the number of floods in the network and thus nodes will consume smaller amount of energy. This helps in extending network lifetime. In our solution, an alternation of the roles is achieved. A flooding node gives up its role when other nodes with higher energy levels are in conflict with it or when its energy level is lower than the network level. This encourages other nodes to declare themselves for these roles and, by that, leads to an increasing in the nodes lifetimes. As a consequence, the lifetime of the whole network is extended. The nodes of the network are then able to forward more data, which, permits to sinks to receive a higher number of events as depicted in figure 4.8.

Traffic effects.

To examine the traffic effect, we placed 100 nodes and used a variable number of sources and sinks. When increasing network traffic, the time before network partition decreases as depicted in figure 4.9. However, our solution behaves better. In the case of a single sink, the improvement is about 24% compared to PCDD and 34% compared to DD. In single source scenario, the improvement achieves 4% and 19% compared to PCDD and DD respectively. As a consequence, the number of events delivered before network partition obtained by our solution is higher than the two other solutions and by that our delivery ratio in both cases is better as shown by figure 4.10.

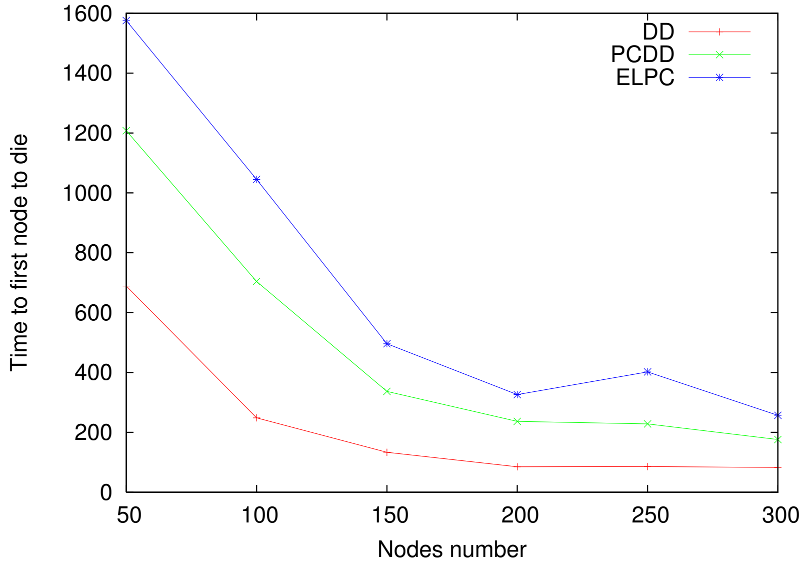


(a)

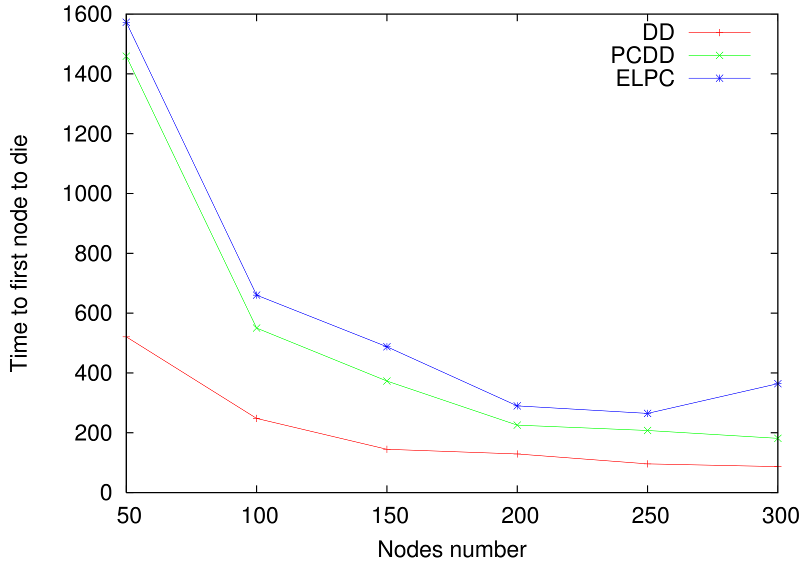


(b)

Figure 4.6: Delivery ratio, (a) fixed area, (b) fixed density

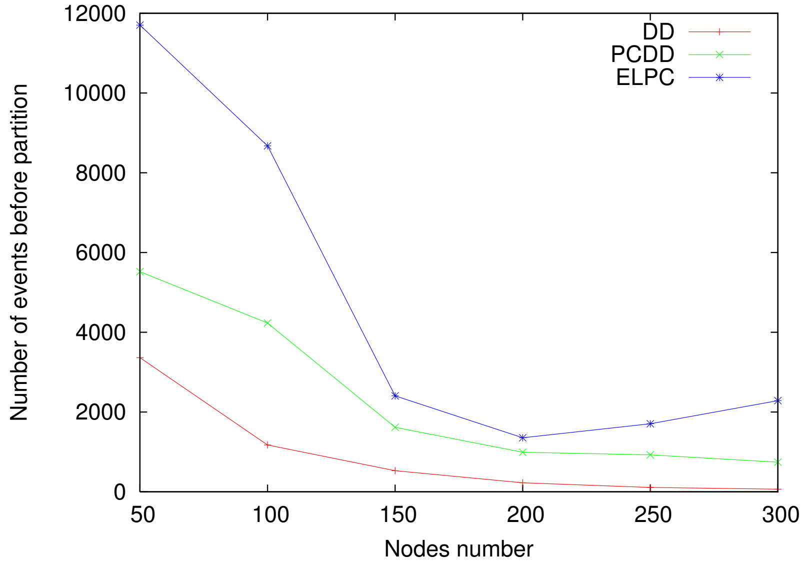


(a)

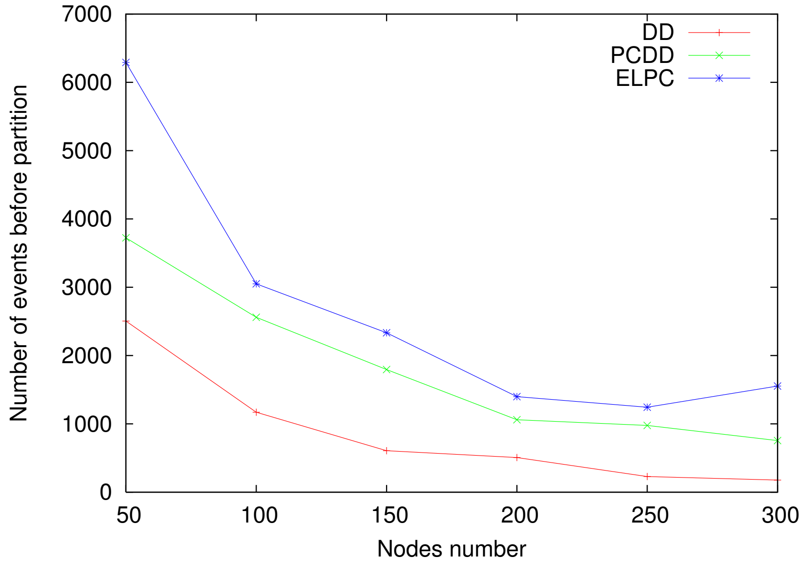


(b)

Figure 4.7: Network partition time (s) (a) fixed area, (b) fixed density



(a)



(b)

Figure 4.8: Number of event before partition, in (a) fixed area, (b) fixed density

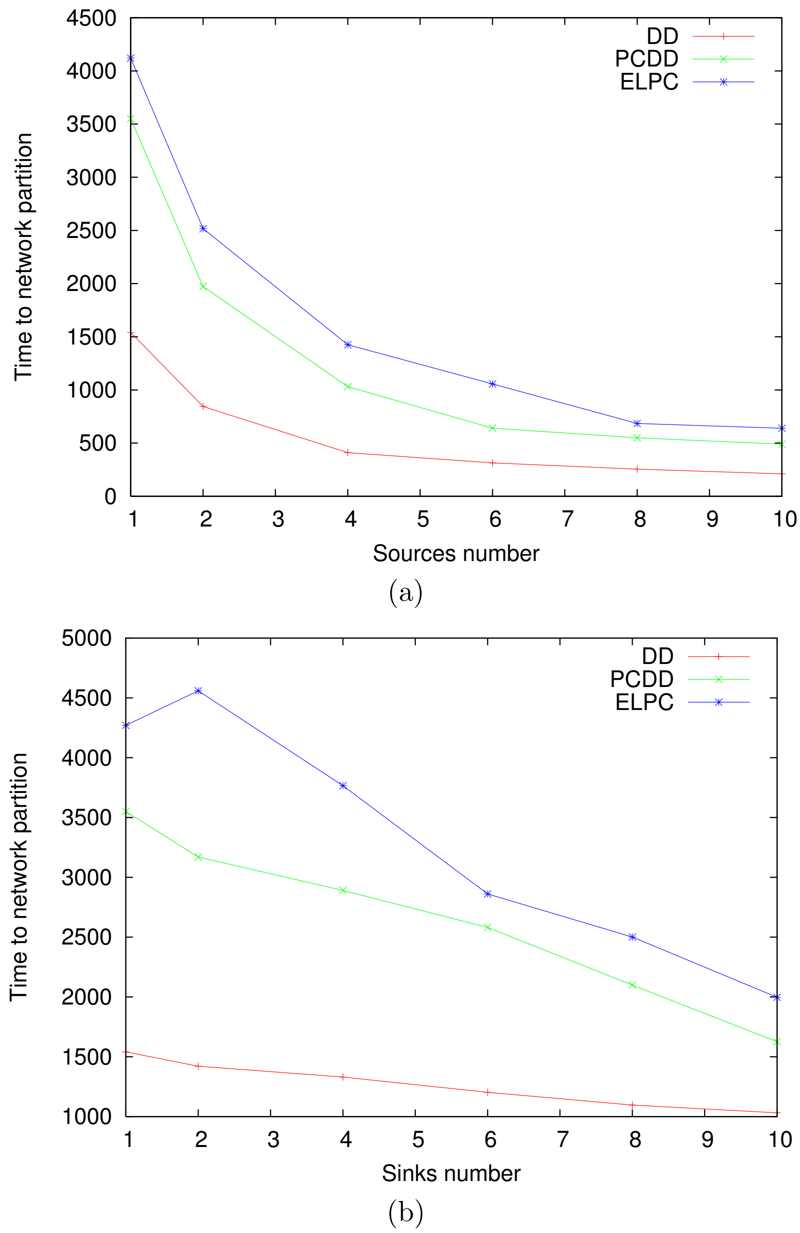


Figure 4.9: Network partition time (s), (a) single sink, (b) single source

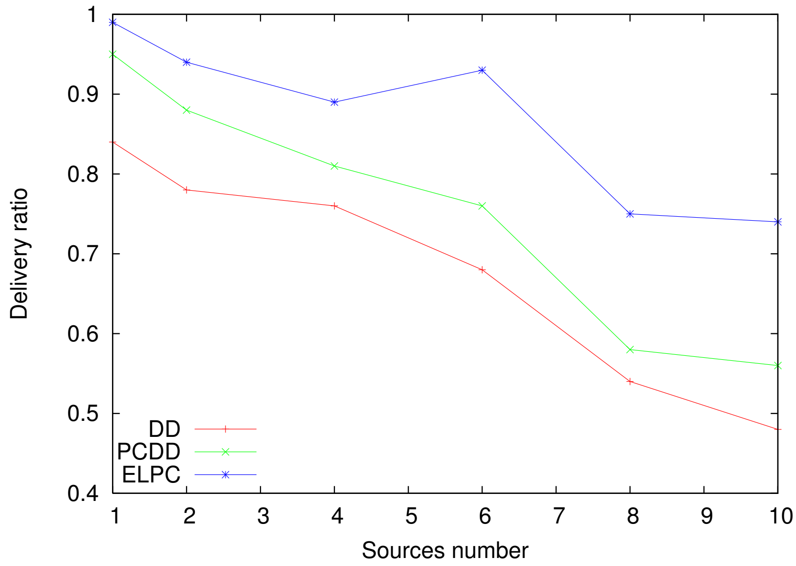


Figure 4.10: Delivery ratio, single sink scenario

4.3.2 Video Data Transport

In this section, we assess the performances of ELPC compared to PC and PCDD when applied to the transport of video data. In all the experiments conducted in this section, the sensors field is of $160 \times 160\ m2$ with a varied number of nodes ranging from 100 to 500 nodes. To evaluate the quality of a video transmitted over our WVSN, One video sensor is assumed to capture and transmit a video sequence. We selected one of the standard video sequences used by a variety of video encoding and transmission studies called "*Hall Monitor*". It lasts 10 seconds and consists of 300 frames in CIF resolution (352×288). The video sequence is encoded in MPEG4 using ffmpeg [2] with a target bit rate of $128Kbps$ and a Group of Pictures (GOP) of 30. Only I (intra) and P (predicted) frames were generated in video traces using the open source EvalVid set of tools [61]. The reference PSNR or the sent video PSNR (Peak Signal to Noise Ratio) obtained is 29.70 dB.

We considered the evaluation, in terms of PSNR of the received video quality, to show the benefit of passive clustering to video applications in WSN. The PSNR between the sent (s) and the received (r), possibly distorted video sequence, is computed using :

$$PSNR(s,r) = 20log\frac{V_{peak}}{MSE(s,r)} \tag{4.4}$$

where MSE is the mean square error which is the average of the square of the errors (pixel differences) of the two images and V_{peak} is the maximum possible pixel value.

We conducted experiments in order to empirically find the optimal data packet size for a good trade-off between energy efficiency and video quality. We considered a 200-node network and vary the data packet size from 32 to 2048 bytes. We obtained similar results for both insufficient and sufficient energy scenarios. We chose to present here only curves related to insufficient energy experiments. Figure 4.11 plots the loss ratio for the three simulated protocols (DD, PCDD and ELPC) as a function of data packets size. It is seen that the performances show a drop for packets size around 128 bytes. This behaviour can be attributed to the higher packet drops caused mainly by collisions for smaller packet sizes as bigger number of packets are to be sent. Even if the number of lost packets is smaller for large packet sizes, these losses affect considerably the loss ratio as the number of packets to be sent is smaller.

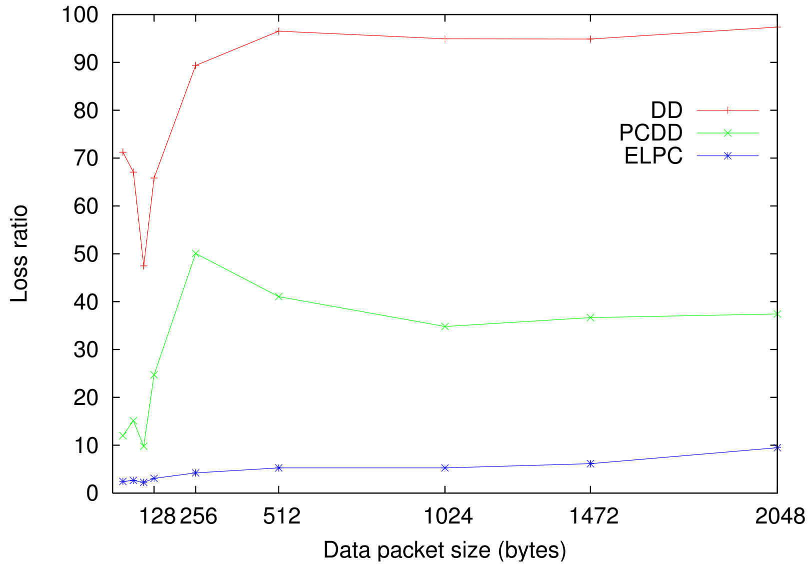


Figure 4.11: Loss ratio

Our experiments show that the empirical optimal data packet size is 128 bytes which corresponds to the smallest loss ratio. This value is confirmed in video quality measurements and network lifetime shown in Figures 4.12 and 4.13 respectively. We can see that the maximum PSNR and lifetime for all the three protocols are obtained for data packets of 128 bytes. These experiments confirm in someway the results presented in [101] where it is shown that for a given bit error probability, energy efficiency decreases when packet size exceeds a threshold which is nearly 100 Bytes. At this stage, it is worth mentioning that ELPC presents the best performances regardless the data packet size used.

In all what follows, we will use data packet size of 128 bytes. In subsequent simulations, the video clip is sent twice. This is done in order to get more insight into both the transient and steady phases of passive clustering in PCDD and ELPC. Each simulation runs until network partition (no way to reach the sink from the video source) or all the data packets composing the two clips are received by the sink. We start by giving the overall performances and then those related to the first and second clip periods.

Overall Performances

We are interested here in overall performances related to the entire simulation time from sending the first packet of the first clip until the last packet of the second clip. Figure 4.14 shows the energy gain obtained in PCDD and ELPC with respect to DD with sufficient

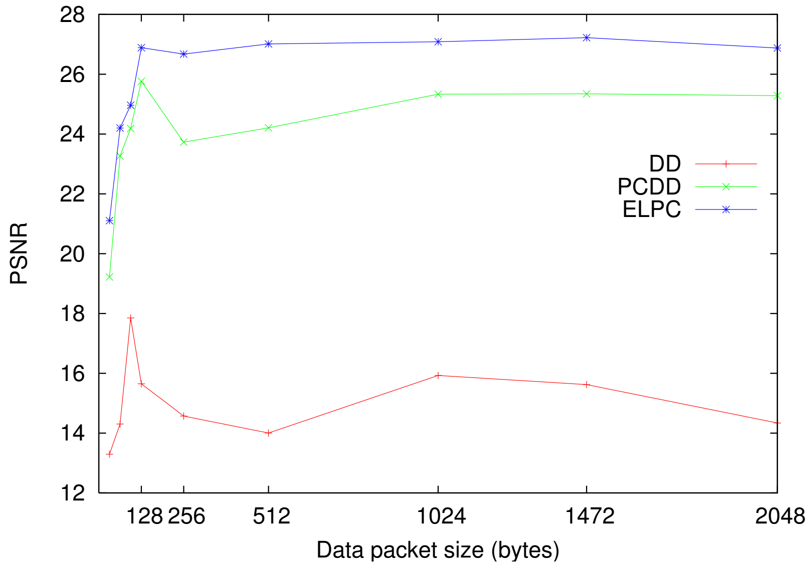


Figure 4.12: Video quality (PSNR)

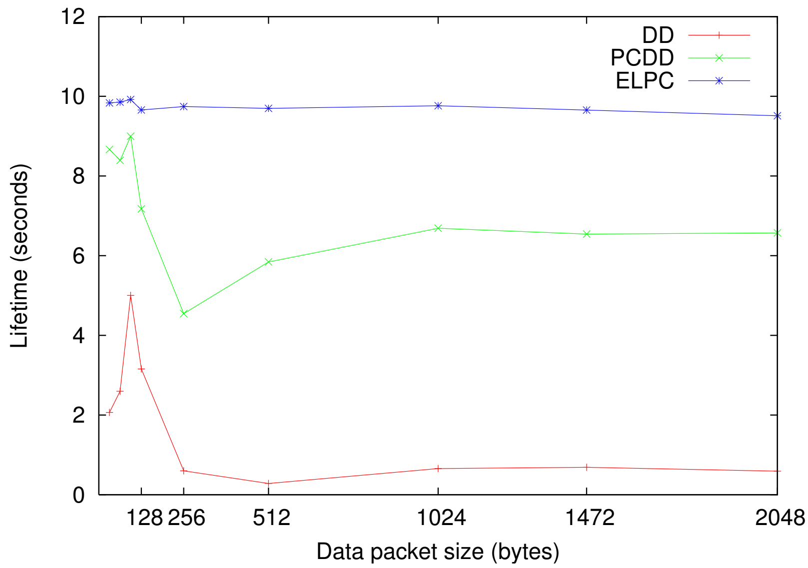


Figure 4.13: Network lifetime

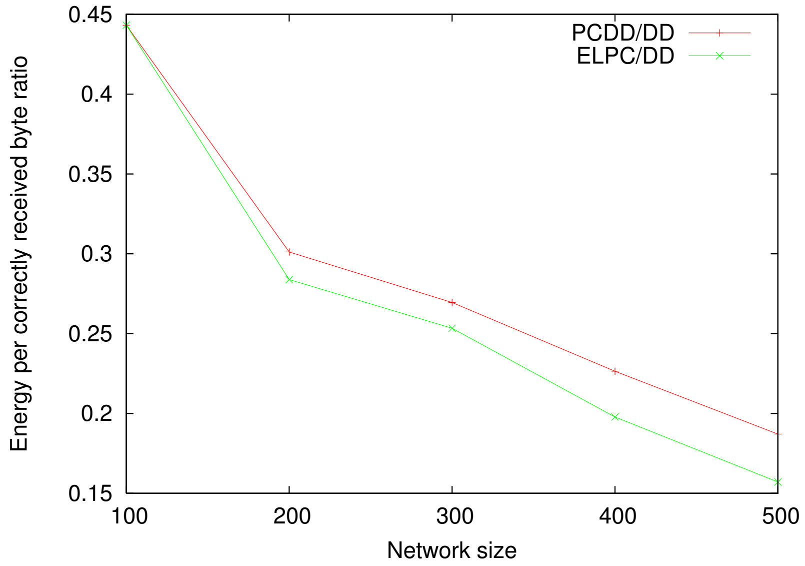


Figure 4.14: Energy ratio per correctly received byte (sufficient energy)

energy. Passive clustering allows energy saving in both ELPC and PCDD where they at most consume 45% of what DD consumes for 100-node network. When increasing the network size, the gain is much improved mainly using ELPC (more than 85% of energy is saved compared to DD for 500 nodes). This is because in ELPC more data packets are delivered than in PCDD as will be shown later on.

The improvement is mainly due to the fact that clustering reduces the number of floods in the network and thus nodes will consume smaller amount of energy. This helps in extending network lifetime. In ELPC, an alternation of the roles is achieved. Clusterheads or gateways give up their roles when other nodes with higher energy levels are in conflict with them or when their energy level is lower than the network energy level (nel). This encourages other nodes to declare themselves for these roles and, by that, leads to an increasing in the nodes lifetime. As a consequence, the lifetime of the whole network is extended. The nodes of the network are then able to forward more data, which, permits to the sink to receive a higher number of events.

Prolonging the network lifetime is our primary goal when proposing ELPC. We conduct experiments with nodes assigned insufficient energy to capture network lifetime. This latter is obtained using the time at which the sink receives the last data packet from the video source. We use as a lifetime metric, the duration of the video received by the sink. Figure 4.15 plots as the network size increases, the network lifetime for the three protocols with insufficient energy. The network lifetime slightly decreases with the number of nodes increasing since a larger number of nodes results in a higher number of floods and hence bigger amount of energy is consumed in the network. Our solution (ELPC), however, achieves better performances compared to the two others. In ELPC, almost the two clips are received and the network lifetime is estimated to be nearly 20 seconds, the two clips duration. However PCDD and DD best lifetime does not exceed 13 and 9 seconds respectively.

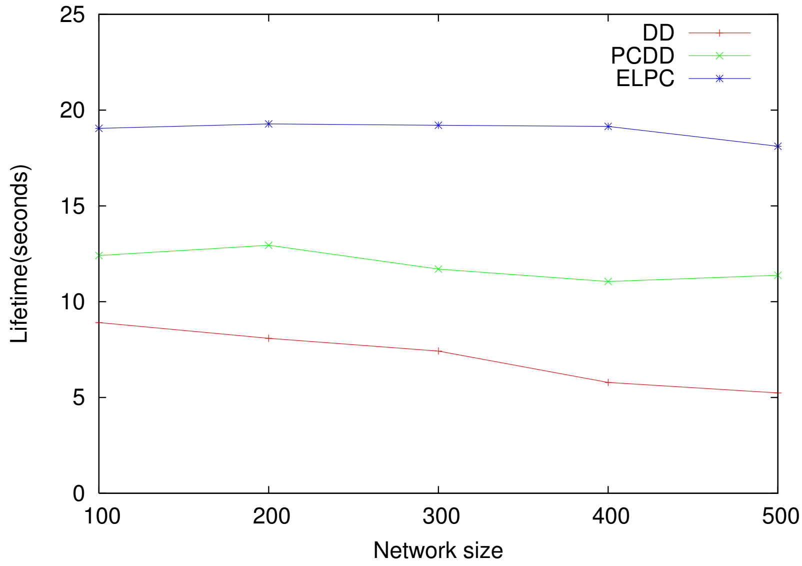


Figure 4.15: Lifetime with insufficient energy

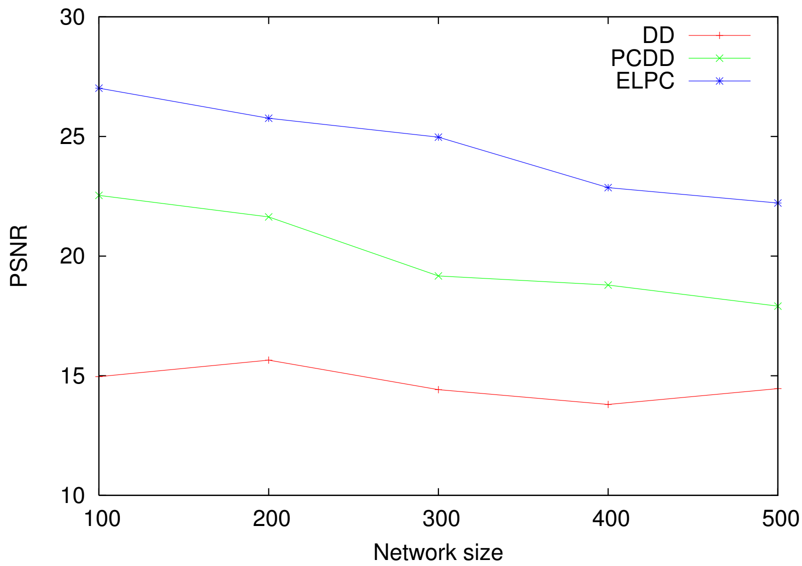


Figure 4.16: Overall PSNR with insufficient energy

Regarding video quality, ELPC outperforms both DD and PCDD mainly for insufficient energy scenarios as shown in Figure 4.16. Video quality decreases with the network size increasing since larger number of nodes results in a higher number of floods and hence bigger amount of losses which affect directly the quality of received video. For sufficient energy as shown by Figure 4.17, ELPC and PCDD presents nearly same performances. Enough energy does not allow distinguishing the two protocols.

First Clip Period

Here, we are interested in studying the transient period of the three protocols mainly PCDD and ELPC since clusters formation needs a given period of time to completely converge (the

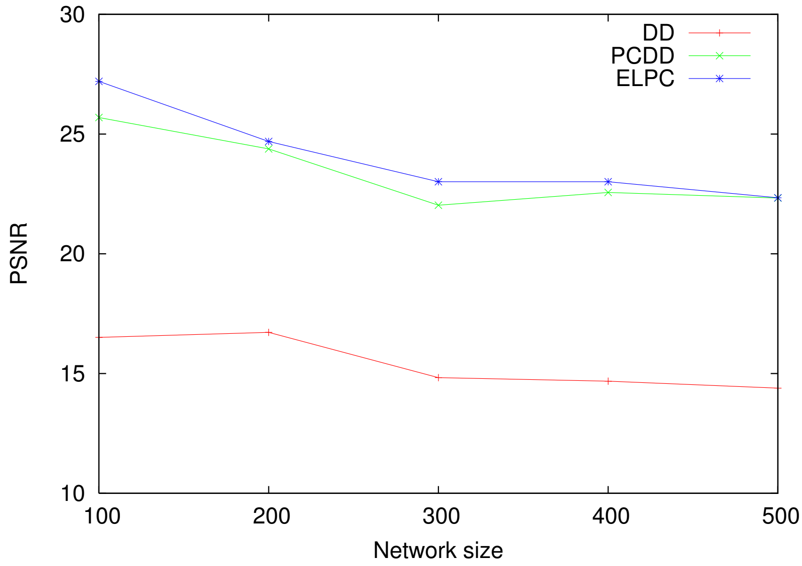


Figure 4.17: Overall PSNR with sufficient energy

clustered topology is entirely built). It is worth saying that first clip related results (mainly for PCDD and ELPC) are nearly the same for both sufficient and insufficient energy scenarios since the amount of available energies are chosen (even in insufficient energy case) so at least a minimum number of the first clip frames are received by the sink.

Figure 4.19 shows the video mean PSNR as the network size increases. We can observe that ELPC and PCDD present relatively same performances. This is was to be expected since ELPC is likely to perform better when there is lack of energy in the network as will be shown in section 4.3.2. Figure 4.20, showing loss ratio of the three protocols as a function of the network size, confirms these results. We can see that ELPC and PCDD achieve roughly similar results which are clearly better than the ones given by DD. ELPC achieves better delivery ratio than PCDD in most cases however as already seen in Figure 4.19, it presents lower PSNR. This can be explained by the fact that in the performed set of experiments, there were more lost I-frames packets in ELPC. There is no way to distinguish I and P frames in all the three simulated protocols.

Figures 4.18 and 4.21 show the evolution of PSNR in per frame basis for one scenario with respectively 100 and 500 nodes for the three protocols as well as the reference PSNR (REF). This latter corresponds to the measured quality of the sent video and allows to consider only network effects on the video quality. It is clear that both PCDD and ELPC outperforms DD thanks to flooding reduction through clustering.

Clustering allows to achieve similar PSNR values as the reference PSNR except for the first 30 frames where ELPC and PCDD performances are as bad as those of DD. These 30 frames correspond exactly to the first transmitted GOP. Their bad quality can be explained by the presence of a transient period where the clusters are not formed yet in ELPC as it behaves as DD at the beginning. Many messages can be lost as the routing paths are not properly established. This took place because flooding nodes are not yet designed in the

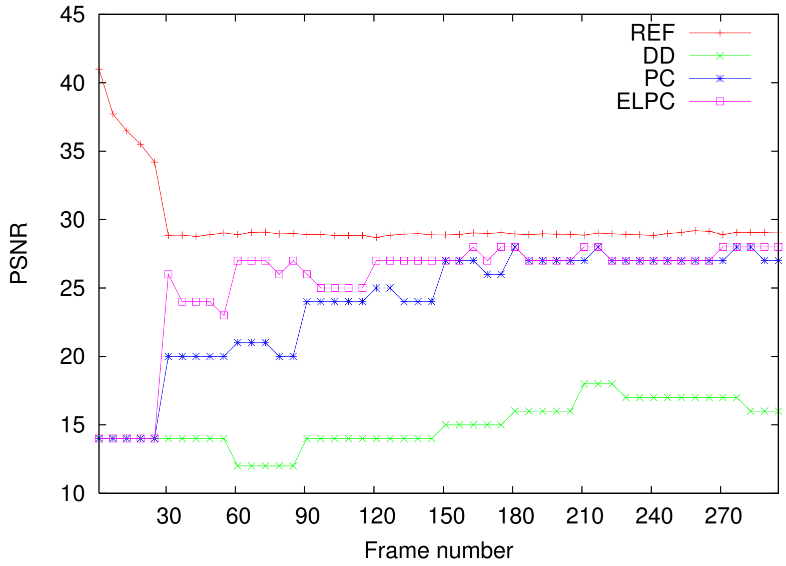


Figure 4.18: Mean PSNR per frame in the first clip video for 100-node network

network.

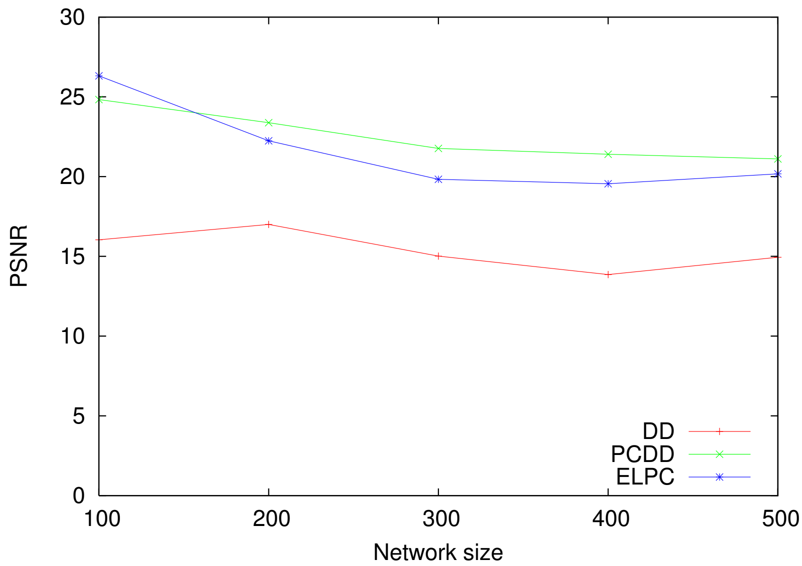


Figure 4.19: Video PSNR - First clip

The mean PSNR obtained with ELPC is of about 26.31 dB for 100-node network while it is of only 16.03 dB for DD. Note that the mean PSNR of the transmitted video is 29.7 dB. DD is unable to reach a PSNR greater than 18 dB which is very bad as can be observed in Figure 4.22. For a 500-node network, similar results are obtained when comparing the three protocols however with lower PSNR values due to scalability issues mainly for DD.

Figure 4.22 shows two sample images as sent (a) and received by the sink using DD (b), PC (c) and ELPC (d). Video quality enhancement of ELPC compared to DD is noteworthy. For instance, the best achieved quality in DD corresponds to the image in the left (14.1 dB)

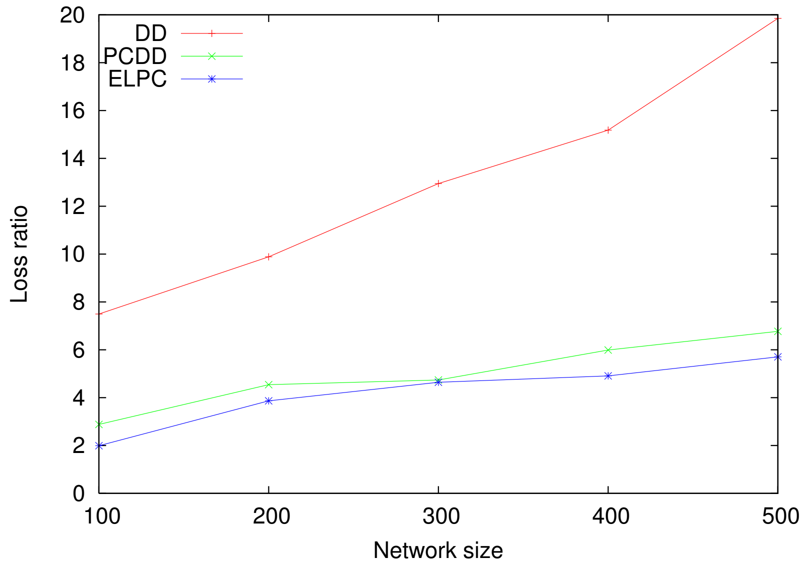


Figure 4.20: Loss ratio - First clip

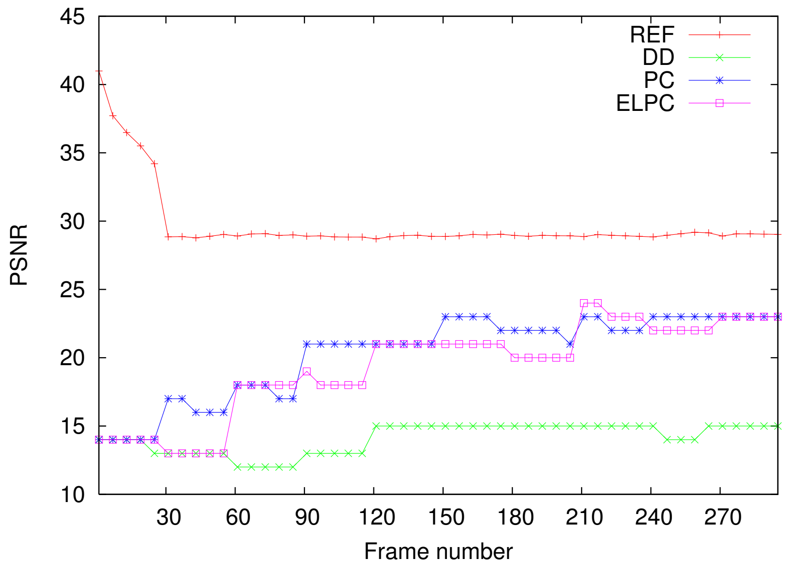


Figure 4.21: Mean PSNR per frame in the first clip video for 500-node network

for which, we can note the bad quality especially compared to the one of ELPC (with a PSNR of 27.56 dB). This can be explained by losses caused by messages dropped due to congestion in the network as large number of flooding are performed according to DD conception.

Second Clip Period

In this section, we are mainly interested in comparing ELPC to PCDD to see how the former compared to the latter is able to enhance video quality mainly for insufficient energy scenarios. Figure 4.23 plots the mean PSNR obtained at the sink as function of the number of sensor nodes with sufficient energy. The first thing to note is that even with sufficient energy, DD performs very bad with a PSNR less than 19 dB. We chose to omit DD results since in many cases mainly for insufficient energy scenarios, only few frames are received from the second clip. This is why in subsequent plots, we only consider ELPC and PCDD.

As shown by Figures 4.23 and 4.24, ELPC allows better video quality in terms of mean PSNR with respect to PCDD regardless of initial amount of energy available at the sensor nodes. The difference is mainly observed in insufficient energy cases. Figure 4.24 shows that PCDD achieves at most a mean PSNR of 20.25 for a 100-node network while ELPC mean PSNR is 27.73 dB. Even if the network size is increased to reach 500 nodes, ELPC obtains a mean PSNR of 24.27 dB.

PSNR results of Figure 4.24 are confirmed by the loss ratio experienced by both protocols as depicted in Figure 4.25. In PCDD, the larger the network, the higher the loss rate since the traffic overheard is more important. This explains why the PSNR is worser when the network size increases. Losses are more important in PCDD because of higher number of nodes ran out of energy since no energy-aware load-balancing is performed. This leads to premature network partitioning and thus shorter lifetime as already shown by Figure 4.15.

Figure 4.26 plots the mean PSNR on a per-frame basis for a 300-node network with sufficient and insufficient energy. In both cases, ELPC outperforms PCDD especially for insufficient energy simulations where ELPC achieves a mean PSNR of 25.87 dB while PCDD a mean PSNR of only 16.57 dB suffering from higher loss rates. We can see that in ELPC, the frames keep a fair PSNR until almost the end of the clip as the network lifetime is longer.

Figure 4.27 shows frames number 30, 60 and 90 as received by the sink in insufficient energy simulations in PCDD and ELPC as well as the reference ones (as sent from the source). The three frames correspond to the last frames of the three first GOPs. This allows assessing video quality using the worst frame in a GOP just before receiving a new I-frame that could increase considerably the observed PSNR. We can see that frames quality in ELPC is better than those obtained in PCDD and is of approximately the same quality of the reference frames. For instance, the frame 30 is received with only a PSNR of 14.20 dB with very bad quality in PCDD while it is received with a PSNR of 29.21 dB in ELPC. An other important observation is that frames 60 and 90 are nearly the same for PCDD. This means that very few data arrived at the sink from the third GOP. In the corresponding simulation scenario, the last received packet using PCDD corresponds to the 69th frame of

29.00 dB 28.950 dB

(a)

14.1 dB 14.1 dB

(b)

18.73 dB 28.9 dB

(c)

27.56 dB 28.90 dB

(d)

Figure 4.22: Sample of received frames (60 and 61) from the first clip : (a) Reference, (b) DD, (c) PC and (d) ELPC

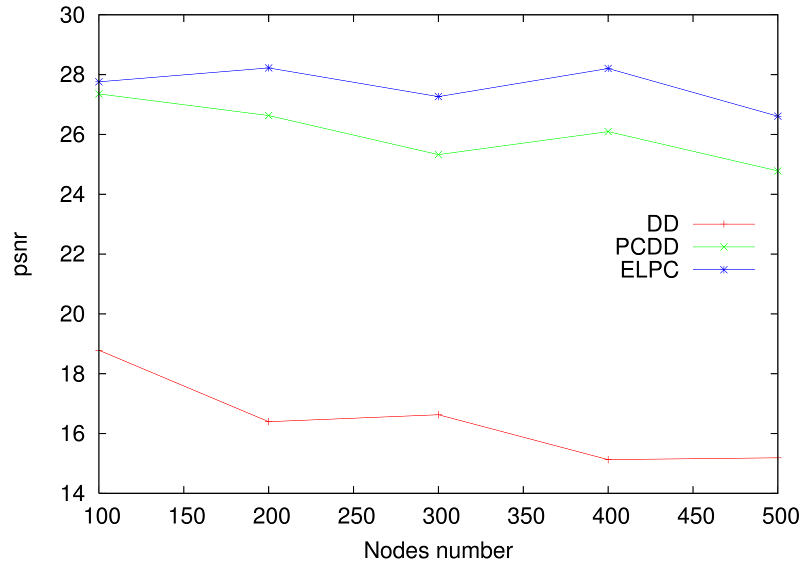


Figure 4.23: Mean PSNR with sufficient energy

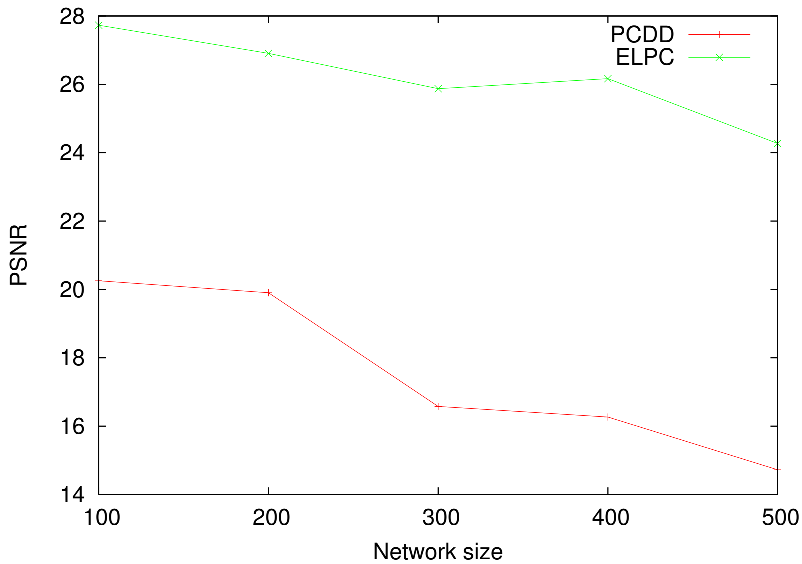


Figure 4.24: Mean PSNR with insufficient energy

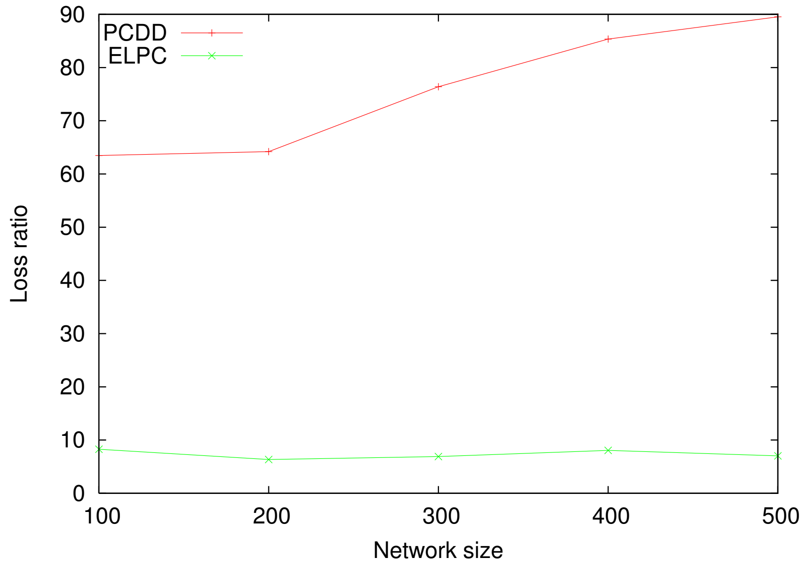


Figure 4.25: Loss ratio with insufficient energy

the second clip. In the same simulation scenario, no frame from the second clip is received using DD.

4.4 Conclusion

In this chapter, we proposed Energy Level passive Clustering algorithm to enhance the lifetime of a sensor network. We also proposed the combination of this algorithm with Directed Diffusion, a well known routing paradigm (DD) in sensor networks. This combination gives better performances in terms of network survivability and data delivery ratio when small amounts of energy are available. We were mainly interested in evaluating video transport in a WVSN using passive clustering. We conducted extensive simulations and showed that an approach like ELPC with energy-aware load balancing feature is very promising. ELPC allows longer network lifetime, lower loss rate and better video quality.

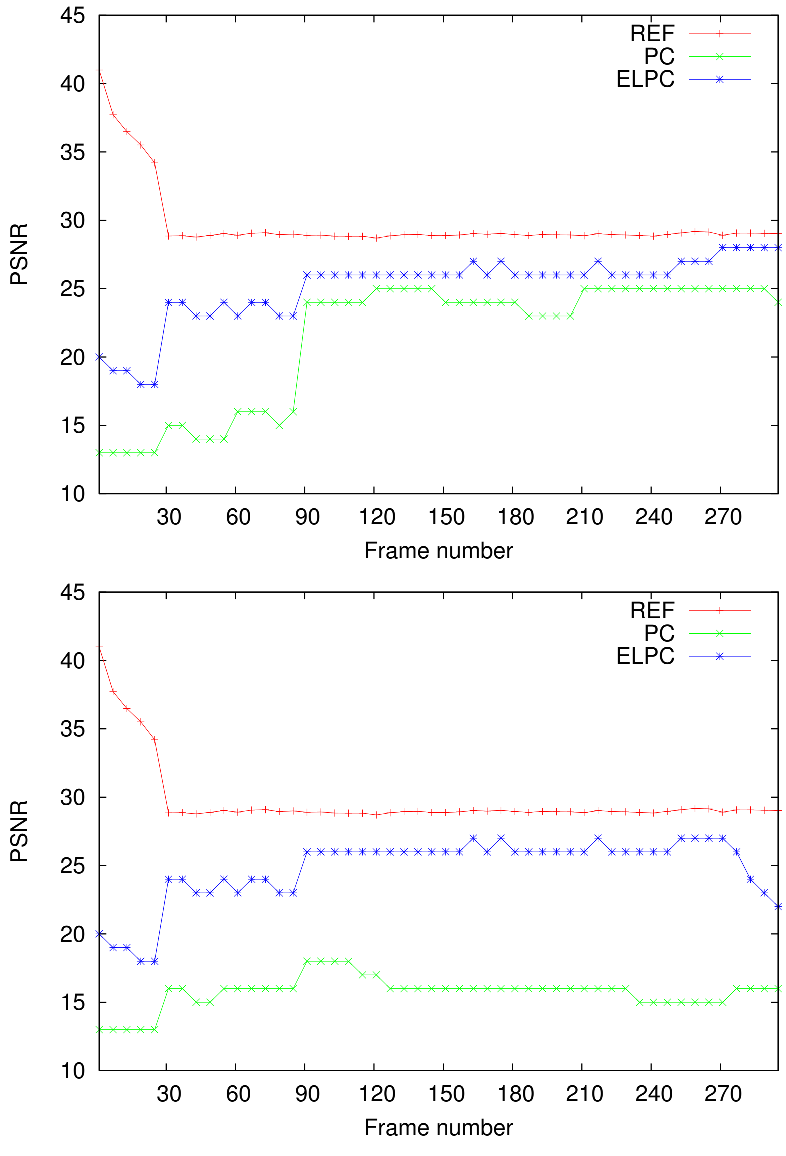


Figure 4.26: Mean PSNR per frame in the second clip video for a 300-node network with (a) sufficient and (b) insufficient energy

33.78 dB 29.00 dB 28.84 dB

(a)

(b) 14.20 dB 26.51 dB 24.31 dB

(b)

29.21 dB 29.00 dB 28.53 dB

(c)

Figure 4.27: Sample of received frames (30, 60 and 90) from the second clip with insufficient energy : (a) Reference, (b) PC and (c) ELPC

Chapter 5

Multipath Routing with Interference Awareness in WMSNs

5.1 Introduction

Multipath routing allows the establishment of multiple paths between a single source and a single destination node. It is typically proposed in order to increase the reliability of data transmission or to provide load balancing. Many of the routing protocols proposed in WMSNs (see chapter 3) use this technique to achieve efficient transport of multimedia data. However, when multiple paths are used in the network, ongoing transmissions over a path may interfere with transmissions over other paths. This is because the nodes of the network communicate through a shared wireless medium. This problem is known as the *route coupling* problem and was first introduced in [89]. In this work, the authors state that using multipath routing in a single channel network results in negligible benefits due to severe route coupling.

The problem of finding two non-interfering paths between a source and a destination is NP-complete [21]. Therefore, few approaches have been proposed to reduce the effects of interference through techniques such as geographic routing, nodes blocking, multichannel transmission, directional antennas and optimization problem solving. When nodes blocking is considered, the nodes that may interfere with an already built path are prevented from participating in the routing process. This technique is easy to implement, however it causes additional overhead in the network as the blocking is generally done by additional control messages.

In this chapter, we propose a multipath routing protocol with interference awareness and study the effect of inter-path interference on video data transmission over WMSNs. We propose to use an implicit nodes' blocking approach by piggybacking additional information in the route request messages. The sink node is the one responsible of blocking the nodes using the piggybacked data when it receives route request messages for other paths and tries to find paths with minimum inter-path interference. We also propose to reduce intra-path interferences by using the RSSI (Received Signal Strength Indicator) metric as a route selection metric.

Our protocol is source-based and consists of one phase of route request and route reply cycle. Several transmission strategies using the built paths with different degree of interference are evaluated through simulation. The impact of interference on video data quality is then considered for these different strategies. Our simulation results show that using less-interfering paths can provide better received video quality. Transmission using less-interfering paths permits to support real-time bandwidth requirements in WMSNs when small frame rates are considered even if the shortest path is not used. We also propose a multiqueue multipriority scheme to improve the performance of the network when congestion occurs in the presence of high data rates.

The rest of the chapter is organized as follows. An introduction to the interference problem in the context of multipath routing, its modeling and a brief taxonomy of the proposed solutions are given in Section 5.2. Afterwards, our interference-aware multipath routing protocol is presented in Section 5.3. Section 5.4 is dedicated to simulation results where the performances of our protocol are assessed and compared to another multipath routing protocol with interference awareness. Section 5.5 presents the multiqueue multipriority scheme and the related simulation results and section 5.6 concludes the chapter.

5.2 Interferences and Multipath Routing

To improve the performances of multipath routing protocols, much research proposed to build node or link-disjoint paths that promise more benefits over the single path strategy [68], [58] [80]. In fact, disjointness between paths provides more resiliency as the failure of a node (or a link) affects only the path to which it belongs. In principle, disjointness also allows for more aggregate resources and more balanced traffic because neither links nor nodes are shared between the paths [86], [90], [113].

However, simultaneous transmition of data over the built paths to increase performances may not be as straightforward as in wired networks even if paths have no common links or nodes. If paths are physically close, transmissions from a node along one path may interfere with transmissions from a node along another path. Consequently, the overall achieved performances in terms of throughout, for example, is far from being the summation of the bandwidth offered independently by the different paths. This is known as the *route coupling* problem and was first introduced in [89]. In this work, the authors state that using multipath routing in a single-channel network results in negligible benefits due to severe route coupling.

Interferences can be classified into two categories : (i) Intra-path interference that may occur within a single path between different wireless links, where transmission cannot take place on a link due to the interference from its up and downstream link and (ii) Inter-path interference that can be experienced by different wireless links belonging to different paths. In multi-session applications, inter-path interferences may occur between wireless links that are transmitting completely independent flows belonging to different sessions (for example: in case of multiple sources) [76].

Moreover, based on experimental results obtained from the MICA2 motes, the authors in

[122], demonstrate that a node may interfere beyond its communication range. In this case, simply determining the connectivity between two nodes is not sufficient to determine if they interfere with each other during concurrent transmissions. This fact further complicates the elimination of interferences in the network.

5.2.1 Interference Modeling

Interferences in a single-channel wireless network can be modeled using either the *physical* or the *protocol* model of interference [44]. The *physical model* states that in order to a transmission between two nodes to be successful, a minimum signal-to-interference ratio (SIR) has to be achieved. In this SIR, noise and the ongoing transmissions in the vicinity are considered. In the *protocol model*, a transmission between two nodes is successful if there is no node simultaneously transmitting that is far from the receiver node by a distance lower than the interference range I. This model is considered to be more simple to implement compared to the physical one [109].

Consider a wireless sensor network with N nodes, which can be modeled using a connectivity graph $G(E, V)$ where V is the set of N nodes and E is the set of links connecting the nodes in V. Let $n_i \in V$ $(1 \leq i \leq N)$ denote a node in the network and $l_{i,j} \in E$ represent a directed link from node n_i to node n_j. Let $d_{i,j}$ denote the distance between nodes n_i and n_j. I_i and R_i represent respectively the interference and the communication ranges of node n_i. In the protocol model, a transmission is successful from the node n_i to the node n_j if $d_{i,j} \leq R_i$ and any node n_k, such that $d_{k,j} \leq I_i$ is not transmitting.

Based on the protocol model, a conflict graph $H = (E, C)$ is proposed in [56] to model interference in a single-channel network. This model incorporates the added constraint that interference range can be twice the communication range ($I \geq R$). The vertices of the graph C correspond to the set of directed links E in the connectivity graph G of the network. There is an an edge between vertices $l_{i,j}$ and $l_{p,q}$ in H if $l_{i,j}$ and $l_{p,q}$ may not be active concurrently (i.e., mutually interfering links). The edges in C represent all the possible interferences between the links in E. Based on the protocol model of interference, an edge is drawn from vertex $l_{i,j}$ to $l_{p,q}$ in H if $d_{i,q} \leq I_i$, and from vertex $l_{p,q}$ to $l_{i,j}$ in H if $d_{p,j} \leq I_p$. This encompasses the case where a conflict arises because links $l_{i,j}$ and $l_{p,q}$ that have a node in common.

To measure the degree of inter-path interferences between two paths, a correlation factor is defined in [112] as the number of the common links between these two paths. This definition is limited by the constraint that the interference range may be twice the communication range. In [109], a new correlation metric is defined to evaluate the quality of a path set taking this constraint into account. This metric is based on the conflict graph model.

5.2.2 Taxonomy of Multipath interference-aware Routing in WSNs

Constructing an interference-free routing topology in a wireless network is not a trivial task. There have been several propositions dealing with the interference problem in the context of routing protocols in wireless networks (wireless ad hoc and sensor networks). However, to the best of our knowledge, no comprehensive survey has been published in this area. Different approaches have been proposed to minimize or eliminate the effect of interference at the routing layer. We present in this section the most important ones:

Geographic Routing

An obvious solution to reduce interferences between multiple paths is to construct them to be physically separated by making use of the location information of nodes [73]. When this latter is available it becomes easy to construct paths with a desired interference range (once or twice the communication range). In [73], the route request message will have information regarding the locations of the first hop and the last hop intermediate nodes on the path. The destination measures the distance between the first hops of the path and the already selected paths and also the distance between the last hops of the path traversed and that of the already selected paths. If both distances are greater than twice the transmission range of the nodes, the path is selected. In WMSNs, DGR [27] (see 3.3.2) is a geographical interference-aware routing protocol which constructs two non-interfering paths based on the angle deviation method. Despite the efficiency of these solutions to construct non-interfering paths, they still require special hardware support to be used.

Nodes Blocking

Another approach to build physically separated paths is to build a path and then prevent the nodes that may interfere with the nodes of this path from belonging to another routing path. The I2MR protocol proposed in [109], discovers maximally-disjoint shortest paths between a source and a set of sinks using minimal location information. The protocols begins by discovering the shortest primary path between the source and the primary sink. Then secondary and backup paths are discovered from the same source to two other sinks. After the primary path is built, a zone marking step is run to mark the interference zone of the primary path so that nodes marked as within the interference zone of the primary path do not participate in the path discovery for both secondary and backup paths. The protocol MR2 presented in [76] deals with inter-path interference in the context of WMSNs (see section 3.3.1). It proposes an incremental approach where for a given session only one path is built. The neighbors of the nodes belonging to each built path are set to passive state in order to not participate in the path discovery process. In [111], two non-interfering routing paths are discovered without the use of location information. Two rounds of route request and route reply cycles are required in this protocol. This latter proposes to block the nodes of the shortest path along with their neighbors to take the condition ($R < I \leq 2R$) into account. This approach may be efficient in reducing the interferences in the network, however, the explicit nodes blocking generates extra overhead which is expensive in terms of energy.

Link quality-based Routing

One approach to reduce interferences is the design of routing protocols with new metrics that integrate interferences in their paths cost. This approach is generally used to assess the link quality between the nodes of a network in order to reduce intra-path interferences. Some of these metrics are ETX (the expected transmission count metric) [32] and ETT (the expected transmission time metric) [36]. The ETX metric [32] is calculated using the forward and the reverse delivery ratios of the link. Measurements on a wireless test-bed show that ETX penalizes routes with more hops which have lower throughput due to interferences between different hops of the same path. The ETT [36] metric is proposed for multi-ratio multi-hop networks (Mesh networks). It is a function of the loss rate and the bandwidth of the link that explicitly accounts for possible interference among links that use the same channel. The authors in [66] present an improved method for computing aggregate ETX for a path that increases end-to-end throughput and minimize delay. They propose EDGE - a greedy algorithm based on directed diffusion that reinforces routes with high link quality using this metric. DCHT [67] is a multipath version of EDGE with application to video transport (presented in chapter 3). However, the protocols of this approach do not take into account inter-path interferences.

Throughput as an Optimization problem

In this approach, the capacity (throughput) of the network under the interference constraints is formulated and solved as an optimization problem using a formal method. In [56], the network is modeled as a multi-commodity flow problem following a graph-theory model. The proposed model is extended by interference-related constraints in order to find lower and upper bounds for the capacity. These additional constraints follow by regarding cliques and independent sets in the conflict graph of the network. A more distributed solution is proposed in [45]. In this work, the authors develop a low-complexity algorithm to find approximate cliques in order to calculate lower and upper bounds for the capacity through an analytical model. The work in [47] studies optimization of network performance while explicitly considering the interference between paths. More specifically, the trade-off between the bandwidth gain using multiple paths on the one hand and the loss of bandwidth due to the additional interference involved when using those paths on the other hand is investigated. The authors show that the optimal network capacity could be obtained by solving an exponential number of linear programming problems. The drawback of this approach is that extensive computations are required, even for small networks. In some works [56], a central scheduling entity is assumed which is impractical in WSNs.

Multichannel Multipath Routing

Using a multichannel approach can be an efficient solution to eliminate interferences between the nodes of the network. In multiple channel networks, route coupling only occurs when paths share common intermediate nodes. Therefore, a multichannel node-disjoint multipath routing approach represents a good solution to the route coupling problem. The authors of [89] propose APR (Alternate path routing), a multipath routing protocol, and show the benefit of the multichannel approach by comparing the performances of the same protocol using a multi and a single channel approach. In WSNs, the authors in [69] propose to make use of the multi-frequency characteristic of CC2420 radio and propose IEMM-FA to minimize interferences and energy consumption of multiple paths. Nevertheless, this approach is not suitable for WSNs as it requires a channel scheduling strategy which consumes energy especially in dense networks.

Routing with Directional Antenna

In this approach, the route coupling problem is minimized by choosing route in a manner that interferences are minimal between the nodes of different paths. This is possible by setting the transmission beam of a node in a particular direction. In [99], a zone-disjoint shortest multipath routing algorithm is proposed. Directional antennas are used by the nodes to select maximally disjoint paths between a source destination pair. A comparison between omni-directional and directional antennas shows the effectiveness of these latter in reducing interferences in the network. However, this approach also requires special hardware support, making it challenging in WSNs.

5.3 Multipath Routing with Interference Awareness

5.3.1 Preliminaries and Assumptions

We consider a wireless sensor network with one data source node, one sink and a set of static sensor nodes distributed randomly but uniformly in a field. Compared to other nodes, the sink is assumed to be less energy-constrained. Additionally, the wireless network links are assumed to be bidirectional and that only a single channel is available. Each node knows its one hop neighbors (called $Neighbors$). This can be done at the network deployment phase through the use of Hello packets. We define the Neighbors list of a path as the union of the sets of the Neighbors of each node belonging to this path except the source and the sink nodes. In fact, these nodes should not be blocked to permit the construction of other paths.

We employ a simple interference model, as the one proposed in [111], where interferences occur between two edges when either the endpoint node of one edge is within the interference range of an endpoint node of the other edge. Therefore, for a given pair of edges (i, j) and (k, l) if $max\{dist(i, k), dist(i, l), dist(j, k), dist(j, l)\} \leq I$ then the two edges are interfering with each other, where $dist(x, y)$ returns the distance between nodes x and y and I is the interference range that is assumed to be at most twice the communication range R (i.e., $I \leq 2R$). An ideal scheme would be for the two endpoints of an edge to be far away from the two endpoints of the other edge by a distance greater or equal to twice the communication range ($2R$) [122]. If $dist(x, y) \leq R$ then the two endpoints are one hop neighbors.

5.3.2 Protocol Overview

The multipath routing protocol we propose makes use of nodes blocking in order to be interference-aware. It is an attempt to provide a simple implementation while minimizing the overhead used to block the nodes in the network. Mainly, it tries to limit inter-path interferences through an implicit nodes blocking by the sink when this latter makes selection of paths to be used by a given source to transmit its data. The discovery process is initiated by the source and paths selection by the sink is performed in one round of route request and route reply cycle. The sink ignores neighboring nodes of already considered paths when selecting subsequent ones. In order to do so, the $Neighbor$ list of an *under discovery* path is piggybacked in the route request messages. If the number of selected paths is insufficient, the sink may consider paths with minimum number of common neighbors. We note that to measure interferences between two disjoint paths we simply use the number of common (one-hop) neighbors between them instead of using the number of links connecting them.

In our multipath protocol, the case where the two paths are adjacent (the nodes of one path are neighbors of the nodes of the other one) is eliminated. When two given paths have larger number of neighbors they are likely to be more physically close to each other, thereby more interfering. We use the intersection between the set of neighbors of the paths to assess their degree of interference. The built paths may still be interfering (when $I \geq R$) but we propose to choose the most physically separated paths when they are available.

The main difference between our proposed protocol and MR2 protocol (see Section 3.3.1) is that instead of blocking the neighboring nodes using explicit messages, we propose to implicitly block these neighbors (ignoring the route request messages) by piggybacking the neighboring information. The set of blocked nodes of the two protocols are slightly different as MR2 proposes to block direct neighbors of the constructed paths whereas we propose to use the intersection between the common neighbors. In this way, our protocol may construct paths which are more physically separated. We propose to modify the MR2 routing protocol and compare it with our protocol.

5.3.3 Paths Discovery Phase

The source node initiates the path construction by flooding the network with an *Explore Message* until the sink node is reached. An *Explore Message* contains the request sequence number, the path ID, the list of crossed nodes, the number of hops, a Metric field , the list of one-hop neighbors of the crossed nodes and the list of the neighbors of the source node. The path ID is the ID of the first node on the path that receives the *Explore Message* from the source. Upon the reception of an *Explore Message*, an intermediate node checks if it has not already processed an *Explore Message* for the same pathId. In this case, the intermediate node increases the number of hops, adds its ID and its Neighbors list and forward the *Explore Message* to its neighbors. In case the hop count is greater or equal for the same path ID the *Explore Message* is ignored. The Neighbors list should not contain redundant nodes' IDs. Therefore, each intermediate node deletes the redundant neighbors IDs in the piggybacked list of Neighbors. When the first *Explore Messages* are received by the sink, it selects the shortest path (in terms of number of hops and delay) and creates a routing entry for this path. The sink node unicasts then a *Build Message* on the selected path. Every intermediate node unicasts the *Build Message* towards the source. The Neighbors list piggybacked in the *Explore Message* is saved by the sink node to select the future path while continuing to receive the *Explore Messages* for other paths for a certain period of time defined by the user.

After the shortest path is selected, the set of its one hop neighboring nodes is blocked, i.e, any received *Explore Message* for a path which contains one of its neighbors is ignored. This is done to eliminate paths which are adjacent to the shortest one. In this way, every node in the future path will be out of the communication range of the nodes of the shortest path.

When the sink node receives another *Explore Message* for a path which does not contain any of the neighboring nodes of the shortest path, it begins by calculating the intersection between the Neighbors list of this path and the shortest one. The selected path is the one with minimum number of common nodes. If two paths present the same number of common nodes, the shortest one is selected. The sink node may use the *Explore Messages* already received (if any) to perform this comparison. In general, it continues to receive *Explore Messages* for a short period of time after the shortest path is selected. This is mainly done to avoid choosing very long paths. This is an important metric as we are dealing with multimedia data transport.

To discover more paths and based on the network connectivity, the sink node may apply the same principle when selecting other paths (if possible). That is, when another path is selected with the first one, the nodes of its Neighbors list are blocked and the intersection is calculated between the path to be selected and the two paths already selected (including the shortest one). This route discovery phase permits to construct non-interfering paths where $I \leq R$. To select paths when $R < I \leq 2R$ and since we are concerned with a few number of paths, we propose to block the shortest path nodes and its neighbors. Two paths can be elected using the same rule (comparing the neighbors list between each path and the shortest path and between each other). These two paths are likely to be the ones above and below the shortest one without location information if selected paths are those that present the minimum hop count.

5.3.4 Intra-path Interferences

When an intermediate node receives the *Explore Message* it processes it if the signal strength of the sending node is acceptable (we set the threshold to be $RSSI \geq -100dB$ based on simulation experiments). This is mainly done to (i) minimize the intra-path interference between the nodes of the same path; and (ii) avoid blind areas in the network. In fact, in Figure 5.1, the area CDE is a blind area. A node located in this area is not belonging to the list of neighbors of the nodes A and B. When another path is selected using the intersection of the neighbors of two paths, such a node may still be exiting between the two paths. This situation may biases the route selection rule. However, a good signal strength between the

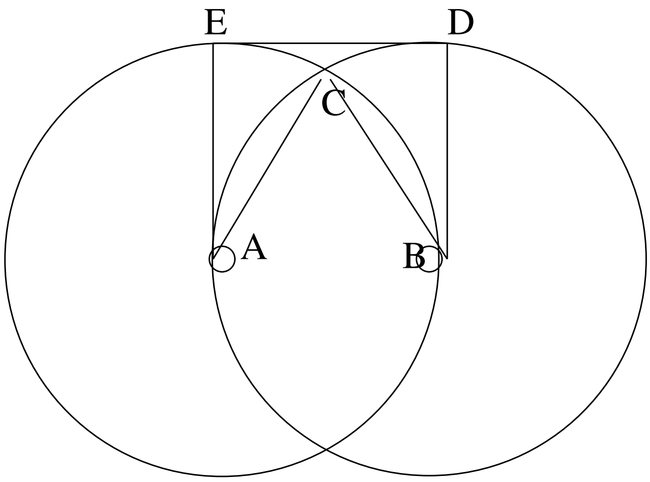


Figure 5.1: Two neighbors A and B forming a blind area

nodes permits to mitigate this situation by reducing the blind areas between the nodes and by that the number of the nodes belonging to these areas.

In this figure, the two nodes A and B are in the edge of the communication range of each other $R = dist(A, B)$. Let us consider this case and calculate the ratio of the size of the blind area to the size of the intersection area. The surface of half the intersection area between A and B is :

$$\|Inter\| = 2R^2 \cos^{-1}(d/2R) - 1/2d\sqrt{4R^2 - d^2} \tag{5.1}$$

Where $d = dist(A, B) = R$, we have :

$$\|Inter\| = (\pi/3 - \sqrt{3}/4)R^2 \tag{5.2}$$

The surface of the blind area is given by :

$$\|CDE\| = (1 - \pi/6 - \sqrt{3}/4)R^2 \tag{5.3}$$

The ratio is then :

$$\frac{\|CDE\|}{\|Inter\|} = 6.98\% \tag{5.4}$$

In general the blind area does not constitute a big area compared to the intersection area when the two nodes are close to each other. Therefore, the number of nodes that *may* be located in this area is small compared to the one located in the intersection area between nodes. In this case the two nodes A and B are located in the edge of the communication range of each other. If the two nodes are closer, this area may be even smaller.

5.3.5 Data Transmission Phase

When two or more paths are built, the source node can use different transmission strategies to send data. Data can be sent alternatively on the constructed paths. Also, important data may be sent many times to ensure its reliable transmission. Another scheme would be to

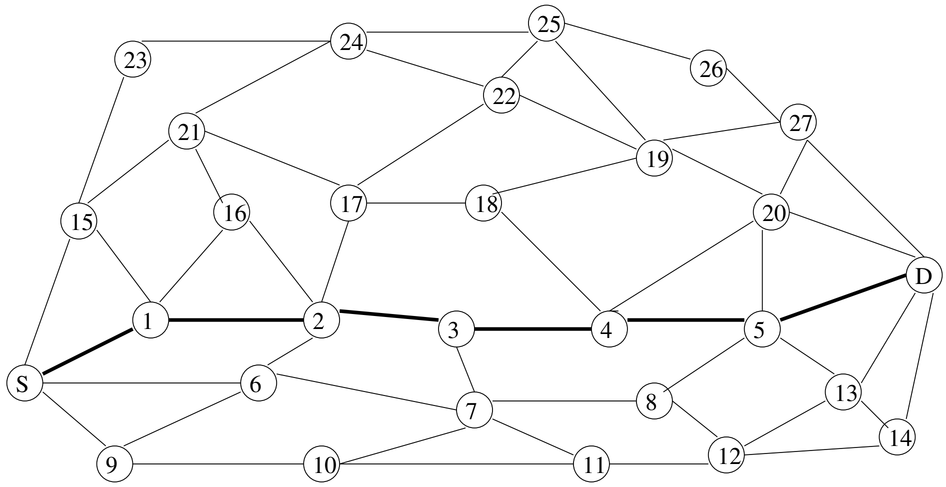


Figure 5.2: Network topology of 29 nodes

send time-constrained data on the shortest path as it should offer the best performance in terms of delay. To study the effect of interferences on the video quality, we use different transmission strategies using two and three built paths. These latter represent different interference degrees between each other.

5.3.6 Illustrative Example

We present an example of execution of our protocol on the network topology depicted in Figure 5.2. First, the Hello step is executed by every node in the network. Therefore, after this step the Neighbors lists of some nodes are : Neighbors(1)= {2, 15, 16},

Neighbors(2)= {1, 3, 16, 6, 17},

Neighbors1(3)= {2, 4, 7},

The source node S starts the discovery process by broadcasting *Explore Messages* containing the list of its neighbors {1, 6, 9, 15} to these latter. When an intermediate node receives it, say node (3), it checks its signal strength according to the Metric field. If the *Explore Message* is to be processed, it piggybacks its Neighbors list, and forward the *Explore Messages* towards the sink. When the first *Explore Messages* reaches the sink, it creates a routing entry for the selected path nodes {S, 1, 2, 3, 4, 5, D}, and unicasts a *Build Message* towards the source. It also extracts and saves the list of the nodes belonging to the shortest path and the Neighbors list of these nodes. Therefore it saves the list of nodes {6, 7, 8, 13, 15, 16, 17, 18, 20}. We can see in this example that there are a lot of redundancies in the neighbors lists which should be removed by intermediate nodes. The nodes belonging to the Neighbors list of the shortest path are blocked and these nodes are prevented from belonging to the next path. The sink continues to receive other *Explore Messages* for other paths and selects the ones with no or minimal number of common neighbors between them and the shortest path selected.

In 5.2, the sink does not accept a path containing one or more nodes from {6, 7, 8, 13, 15, 16, 17, 20}. Therefore, paths $S-15-21-17-18-19-20-D$ or $6-7-8-12-13-D$ are not accepted. If many paths exist in the network, the sink chooses a path which has the minimum number of common neighbors with the shortest one (using the Neighbors list). If the sink receives requests for the three paths $S-9-10-11-12-14-D$, $S-15-23-24-25-26-27-D$ and $S-15-21-24-22-19-27-D$. The path $S-15-23-24-25-26-27-D$ is chosen over the two others as the number of common neighbors between it and the shortest path is the smallest.

5.4 Evaluation and Simulation Results

We implemented our multipath routing protocol with different variants in addition to MR2 [76] using Castalia [1], an Omnet++ based simulator for wireless sensor networks. In our simulations, N static nodes are placed randomly but uniformly in a grid area of $400m \times 400m$ size. The communication range R of a node is varied using the following formula :

$$R = \frac{\alpha \times Dim}{\sqrt{N}} \tag{5.5}$$

Where N is the number of nodes, α is a parameter that allows the control of the nodes mean degree and $Dim = 400$ is the length of the network area. The source and the sink are respectively located at the left and the right side of the simulation area. The CC2420 radio model provided by Castalia is used for all simulations with a data rate of 250 kbps. We also used the Additive Interference model to simulate the interference effects in the network. We used the Tunable MAC layer provided by Castalia which is a contention based MAC that employs a CSMA mechanism for transmissions. Each scenario is simulated 10 times using different simulation seeds.

5.4.1 Preliminary Simulation Results

In a first variant of our protocol, we select as much as paths with minimum common neighboring nodes. If another path is selected along with the shortest one, the sink chooses the next path using the same rules as when selecting the second path and so on. We fixed the timer for path discovery (reception of *Explore Messages*) to a maximum of 40 seconds.

Figure 5.3 compares the number of built paths versus the number of nodes for different communication range values. We can see in this figure that the bigger the communication range, the smaller the number of built paths. This is mainly due to interferences between nodes when larger communication ranges are used. However, the number of built paths is still small even for large number of nodes. For example, when 450 nodes are deployed, only 4 paths are built using our protocol.

Figure 5.4 shows the total consumed energy in Joule of the two protocols to build two paths. We changed MR2 to construct paths consecutively without starting the data transmission phase. In our protocol, the shortest path along with another path are selected. Our protocol gives the best performances in terms of consumed energy when the smallest communication range is considered (that corresponds to a node degree equal to 5). In this case,

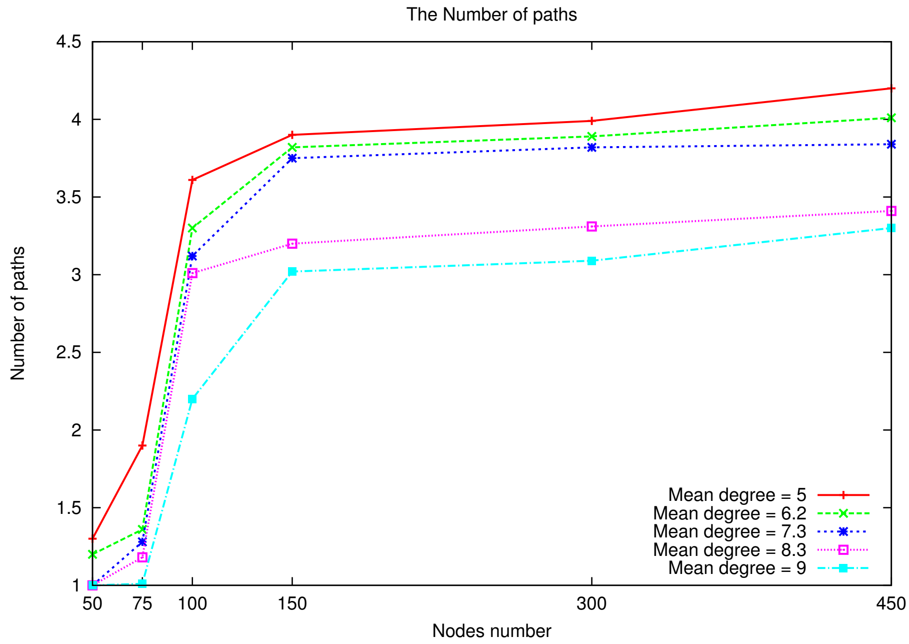


Figure 5.3: The number of built paths

it outperforms MR2 because this latter uses control messages to block the neighbor nodes of the built path and two flooding phases to construct the two paths. We can see in the figure that when the communication range is large (the degree of a node is large) the energy consumption is more important. This is due to the fact that when a node has more neighbors the piggybacked information (in the *Explore Message*) is larger which consumes more energy.

The mean paths length built by the two protocols is compared in Figure 5.5. In this experiment, we fixed the communication range so that the mean degree of nodes is at least equal to 5. We used two versions of our protocol. The first one refers to the case where paths are built with the assumption that ($I \leq R$) whereas in the second version, the shortest path nodes along with their one hop neighbors are blocked (which corresponds to the case $R < I \leq 2R$). This latter version produces paths with larger number of hops. We can see in the Figure 5.5 that MR2 permits to build paths with lengths close to the single path length when the number of nodes increase. The first version of our protocol permits to construct paths that are longer than those of MR2 because it tries to construct path which are more than one-hop away from the shortest path as the intersection between the common nodes is used.

5.4.2 Video Transport Evaluation

To evaluate the video quality when using our multipath routing protocol, we selected one of the standard video sequences used by a variety of video encoding and transmission studies called Hall Monitor. The video lasts 10 seconds and consists of 300 frames in QCIF resolution (128×128). Two types of gray-scale frames, M (Main) and D (Difference), are generated for this video using a modified version of MPEG [20]. Each frame is further encoded into

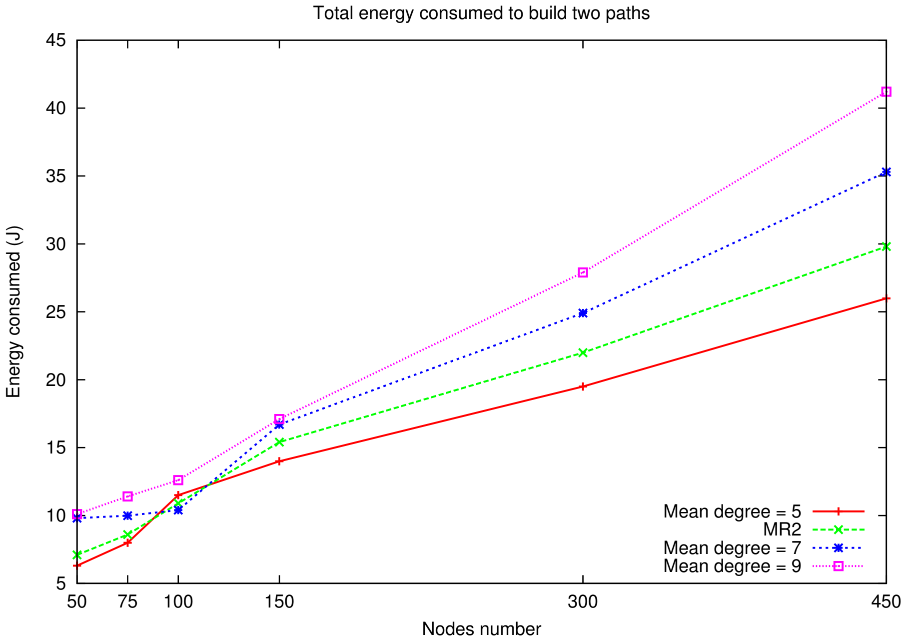


Figure 5.4: The total energy consumed to build two paths

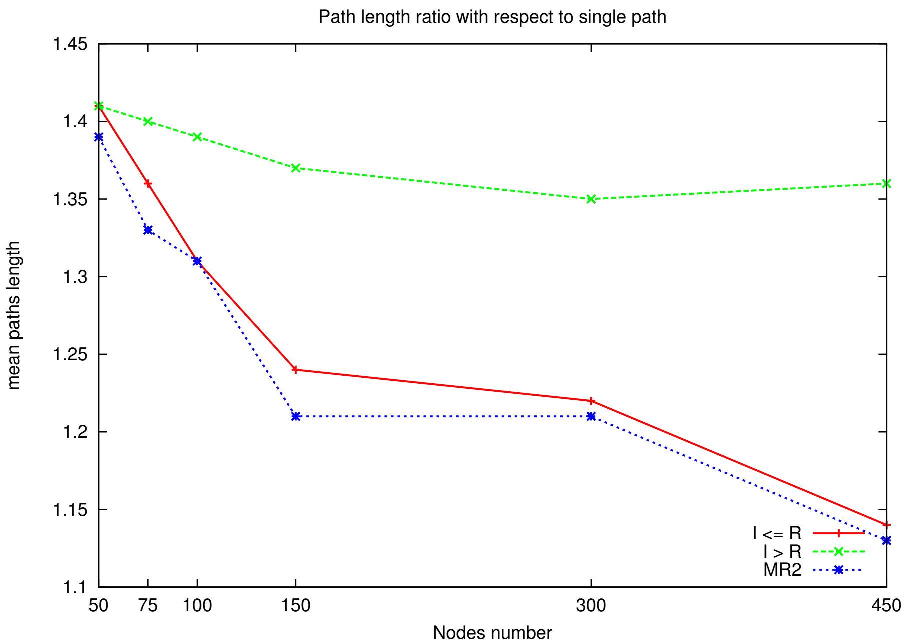


Figure 5.5: The mean paths length

Table 5.1: Video characteristics

Video sequence	Hall Monitor
Frame rate	6 FPS, 3 FPS, 2 FPS, 1 FPS
Threshold of similarity	0
Number of priority levels	13
Coefficient of Quality (%of M frames)	25% M 75% D
Packet size	256 byte

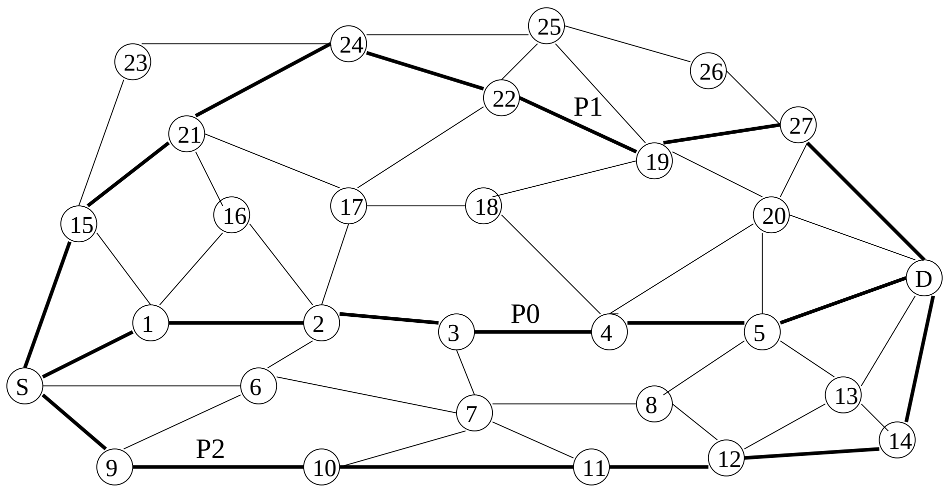


Figure 5.6: Example of built paths

n levels of priority. Therefore, packets of the video can have different levels of priority. In our simulation 13 priorities are used for the M and D frames. Table 5.1 summarizes the parameters of the video. We fixed the number of nodes in the network topology to 450 nodes and used a communication range so that the mean degree of each node is 5. One video source is assumed to capture, encode and send video sequences to a single sink node. We consider small values for frame rates as high frame rates are not achievable because of the severe bandwidth limitations in WMSNs [13]. We varied the frame rate from 1 fps to 6 fps and assess the video quality for different transmission strategies.

It has been shown that at most three paths are able to improve transmission performances [76] and since paths discovery process is a time and resource demanding task, we limit the number of built paths to three. We define the following transmission strategies :

- Strategy 0 : Transmission using the shortest path P0
- Strategy 1 : Transmission using the two more interfering paths P0 and P1
- Strategy 2 : Transmission using the two less interfering paths P1 and P2
- Strategy 3 : Transmission using the three paths P0, P1 and P2

Figure 5.6 illustrates these strategies on the network topology of Figure 5.2.

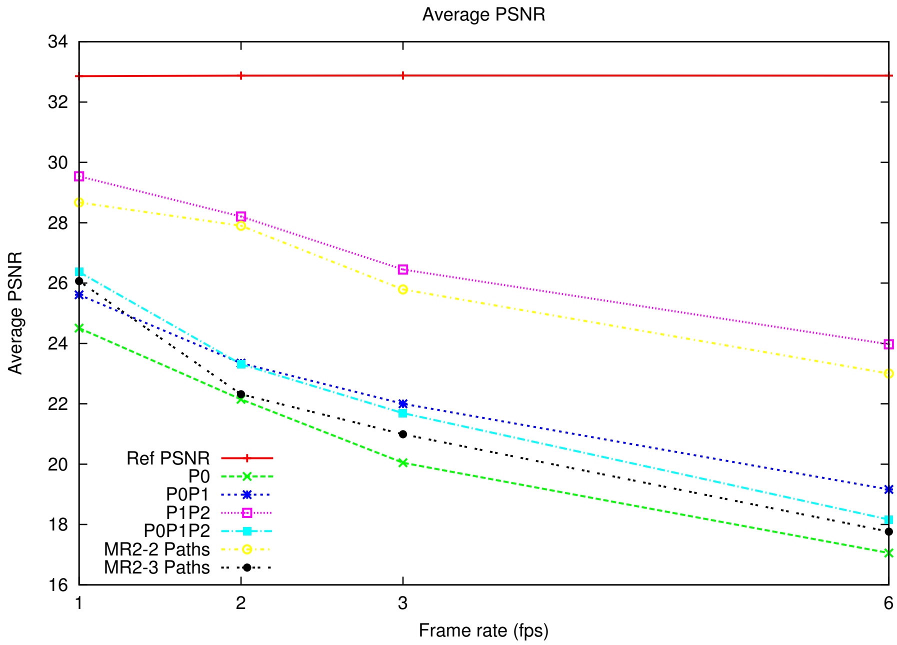


Figure 5.7: Average PSNR for different frame rates

Figure 5.7 compares the average PSNR versus the frame rate for the different transmission strategies. We can see that using less interfering paths (Strategy 2, P1P2) permits to achieve maximum average PSNR over the other strategies. Thus, better video quality is to be expected. When the frame rate increases, the average PSNR of all the strategies decreases as more data losses are noticed in this case (depicted in Figure 5.8). We can see in this figure that using the less interfering (the most physically separated) paths in MR2 achieves the best performance for this protocol. However, using strategy 2 still outperforms MR2 performance because in MR2 only the one-hop neighbors are blocked which results in paths less separated compared to our protocol. In this latter, using the intersection between the neighbors of the paths results in more physically separated and less interfering paths. When only one path is used for transmission, losses are mainly caused by radio non-readiness (service time). Multipath routing is then used to load balance the traffic between the different paths. However, using interfering paths for data transmission does not permit to achieve good performances. The losses are mainly caused by mutual interference from the simultaneous transmissions over the adjacent paths. Thus, the receivers fail to receive data packets transmitted by the senders.

When we examine Figure 5.8, we can see that the graph depicted in it does not exactly match the graph of average PSNR. This is mainly due to the fact that data has different levels of priorities. Therefore, losing more important data affects the video quality even if the number of losses is lesser. For example, the average packet loss of the two strategies P0P1 and P0P1P2 for the case 6 FPS is respectively 50.39% and 50.32%. However, the average PSNR is respectively 19.16 and 18.16. This can be explained by examining the average packet loss of M frames which is of 51.876% and 53.634% respectively. The M packet loss for the four

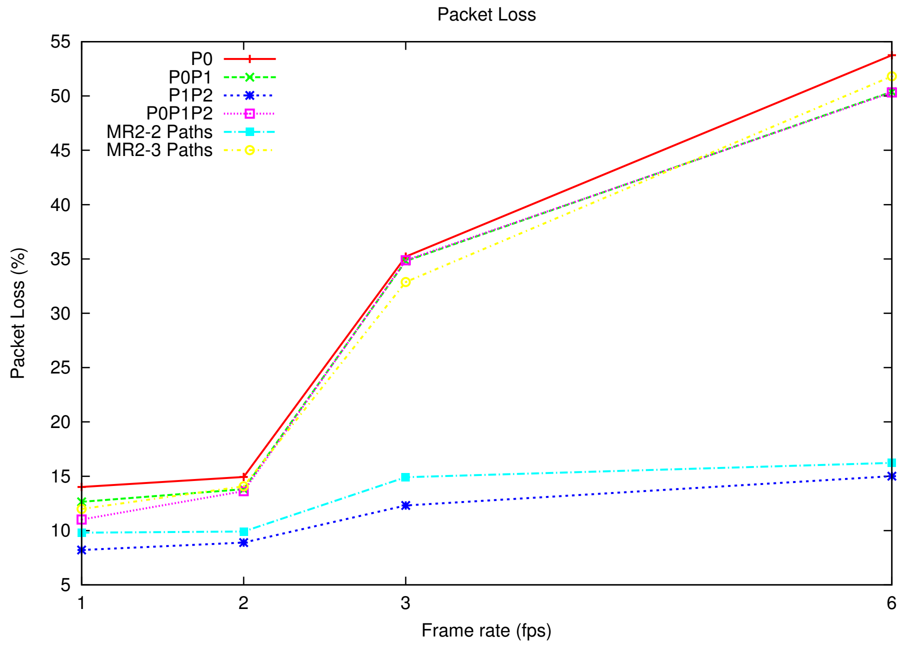


Figure 5.8: Packet Loss for different frame rates

strategies is depicted in figure 5.9 which corresponds more to the PSNR graph.

In Figure 5.10, we can see the average delay for the different strategies. The shortest path strategy clearly outperforms the others in terms of average delay by received packet. In fact, the received packets have minimum delay as they traverse the minimum number of hops. Larger delays are noticed when longer paths are used especially the non-interfering path strategy.

Figure 5.11 shows the mean throughput improvement for the different transmission strategies as function of time and confirms the previous observations (concerning PSNR and video quality). Mainly, we observe that the strategy 2 clearly shows better performances. The achieved throughput can be used to support real-time requirements for these frame rates. Also, this strategy allows for better energy consumption per received packet as depicted in figure 5.12.

Figure 5.13 shows a sample of images as received by the sink using the different strategies in addition to the coded image (Figure 5.13 (a)). We can notice the achieved video quality when the paths used for transmission are less interfering (strategy 2) in Figure 5.13 (e). For instance, the achieved quality when the shortest path is used and when two (more interfering) and three paths are used correspond respectively to the images in the right (b) and the two images (c) (d) for which, we can note the bad quality especially compared to the image (e).

5.5 Multiqueue Multipriority Scheme

In general, multipath routing constitutes a good solution for load balancing in WSNs. However, due to the high data rates used for video applications congestion still occur in the

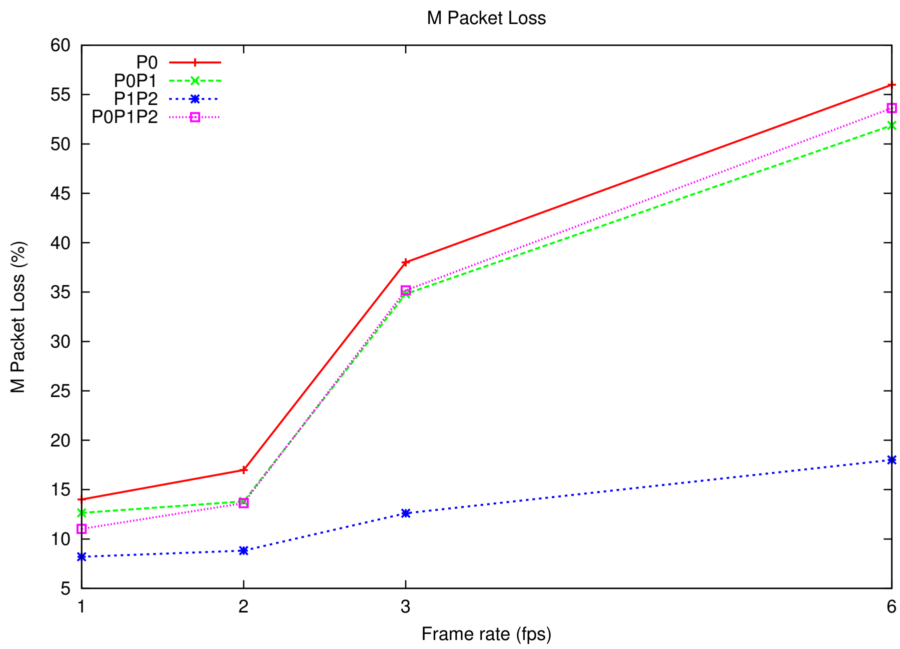


Figure 5.9: M Packet Loss for different frame rates

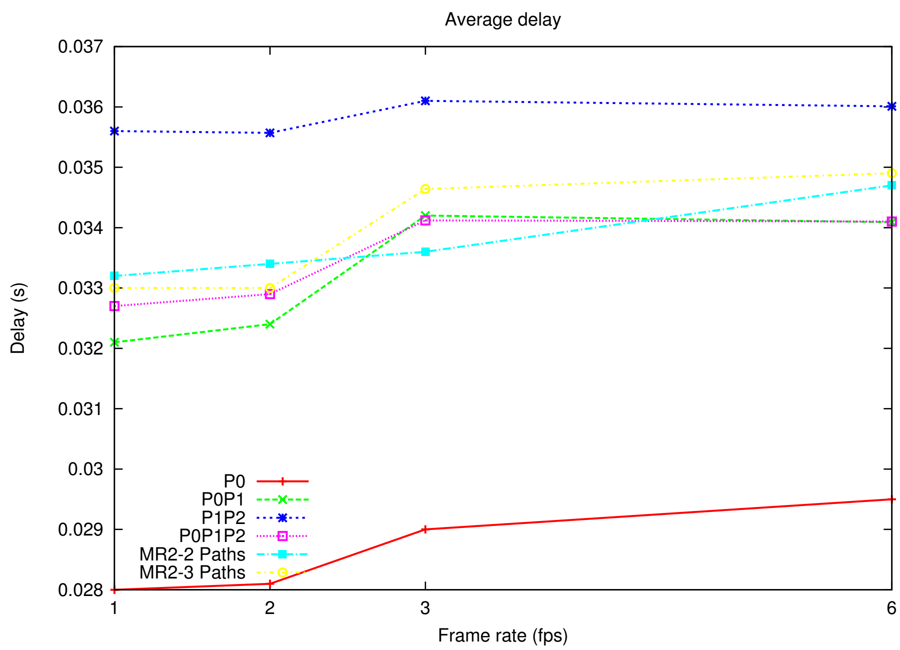


Figure 5.10: Average delay for different frame rates

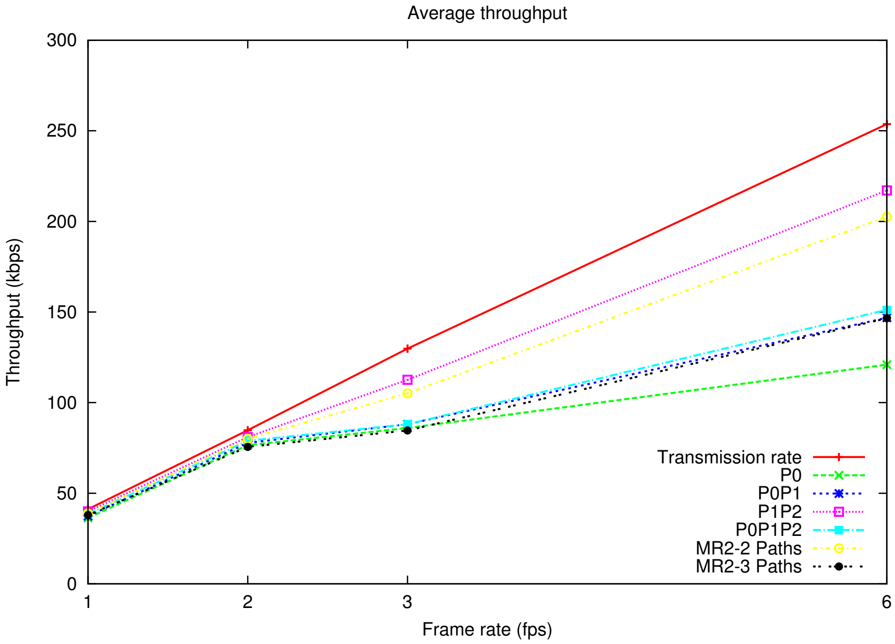


Figure 5.11: Throughput for different frame rates

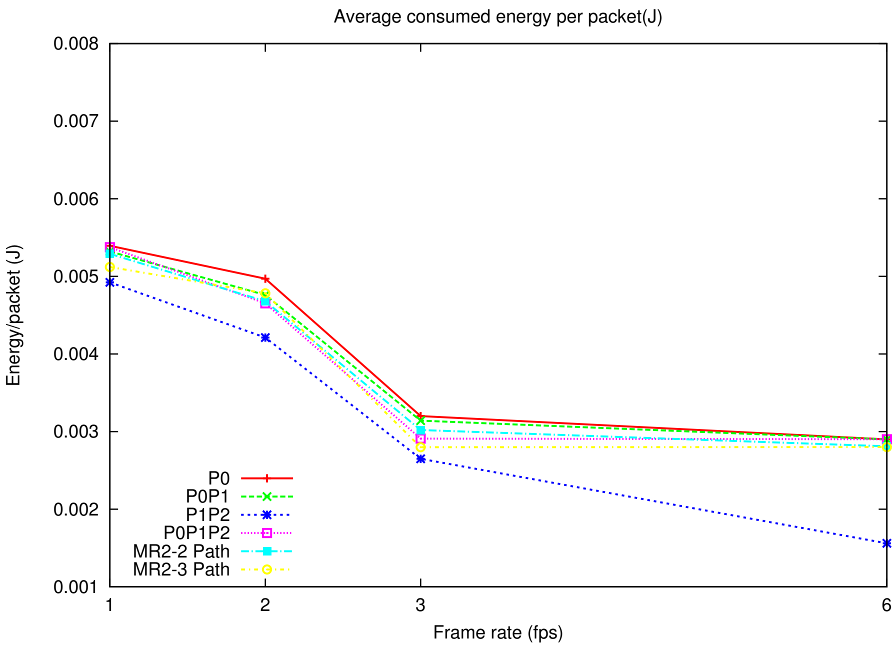
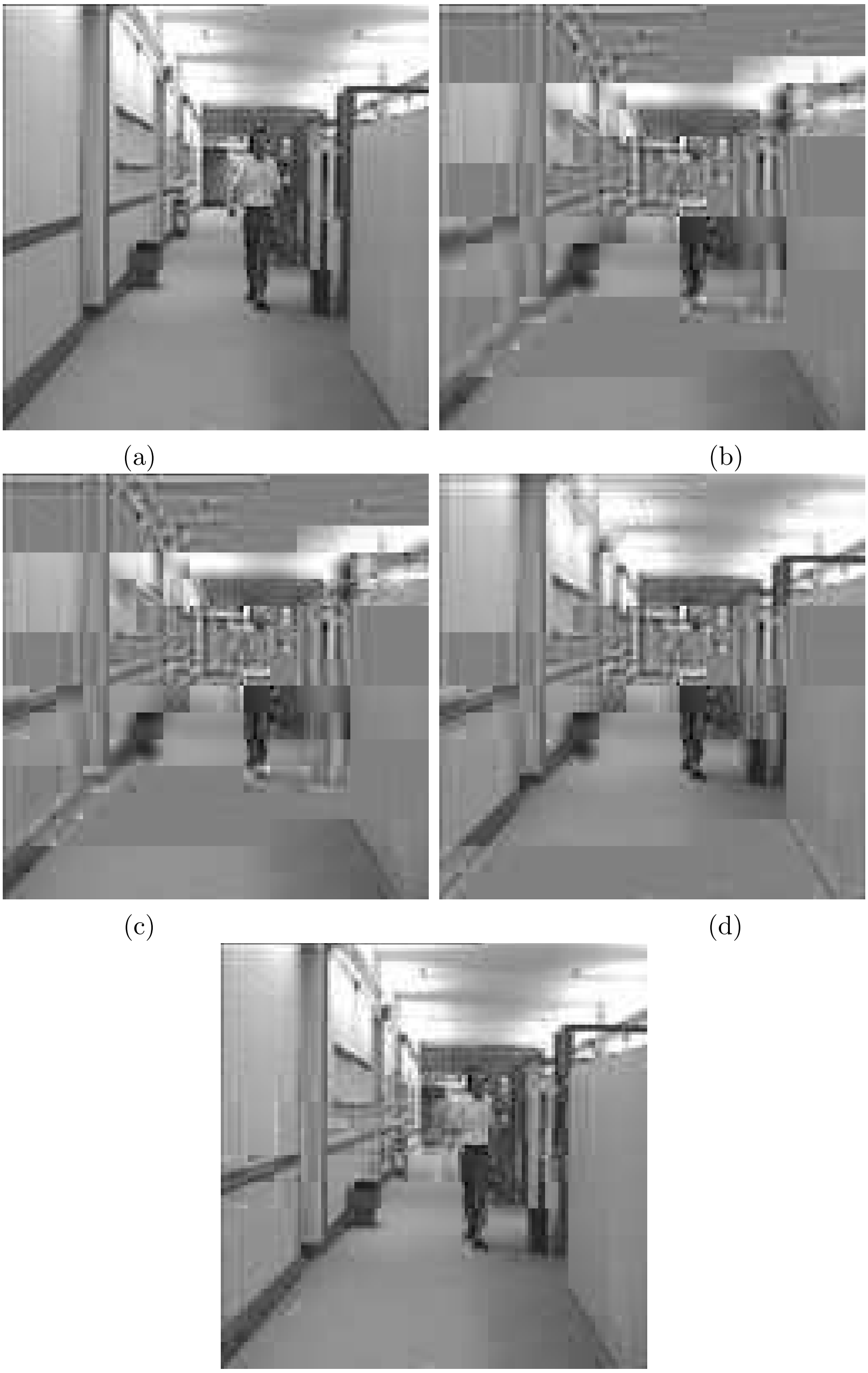


Figure 5.12: Average consumed energy per packet for different frame rates



(a) (b) (c) (d) (e)

Figure 5.13: Received frame number (54) with (6 fps): (a) Reference frame, (b) P0, (c) P0P1 (d) P0P1P2, and (e) P1P2

network even if multiple paths are used to transport data. In fact, high volumes and high speed of video data may cause congestion in the sensor nodes if the available bandwidth resources can not support the video data rate.

Packet loss due to congestion can lead to impairments in the quality of service (QoS) of multimedia applications. In video sensor networks the impact is more important as data may have different levels of importance and random loss can affect more important data. Moreover, adjusting the data rate blindly without taking the importance of data into consideration, as proposed in [109] is not interesting in WVSNs. For example, the frames produced by the encoding system in [20] can be divided into two categories : M-frame, D-frame where M-frames are the key frames and D-frames are non-key frames. Therefore, for the receiver, an M-frame loss affects the video quality more than a D-frame loss. Also, packets that transport higher priority data of a frame are more important for the decoding process of this frame. This was confirmed in the previous section as we saw that M packet losses significantly affect the received video quality.

An ideal scheme would be to experience losses only for less important data by considering the priority of each packet depending on the data it contains when scheduling/dropping packets at intermediate nodes. This can be achieved through a *multiqueue multipriority scheduling scheme*. We propose to use three queues and send packets from the highest priority queue to the lowest one. The first and second highest priority queues are used for M frame packets. Whereas, the third queue is used for the D frame packets. Since the real sensor node only has a single queue, the multiple sub-queues are maintained logically. Thus the multipriority multiqueue scheme is easy to implement without extra hardware requirement.

We consider the evaluation, in terms of PSNR, to assess the video quality of our transmission scheme. We selected the same video sequence, (used in the previous section) Hall Monitor video encoded using M-MPEG [20] with 13 priorities for each M and D frame. We used the same simulation parameters as in our previous experiments. The selected video is transmitted using the strategy P1P2 (the best strategy in terms of throughput).

In the first experiment, we used a single queue at the sensor nodes whereas in the second, a multipriority multiqueue is employed. We used two queues for M packets, the first one contains M packets with priority 1 to 6 and the second one contains M packets of priority 7 to 13. The third queue is used for all D packets (all priorities). The length of the single queue is equal to the summation of the length of the three queues used in the second case. In case the multiqueue strategy is used, a sensor first transmits packets from the highest priority queue.

Figure 5.14 plots the packet loss ratio and M packet loss ratio with the P1P2 strategy with and without the multiqueue multipriority scheme when FPS is varied. As the frame rate increases, we can see in this figure that using the multiqueue multipriority scheme allows for better performances. This can be explained by the fact that in case multiqueue scheme is used, M packets are served first (higher priority queues are served first) which leads to drop packets in lower priority queues.

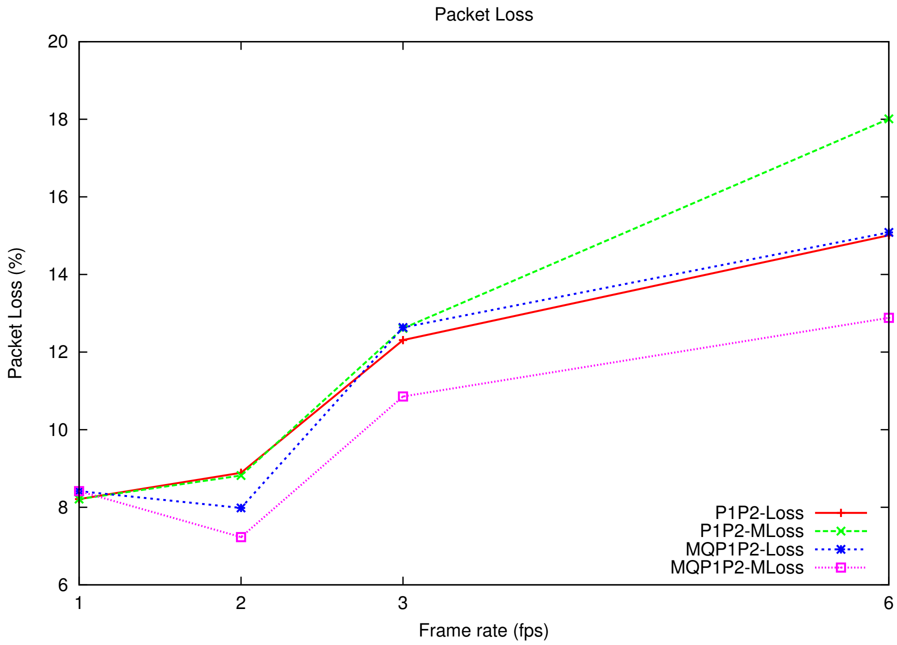


Figure 5.14: Packet and M packet loss ratio

These results are confirmed in Figure 5.15 which plots the PSNR values per frame for the two cases when 60 frames are sent by the video source (6 FPS). In fact, better PSNR values are noticed for the different frames as the packets of higher priority are well received. As a result, the average PSNR for the multiqueue scheme is better than when a single queue is used (Figure 5.16)

5.6 Conclusion

In this chapter, we presented a simple multipath routing protocol with interference awareness in WMSNs. Also, we investigated the use of multipath routing for video data transmission in WSNs when considering inter-path interferences. We study the effects of inter-path interference on received video quality. Our simulation results show that using less interfering paths permits to achieve better video quality in terms of PSNR. In fact, multipath routing allows for load balancing and supports real-time transmission if small frame rates are used. We also proposed a multiqueue multipriority scheme to prevent important packets from being dropped when congestion occurs in the network due to high data rates.

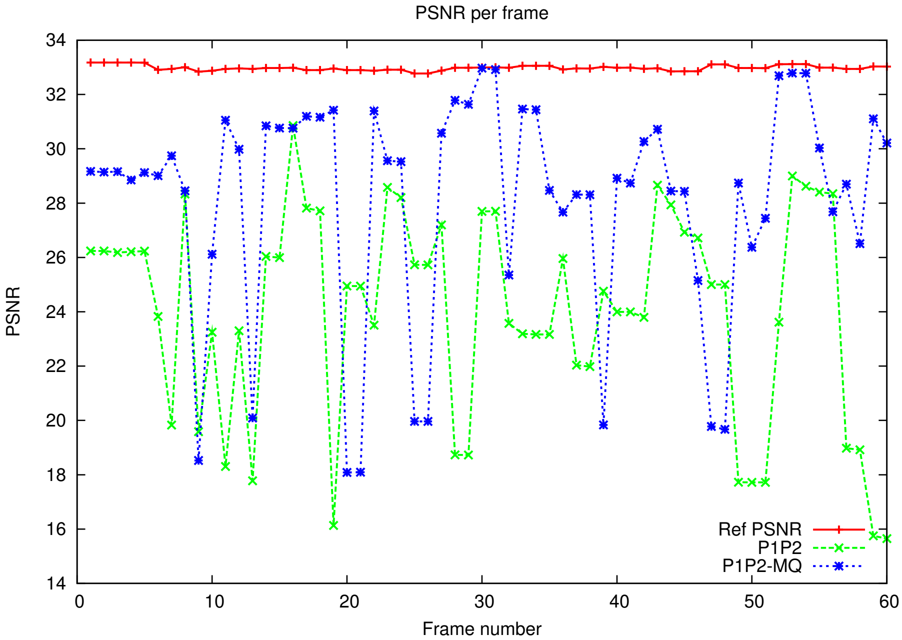


Figure 5.15: PSNR per frame

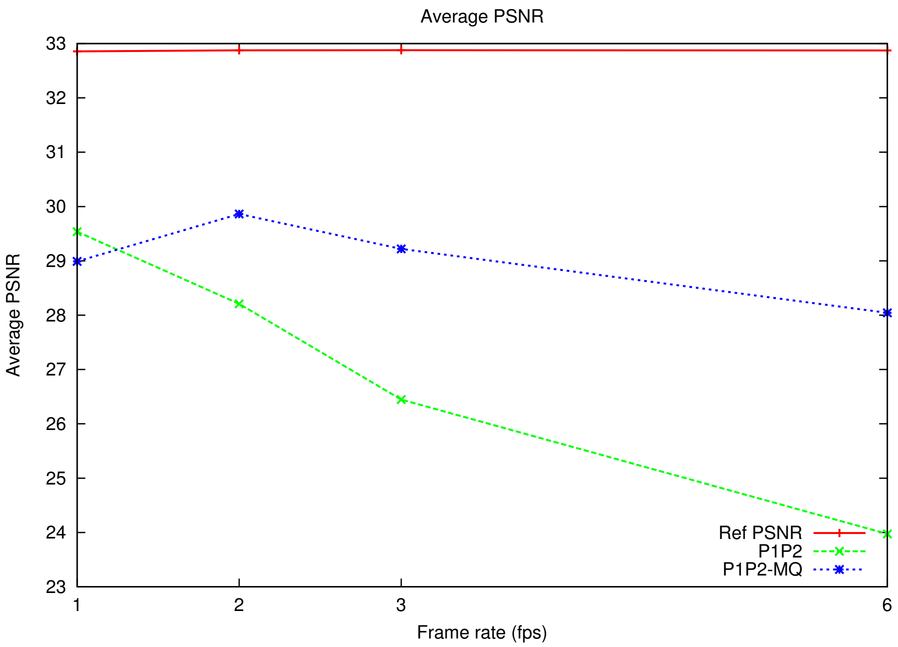


Figure 5.16: Average PSNR

Chapter 6

Conclusion

Wireless multimedia sensor networks (WMSNs) have a wide range of potential applications in a variety of domains. These applications require the design of efficient communication protocols providing a certain level of quality of service. This is not a trivial task considering the unique challenges and constraints imposed by WMSNs paradigm and multimedia communication requirements.

In this thesis, we discussed several communication problems in the domain of WMSNs with a focus on the routing problem. Routing techniques in WMSNs should support one or multiple QoS constraints imposed by WMSNs applications. In these networks, multipath routing appears to be a mandatory technique to support QoS constraints of multimedia data. Also, hierarchical solutions constitute good solutions to routing multimedia data over WSNs. This is due to the fact that sensor nodes in a WMSN have different characteristics and capabilities. For instance, low-power scalar sensors only take part in relaying in addition to sensing environmental data. Sensors with higher capabilities could do more and for instance, taking part in a distributed compression task in order to not overwhelm video sensors by all the tasks (capture, compression and transmission). They also could contribute in the energy-consuming tasks (flooding tasks) for the purpose of communicating multimedia data.

In this thesis, we proposed two routing solutions. First, we proposed Energy Level passive Clustering (ELPC) algorithm to enhance the lifetime of a sensor network. The proposed protocol permits load balancing among the nodes by alternating the role of flooding nodes among nodes depending on their energy level. We also proposed the combination of this algorithm with a flooding based data-centric routing solution in WSNs. This combination gives better performances in terms of network survivability and data delivery ratio when only small amounts of energy are available. We were mainly interested in evaluating video transport in a WVSNs using passive clustering. We conducted extensive simulations and showed that an approach like ELPC is very promising. ELPC allows longer network lifetime, lower loss rate and better video quality.

Our second contribution consists in a multipath routing protocol with interference awareness. We investigated the use of multipath routing for video data transmission in WSNs while considering inter-path interferences. We studied the effects of inter-path interference on received video quality. Our simulation results show that using less interfering paths permits better video quality. In fact, interference-aware multipath routing allows for load balancing and supports real-time transmission if small frame rates are used. We also proposed a multi-queue multipriority scheme in order to take into consideration the importance of data when an intermediate node has to drop a data packet due to congestion.

We plan to extend our work in several directions. First, we plan to evaluate the performances of our multipath routing algorithm considering random topologies. In fact, our simulation experiments were conducted on a uniform topology. Despite this fact, the route selection was a very difficult task. Second, we plan to exploit the unique characteristics of visual data (video and image) in the communication task. That is, to make use of the redundancy (spatial and temporal correlation) that exists between the captured data to achieve a trade-off between the energy consumption in the communication and the processing phases. This redundancy can also be exploited to alleviate the congestion problem in WMSNs. Moreover, we plan to achieve a node scheduling scheme to distribute the compression and the communication tasks across the network.

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