People's Democratic Republic of Algeria

Ministry of Higher Education and Scientific Research

Larbi Ben M'hidi University of Oum El Bouaghi

Faculty of Exact Sciences and Sciences of Nature and Life

Departement of Mathematics and Computer Science

Research Laboratory in Complex Science's Complex Systems ReLa(CS)^2

Doctorat Thesis

Submitted in partial fulfillment of the requirements

Doctorat's degree in Computer Science

Option: Networks and Distributed Systems

2021-2022

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Multipath Multichannel Routing for Wireless Multimedia Sensor Networks

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Acknowledgement

This thesis is the product of a lot of hard work and study, but it is also the result of guidance and support that I have kindly received from many people. I would like first to express my sincere appreciate to my Co-supervisor Dr. Maimour Moufida, who gave me the golden opportunity to do this wonderful dissertation, and which also helped me in doing a lot of research. Without his assistance and dedicated involvement in every step though the process, this project would have never been accomplish. Your insightful feedback pushed me to sharpen my thinking, thank you very much for your support and understanding over these past five yours. Secondly, I would like to thank my supervisor Prof. Derdouri Lakhdar for providing guidance and feedback throughout this dissertation.

In addition, I am so grateful to all my family members specially my beloved parents Kettouche Ramdane and Bentimama Fadila for their support and great love. You are always their for me. I can't possibly express my gratitude to my beloved husband Dr. Bousbia Badreddine. His care and love have always been the source of my ambitious aspirations.

Finally, my sincere appreciation goes to the Higher Education Ministry of Algeria and to University of Larbi Ben M'hidi for providing me with the opportunity to continue my graduate studies. Special thanks to the for their invaluable support.

ABSTRACT

The Internet of Multimedia Things (IoMT) has undergone unprecedented development in recent years. This is confirmed by the massive use of multimedia applications in various fields such as smart homes and industrial monitoring. However, IoMT has stringent requirements compared to traditional IoT in terms of quality of service (QoS) as well as quality of experience (QoE). The design of a routing protocol can be hampered by the underlying limitations and challenges of which motivate the quest for efficient solutions. Firstly, this thesis investigated the feasibility of real video streaming using RPL (Routing Protocol for Low power and lossy network) focusing on the impact of radio duty cycling on the quality of received video and the network energy footprint. To do so, we adopted a low complexity compression technique that is more suitable for LLNs and used Cooja simulator in the Contiki Operating System to carry out our experiments. We mainly showed that RPL along with ContikiMAC, the Contiki default radio duty cycling, is not able to handle real-time video transmission in the context of constrained networks. To deal with such a shortcoming, We proposed to extend RPL to enable simultaneous use of disjoint multiple paths. This is done on top of the already maintained DODAG structure with the least induced overhead. Once again, we made use of a low-complexity encoding method on the captured images. Based on both QoS and QoE metrics, we evaluated the performance of our disjoint multipath RPL (DM-RPL) for video transmission using both a network emulator and a real testbed. Our results showed that our multipath extension provides more bandwidth as the packet delivery ratio is increased. Video quality is further improved thanks to the adopted data reduction at the source along with a priority-based mechanism. All of this translates into less energy being consumed and a longer network lifetime.

Keywords : Internet of Multimedia Things (IoMT).RPL. Multipath routing. QoE QoS . Cooja . IoT-Lab

Résumé

L'Internet des objets multimédias (IoMT) a connu un développement inédit ces dernières années. Ceci est confirmé par l'utilisation massive d'applications multimédias dans divers domaines tels que la maison intelligente et la surveillance industrielle. Cependant, l'IoMT a des exigences strictes par rapport à l'IoT traditionnel en termes de qualité de service et d'expérience (QdS/E). La conception d'un protocole de routage peut être entravée par les limitations et les défis sous-jacents motivant la recherche de solutions efficaces. D'abord, cette thèse s'est intéressée à la faisabilité d'un streaming vidéo en temps réel en utilisant RPL (the Routing Protocol for Low power and lossy network) en se concentrant sur l'impact du RDC (radio duty cycling) sur la qualité de la vidéo reçue et la consommation énergétique. Pour ce faire, nous avons adopté une technique de compression de faible complexité plus adaptée aux réseaux à fortes contraintes et avons utilisé le simulateur Cooja fourni par Contiki pour réaliser nos expériences. Nous avons principalement montré que RPL avec ContikiMAC, le RDC par défaut de Contiki, ne permet pas la transmission vidéo en temps réel dans les réseaux contraints. Pour faire face à ce problème, nous avons proposé d'étendre RPL permettant l'utilisation simultanée de plusieurs chemins disjoints. Ceci est fait par-dessus la structure du DODAG déjà maintenue par RPL avec un minimum de surcharge. Nous avons utilisé une méthode de codage à faible complexité sur les images capturées. L'évaluation de performances de DM-RPL (Disjoint Multipath RPL), notre extension de RPL, pour la transmission vidéo a été menée à la fois sur un émulateur de réseau et une plate-forme de capteurs réelle. Nos résultats, selon des métriques de QdS/E, ont montré que notre extension fournit plus de bande passante vu que le taux de réception des paquets augmente. la qualité de la vidéo est, en outre, améliorée due à la réduction des données effectuée à la source en plus du mécanisme des priorités adopté. Tout cela se traduit par une consommation d'énergie moindre et une durée de vie du réseau plus longue.

Mots clé: Internet des Objets Multimédia ,Routage multi chemins, .QoE QoS . Cooja . IoT-Lab

ملخص

شهدت إنترنت الأشياء متعددة الوسائط (IoMT) تطورا غير مسبوق في السنوات الأخيرة. وهذا ما يؤكده الاستخدام المكثف لتطبيقات الوسائط المتعددة في مختلف المجالات مثل المنزل الذكي والمراقبة الصناعية. إلا ان IoMT لديها متطلبات صارمة مقارنة بإنترنت الأشياء التقليدية من حيث جودة الخدمة والخبرة ، هذه القيود تؤدي إلى إعاقة تصميم بروتوكولات التوجيه الأمر الذي حفز الباحثين للبحث عن حلول فعالة. هذه الأطروحة تدرس تدفق الفيديو في الوقت الفعلي باستخدام (
RPL (the Routing Protocol for Low power and lossy network مع التركيز على تاثير (
RDC (radio duty cycling على
جودة الفيديو المستلم واستهلاك الطاقة. للقيام بذلك، اعتمدنا تقنية ضغط منخفضة التعقيد أكثر ملاءمة للشبكات عالية القيود واستخدمنا المحاكي Cooja لإجراء تجاربنا. لقد أظهرنا بشكل أساسي أن RPL مع RDC، ContikiMAC
الافتراضي النظام التشغيل Contiki ، لا يسمح بنقل الفيديو في الوقت الفعلي في الشبكات المقيدة. للتعامل مع هذه المشكلة ، اقترحنا تمدىد RPL للسماح بالاستخدام المتزامن لعدة مسارات منفصلة. يتم ذلك فوق هيكل
DODAG الذي تم صيانته بواسطة RPL و ذلك بأقل قدر من النفقات العامة . استخدمنا طريقة ترميز منخفضة التعقيد على الصور الملتقطة. تم إجراء تقييم مقترحنا
DM-RPL (Disjoint Multipath RPL) ، لنقل الفيديو على كل من محاكي الشبكة ومنصة استشعار حقيقية . أظهرت نتائجنا، أن امتدادنا يوفر مزيدا من النطاق الترددي مع زيادة معدل
استقبال الحزم. تم تحسين جودة الفيديو بشكل أكبر بسبب تقليل البيانات التي يتم إجراؤها في العقدة الصدر بالإضافة إلى آلية الأولوية
المعتمدة. كل هذا يترجم إلى استهلاك أقل للطاقة وعمر أطول للشبكة.

الكلمات المفتاحية : أنترنيت الأشياء RPL ، التوجيه متعدد المسارات ، جودة الخدمة، جودة الخبرة
Cooja . IoT-Lab

Contents

LISTE OF ABRIVIATIONS

IoMT Internet of Multimedia Things

IoT Internet of Things CCR

Channel Check Rate ContikiOS Contiki

Operating System CSMA Carrier

Sense Multiple Access

DAO Destination Advertisement Object

DIO DODAG Information Object

DIS DODAG Information Solicitation

ETX Expected Transmission Count

ICMP Internet Control Message Protocol

IEEE Institute of Electrical and Electronics Engineers

IETF Internet Engineering Task Force

LLN Low-power and Lossy Network

MAC Medium Access Control

RDC Radio Duty Cycle

RPL IPv6 Routing Protocol for LLNs

PSNR	Peak Signal to Noise Ratio
SSIM	Structural Index Similarity
QoS	Quality of Service
QoE	Quality of Experience
PID	Path ID
FFC	Frame Frequency Capture
DODAG	Destination Oriented Directed Acyclic Graph
DAG	Directed Acyclic Graph
DM-RPL	Disjoint Multipath Routing Protocol for LLNs
QF	Quality Factor

Introduction

The Internet of Things (IoT) idea was first suggested and coined by the co-founder of the Auto-ID Center at MIT, Kevin Ashton, back in early 2000 [1] . This concept envisioned a world in which the Internet controlled every aspect of our life. Things, in this context, refer to everyday physical devices that are embedded with sensing/actuating hardware, the smartness and connection capabilities integrated into IoT devices enable a plethora of smart applications to be used in our daily lives such as smart grids, smart homes, smart cities, automated industrial monitoring, just to name a few. To satisfy the big scale and low-cost demands, most IoT deployments rely on devices with limited resources, resulting in Low-power and Lossy Networks (LLNs). LLN devices are battery-powered and have limited storage and processing capabilities. On the other hand, the networks that connect them have a high probability of delivery failure, small packet sizes, low data speeds.

Internet of Multimedia Things (IoMT) is one extensively current topic of the IoT due to the immersive growth of multimedia applications in several fields. However, the IoMT has more severe requirements in terms of quality of service (QoS) and quality of experience (QoE). When compared to scalar data collected by standard IoT devices, multimedia content, such as audio, video, and so on, gathered from the physical environment has special features. To process the collected multimedia information, multimedia devices demand more processing and memory resources. Furthermore, multimedia transmission consumes more bandwidth than traditional scalar data traffic. Meanwhile, Designing appropriate routing protocols to meet the various performance demands of various applications is a critical issue. The majority of existing WSN routing methods are based on a single-path routing technique, without taking into account the consequences of varied traffic load intensities. In this strategy, each source node chooses a single path for transmitting traffic to the sink node. However, when the active path fails to transmit data packets, finding an alternate path to continue the data transmission process may result in additional overhead and a delay in data delivery. Multipath routing [2] has emerged in the last decades as a promising solution to provide sufficient bandwidth to handle high data rate flows. Since a wireless network capacity is limited even with multipath routing, it still remains difficult to provide sufficient bandwidth able to satisfy the requirements of data intensive applications such as IoMT ones. Low complexity in-network data reduction is more than necessary to lower transmissions and the corresponding energy expenditure.

Multiple paths can be used simultaneously to improve data transmission reliability by sending several copies of an original data packet via different paths to ensure packet recovery from several path failures. RPL [3] is the IETF standardised IPv6 Routing Protocol for low-power and lossy networks (LLNs) where directed-oriented acyclic graphs (DODAG) rooted at the sink are maintained. An objective function is used by each node to select its preferred parent toward the root node. Despite the fact that RPL almost meets the requirements of LLNs to handle scalar data routing, it is still far from being able to allow real time streaming of video flows as it was mainly designed for low data traffic network. Because RPL was created primarily to fulfill the needs of LLNs, the major effort is made on handling low data rate traffic. In our study, we aim to handle video delivery in the IoMT by addressing both facets of bandwidth scarcity problem. First, we propose a new algorithm to obtain disjoint multiple paths in RPL. Uses existing RPL control messages to insure disjointness through the use of the IDs of the last hop nodes toward the DODAG root. Second, we make use of low-complexity video encoding more adapted to LLNs to reduce the amount of transmitted data. In our work, disjointness is guaranteed before data transmission, hence allowing for load-balancing strategies. Our performance evaluation is conducted using both simulation and real sensor testbed (IoT-LAB [4]).

Main Contributions of the Thesis

In this thesis, we started by evaluating video transmission using RPL. To the best of our knowledge, this is the first work that evaluates video transmission using RPL where both QoS and QoE metrics are considered along with a low-cost compression technique more suitable to LLNs.

An extension to RPL called Disjoint Multipath RPL (DM-RPL) is presented in Chapter 3. We suggest transmitting a flow on multiple disjoint paths. To do so, we exploit the DODAG structure, already maintained by RPL, to build disjoint paths without incurring extra overhead. To reduce the amount of data to send while considering the low computation resources of video sensors.

Our conducted experiments were performed using both cooja simulator and IoT-LAB testbed. In addition, we considered evaluating a replication mechanism where higher priority packets are sent twice each on a different path. Our obtained results proved that using two paths along with the priority mechanism achieves the highest performances.

Manuscript Content

This thesis is part of the studies of routing in wireless multimedia sensor networks that considers QoS as well as QoE metrics. It is divided into four chapters as follows.

In chapter 1, a brief introduction to the IoMT, the main scope of this thesis, is offered. Then, an analysis of wireless sensor networks and wireless multimedia sensor networks is carried out. We, in particular, focus on multipath routing protocols giving their techniques and benefits. In addition, a survey on relevant routing protocols to low power and lossy networks is presented.

Chapter 2 provides a performance evaluation of video transmission using RPL. It outlines the motivation and the need for extending RPL to support multimedia transport.

Chapter 3 describes DM-RPL, an extension of standard RPL to allow for building and maintaining multiple disjoint paths. This chapter begins with a discussion of routing multimedia traffic using RPL limitations that motivate the need for our proposed protocol DM-RPL.

In chapter 4, a detailed performance analysis of DM-RPL is presented where both QoS and QoE metrics are considered. We mainly evaluate the improvement provided by our disjoint multipath routing combined with a priority-based forwarding strategy when compared to single-path RPL.

Chapter 1

Routing in the Internet of Multimedia Things

1.1 Introduction

The Internet of Things (IoT) has undergone an unprecedented development these last years. This is confirmed by the massive use of their applications in various fields such as smart homes, military applications, environmental, habitat, medical and industrial monitoring. IoT devices are connected to an IoT gateway or other edge device to collect the sensed data. Multimedia sensors and devices are an important part of IoT applications where a large amount of data with different features and needs can be handled. The main challenges of IoMT is the efficiency and timely delivery of the data.

This chapter is dedicated to presenting routing in the Internet of Multimedia Thing that defines the scope of this thesis. In Section 1.2, we introduce wireless sensor networks (WSN) with a focus on the routing function. We then present wireless multimedia sensor network in Section 1.3. After that, we discuss multipath routing protocols in WSN and their benefits in Section 1.4. An overview of RPL is given in Section 1.5 before the concluding the chapter.

1.2 Wireless Sensor Networks

Wireless Sensor Networks (WSN) are a particular type of ad-hoc networks used within IoT systems that consists in a large collection of small wirelessly communicating sensors deployed in a particular region to sense various environmental parameters related to specific applications. These sensor nodes are typically in charge of reporting information to a central gateway or a base station called the Sink. The Sink transmits a query throughout the network. When a node discovers the data matching the query, a response message is routed back to the base station. However, these sensor nodes have limited resources in terms of power consumption, processing speed, communication range, available bandwidth and additionally, they communicate over wireless lossy links. In order to maximize the lifetime of the network, communication protocols must be designed from the beginning with the objective of efficiently managing the limited resources. That is features like flexibility, energy efficiency, fault tolerance, high sensing fidelity and low-cost are highly sought after by researchers when developing technologies and strategies at the different layers of the WSN protocol stack to meet the requirements of diverse applications in terms of energy, delay and bandwidth.

1.2.1 WSN's Protocols Design Challenges

Despite the immersive growth of WSNs applications in several fields, these networks have several limitations. Researchers need to consider these challenges when designing a new routing protocol, such as data aggregation, limited bandwidth, fault-tolerant network, deployment region, power consumption, delay, etc.

Scalability

The sensing area may contain hundreds, thousands or more sensor nodes. In addition, more nodes can be added to the network at any time [5], which means that WSN protocols must be able to accommodate these changes and different network sizes.

Energy Efficiency

The key factor that restricts the application of WSNs is energy [6, 7], as sensor nodes have a limited energy capacity. Energy consumption becomes a major concern in many WSN applications. When the sensor node battery reaches a certain threshold, the sensor will not be able to function properly which can lead to significant changes in the WSN topology, affecting the overall lifetime of the network.

Limited Banthwidth

Wireless network capacity is limited even in the presence of bandwidth aggregation techniques [8] while this is required to perform realistic analysis in WSNs.

Sensor Locations

Correct localization of sensor nodes is another challenge that needs to be considered by the designers of WSNs. The use of a localization technique has been proposed as an effective solution for obtaining location information of sensor nodes [9].

Delay

Minimal delay is required for real-time applications [10, 11] such as alarm monitoring and real-time multimedia applications.

Data Aggregation

Data aggregation presents an additional challenge in the design of routing protocols for WSNs [11, 12] since sensor nodes may generate and transmit redundant data, which can affect the overall performance of the whole network.

1.2.2 Routing Protocols and Algorithms

The main purpose of a WSN is to sense data and route it to the Sink through multiple hops which makes the routing function essential. Much research has been undertaken to develop protocols and algorithms for selecting a routing path between a source node and the base station. The design of routing protocols for WSNs must take into account the limited resources of both sensor nodes (energy, processing means, . . .) and the wireless medium (losses, . . .). These are major constraints for all WSN's applications, therefore routing protocols proposed for ad hoc networks are not suitable for WSNs. It is crucial to find a suitable method of routing data from each source to the Sink while taking into account these design requirements.

Routing protocols in WSNs are classified in the literature in many different ways. We review in brief the basic flat classification as well as the hierarchical routing solutions proposed for WSNs :

Hierarchical Routing

Hierarchical routing technique was first introduced in [13]. It has the advantage of scalability and efficiency. Hierarchical routing protocols are either cluster-based or chain-based. In the former, nodes are organized into clusters where a cluster head is defined as a led for each cluster. In the latter, nodes are organized into chains, the chain leader has higher energy to send data from normal nodes to the base station. Two main phases are required to design a hierarchical routing protocol, the first is the configuration phase where the sensor nodes are organized to form a hierarchical architecture. The second phase is used for routing the data from the sensor nodes to the base station. LEACH (Low Energy Adaptive Clustering Hierarchy protocol) [14] is proposed to extend the lifetime of the network by distributing the energy equally among the nodes. Normal nodes are used to sense the data from the environment and send it to the cluster head. Selected according to the remaining energy, the cluster head has special functions such as receiving the data, processing and sending the compressed data to the base station, so that the depleted energy affects only that node.

The authors of [15] proposed PEGASIS (Power Efficient Gathering Sensor Information System) where the nodes are organized in a chain structure built using a greedy algorithm at the beginning of the round. PEGASIS outperforms the LEACH protocol in terms of scalability and network lifetime. However, the data passes through many intermediate nodes, which explains the very long delays that can occur. Therefore, it is not suitable for real-time applications. TEEN [16] and APTEEN [17] outperform the previously cited hierarchical WSN protocols in terms of energy since they reduce unnecessary transmissions by controlling the frequency of data transmissions.

Flat Routing

In flat routing, nodes play an equal role in sensing, processing, and transmitting data. Flat routing protocols can be classified into several categories. In data-centric routing protocols, data is requested through queries issued by the Sink to certain regions, then it waits for data from sensors located in the selected region. The main data-centric protocols in WSNs include Sensor Protocols for Information via Negotiation (SPIN) [18], Directed Diffusion (DD) [19].

Geography-based protocols avoid the overload of information exchanged between nodes to obtain the network topology or routing tables. The authors in [20] and [21] proposed geographical routing protocols that guarantee scalability because only the local information is stored and used. The periodic exchange of control packets allows the nodes to build their position table. Indeed, when a node does not receive a “beacon” message from a neighbor after a given period of time, it considers that the neighbor is not in the coverage area.

Multipath routing technique has emerged in the last decades for its reliability and its ability to balance the traffic load over the network. This approach is considered as one of the existing solutions to cope with the limitations of single path routing by the use of diverse paths to route packet streams towards the destinations.

1.3 Wireless Multimedia Sensor Networks (WMSN)

The IoMT paradigm has gained broad-spectrum attention due to its great potential influence on several aspects of everyday life. In Low Power and Lossy Networks (LLNs) where sensor nodes are a key component, providing a satisfactory quality of service (QoS) as well as a user quality of experience (QoE) in such applications is a challenging task. However, IoMT has more stringent requirements than traditional IoT. When it comes to handling multimedia applications characterized by high data rate in WSNs, one of the basic building blocks of IoT, the problem becomes more challenging due to their limited resources.

Wireless multimedia sensor networks (WMSN) are networks of wirelessly interconnected devices that are able to ubiquitously retrieve multimedia content such as video and audio streams, still images, and also scalar sensor data from the environment using multimedia sensors. The various applications of WMSN include battlefield visual monitoring, traffic monitoring, environment monitoring, safety monitoring, medical treatment, intelligent home, public healthcare and various other applications. These applications are bandwidth intensive. In addition to processing and transmitting, the data in WMSN requires considerable energy. However, the devices are powered with limited battery capacity, limited computation capabilities and have a narrow bandwidth. Therefore, a method must be found to route data from each source to a destination with consideration of QoS and QoE.

1.3.1 WMSN Applications

In the last few years, researchers drawn enormous attention to the area of routing in WMSNs because of their applications in various domains, especially those related to surveillance and monitoring.

- **Surveillance.** Video and audio streams can be used to enhance existing surveillance systems against crime and terrorist attacks by identifying criminals and missing persons.

- **Traffic Monitoring and Enforcement.** It will be possible to monitor car traffic in big cities or on highways, control the speed and the number of traversed cars in each time and deploy services that offer traffic routing advice to avoid congestion. Multimedia sensors could also be used to capture accident and violations, which may help the law enforcement agencies to identify criminals and violators.

- **Personal and Health Care.** Emergency situations can be inferred using multimedia sensor network incorporated with third and fourth generation (3G/4G) cellular networks. Medical centers can monitor their patients remotely based on various parameter such as body temperature, blood pressure, pulse oximetry, electrocardiogram, and breathing activity.

- **Gaming.** Enhancing the effect of the game environment on the player has a significant effect on popular recreational activity. To this end, WMSN researchers are attempting to improve and design pervasive systems involving rich player-environment interaction such as virtual reality games that assimilate touch and sight inputs of the user as part of the player response [22].

- **Environmental and Structural Monitoring.** Habitat monitoring projects such as that are used by oceanographers to determine the evolution of sandbars.

- **Industrial Process Control.** WMSNs can help make systems more flexible for visual inspections and automated actions. In addition, multimedia content such as imagery, temperature or pressure can be used for time-critical industrial process control.

1.3.2 Video Transmission Challenges in WMSNs

Designing a routing algorithm for multimedia applications is very challenging due to the resource constraints of WMSNs in terms of energy, bandwidth, and processing storage. The following essential challenges should be addressed by WMSNs designers:

1. **High Volume Traffic.** Multimedia applications produce high volume of traffic that requires a high transmission rate. Hence, transmission techniques for high data rate and low power consumption need to be leveraged.

2. **Compression Technique.** A compression technique is also required before transmission to limit the amount of data to route and hence limit power consumption by using low-complexity data reduction at the video source to support multimedia traffic in low-power and lossy networks.

3. **Quality of Experience (QoE).** Meeting QoS/E requirements is the most important challenge in the design of WMSN protocols as multimedia content requires additional time periods to be generated and typically needs to be delivered in real-time with acceptable jitter, power consumption, delay and bandwidth, making the provision of QoS a difficult task. Multimedia applications particularly need this type of guarantees for efficient transmission of a detected phenomenon.

4. **High Bandwidth Demand.** Providing sufficient bandwidth to handle high data rate flows is required. The compressed information still exceeds the capabilities of wireless sensor nodes. More specifically, the video stream requires a transmission bandwidth greater than that supported by the sensors nodes.

5. **Energy Consumption.** Energy consumption is a major concern in traditional sensor networks. This is even more marked in WMSNs since the sensors have limited life batteries while multimedia applications produce large volumes of data which require high transmission rates and therefore intensive power consumption. Energy-aware computation and communication are required to allow for a longer lifetime for the WMSN.

1.3.3 Routing in Wireless Multimedia Sensor Network

WSNs meet the requirements of LLNs for handling scalar data routing. The proposed routing protocols for WSNs are designed for the transfer of small amounts of data, which requires the development of new techniques that take into account the requirements of multimedia streaming. These protocols can be classified according to their mode of operation into three main mechanisms, namely single-path, multi-path, and multi-channel communications. In single-path mode, the best path is selected based on the application requirements for transferring data streams from source to destination, while in multipath mode, two or more better paths are used. To improve throughput, bandwidth and mitigate the effect of interference in WMSN, multichannel communication is an effective solution.

ASAR [23] is a QoS routing protocol model for multimedia wireless sensor network. ASAR selects optimal paths based on traditional ant-based algorithm to meet multimedia application requirements. The proposed protocol is a cluster-based architecture and only addresses the routing scheme between cluster heads and the Sink node. The ASAR algorithm has proven its effectiveness through experimental results.

More recently the authors of [24] proposed an Optimized Compressed Sensing Routing Protocol (OCSRP) that performs multimedia data routing in a very efficient manner. The model focuses on improving the QoS with a high level of security. Performance analysis has proven that this technique increases packet delivery rate and end-to-end delay and achieves a high level of security of multimedia data transmitted over unsecured WMSNs.

Rehan et al [25] designed QoS aware Cross layer Multichannel MultiSink Routing protocol (QCM2R). Multichannel mechanism is used in order to handle the congestion occurrence in the network. This improve network lifetime, reliability, delay and throughput.

Ahmed proposed a real-time protocol with adaptive traffic shaping for multimedia file communication using WMSNs (ARTVP) [26]. ARTVP uses multipath forwarding with dynamic cost calculation for selecting the next hop. The proposed model guarantees high QoS performance, in particular high PDR (Packet Delivery Ratio), less end-to-end delay and smooth routing reliability.

1.3.4 Data Compression Techniques in WMSN

In Wireless Visual Sensor Networks (WVSN), large amounts of video data are sensed, processed in real-time, and then transferred over wireless networks. However, sensor nodes have limited energy capacity as they are usually powered by batteries. This critical issue necessitates more sophisticated data compression strategies to save the energy consumption of sensor nodes. Hence, in order to extend the network lifetime, a number of techniques have been proposed considering both lossy and lossless compression techniques. Discrete Cosine Transform (DCT) [27] is a multimedia transform compression technique that have been analyzed in different ways, including reducing the computation complexity, increasing the compression ratio, and minimizing the energy consumption. One of the most popular DCT-based compression schemes is Joint Photographic Experts Group (JPEG). Researchers, in [28–30], have proposed new methods to reduce the DCT computational complexity by eliminating redundant operations which reduce the overall energy footprint.

Vector Quantization (VQ) is a data compression technique based on the principle of block coding. Several researches have been conducted on VQ-based data compression [31, 32] with the aim of reducing power dissipation and the number of memory accesses. Discrete Wavelet Transform (DWT) technique is a method for increasing the features of DCT in which two filters are used to decompose a signal. DWT decomposes a given signal into a set of mutually orthogonal wavelet basis functions.

To assess the performance of WVSN proposals, a video transmission and evaluation tool is required. EvalVid [33] is a common tool developed to be used in less constrained networks for evaluating video quality where trace files are produced. However, the encoders supported by EvalVid are resource intensive while video sensors have do not have sufficient processing power and enough energy to perform complex compression algorithms, making the use of these codecs unsuitable for resource-constrained networks like WSNs. As a result, effective compression methods are required to handle video transmission in WSN, both in terms of processing and energy requirements. Authors in [34] have designed an extended version of WiSE-MNet (Wireless Simulation Environment for Multimedia Networks) [35] called

WiSE-MNet++. WiSE-MNet++ is a significant step forward in valuing distributed vision algorithms as well as communication issues, while offering an energy model for camera systems. However, it does not consider WSN-compatible encoding schemes.

A proposed technique for analyzing image transmission, called SIMulator for Lossy Image Transmission (Sim-LIT), is presented in [36]. However, the model used is inefficient for video transport because it is only concerned with intra-coded still images. Besides, the authors do not mention any energy-related metric to evaluate the performance of their proposal. M3WSN (Mobile MultiMedia Wireless Sensor Network) [37] combines WiSE-MNet and EvalVid, as well as the WVSN model, to take advantage of their features. It was developed to allow real-time video transmission, control, and evaluation in mobile WMSNs. M3WSN relies on traffic trace files generated by EvalVid which have encoders not adopted to WVSN. EvalVSN [38] is a new video transmission and evaluation tool that considers WSN specific characteristics. It uses a modified version of MPEG-2 while the interface with the real or simulation-based experiment is insured by using the sender and the receiver trace files. However, EvalVSN framework does not provide any energy-related metrics and the adopted inter-frame coding is inefficient in terms of compression ratio.

SenseVid [39] is a traffic trace based tool for QoE Video transmission assessment dedicated to WVSNs. It uses a traffic trace model that allows it to be used in both simulation and real-world sensor network testbeds. It integrates low-complex video encoding techniques that suits the constraints of WMSN. A consumption power model is offered to estimate the amount of energy spent by video capture and compression. Both QoS and QoE metrics are also provided. This is the tool we chose to use in assessing the proposals of our thesis.

1.4 Multipath Routing Techniques

Multipath routing considered as one of the existing solutions to cope with the limitations of routing by the use of diverse paths to provide sufficient bandwidth to handle high data rate flows, load balancing which can be achieved by balancing energy utilization across the nodes in the network, reduced delay and assuring fault-tolerance, which results in enhanced network lifetime. Multipath routing has three main phases : paths discovery, traffic distribution, and paths maintenance. The path discovery phase determines the available paths from the source to the Sink. In the traffic distribution phase, the traffic is routed after a possible choice of the number of paths to use. Paths maintenance is initiated after path failure to repair an existing route or to regenerate a new one. The paths between a source node and the base station can be either disjoint or non-disjoint paths. In the latter case, the routes can have common nodes or links. Non-disjoint multipath can be qualified according to the degree of its routes disjointness as (Figure 1.1) :

- **Link-disjoint Multipath.** The built paths have no common links but may share some common intermediate nodes.
- **Node-Disjoint Multipath.** The constructed paths do not share any nodes other than the source and the destination nodes. Failure in a path does not affect the other paths.
- **Totally disjoint Multipath.** This refers to set of paths that have Zero-edge connected.
- **Maximally link/node Disjoint Multipath.** A minimum links or nodes are shared.
- **Radio Disjoint Multipath.** This refers to the set of paths with minimum radio interference required to mitigate the effect of interpath interference. This includes : Full Radio Disjoint Multiple Paths, Partial Radio Multiple Disjoint Paths and Non Radio Disjoint Multiple Paths.
- **Partially Disjoint paths (Braided Multipath).** For each node on the primary path, an alternative path does not include that node is referred to as Partially Disjoint paths.
- **Zone–Disjoint Multipath.** Set of paths in which data communication on one path will not interfere with other communications on the other paths.

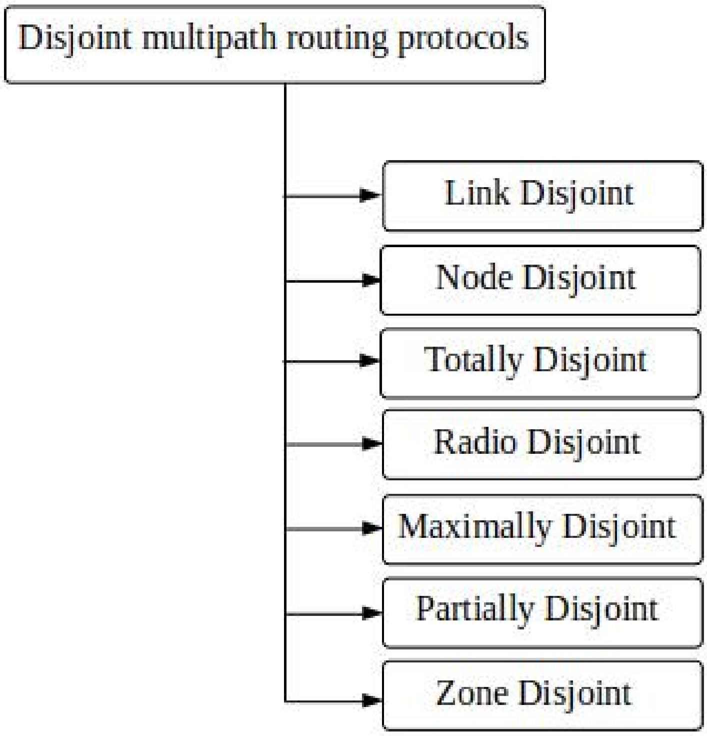


Figure 1.1: Disjoint multipath routing protocols types

1.4.1 Benefits of Multipath Routing

Multipath routing is an effective technique or routing data in WSNs because it can provide reliability, Load balancing, fault tolerance, extending the lifetime of the system.

- **Improving the fault tolerance.** One of the critical issues in WSN is to get a high reliable fault-tolerant system, as nodes may die due to limited capacity batteries, environmental changes or malicious destruction. Multipath technique is an appropriate solution to get systems more resilient to failures by using alternative paths to route redundant information, minimize possible routing overhead to find alternative path, distribute traffic over alternate paths to balance the load over the nodes, etc.

- **Bandwidth aggregation.** Providing sufficient bandwidth to handle high data rate flows is required. It is necessary to use a new transmission technique to provide additional bandwidth with a reduced computation resource level. Multipath routing protocols provide more bandwidth by splitting the data into multiple streams that are routed through different routes.

- **Load balancing.** Load balancing can be achieved by spreading the traffic over different paths which leads to minimize the risk of traffic congestion by easing the burden of the congested link.

- **Reliability.** The main technique used in WSNs to achieve reliability is redundancy. Multipath protocols allow a source node to send multiple copies of the same data on multiple paths in order to achieve data transmission reliability.

- **End to end delay reduction.** In single path routing protocols, route failures leads to a new discovery process to find alternative path, whereas in mutipath protocols, discovery process of backups routes is initiated during route discovery, thus reducing the end-to-end delay.

- **Mitigate congestion.** Distribute the traffic among two or more paths allow to mitigate the effect of congestion, especially for height data rate real-time applications.

- **Energy.** The main challenge of WSN is to efficiently use the available energy. Splitting the data around many paths allow to reduce the number of retransmissions.

1.4.2 Multipath Routing Protocols

Multipath routing strategy is frequently employed to improve network performance through efficient utilization of available network resources. The existing multipath routing protocols for WSN demonstrate the effectiveness of traffic distribution over multiple paths to satisfy the QoS requirements of different applications. Many different WSN routing protocols have been proposed in the literature.

Maimour [40] investigated the problem of interfering routes in WMSN, considering both intra-session and inter-session interference. The main objective is to provide sufficient bandwidth to multimedia applications through non-interfering paths while extending the network lifetime. An incremental approach in which just one path is built at a time for each session is used. Additional paths are built when needed such as when there is congestion.

Multipath Prefix Routing protocol (MPR) [41] adopts a compact routing scheme called prefix routing for WSNs. MPR builds multiple disjoint paths from one node in the sensor network to the Sink to achieve load balancing by distributing the data traffic over a set of available node disjoint paths. MPR relies on an already built spanning tree rooted at the Sink. It is both proactive and reactive multipath routing protocol. MPR is proactive since at least one path can be inferred from the tree structure : the source is able to immediately start transmitting data on at least one path. It is reactive since, if required, it builds additional paths based on a very light discovery process based on the tree structure using its labelling scheme and neighbors tables.

Robust and energy efficient multipath routing protocol (REER) [42] proposed two traffic allocation methods : the first version (REER-1) uses a single path among the discovered paths for data transfer, when the cost of the used path falls below a certain threshold, it then switches to the next alternative path. The second version (REER-2) adds data redundancy through a Forward Error Correction (FEC) technique to the original data message and uses multiple paths to transmit the data. Using this technique, failure in one or more paths can be recovered without invoking data re-transmissions. REER-2 splits up the transmitted message into a number of segments of equal size, adds FEC codes, and then transmits it simultaneously over multiple paths.

TPGF (Two Phase geographical Greedy Forwarding) routing protocol [43] focused on exploring and establishing the shortest routing path (or near shortest routing path when holes exist) for minimizing the end-to-end transmission delay, when hole information is not identified in advance. The first phase of TPGF is responsible for exploring the possible routing path using two methods : (i) greedy forwarding (forwarding node chooses the next-hop node that is closest to the base station among all its neighbor nodes) and (ii) step back&mark used when greedy forwarding cannot find the next-hop node. The second phase is responsible for optimizing the found routing path with the least number of hops. TPGF supports hole-bypassing, the shortest path transmission, multipath transmission and at the same time improves the energy efficiency.

The Greedy Perimeter Stateless Routing (GPSR) [20] method makes packet forwarding decisions based on the positions of routers and the destination of a packet. Packet forwarding is done in two modes, namely greedy forwarding and perimeter forwarding. Instead of creating and maintaining a routing table, GPSR simply transmits a packet to the nearest neighboring node to the Sink. The main drawback of this protocol is that the source may not receive the update of the positions of these neighbors because of the rapid change of the topology.

The TIGMR (Geographic Multipath Routing based on Triangle Link Quality Metric with Minimum Inter-path Interference for Wireless Multimedia Sensor Networks) routing protocol [44] finds multiple node-disjoint paths in an IEEE 802.15.4 compliant network using a routing cost function with emphasis on link quality, remaining energy, and distance between the one-hop neighboring node and the Sink. In the neighbors discovery phase, TIGMR identifies all the nodes in the communication range of a given node that the node can communicate with directly. In the Path discovery phase, the source node selects its forwarding node which has a lowest cost, and sends Route Request (RREQ) packet to this node, this operation continues at every intermediate node until RREQ packet reaches the Sink. TIGMR protocol improves network lifetime and ensures high packet delivery ratio (PDR), low end-to-end delay, and low jitter at a reasonable energy cost. However, it consumes more energy due to delivery of more number of data packets during TIGMR neighbors discovery period.

1.5 Routing Protocol for Low Power and Lossy Networks (RPL)

The Routing protocol for low power and lossy networks (RPL) is a single path IPv6 routing protocol designed by IETF ROLL working group [3] which is implemented in Contiki IPv6 network stack. Three main types of ICMPv6 packets are defined in RPL for exchanging information about maintaining and building the DODAG. DODAG Information Object (DIO): it is the main source of routing protocol which stores information about objective function like network information, ranks and routing costs. DODAG Destination Advertisement Object (DAO) sends information in upward direction along the DODAG. The DIS messages (DODAG Information Solicitations) sends from reachable neighbors to solicit DIO messages. Figure 1.2 shows the behavior of these control packets to create and maintain the DODAG topology.

1.5.1 RPL Objective Function

The construction of the network topology in RPL protocol is determined by the objective function (OF) which is based on one or more metrics to produce a rank value. The OF defines how a node selects its preferred parent among the set of candidate parents nodes in a way that meets the requirements of various applications. Two objective functions have been standardized in RPL namely, the Objective Function Zero

(OF0) [45] and the Minimum Rank with Hysteresis Objective Function (MRHOF) [46]. The OF0 is designed to select the nearest neighbor to the DODAG root as a preferred parent using hop count metric. However, OF0 does not reflect node and link conditions. MRHOF chooses routes that minimize additive routing metrics such as latency, hop-count and ETX. ContikiOS uses MRHOF with Expected Transmission Count (ETX) routing metric as default objective function. However, considering MRHOF as a single routing metric may lead to high latency.

In [47], a new load balancing mechanism called LBSR is proposed that combines the default objective function with the number of children based on data plane messages metrics to balance the traffic over the network. The authors introduced a new primitive to schedule the parent selection in order to mitigate the effect of herding-effect. The performance evaluation shows that LBSR is effective in terms of PDR, energy consumption and load distribution compared to standard RPL. In [48], a new objective function for RPL is developed based on the ETX and buffer occupancy metrics in order to minimize lost packets in the congested nodes and select the less congested path toward the DAG root. Simulation results proved that CA-OF produces high ratio and less lost packets and consumed energy compared to RPL-OF0 and RPL-ETX. In [49], a Load Balanced objective function (LB-OF) is proposed to extend the network lifetime taking into account the number of children for each preferred parent as a metric. To do so the authors amended the DIO messages by injecting the chosen parent ID into the broadcast DIO, at the reception of DIO messages the node increment its number of children if there is a matching between its own ID and the preferred parent ID. Performance analyses proved that this technique extend the packet delivery ratio and the network lifetime by achieving the load balancing of bottleneck nodes. In [50], a traffic aware load balancing objective function based on MRHOF is proposed. ALABAMO uses the ETX and traffic profile as metrics in order to tackle imbalance problem in the selection of the preferred parent. Simulation results shows that ALABAMO extend the network lifetime of the nodes and alleviate the deviation of energy consumption of all nodes compared with default MRHOF.

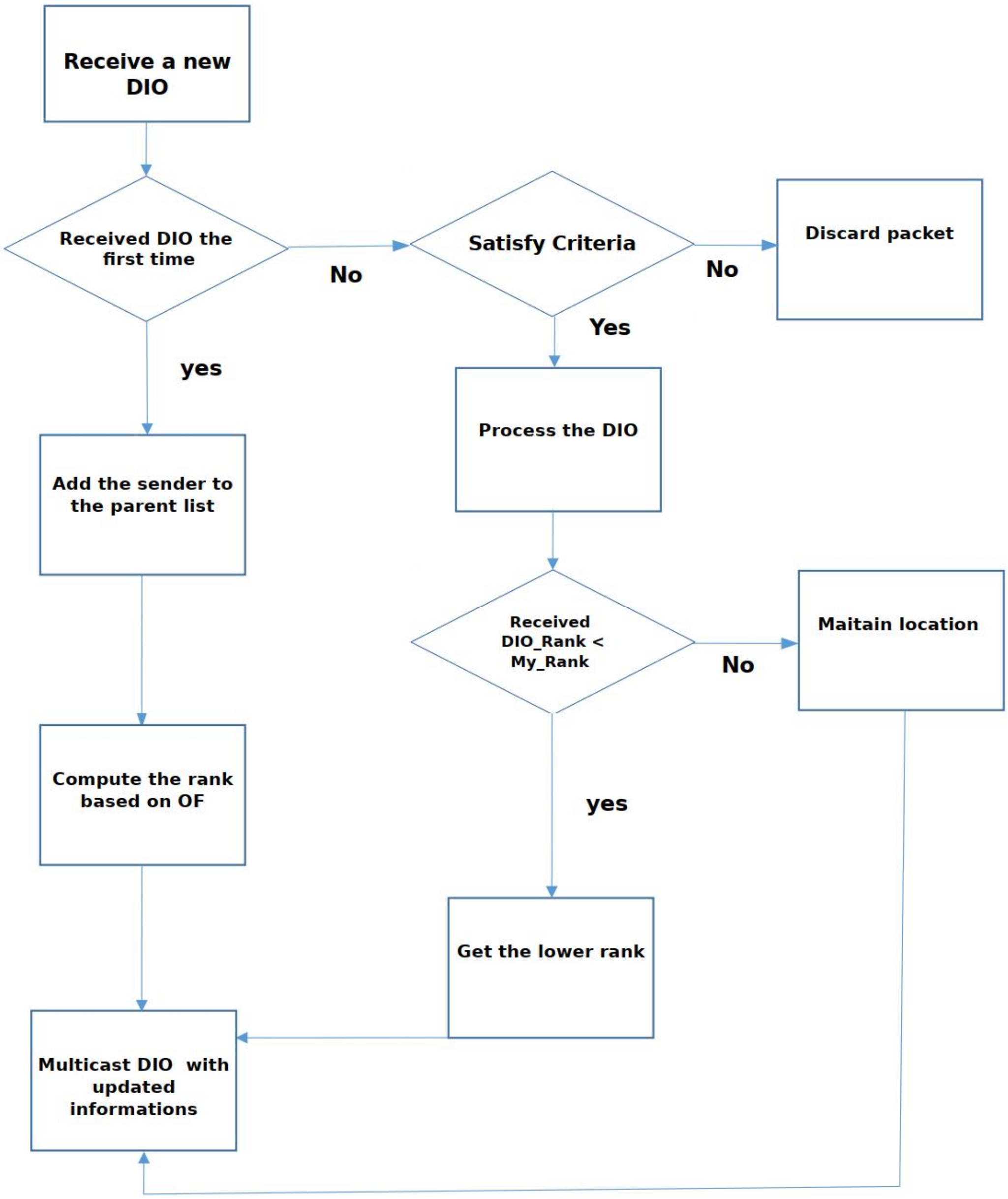


Figure 1.2: DODAG formation Process

1.5.2 Multipath RPL

The researchers have investigated the extension of the RPL protocol to enable multipath routing to provide increased reliability and its ability to transfer more data. In [51], an energy-balancing routing protocol is designed to balance the energy consumption using multipath approach. A new metric called Expected Life Time (ELT: the time before a node dies) is proposed to identify the most constrained nodes referred to as bottleneck nodes. Each node : (1) advertises its bottleneck nodes along the topology; (2) for each parent of this node, computes the ELT of bottleneck nodes and the lifetime of this node when choosing this parent as a best parent; (3) chooses as preferred parent the node that maximizes the network lifetime of the bottleneck; (4) assigns a load-step (weight of traffic) to the best parent; (5) re-identifies the preferred parent to forward the next load-step, at this end the traffic rate is balanced among parents nodes. Simulation results showed that multipath versions of RPL help to provide best reliability and extend the network lifetime compared to single-path RPL. However additional DIO bytes is required to identify the information of bottlenecks, which increase the protocol overhead.

Lodhi et al [52] defined temporary disjoint multipath routing when congestion is detection along a path. The authors proposed to use buffer size or the PDR metrics to detect congestion. Each node triggers congestion detection at the reception of any incoming packets; the parent node sends congestion notification (CN) in DIO messages to the child nodes if the PDR (or buffer size) exceeds a certain threshold. When a parent node detects a congestion after the expiry of congestion interval (CI) it checks if the remaining time of trickle timer is less than half CI then DIO will carry the CN, else emergency DIO is transmitted to notify congestion. The child node checks the status of their parent nodes, if parent nodes are not congested then start splitting the traffic, otherwise re-send CN to their children. Simulation analyses proved that M-RPL increases significantly the throughput and decreases slightly the depletion of energy as retransmissions are reduced. However, the final built paths are far and long when increasing the network size which decreases the success ratio. In addition, the new control messages may cause more overhead.

In [53], the authors proposed a new objective function based in the node and link metrics (life cycle index LCI with consideration of link quality, node energy, energy consumption rate, throughput, data transmission speed, congestion detection factor CF(N), in this scheme a LCI measurement has been introduced in order to select the bottlenecks of a the candidates paths. Each node saves a list of parents that meets the conditions then chooses the node that has a larger LCI as a next jump; alternative paths are used when congestion occurs by splitting the forwarding rate to half. Simulation results proved that the improved RPL maximized considerably the network lifetime, achieved better PDR and low delay compared to default RPL.

In [54] the authors suggested a braided multipath extension based on the standard RPL to extend the network lifetime by distributing the traffic load between equi-depth nodes using the Heuristic load distribution (HeLD) algorithm. In HeLD the nodes adjust the input traffic rate of the parents in order to equalize the energy consumption between the nodes in equal depth. The authors evaluated performance via OMNET++ and MATLAB, this scheme significantly increased the network lifetime and throughput. However using braided paths may lead to inter-path interference and exploiting less reliable links for multipath routing affect the performance of the network.

The authors in [55] studied the use of replication and elimination mechanism in multiple paths, for this aim, they proposed different algorithms to select backup parents. Wireless medium overhearing allows alternative parents to receive the packets sent by the child nodes to their preferred parent. The second best ETX selects alternative parents who have the best link quality among the set of parent candidates. In common ancestor approach the child node selects a node as its alternative parent if it is a common ancestor with the preferred parent, if more than one parent meets the condition; the node with the best link quality will be selected. Finally, the non common ancestor creates partially and completely disjoints paths by selecting the node that does not have any ancestor with the best parent. Simulation results showed that the use of replication and elimination significantly improved PDR, and using overhearing technique offers almost the same results without selecting an alternative parent. However, using this technique can flood the network with replicated messages, consuming a large amount of power. Moreover, additional fields on the DIO message are necessary to identify additional information which increases the protocol overhead. In [56], a multipath traffic loading distribution mechanism is proposed, to extend network lifetime taking into account energy consumption and delay as a metrics. Simulation based-results show that the proposal extends network lifetime and decreases end-to-end delay.

1.5.3 RPL and Multimedia Applications

The authors in [57] designed an enhanced version of RPL called Green-RPL in an attempt to minimize energy consumption. Simulation results proved that Green-RPL has butter QoS performances in terms of energy efficiency, number of successful packet transmissions and delay. In [58], a new objective function based on remaining energy for the IoMT is developed. Simulation results proved that this technique extends the network lifetime compared to ETX-based RPL. The authors in [59] proposed FreeBW-RPL that uses a new objective function. FreeBW-OF allows to deliver better performance of the multimedia applications by selecting the best forwarding candidate based on the maximum free bandwidth provided from the ascending nodes. Performance analyses showed that FreeBW- RPL improves upon the predefined RPL objective functions in terms of PDR, energy consumption, throughput and delay. In [60], the authors exploit the multi-instance version of RPL to builds nodes and links two disjoint paths to enhance the transport of compressed video traffic toward the Sink node (upward routing), the first path uses MAHROF as an objective function to transport the first priority frames (M-frames), and the second uses the shortest path (OF0) to carry the second priority frames (S-frames). Simulation results prove that multi-instance RPL help to improve the quality of the received video for both QoS (PDR, jitter and delay) and QoE (PSNR and SSIM) requirements.

1.6 Conclusion

Because of its great potential impact on many parts of daily life, the IoMT concept has gotten a lot of attention. It has been studied in general in this chapter. WVSN is one of the building blocks to realize the vision function in the IoMT. When sending visual data in WVSN, the problem is made more difficult by their constraints and limited resources. In particular, WMSN protocols and their applications in various fields were detailed. The need of multipath mechanism to transport multimedia traffic has been motivated. In the next chapter, we consider the feasibility of transporting video traffic using RPL.

Chapter 2

QoE-based Performance Evaluation of Video Transmission using RPL

2.1 Introduction

Technology advances foster the development of low-power and low-cost visual modules [61] that allow the emergence of WVSN, a key building block of the IoMT. Visual data provide an added value to numerous applications especially those related to surveillance and monitoring. Despite the fact that RPL almost meets the requirements of LLNs to handle scalar data routing, it still far from being able to allow real time streaming of video flows. Visual sensors with limited resources have to deal with large amount of data to capture, encode and transmit. These tasks result in significant power consumption while sensor nodes are equipped with limited batteries capacity.

Authors of [62] considered video traffic routing using RPL and proposed a new objective function in an attempt to minimize energy consumption while assuring a required QoS. However, the performance evaluation does not consider a real video traffic and as a result the user QoE is not evaluated either. More recently, the work in [63] defined another objective function based on the remaining energy to choose a node's parent. However, the user QoE is not considered. Moreover, H. 264 compression is not adapted to low-power video sensors [64].

Network lifetime can be maximized by minimizing the radio activity characterized by its high power consumption in the transmit, receive as well as idle listening periods. In order to save energy, radio duty cycling (RDC) protocols are suggested to switch off the radio as much as possible. With respect to visual data, compression is also required before transmission to limit the amount of data to route and hence limit power consumption.

In this chapter, we investigate the feasibility of real video streaming using RPL. We mainly address radio duty cycling impact on the transmission of low complexity compressed images. As opposed to [62] and [63], we consider a compression technique that is more adapted to LLNs. Moreover, we do not restrict our evaluation to traditional QoS metrics such as packet delivery ratio. Rather, we assess the quality of received video using QoE metrics namely PSNR (Peak Signal to Noise Ratio) and SSIM (Structu-ral SIMilarity). To the best of our knowledge, this is the first work that evaluates video transmission using RPL where both QoS and QoE metrics are considered along with a low compression technique more suitable to LLNs.

This chapter is organized as follows. First, the used environment and simulation tool are presented in Section 2.2. Then, the adopted compression method is overviewed in Section 2.3 along with the adopted QoE metrics used. The simulation scenario is detailed in Section 2.4 and the obtained results are discussed in Section 2.5 before concluding.

2.2 Contiki, ContikiRPL, Cooja-Simulator

Contiki is a wireless sensor network operating system (OS) that implements an IPv6 protocol stack, designed to run on types of hardware devices that are severely constrained in memory, power, processing power, and communication bandwidth. It provides the OS kernel, libraries, a program loader, and a set of processes. Contiki-OS is implemented in the C language and has been designed to be easily portable to new platforms.

A Contiki system is partitioned into two components, the core and loaded programs. The core consists of the Contiki kernel, the program loader, the language runtime and a communication stack with device drivers for the communication hardware. Contiki provides two MAC layers : a CSMA, the default MAC driver and a NullMAC mechanism. The latter does not do any MAC-level processing while the former schedules a packet retransmission (up to five times) if radio layer detects a radio collision. The RDC layer sits below the MAC layer and it implements radio duty cycling mechanisms to switch on and off the radio transceiver to save energy. Contiki incorporates an RFC-compliant implementation of the IPv6 protocol stack. The IPv6 stack also contains a prototype implementation of the RPL standard, called ContikiRPL, which consists of four main components : i) a module for message construction and parsing; ii) a module for handling timers; iii) a module that implements the rules for route discovery and maintenance; and iv) a module that implements the Objective Function.

Cooja [65] is a Java-based simulator designed for simulating sensor networks running the Contiki sensor network operating system [66]. The simulator is implemented in Java but allows sensor node software to be written in C. In Cooja all the interactions with the simulated nodes are performed via plugins like Simulation Visualizer, Timeline, and Radio logger. It stores the simulation in an XML file with extension 'csc' (Cooja simulation configuration). This file contains information about the simulation environment, plugins, the nodes with their positions, random seed and radio medium etc.

2.3 Low Complexity Compression

In order to suite the constrained nature of processing resources of low-power motes, we made use of a low complexity image compression provided by SenseVid [39], a video transmission and evaluation tool that considers WVSN specific characteristics. As shown in Figure 2.1, SenseVid follows the main principle of EvalVid [67] where the interface with the experiment is insured by the use of traffic trace files. According to the user parameters, two trace files are generated. The frame trace file that includes information on the encoded images and the sender trace file gives the list of data packets to be sent by the source. The sink records the received data packets in a receiver trace file. Based on the trace files, SenseVid reconstructs the video received images allowing their subjective assessment by the user. Moreover, it generates QoE video related metrics. PSNR and SSIM metrics allow to assess the quality of both the encoded video before transmission (reference PSNR or SSIM) and the received video with respect to the initial lossless encoded video. The PSNR between the sent and the received, possibly distorted video frame is computed using :

$$PSNR = 20 \log \frac{V_{peak}}{MSE} \tag{2.1}$$

where MSE is the mean square error and V_{peak} is the maximum possible pixel value. The SSIM metric is computed as follows :

$$SSIM = \frac{2\mu_x\mu_y + C_1}{\mu_x^2 + \mu_y^2 + C_1} \text{ x } \frac{2\sigma_x\sigma_y + C_2}{\sigma_x^2 + \sigma_y^2 + C_2} \text{ x } \frac{\sigma_{xy} + C_2/2}{\sigma_x\sigma_y + C_2/2} \tag{2.2}$$

where x and y are two non negative image signals, μ_x, σ_x and μ_y, σ_y are the mean and standard deviation of x and y respectively. σ_{xy} is the sample cross-covariance between x and y. C_1 and C_2 are set respectively to 6.5025 and 58.5225.

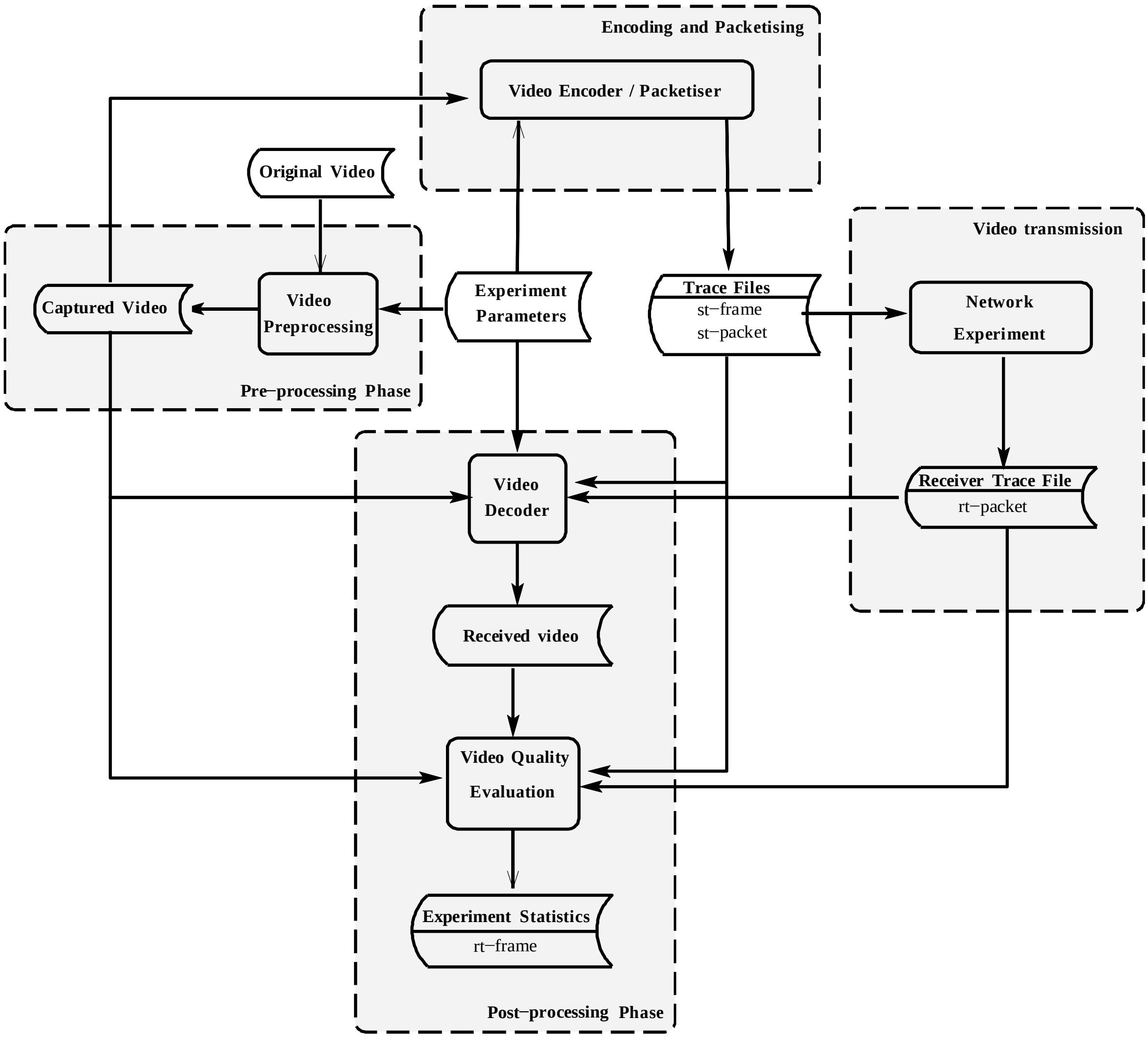


Figure 2.1: SenseVid Architecture (redrawn from [39])

In this work, we considered encoding the different captured images as main frames (M). Figure 2.2 shows the different steps of an M-frame encoding process. First, each captured image is decomposed into blocks of 8x8 shifted from range $[0, 255]$ to $[-128, 127]$. Then, a fast pruned DCT (binDCT-C [68]) is applied on each block with a triangular pattern [69]. Only coefficients located at the upper left triangle of side length $\rho \leq 8$ are considered. The resulting DCT block coefficients are quantized using the JPEG standard quantisation matrix. Trade-off between quality level and compression rate can be obtained by selecting a proper quality factor (QF) that allows adjusting the quantisation matrix values. An image visual quality ranges from the poorest (QF = 1) to the best quality (QF = 100). We set QF = 8 in our experiments allowing for a compression of about 1 bpp when $\rho = 8$ (default value). The obtained block is then linearised using the traditional zigzag scan. Finally, exponential-Golomb code [70] is applied as a lossless entropy encoding.

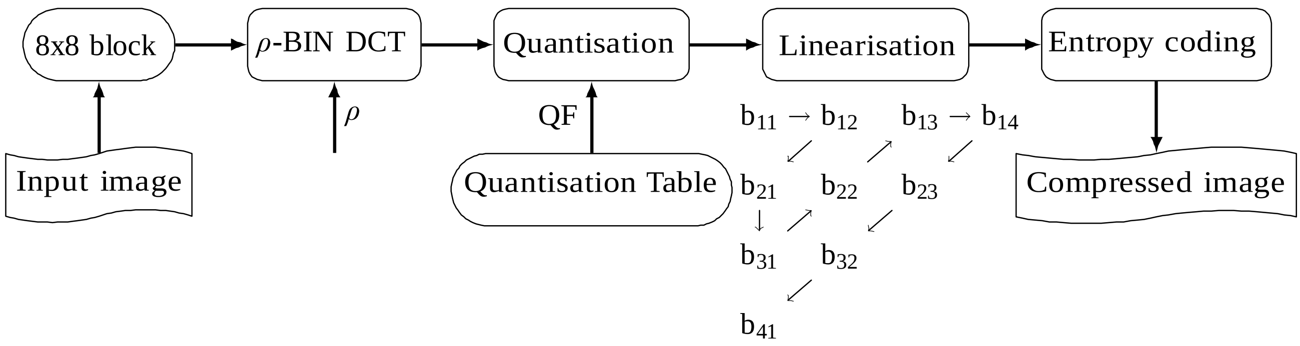


Figure 2.2: M-frame block encoding sequence (linearisation for $\rho = 4$).

2.4 Performance Evaluation Scenario

In order to carry out our performance evaluation of visual data transmission in a constrained network, we made use of Cooja, the Contiki network simulator. As a routing protocol, we used RPL implementation provided in the Contiki IPv6 network stack. We chose ContikiMAC [71] as the radio duty cycling protocol. When a sender has to transmit a unicast packet, it repeatedly sends that packet during a predefined period or till an acknowledgement (ACK) is received. For each of its neighbours, the sender stores the timing of received ACKs. This allows the sender to start transmitting a unicast packet just before the destination wakes up. Duty cycling can be tuned using Channel Check Rate (CCR) parameter defined as the frequency a node will listen to the medium to eventually receive data from its neighbours. When some activity is detected the node stays awake to receive data ; otherwise the node goes back to sleep mode for another duty cycling period.

In our simulations, we considered a square sensor field of size 90 x 90 m^2 where 16 static sensor nodes (Tmote Sky) are deployed in a grid topology. The sink is located at the upper left corner (coordinates 90,90) and the video source is located the lower right corner (coordinates 0,0). Transmission range is set to 50 meters resulting in a maximum node degree (neighbours) of 8 and 3 as the minimum number of hops from source to the sink. The interference range is set to twice the transmission range.

Tmote Sky motes are equipped with chipcon CC2420 radio (IEEE 802.15.4 compliant) for wireless communications. According to the Tmote Sky data sheet [72], radio power dissipation is 75.6 mW, 82.8 mW and 4.32 mW for respectively active, listen, and idle states. We used the Contiki OS provided powertrace tool to estimate power consumption in our experiments. Performance evaluation metrics are averaged over at least 10 simulations. Main experiments parameters are summarised in Table 2.1.

We modified the Contiki RPL-UDP server and client code to allow the use of trace files generated by SenseVid. The sender transmits data packets with a maximum payload of 112 Bytes following the sender trace file. The sink records the list of received packets in the receiver trace file. The sender trace file results from the encoding of gray scale captured images from the hall monitor video clip [73] down-sampled to half QCIF resolution. Instead of 25 frames per second, the frame frequency capture (FFC) is set to values ranging from 10 to 60 frames per minute. Sending video sequences in a 25 frames per second is simply unfeasible due to the limited resources of the considered Tmote Sky sensor motes in our topology.

2.5 Simulation Results

We first study the impact of varying the channel check rate of sensor nodes on packets delivery ratio, the quality of reconstructed images by the sink as well as the amount of consumed energy. The frequency of images capture is increased in order to estimate the highest FFC for which an acceptable images quality is obtained. Afterwards, in

Table 2.1: Simulation Parameters

Area dimensions	90x90
Number of sensors	16 - grid 4x4
Sensors type	Tmote Sky
Packet maximum payload	112 Bytes
Transport protocol	UDP
Routing protocol	RPL (IPv6)
RPL DiO min/max interval	4 s / 17.5 min
RPL objective function	ETX
MAC	CSMA / link-layer bursts
Radio Duty Cycling	ContikiMAC, NullRDC
Channel check rates (Hz)	8, 16, 32, 64, 128
Physical	IEEE 802.15.4
Radio active power	75.6 mW
Radio idle power	4.32 mW
Radio listening power	82.8 mW
Video duration	12 seconds
Frame resolution	88x72
Frame frequency capture (FFC)	10, 15 . . . 55, 60 frames/mn
Number of captured Images	2, 3, . . . 11, 12
GOP Coef.	0 - all images are intra-coded (M-frames)
Quality Factor	8
DCT	Triangular BIN DCT
DCT triangle side length ρ	3, 6, 8
Entropy coder	Exponential-Golomb (EG)

an attempt to further decrease the amount of data to transmit, we diminish the DCT triangular side length (ρ).

2.5.1 Impact of Duty Cycling

Figure 2.3 plots the obtained ratio of successfully delivered packets to the sink when increasing the FFC from 10 to 60 images per minute for different duty cycling settings (CCR values). We can see that the higher the CCR, the higher the packets delivery ratio. This ratio decreases when increasing the number of captured frames. Almost all packets are received when CCR is set to 128 Hz for 10 and 15 frames sent per minute. However, when the CCR is lowered to 8 Hz, the success ratio falls down to, for instance, less than 20% for 15 frames per minute.

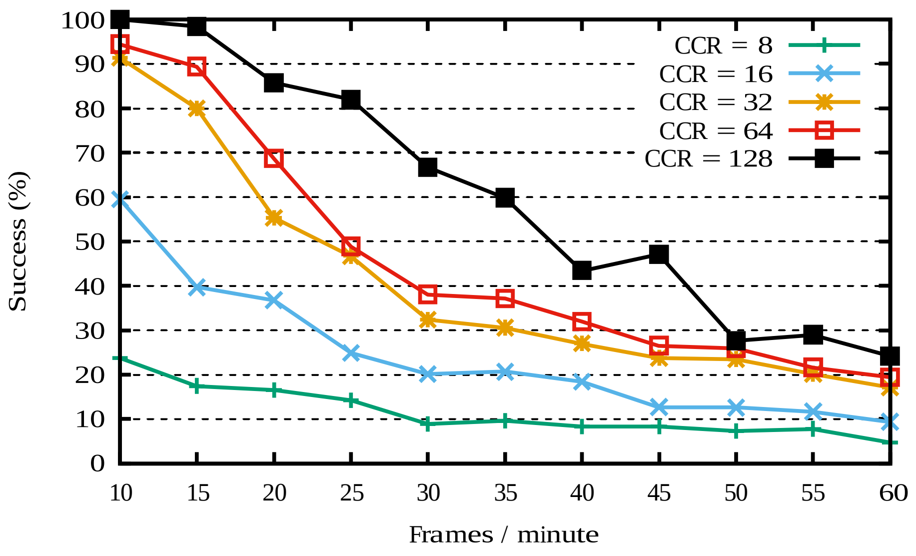
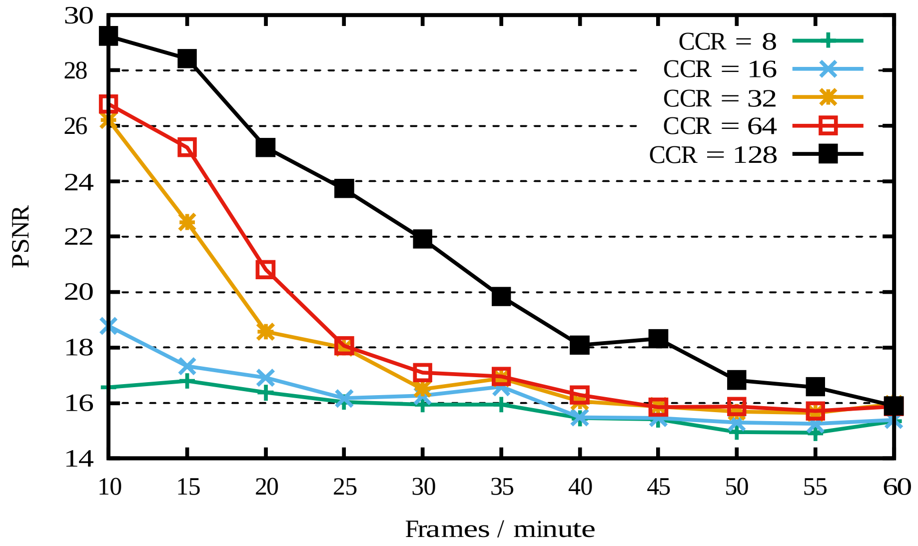
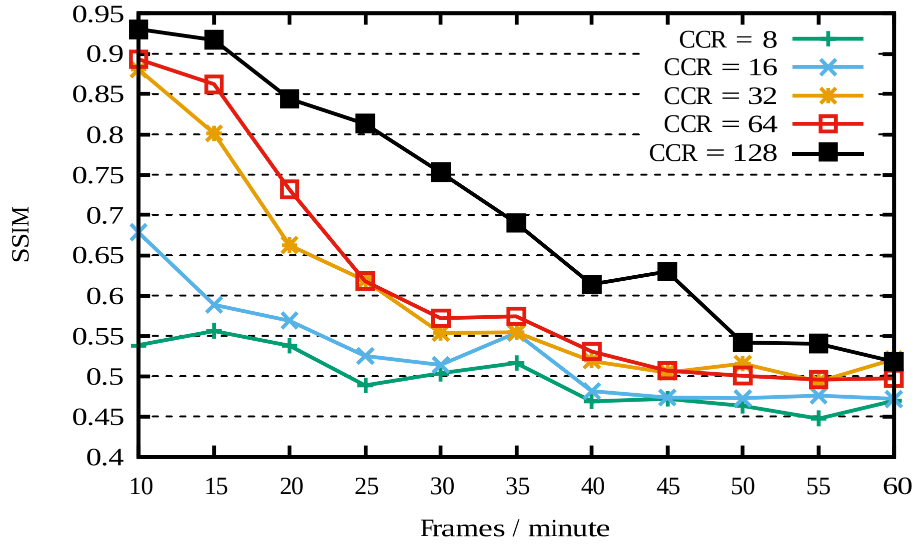


Figure 2.3: Success ratio.

Figure 2.4 shows the average PSNR and SSIM obtained after images are reconstructed by the sink. Recall that according to the mean opinion score (MOS), an acceptable quality is achieved with at least a PSNR of 20 dB. With the highest CCR, we are only able to obtain a fair image quality for a maximum rate of 35 frames per minute. Lower CCR values exhibit very poor image quality even with only 10 frames sent per minute.



(a) PSNR (dB).



(b) SSIM.

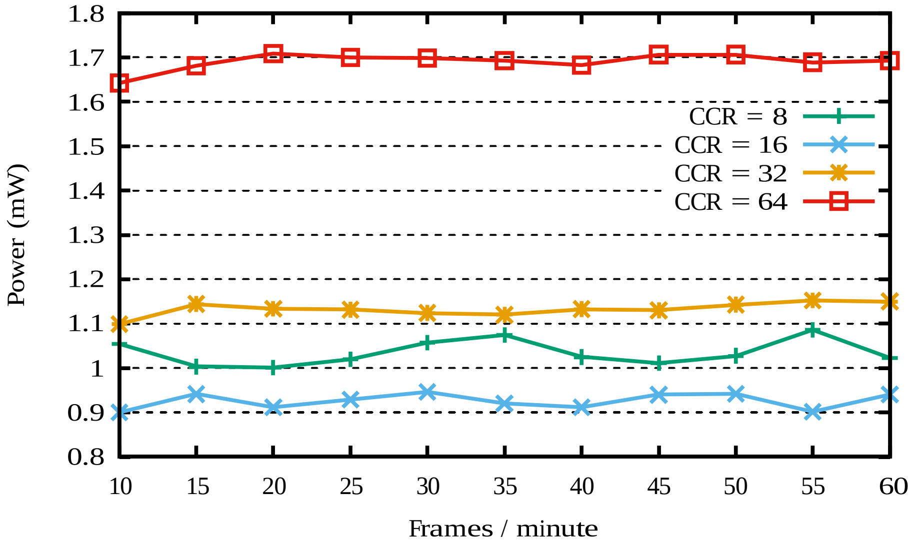
Figure 2.4: Quality of received images.

In order to get more insight on the observed delivery ratio, we plot the mean consumed power based on averages over time and individual power consumption records of the different nodes in the network. Figure 2.5a plots the overall depleted power as the number of sent frames per minute is increased. The case CCR = 128 where more than 21 mW of overall power is measured, is omitted for clarity. Figure 2.5b plots the depleted power due to radio transmission activities. The main observation is that power consumption does not depend on the transmission rate (FFC). Figure 2.5a shows that the more the CCR, the more consumed energy except for CCR = 8. In fact, a CCR set to 16 triggers less energy consumption compared to a CCR of 8. This is due to the fact that in the later case, the number of retransmissions is higher as confirmed by Figure 2.5b. We note that the highest depleted transmission power corresponds to a CCR set to 8 which attests the highest experienced transmission attempts.

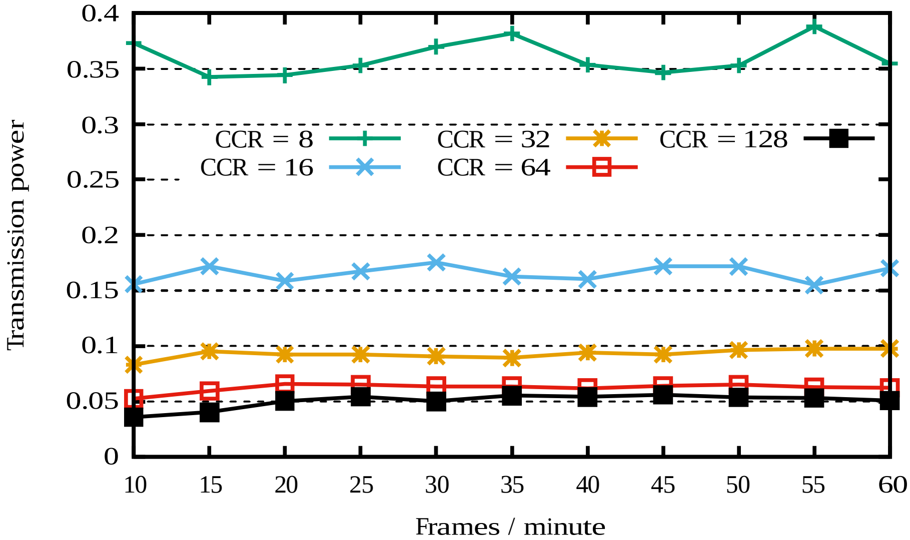
Figure 2.6 plots the depleted power due to radio transmission activities as time evolves for an FFC of 10 and 40 frames per minute. Recall that the video lasts 12 seconds and the frames are captured as required by the FFC parameter within this duration. Frames transmission is started approximately around 8 seconds. We can observe that the higher the CCR, the lower the interval where power consumption is maximised and the lower the consumed power. We can see that for the lowest CCR, transmissions last longer and power consumption achieves much higher values, more than 1.8 mW for FFC = 40.

2.5.2 Impact of Reducing the Bit Rate

The high losses experienced in the previous section are mainly due to the amount of data that the source has to transmit in a limited time window. In order to reduce the number of lost packets, we performed simulations where only a subset of the upper triangle of each block are compressed and transmitted. This is done by setting the triangle side length (ρ) to 3 instead of 8. Reducing ρ from 8 to 3 allows to reduce the bit rate from 0.99 to 0.52 bpp. The reference PSNR however decreases from about 29 dB to about 22 dB. It is worth to mention that power consumed by the radio module is not influenced by decreasing the bit rate. The source, however, can gain some energy



(a) Overall power.



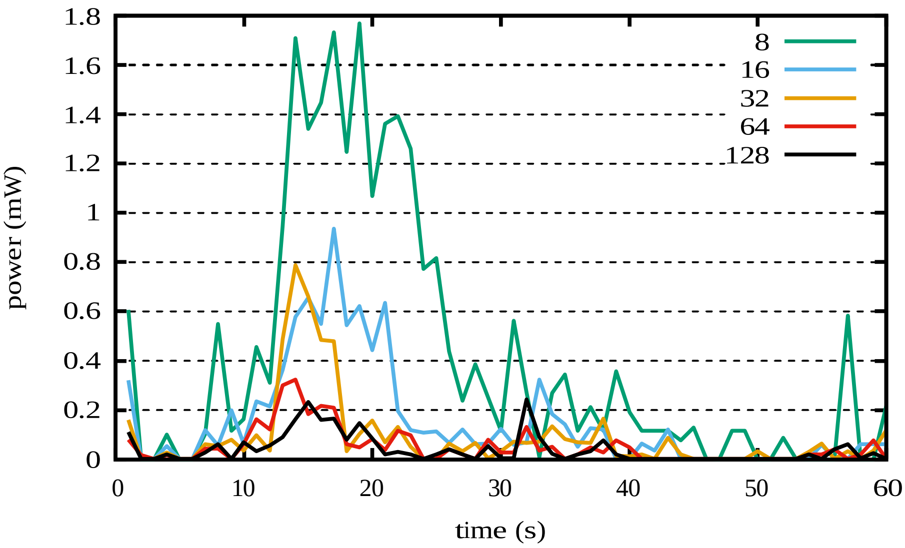
(b) Transmission power.

Figure 2.5: Power consumption (mW).

due to less computing tasks related to the compression of captured images.

Figure 2.7 plots the packets delivery ratio with $\rho = 3$ in addition to $\rho = 8$ for

(a) FFC = 10 frames per minute.



(b) FFC = 40 frames per minute.

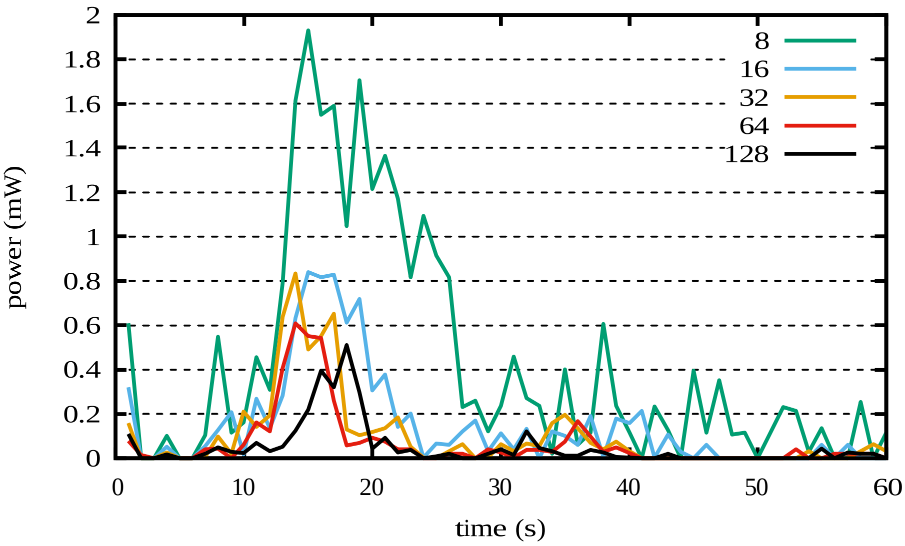


Figure 2.6: Transmission power (mW)

CCR set to 64 and 128. Lower CCR values are no longer considered since the received images quality is not satisfactory as already shown. We note that the delivery ratio is increased when ρ is set to 3 since the amount of data to send per time unit is reduced. We, for instance, observe up to 61% success ratio improvement for a capture rate of 50 frames per minute when CCR = 128.

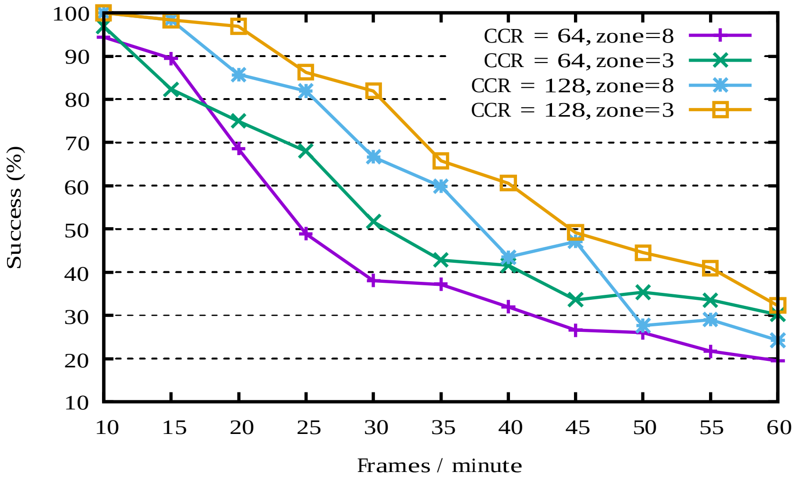


Figure 2.7: Success

Although packets delivery ratio is improved when decreasing the triangle length side, we observe that the quality of received video is not enhanced as shown by Figure 2.8. This is due to the fact that the reference PSNR is lowered when the number of considered coefficients in each block is reduced. We also can note that images quality becomes almost equivalent when the transmission rate achieves a given threshold. This rate corresponds to 40 and 25 frames per minute for a CCR of 128 and 64 respectively.

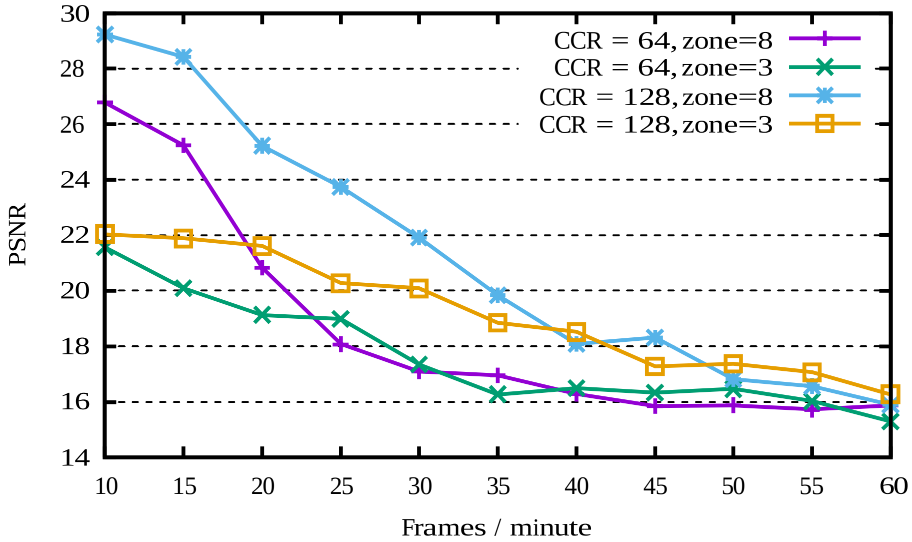


Figure 2.8: PSNR

2.6 Conclusion

RPL is the standardized routing protocol to fit the constrained nature of LLNs. In this chapter, we investigated the feasibility of visual data transmission using RPL. We adopted a low complexity compression to cope with limited resources at the source node. We mainly proceed by varying the duty cycling in order to assess its effect on power consumption as well as the overall performances of the visual data transmission. In addition to traditional QoS metrics, we used QoE metrics such as PSNR and SSIM to evaluate the quality of received images.

We showed that RPL allows to transmit images at low rates up to 35 frames per minute when images are encoded using our low power technique. As a result, RPL is far from being able to handle real time video transmission. In fact, our results proved that the radio duty cycle has a significant effect in the quality of received images. However, maximising the radio activity affects the network lifetime as more energy is depleted. In the next chapter, we suggest enhancing RPL using multipath routing to raise the available bandwidth to accommodate high data rate applications.

Chapter 3

Disjoint multipath RPL for QoE/QoS provision in the IoMT

3.1 Introduction

In LLNs, providing a descent QoS along with a user QoE for multimedia applications is challenging. High bandwidth and significant computation capabilities are necessary while LLNs are very resource constrained. To raise the available bandwidth to accommodate high data rate applications, we propose to simultaneously transmit a flow on multiple disjoint paths. RPL multipath extension has already been considered in the literature mainly for scalar data reporting and mostly make use of braided (non-disjoint) paths [51, 74, 75]. In our work, we propose a new extension of RPL to allow building and the use of disjoint multiple routes. Our extension uses existing RPL control messages to insure disjointness rather than leveraging the multi-instance opportunity provided by RPL as done by authors of [60]. As for [76], complete disjointness can be achieved using a detection mechanism at a common node during data transfer. This is allowed by the fact that these routes are used in a replication scenario. In our work, disjointness is guaranteed before data transmission, hence allowing for load-balancing strategies.

In this chapter, we begin by giving motivations behind our proposal in Section 3.2. Then, our extension of RPL to allow for multiple disjoint paths is presented in Section 3.3 before concluding.

3.2 Motivations

Since RPL was chiefly designed to meet the requirements of LLNs, the major effort is made on handling low data rate traffic. However, modern applications are increasingly involving high speed sensing and reporting due to the growing number of sensors along with higher data acquisition frequency. Under heavy traffic, RPL may suffer from severe congestion [77]. As a result, high data loss rates, significant energy expenditure and a bad QoE are experienced especially when real time video delivery is required [78]. Based on the fact that most of losses in the presence of heavy traffic are the consequence of congestion, [77] proposed that a node chooses its parent based on queue utilization of its neighbor nodes as well as its hop count to the Sink. [79] emphasized the fact that the produced DAGs based on objective functions may not utilize the full network capacity and proposed to combine RPL object function with backpressure routing. One of the proposed algorithms is targeted to time-varying data traffic loads. To meet the requirements of multimedia applications, [59] proposed FreeBW-RPL that uses a new objective function that estimates the maximum available bandwidth. Performance analyses showed that FreeBW-RPL improves upon the predefined RPL objective functions in terms of PDR, energy consumption, throughput and delay. However, the authors did not consider QoE metrics that are decisive in evaluating the quality of the video received by the end users.

With regard to high data rate applications, routing protocols need to leverage the WSN density to augment its capacity by implying more nodes in the data transfer. Multipath routing is a good candidate to allow for bandwidth aggregation [80]. Load distribution in multipath routing can result in even energy consumption among sensors which improves the network lifetime by delaying the appearance of network partition. There is an abundant literature on multipath routing in adhoc wireless networks. Regarding WSNs and the particular case of a convergecast scenario, [81] leveraged the tree structure to discover extra paths with minimal overhead. As for RPL, multipath extensions have been proposed where additional paths may serve for backup [82], balance traffic when bottleneck nodes are identified [51, 54, 56, 83], improve reliability through replication [75] or avoid/control network congestion [52, 53, 74]. All the above multipath routing are opportunistic and have one hop look-ahead.

More recently, to improve reliability, multipath-based replication strategies are studied in [75, 76]. In [75], a non common ancestor alternate parent selection is proposed to allow for disjoint paths without guaranteeing complete disjointness. In [76], the Controlled Scenario is suggested to allow replicas that cross a common node to follow different paths which grants them disjoint paths. It is worth noting that this detection mechanism is made possible by the fact that these routes are used in a replication scenario. This cannot benefit load-balancing scenarios that aim to increase the available bandwidth rather than improving reliability. Our proposal allows to build multiple disjoint paths that can be used concurrently without requiring common node detection mechanism. All this without additional communication overhead.

To sum up, the above mentioned multipath RPL protocols are targeted to scalar data transfer and mostly employ braided (non-disjoint) paths. In [60], the authors exploit the multi-instance opportunity of RPL to build two disjoint paths to transport compressed video traffic. The first instance adopts MRHOF and the resulting path is used to transport the highest priority frames while the second instance uses the shortest path (OF0) to carry low priority frames. Simulation results showed that multi-instance RPL helps improving the quality of the received video based on QoS (PDR, jitter and delay) and QoE (PSNR and SSIM) metrics. However, the adopted scenario with respect to real-time streaming is unrealistic. In fact, the transmission rate is increased without raising the frames capture frequency. This does not allow a fair QoE assessment. Our real-time scenario takes into consideration the availability of the visual data to transfer. Finally, rather than multi-instance RPL, our proposal leverages the existing RPL control messages to grant paths disjointness.

3.3 Disjoint Multipath RPL (DM-RPL)

High data rate applications such as multimedia ones are bandwidth demanding. Simultaneous use of multiple disjoint paths is a promising solution to offer additional bandwidth to ensure a good QoS/QoE. We propose to augment RPL without incurring much more overhead in such a way multiple disjoint paths are made available for a given source. This is why we build on the already existing DODAG structure maintained by RPL. We refer to this extension as DM-RPL for Disjoint Multipath RPL.

3.3.1 Network Model

We model our WSN as a connected graph $G(V, E)$ where V is the set of sensor nodes and E is the set of links connecting them. Sensors are generally in charge of reporting information to a border router (the Sink), $r \in V$. This delivery model is known as convergecast or multipoint to point communication. This is why, based on a relevant objective function, RPL builds and maintains a DODAG structure rooted at the network Sink. That is, each node x maintains its set of parents, one being designated as the preferred parent, we refer to as $\pi(x)$. When a node has to send a data packet to the Sink, it transfers it to its preferred parent. The so formed path, noted $P^+(x)$, (following child-preferred parent links) is called the RPL path . The obtained spanning tree of G rooted at the Sink is noted $T(V, E_T)$. Each tree rooted at a node $x \in T$ where $\pi(x) = r$ is called a subtree and is noted T_x. Its root x is called a subroot.

3.3.2 Paths Disjointness

The main challenge in an RPL-based multipath routing is to guarantee disjointness while keeping the related overhead as low as possible. In our work we consider disjointness in a per source based.

Lemme 3.1. In $T(V, E_T)$, a subtree T_x contains one and only one disjoint path from a source $s \in T_x$ to the root r. This path (and the corresponding subtree) can be uniquely identified by the ID of the subroot x.

Proof. (absurd reasoning) In the spanning tree $T(V, E_T)$, there is at least one path from s to r. Assume that there are two paths from s to r in the subtree T_x. The two paths will have node x as the penultimate node to reach the tree root r. This leads to non disjoint paths which is contradictory to the initial assumption.
As a subtree T_x can be uniquely identified by its root x, then the disjoint path it contains can be uniquely identified using the ID of x. □

Théorème 3.2. Let u and v be two nodes in $T(V, E_T)$. If u and v belong to two different subtrees, then their respective RPL paths $P^+(u)$ and $P^+(v)$ are node disjoint : $u \in T_x \wedge v \in T_y \wedge x = y \Rightarrow P^+(u) \cap P^+(v) = \emptyset$

Proof. Let $u \in T_x \wedge v \in T_y \wedge x = y$ and assume that $P^+(u)$ and $P^+(v)$ are not node disjoint, i.e. $\exists a \in P^+(u) \cap P^+(v)$. It follows that $a \in T_x \wedge a \in T_y$ meaning that a has
two preferred parents one in T_x and the other in T_y which leads to a contradiction. □

In DM-RPL, Theorem 3.2 is used to guarantee the disjointness of paths used by one source. Each subtree in T contains one and only one disjoint path [81]. For a given source s, to obtain disjoint paths, in addition to its RPL path $P^+(s)$, it has to designate alternate parents from disjoint subtrees. An alternate parent v (Figure 3.1), for instance, can be used by the source s as the next node in another path. Node v forwards received packets via its RPL path $P^+(v)$. To be able to identify the subtree to which belong each node (based on Lemma 3.1), we need to propagate the ID of each subroot downward. We suggest to do that using a new field, we call PID (Path ID), in DIO messages. When a DIO from the DODAG root is received, a subroot inserts its ID in the PID field before advertising the obtained DIO to its neighbors. Upon the reception of a DIO by a regular node (other than root and subroots), it updates its parents list as suggested by default RPL but additionally it records their PID before broadcasting it as it is. When the process converges, each node will get its PID and hence will be aware of its subroot, the last node before the root as well as the parents leading to the root via disjoint paths. It is worth noting that DM-RPL correctness relies on the uniqueness of the PID. This can be achieved using any addressing (naming) scheme where simply the address of the subroot is used. The main concern is to keep

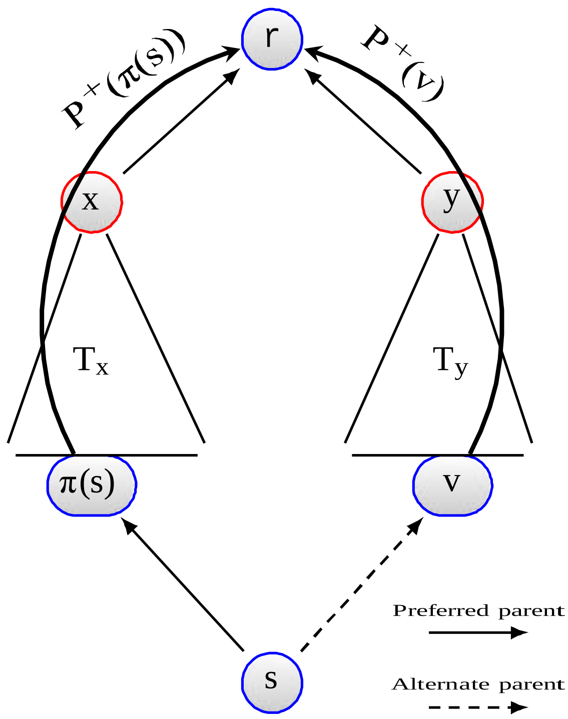
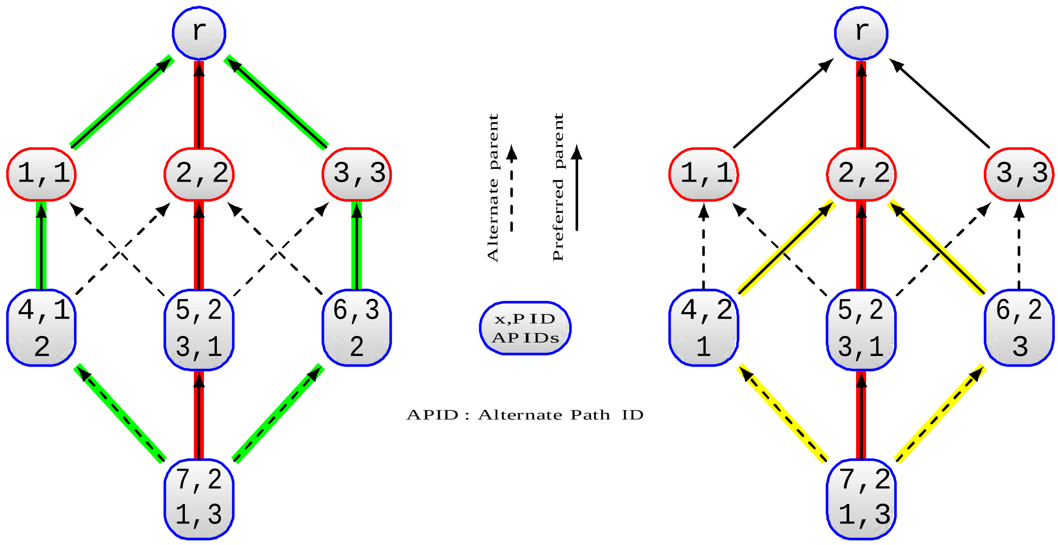


Figure 3.1: Paths Disjointness

the PID length as short as possible, this is why we consider an ID instead of the whole (IPv6) address.

To illustrate how DM-RPL operates to propagate PIDs downward using DIO messages, thus allowing the use of multiple disjoint routes, a simple topology with a DODAG structure are shown in Figure 3.2(a). In this example, we note the presence of three subtrees rooted at nodes 1, 2 and 3, direct children of the root r. These nodes have chosen r as their preferred parent after receiving a DIO from it. Before broadcasting a DIO, each subroot inserts its ID in the PID field. Regular nodes (i.e. 4, 5, 6 and 7), upon the reception of such modified DIO, update the list of their parents and keep track of the corresponding PID of each parent. Node 6, for instance, has two disjoint paths via 2 and 3 respectively. Node 7 can benefit from three paths, the red one is the RPL path and the two green are the alternate paths.



(a) 3-path scenario (b) Absence of disjoint paths

Figure 3.2: Illustrative examples

3.3.3 DM-RPL Disjoint Paths Discovery Procedure

The above described mechanism allows to know if a path via a given alternate parent is disjoint from an RPL path. However, it does not guarantee the existence of disjoint paths for a given source. Figure 3.2(b) illustrates one scenario where all the parents of node 7 have the same PID. This is likely to be the case in RPL which is commonly known as the Thundering Herd Phenomenon [84] that occurs mainly when a node with a small rank attracts much more nodes. This motivates introducing the DM-RPL disjoint paths discovery procedure. A node x willing to send data using multiple disjoint paths that has only parents with the same PID, enters the disjoint paths discovery procedure upon the reception of Δ consecutive DIO messages. Whenever, no new PIDs are obtained during this period, the next DIO is propagated with the flag field set to $\pi(x)$, the preferred parent of this node. On the reception of a such DIO, an alternate parent (node $y = \pi(x)$) will replace its preferred parent by another one with a different PID than its own. For instance, in Figure 3.2(b), nodes 4 and 6 change their preferred parent from 2 to 1 and 3 respectively as their PID is different from their current one (i.e. 2). We thus come across the same case as in Figure 3.2(a).

To avoid that replacing preferred parents is made by all the neighbors which may lead to lower quality unstable paths, a parameter $\alpha \in \{0, ..., 10\}$ is introduced to control the trade-off between the number of disjoint paths and their quality. As the path via the preferred parent is the best one according to the adopted RPL objective function, changing to an alternate parent is not always beneficial. Hence, it is required that the change only takes place if the quality of the path via the alternate parent is above a specified threshold. Upon the reception of a DIO with the a non zero flag field, an alternate parent pull a random integer from $\{0, ..., 9\}$. If it is less than α, then it keeps its preferred parent ; otherwise, it replaces it by the best alternate parent among those with a different PID than its current PID. The parameter α controls the mean ratio of the source alternate parents that have drawn to change their preferred parent. The probability that an alternate parent changes its parent is $1 - \alpha/10$. For instance, when $\alpha = 0$, all the alternate parents change their preferred parents to obtain a different PID. In a dense network where a node is likely to have a large number of neighbors, it is more interesting to increase the value of α as to bound the number of alternate parents that change their preferred parent. Increasing the number of paths through preferred parents substitution would lead to lower quality (possibly longer) paths which may result in a decrease of the multipath overall performance. Let reconsider Figure 3.2(b). Assume that α is set to 5 and that nodes 4 and 6 pull 2 and 7 respectively, then node 4 will keep its PID while node 6 will change its preferred parent from 2 to 3. In this case, we obtain two disjoint paths instead of three. Further analysis of DM-RPL behavior with respect to α and Δ parameters is done by simulation in Section 4.3.1. Algorithm 1 summarizes the main actions of DM-RPL.

3.3.4 Discussion

To handle multimedia applications, one has to deal with the issue of bandwidth scarcity in WSNs. Therefore, we considered the use of multiple disjoint paths to

Algorithm 1: DM-RPL

Data:
x is this node and $\Pi(x)$ is its parents set;
$\pi(x) \in \Pi(x)$ is the x's preferred parent. Let $\Pi^*(x) = \Pi(x) - \pi(x)$;
$\Delta \geq 2$, the minimum number of DIO a source receives before entering the DM-RPL disjoint paths discovery procedure;
$\alpha \in 0..10$, a trade-off parameter that mainly controls the replacement of the preferred parent;
Each regular node maintains an additional field PID for each parent entry in the neighbors table. This is referred to as y.PID for $y \in \Pi(x)$;

Result: Two disjoint paths for a given source. The generalization to more paths is straightforward

The root broadcasts the initial DIO message with $DIO.PID \leftarrow 0$ and $DIO.flag \leftarrow 0$;

Upon the reception of a DIO :
handle the DIO as in default RPL
if $\pi(x) = r$ **then** `// I am a subroot`
  broadcast the DIO with $DIO.PID \leftarrow x$

if $\pi(x) = r$ **then** `// I am a regular node`
  if $DIO.flag = 0$ **then**
    broadcast the DIO as it is : DIO.PID field set to this node subroot
  else `// Enter the DM-RPL disjoint paths discovery procedure`
    pull a random integer number $rdm \in 0..9$;
    if $rdm \geq \alpha$ **then**
      let y^* be the best parent of x in $\Pi^*(x)$ with $y.PID = x.PID$, then $\pi(x) \leftarrow y^*$;
      broadcast the next DIO with $DIO.PID \leftarrow y^*.PID$

A source (regular) node willing to transmit data using multipath :
The first path is the one that follows the preferred parent i.e. via $\pi(x)$;
$countDIO \leftarrow 1$;
if $\exists y \in \Pi^*(x)$ with $y.PID = x.PID$ **then**
  choose the best parent y^* to be the next hop for the second disjoint path
else
  wait for a new DIO;
  $countDIO \leftarrow countDIO + 1$;
  if $countDIO < \Delta$ **then**
    if $\exists y \in \Pi^*(x)$ with $y.PID = x.PID$ **then**
      choose the best y^* to be the next hop for the second disjoint path
  else `// Trigger DM-RPL disjoint paths discovery procedure`
    broadcast the next DIO with $DIO.flag \leftarrow \pi(x)$

obtain additional bandwidth. Also, multipath routing distributes the communication load on a larger number of nodes. This results in a more even energy consumption which may increase the network lifetime. Lastly, multipath allows multimedia traffic to be prioritized on a per-path based strategy. Compared to non-disjoint (opportunistic) multipath, disjointness requires more information to be satisfied. The probability of finding disjoint paths is lower, which requires a minimal network density. In sparse networks, finding disjoint paths is more difficult. When multiple routes are not available, the source simply uses the RPL path and thus operates in degraded mode.

The main idea in this work is to take advantage of a tree structure to build disjoint paths to meet the bandwidth needs of a multimedia application. The tree structure allows for small-state routing. Instead of implementing from scratch all the operations required to build and maintain the tree structure, we chose to use the DODAG structure provided by RPL. Any other tree-base protocol could have been used. RPL is chosen since it is considered as the de facto IoT routing protocol. Improving RPL is a hot research topic, more and more efforts are made to allow for IoMT using RPL (Section 3.2).

DM-RPL Cost

As DM-RPL builds on an already existing routing protocol, we consider here the additional cost incurred by our multipath protocol with respect to RPL in terms of both communication and processing overhead. In DM-RPL, there is no additional messages since we make use of the already existing DIO messages. Moreover, no extra fields are added, the flag and two unused 1-byte fields in the DIO message are used to store the flag and the PID required for the effective operation of DM-RPL. Additional processing is limited to the "DM-RPL disjoint paths discovery procedure" triggered every "Δ" DIO messages whenever the current configuration does not allow for the required number of paths. The source has to maintain and update a counter. The procedure is then executed by the source's alternate parents with a probability $1 - \alpha/10$. This gives an idea on the frequency of performing such a procedure that remains of a limited complexity since it consists in invoking a function that chooses the second best parent in the parents list. Simulation based results presented in Section 4.3.1 give other elements to get more insight on the frequency of this procedure.

Routes Maintenance

As DM-RPL builds on RPL, the former relies on the latter maintenance and repairing strategies. This motivated extending RPL instead of implementing a new tree-based multipath routing protocol. To maintain the DODAG structure, repair mechanisms are provided by RPL. For instance, when a node detects a network inconsistency, it can trigger a local repair that consists in urgently finding a backup path without trying to repair the whole DODAG. In some circumstances, a global repair can be initiated by the DODAG root. Note that due to network dynamics, transient periods where paths disjointness cannot be guaranteed may occur. Hence, built paths are subject to changes since they have to follow the DODAG structure. With respect to disjoint multipath maintenance, it is the responsibility of the source to ensure that the used parents always belong to different subtrees.

Multiple Sources

The main focus of DM-RPL is to propose multiple disjoint paths for one source in a DODAG structure. The protocol can be generalized to multiple sources using some additional mechanisms that have to be effective while being of low cost. One solution consists in isolating each already used subtree as proposed in [81]. This being said, one can relax inter-session disjointness as to reduce the associated overhead. Instead, one can rely on an appropriate objective function that avoids overloaded nodes. The OF we chose in our performance evaluation is based on ETX that tends to avoid overloaded nodes and less quality links.

3.4 conclusion

In an attempt to handle multimedia traffic in constrained LLNs, we proposed to extend RPL such that multiple disjoint paths can be maintained and used by video sensors. Paths disjointness is guaranteed at the source before starting transmission without incurring additional overhead. The extra bandwidth obtained is still insufficient for multimedia traffic in an LLN environment. That is, a low complexity compression technique has to be leveraged to raise the available bandwidth without omitting to cope with limited sensors resources. To prove the effectiveness of our proposal along with an efficient reduction technique, we carried out extensive simulations along with experiments on a real testbed. A detailed performance evaluation is the object of the next chapter.

Chapter 4

Performance Evaluation of Video Transmission using DM-RPL

4.1 Introduction

In this chapter, we are concerned by assessing the performance of our multipath extension we proposed in Chapter 2.6. Motivated by the fact that the extra bandwidth gained through the use of our disjoint multipath routing is not sufficient with respect to WSN's limitations, we suggest to make data reduction at the video source. This way, the quantity of the data to transmit is reduced as well as the required energy to deliver it to its final destination [85, 86]. Since widely used standard video encoding techniques such as MPEG-4, H.263 or H.264 do not fit sensor nodes constraints [64], we suggest to use a low-complexity video encoding technique more adapted to LLNs. We mainly made use of fast pruned DCT [87] where only a subset of its coefficients (lower frequency) are computed using optimized integer operations. In addition to this intra-frame compression, a low cost inter-frame encoding is provided to further reduce the amount of data to be reported. A priority encoding and packetization is also proposed. To compensate for the distortion caused by this so lossy compression, one may rely on the computational power of the Sink for an optimal reconstruction of the received images. In our experiments, we made use of a simple algorithm [88] to inpaint the lost pixels to further improve the QoE of our multimedia application.

Our performance evaluation is conducted using both simulation and real sensor testbed (IoT-LAB [4]). We mainly assess the improvement offered by our disjoint multipath routing along with a priority-based transmission strategy when compared to one-path RPL. The traffic trace model is adopted to emulate the transmission of real video flows using an actual video encoder. Pure simulation evaluation may not fairly reproduce real-life scenarios and may not provide appropriate measures to assess the performances of a given proposal. QoS metrics such as PDR (Packets Delivery Ratio) remain pure network related measures that give limited insight into the video quality as perceived by a human and do not capture its related subjective factors. Human Perception can be assessed using QoE measures such as PSNR (Peak Signal to Noise Ratio) which can be mapped onto the MOS (Mean Opinion Score) measure and the structural similarity index (SSIM) [89].

This chapter is organized as follows. The low-complexity compression method is presented in Section 4.2. The evaluated scenarios and the obtained results are discussed in Section 4.3. Section 4.4 concludes the chapter.

4.2 Priority-based Low Complexity Visual Data Reduction

Authors of [90] have shown that using multiple routes allows doubling the overall throughput. Nevertheless, a descent video quality was difficult to obtain even when capturing and transmitting at only 6 fps a gray-scale low resolution video compressed using MPEG-4. This is due to the limited capacity of an LLN network. Even with multiple paths, it is still difficult to provide enough bandwidth to meet the needs of data intensive applications that are often encountered in the IoMT. Having sensors to deliver all the visual data captured is inefficient and should be avoided. Therefore, in-network data reduction is definitely needed to reduce transmissions. As mentioned earlier, MPEG-4 is not adapted to low power video sensors. Not even the low complexity JPEG still image compression algorithm. This is mostly driven by the discrete cosine transform (DCT) step [91, 92].

In order to accommodate the limited computational capabilities of low-power video sensors, we adopted a priority-based low complexity image compression method proposed in [39]. A captured frame is encoded as a main (M) or a secondary frame (S). An M-frame is intra-coded and an S-frame is inter-coded where only the difference with the previous M-frame is encoded. The choice between M and S encoding depends on a parameter, g, we call the GOP coefficient. If the mean square error (MSE) with respect to the previous M-frame is less than g^2, then the frame is S-encoded ; otherwise, it is M-encoded. Note that if $g = 0$ then we get all M-frames. Raising its value produces more S-frames which reduces the data transmission rate. A lossless entropy encoding is applied at the last step for both M- and S-frames.

4.2.1 Main Frame Encoding

Figure 4.1a shows the steps of encoding an M-frame. The image is first decomposed into 8x8 blocks. Then, a fast pruned DCT called binDCT-C [68] is applied on each block with a triangular pattern [69]. Only coefficients located at the upper left triangle of side length $\rho \leq 8$ are considered. This is done to reduce the DCT computational complexity as well as the amount of data to encode and transmit. The resulting DCT block coefficients are quantized using the JPEG standard quantization matrix. A quality factor (QF) that allows adjusting the quantization matrix values can be adjusted to control the trade-off between the compression rate and the obtained quality. The resulting block is then linearized following a zigzag scan and a priority mechanism is implemented. Since the useful signal information is concentrated in the lower DCT coefficients, we propose to divide each block coefficients into two levels. The highest priority level is composed of the DC component (b_{11}) and the following two AC components (b_{12} and b_{21}). The remaining coefficients of the block are put in the low priority level.

4.2.2 Secondary Frame Encoding

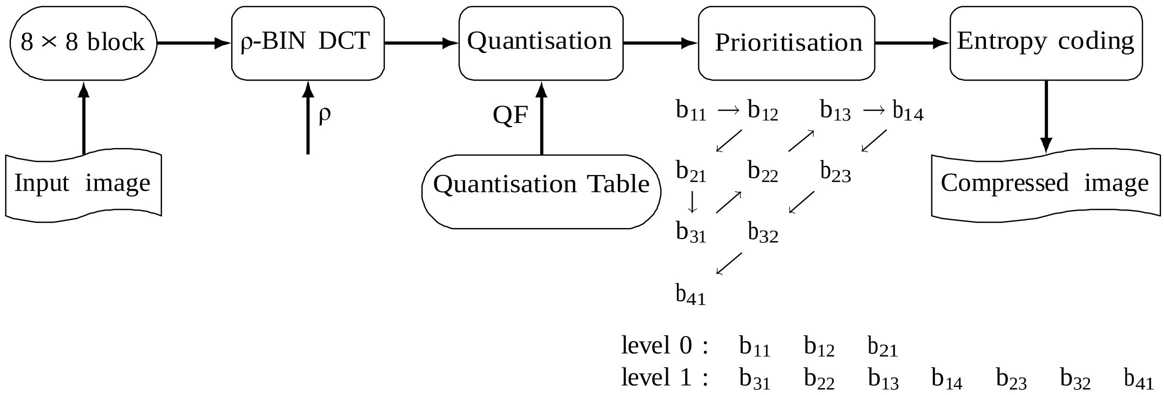
As shown in Figure 4.1b, the difference between the current frame and the previous M-frame is divided into 8x8 blocks. Then, a MOS-based prioritization scheme is performed on each difference block d. Based on its mean square $MS = \sum d_{ij}^2/64$, a mapping is established to characterize the quality we would obtain if this block is lost. For instance, the highest priority is given to blocks with $MS > 650$. If such a block is lost, then when reconstructed based on the previous M-encoded block, it will obtain a bad quality with a $PSNR < 20$ dB. To further save video sensors and network resources, a thresholding is applied on the obtained blocks where values less than θ, a threshold similarity parameter, are simply zeroed.

4.2.3 Frames Reconstruction at the Sink

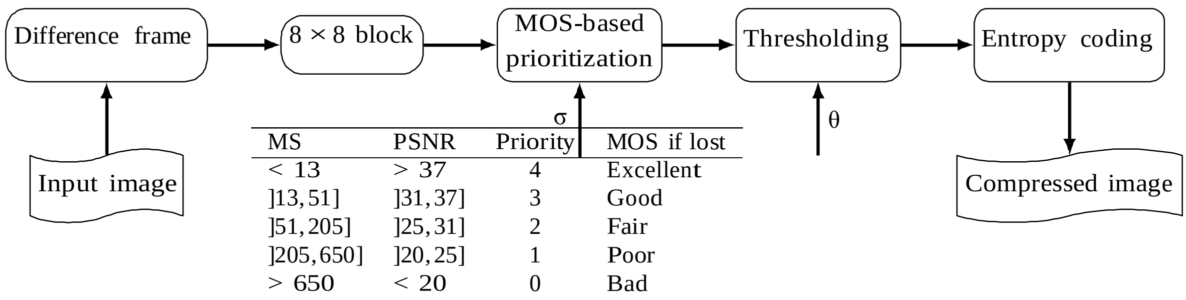
Data reduction combined to multipath transmission do not avoid data packet losses due to the constrained nature of our target network. When the Sink reconstructs the images based on the received packets, bands of damaged pixels appear. In order to fill in the lost pixels in an image, we propose to benefit from a digital inpainting algorithm. We adopted the simple and fast algorithm of Telea [88] based on the fast marching method for level set applications.

4.3 Performance Evaluation

To conduct our performance evaluation using both simulation and real experimentation, we extended the Contiki 3.0 implementation of RPL [93]. Real video clip transmission is emulated through the use of traffic trace file (st-packet) generated by SenseVid [39], a tool for QoE video transmission evaluation in WSN. The RPL-UDP sender application is modified to enable the transmission of packets according to the instructions (from the traffic trace file) received via the serial connection. Similarly, the receiver modules is modified to enable the retrieve, via the serial connection, the



(a) M-frame



MS	PSNR	Priority	MOS if lost
< 13	> 37	4	Excellent
]13, 51]	]31, 37]	3	Good
]51, 205]	]25, 31]	2	Fair
]205, 650]	]20, 25]	1	Poor
> 650	< 20	0	Bad

(b) S-frame

Figure 4.1: Low-complexity Compression Scheme

list of received packets to store in a receiver trace file (rt-packet). SenseVid, based on the list of received packets, reconstructs the images considering the experienced losses. QoE video related measures are computed. In addition to the QoE metrics, we consider in our performance evaluation, traditional QoS metrics such as energy and PDR (packet delivery ratio). Each experiment is repeated at least 20 times to avoid fluctuation.

To get insight into the performances of our disjoint multipath extension, we made extensive simulations using Cooja [65], the Contiki network simulator. We began by studying some properties of our multipath discovery procedure with respect to its parameters α and Δ. Then, the performances of DM-RPL are assessed with respect to standard RPL. Finally, real time video frames transmission is considered in real testbed experiments.

4.3.1 Preliminary Analysis

In order to get some insights into the behavior of DM-RPL with respect to the required time to obtain additional paths and their number, we performed simulations using a random topology of 25 sensor nodes distributed in a square area of side 120m. The propagation model is a Unit Disk Graph Model with a transmission range of 45m which results in a mean degree (number of neighbors) of 3.2 for each node. Despite the fact that our multipath protocol allows to build more paths, with such a density, we used only two paths to be able to perform a sufficient number of experiments. The source node obtained at least 2 paths in more than 50% of the simulations for $\Delta = 5$. When the DM-RPL disjoint path discovery procedure is triggered, the source is able to get at least 2 paths in all the simulations when $\alpha = 0$. When α is increased to 3, 5 and 7, the source gets at least 2 paths in 88%, 76% and 53% of cases respectively.

Figure 4.2 shows using box plots the required time to get the second path when the DM-RPL disjoint discovery procedure is triggered for different values of Δ and α. The number of built paths is depicted using black squares when α is varied. As expected, the number of paths decreases when α is increased. Moreover, the required time to get a second path increases with Δ. Although in half of the cases, this delay remains

below 50 sec, it can rise to high values. Note that this delay bounds (minimum and maximum values) depend on the min/max DIO intervals set to their default values (4 sec and 17.5 min, respectively) in our simulations. When these latter are set to lower values, we can consider rising Δ. In order to reduce the convergence time, one
can consider the use of the DIS-Trickle mechanism in a selective (both temporal and spatial) way to accelerate the convergence of the multipath routing.

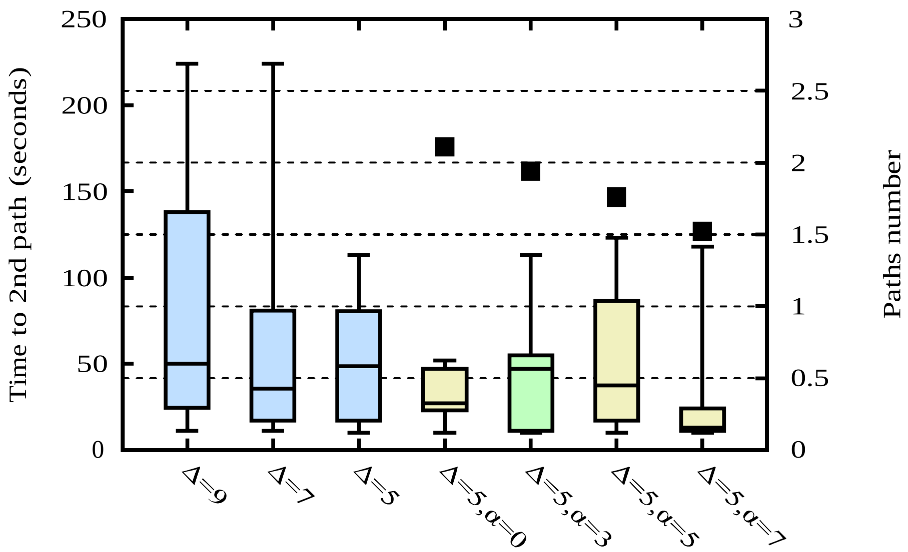


Figure 4.2: DM-RPL parameters (α and Δ) impact

4.3.2 Simulation Results

In this section, Cooja simulations are performed with the aim of comparing DM-RPL using two paths with default RPL. In cooja, the least significant bytes of the IPv6 address are set to the ID of a node that corresponds to the order in which the node was created. To designate a disjoint path, we use as a PID, the ID of the corresponding subroot. The sent traffic corresponds to 25 gray-scale images (giving a frame capture rate of 2 fps) extracted from the 300 frames that composes the hall monitor video clip [73]. To further fit the LLN limited capacity, we consider down-sampling the images to 128x128 resolution. In these simulations, all the captured images are encoded independently of each other (M-encoded). We consider two main scenarios. First, all the packets get the same priority and are sent without differentiation. In the second scenario, two levels of priority are used and packets with higher priority are sent twice by the source, each on one path in the case of DM-RPL. A contention-based CSMA MAC protocol is used to avoid collisions. At a higher layer, the OF when appropriately chosen can also play a role in avoiding packet losses. We considered the MRHOF in this work. Table 4.1 summarizes the simulation parameters.

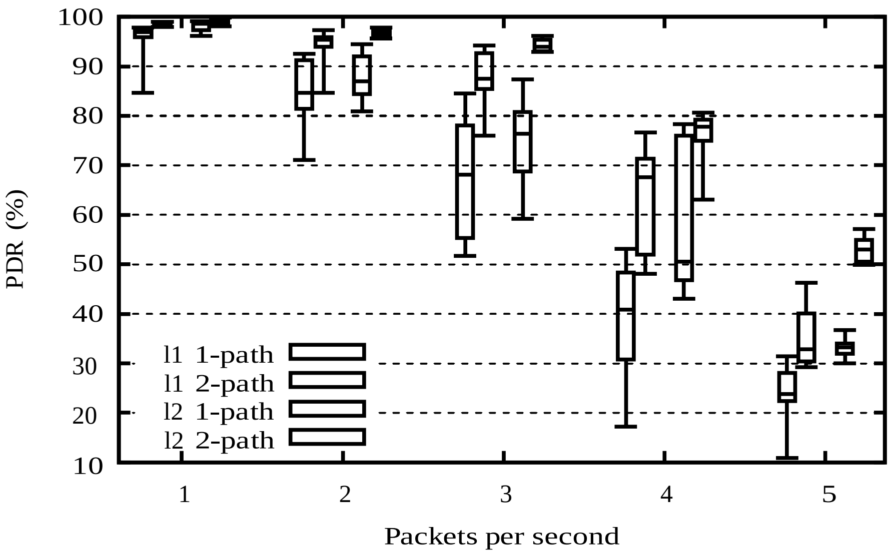
Figures 4.3a-4.3b show respectively the distribution and mean PDR obtained by RPL (1-path) and DM-RPL (2-path) for one (l1) and two (l2) priority levels when the transmission rate is varied from 1 to 5 packets per second (pps). While the mean PDR decreases for all scenarios, we note that with two priority levels, we obtain better performances in both RPL and DM-RPL. This is due to the replication of a subset of the data packets which results in an improved reliability. Besides, using two paths allows obtaining higher PDR with or without replication. DM-RPL allows getting more bandwidth thanks to data splitting on two disjoint paths. We observe that the priority-based scenario coupled with multipath routing obtains the highest PDR with values more concentrated around the median.

Figures 4.4a-4.5b depict the quality of the received images as reconstructed by SenseVid considering the experienced packet losses. When the transmission rate is low as 1 pps which results in a very low loss rate, we note that the obtained quality is close to that of the transmitted (reference) frames mainly for DM-RPL. Note that the reference PSNR and SSIM are respectively 34.0920 dB and 0.9629. When the transmission rate is increased the quality deteriorates due to the experienced losses. We observe, however that the quality is improved when higher priority packets are replicated (l2) regardless of the number of used paths. This is more noticeable when two paths are used. In fact, we observe that the minimum quality obtained using DM-RPL with two priorities is always higher than the maximum quality obtained by one path and one priority. Paths diversity reduces losses and important visual data success transmission is likely to be maximized with replication of higher priority packets.

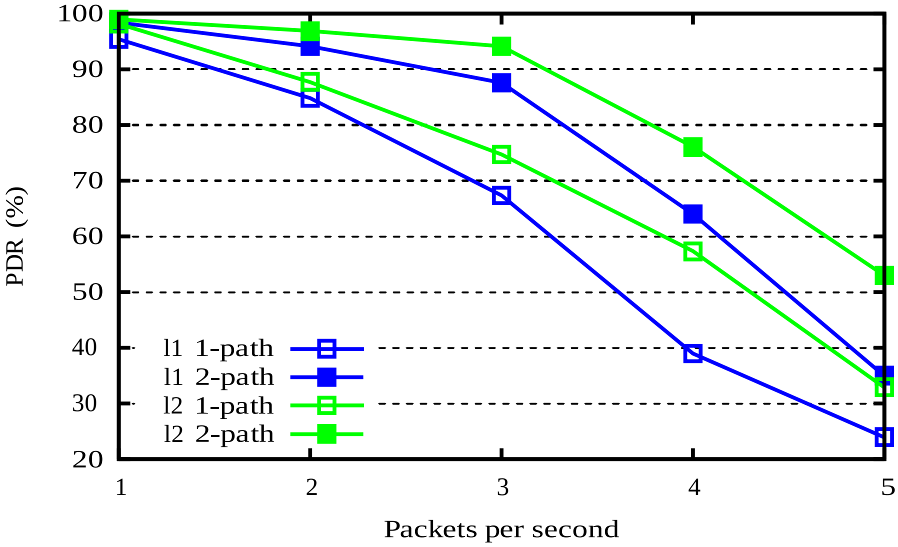
Figure 4.6 shows visual samples of frame 22 with the corresponding PSNR and

Table 4.1: Simulation Parameters

Operating system	Contiki OS
Sensors type	Tmote Sky
Number of sensors	25
Area	120 m x 120 m
Transmission range	45m
Interference range	50m
Packet max. payload	128 Bytes
Transport protocol	UDP
Routing protocol	RPL, DM-RPL (IPv6)
DIO min/max intervals	4 sec/17.5 min
RPL objective function	MRHOF
DM-RPL default param.	$\Delta = 5, \alpha = 3$
MAC	CSMA
Radio Duty Cycling	ContikiMAC
Channel check rate	128 Hz
Video duration	12 seconds
Frame resolution	128x128
Frames per second	2
Number of frames	25
Quality Factor	20
DCT	Triangular ($\rho = 8$) BIN DCT
Number of priority levels	1, 2
Entropy coder	Exponential-Golomb (EG)

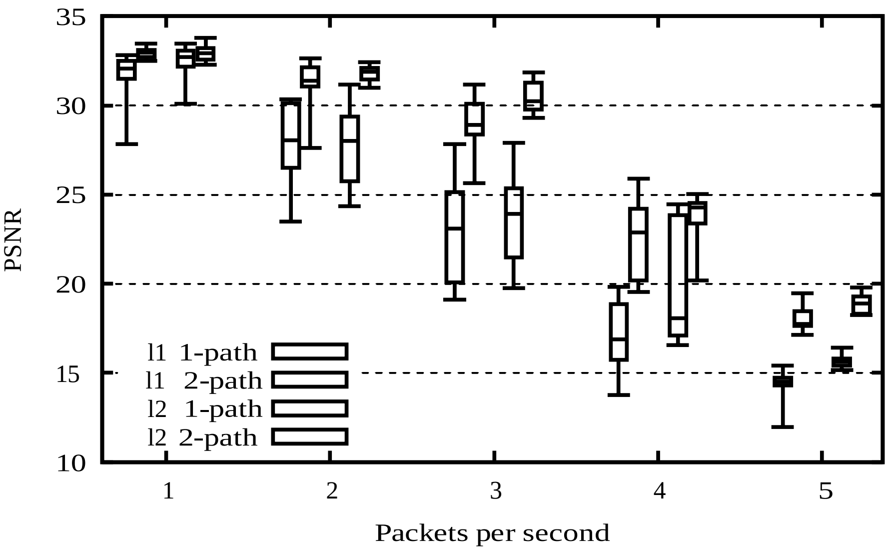


(a) PDR distribution

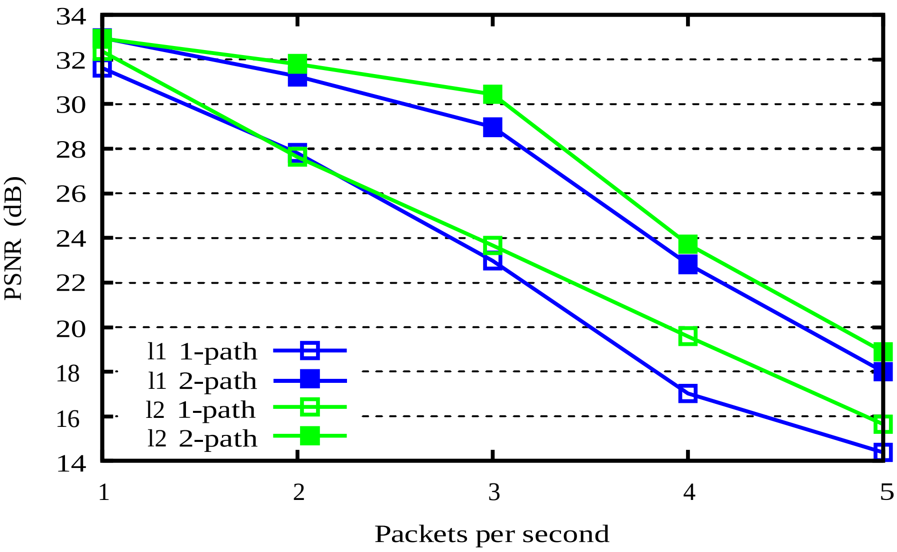


(b) PDR mean values

Figure 4.3: Simulation results - Packet Delivery Ratio

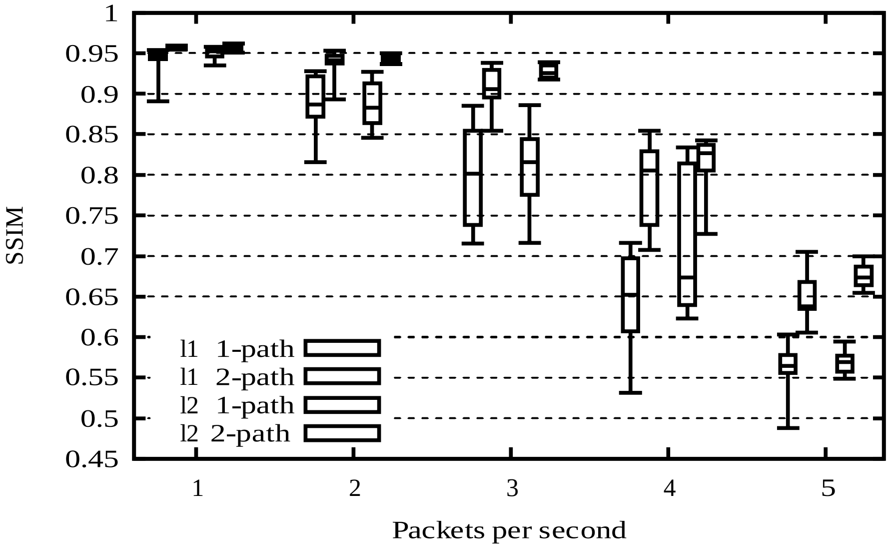


(a) PSNR distribution

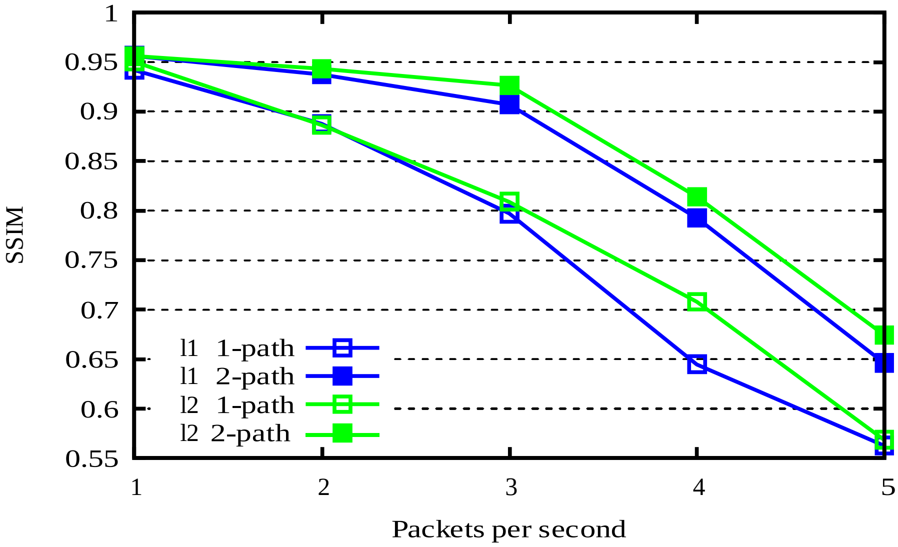


(b) Mean PSNR

Figure 4.4: Simulation results - PSNR (dB)



(a) SSIM distribution



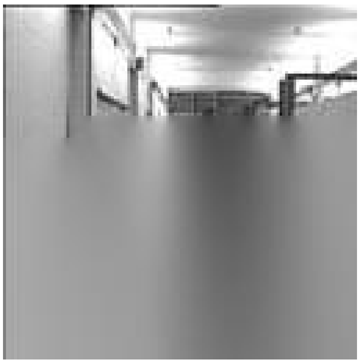
(b) Mean SSIM

Figure 4.5: Simulation results - SSIM

SSIM when transmitted at 4 pps. The rightmost one is the reference frame transmitted by the source. The other images are those received by the Sink when using the different transmission scenarios. We observe that the image that corresponds to the first scenario (1 path and 1 priority level) is useless. When using 2 paths along with replication of higher priority packets, we are able to distinguish the man walking in the corridor.

Finally, to get some insight on the impact of our transmission strategies on energy, we represent the distribution and mean values of the consumed power by the radio for transmission. Figures 4.7a-4.7b show that transmitting at a higher rate consumes more energy especially when only one path is used. More interesting, we observe, for higher data rates, a significant increase in power consumption when replication is used with RPL while it remains mostly the same with DM-RPL. Our multipath protocol allows obtaining the lowest energy expenditure especially for high data rates. This is mainly due to the absence of retransmissions due to an improved reliability as shown by PDR curves.

(a) Reference frame
PSNR 34.244 dB
SSIM 0.9620



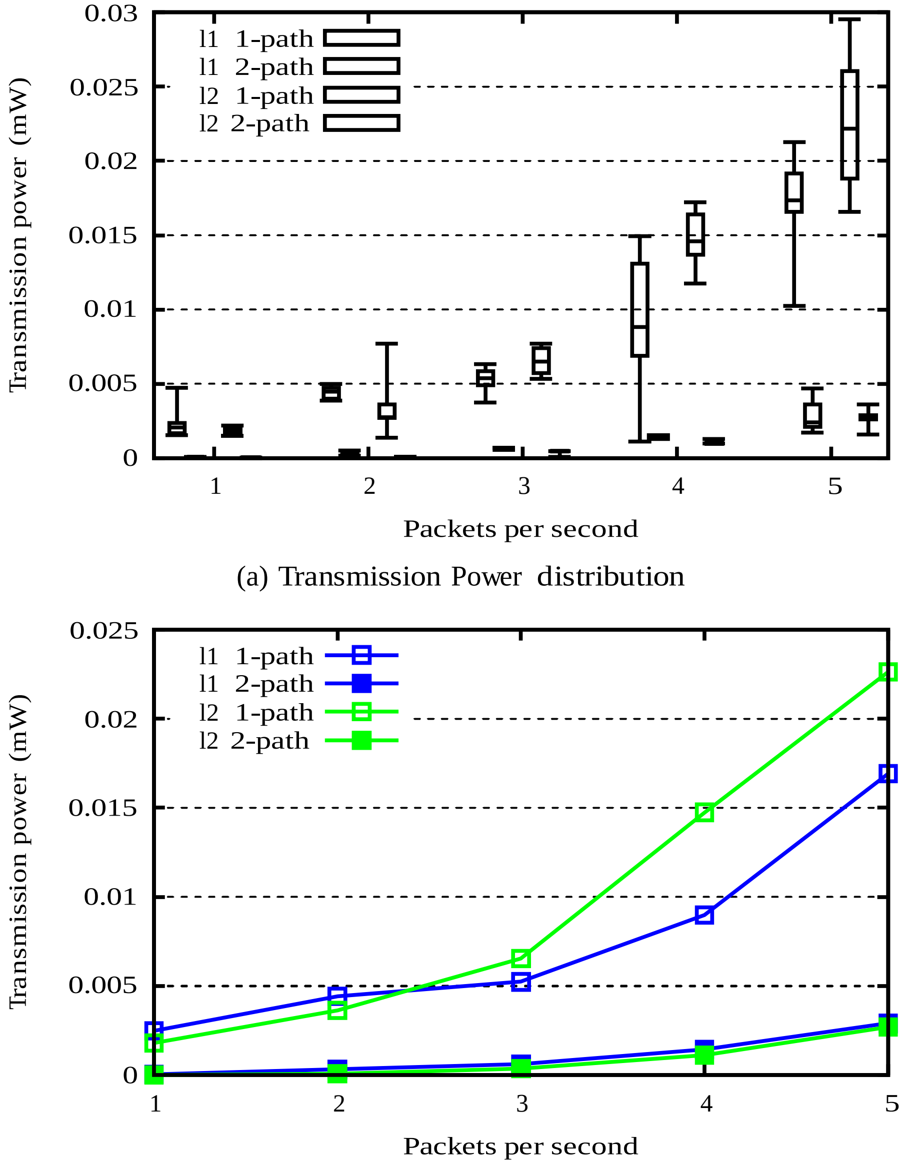
(b) l1 1-path
PSNR 17.315 dB
SSIM 0.6650

(c) l1 2-path
PSNR 22.416 dB
SSIM 0.7940

(d) l2 1-path
PSNR 20.841 dB
SSIM 0.7610

(e) l2 2-path
PSNR 24.030 dB
SSIM 0.8400

Figure 4.6: Sample images for frame 22 when transmitted at 4 packets per second.



(a) Transmission Power distribution

(b) Mean Transmission Power

Figure 4.7: Simulation results - Power consumption (mW)

Table 4.2: Transmitted video characteristics (IoT-LAB)

Images number	ref. PSNR (dB)		ref. SSIM		compression (bpp)		bit rate (Kbps)		packets to send		Frames sequence when g = 15
	g = 0	g = 15	g = 0	g = 15	g = 0	g = 15	g = 0	g = 15	g = 0	g = 15	
9	29.50	28.52	0.9081	0.8980	0.66	0.57	7.8	6.73	99	90	MMMMSMSMS
12	29.50	28.81	0.9010	0.8997	0.66	0.57	10.40	8.98	132	116	MMMMMSMMSMSM
15	29.50	28.05	0.9077	0.8959	0.66	0.52	13.01	10.32	165	140	MSMMMMSMSMSMSSM
18	29.51	28.31	0.9078	0.8960	0.66	0.51	15.6	11.94	198	162	MSMMMSMSSMSMSMSSMM

4.3.3 Experimental Results

In this section, we compare DM-RPL to default RPL by focusing on the impact of increasing images frequency capture on their real time transmission. To do so and coping with the limitations of the used sensors, we consider the transmission of only 9 to 18 gray-scale images of the hall monitor video. Moreover, we lower the quality factor to 5. To further reduce the data transmission rate as shown in Table 4.2, we include some S-frames by setting the GOP coefficient g to 15. σ is set to zero so only their highest priority level data are encoded and transmitted. The threshold similarity θ is set to 1. All the resulting packets are assigned the same priority level.

Our real experiments are made using IoT-LAB [4], an open experimental IoT testbed composed of thousands of nodes distributed over six sites in France. We made use of 15 M3 open nodes[1] located at the F4 corridor of Grenoble site. In order to be able to find disjoint paths in DM-RPL, we need to propagate downward the PID that must uniquely designate each subroot in the DODAG. We used in our implementation, the last two bytes of the IPv6 address of each subroot. The PID uniqueness is guaranteed since only these bytes are varied in the IPv6 address assignment and subnetting in IoT-LAB testbeds. The unused 7th (Flags) and 8th (Reserved) bytes of the DIO packet are chosen to constitute the PID field. We access the IoT-LAB testbed using provided command-line tools and retrieve our experiments results using serial ports. Figure 4.8 shows how transmission instructions based on st-packet file are given to the source (node 207) that sends in a real time the captured images to the root (node 240). A possible tree structure is also shown where the links are those connecting each node to its preferred parent.

[1] https://www.iot-lab.info/docs/boards/iot-lab-m3/

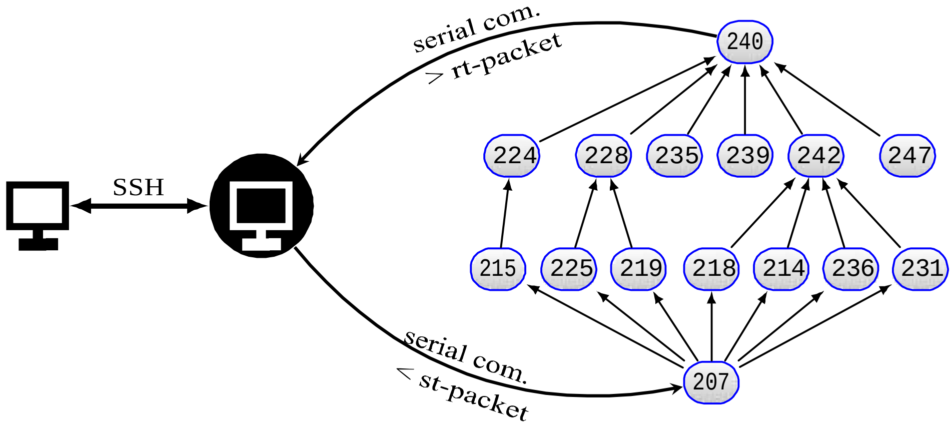


Figure 4.8: IoT-lab Experiment Setup and Interface with SenseVid.

Figure 4.9 shows the mean PDR obtained when RPL and DM-RPL are used to send the two sequences of frames (g0 and g15). We observe that the PDR decreases when the number of images to transmit is increased. This was expected since the data rate transmission is increased. DM-RPL outperforms RPL in terms of PDR whatever the transmission rate. Reducing the transmission rate by inter-coding some frames ($g = 15$) allows achieving higher PDR with respect to the case where all frames are intra-coded ($g = 0$). This observation applies for both RPL and DM-RPL.

Figure 4.10 depicts the mean consumed power for the different schemes as a function of the number of captured frames. Compared to RPL, DM-RPL consumes lower amount of energy. This is the consequence of traffic load balancing when using DM-RPL. Lower packet losses are experienced and thus reducing the amount of MAC level retransmissions. This translates in lower energy consumption.

Figures 4.11a-4.12b show mean and distribution plots of the obtained PSNR and SSIM of the received images by the Sink. Triangles in the box plot depict the reference PSNR and SSIM. Data reduction due to the introduction of S-frames brings lower image quality with respect to the use of only M-frames as shown by the reference PSNR and SSIM in Table 4.2. We note that the quality is lowered when increasing the transmission rate. The images quality is still fair ($PSNR > 20$) for all schemes when the number of frames does not exceed 12. Using two paths with more data reduction

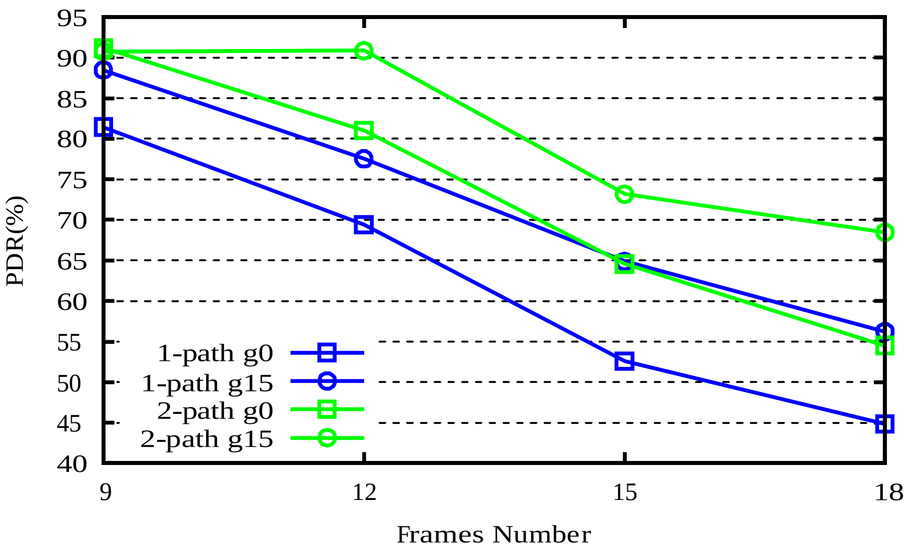


Figure 4.9: IoT-LAB experimental results - Mean PDR

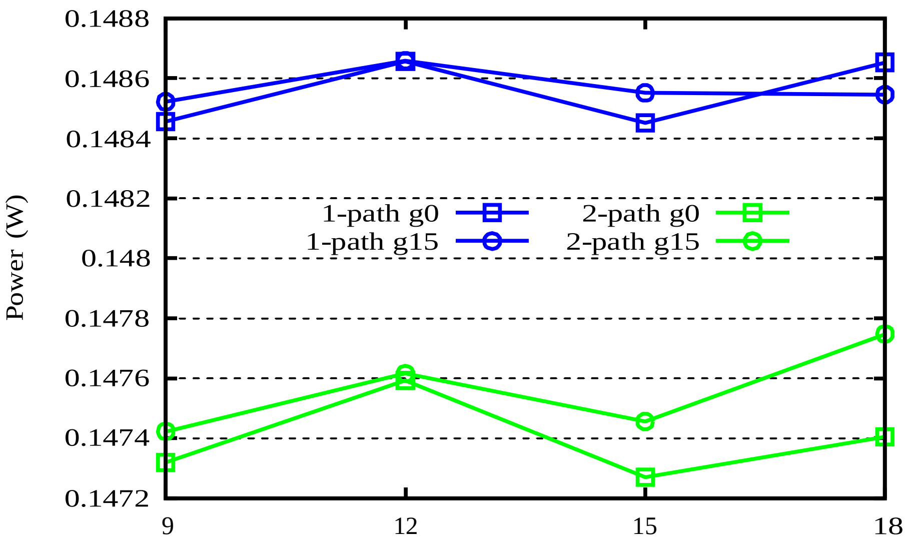
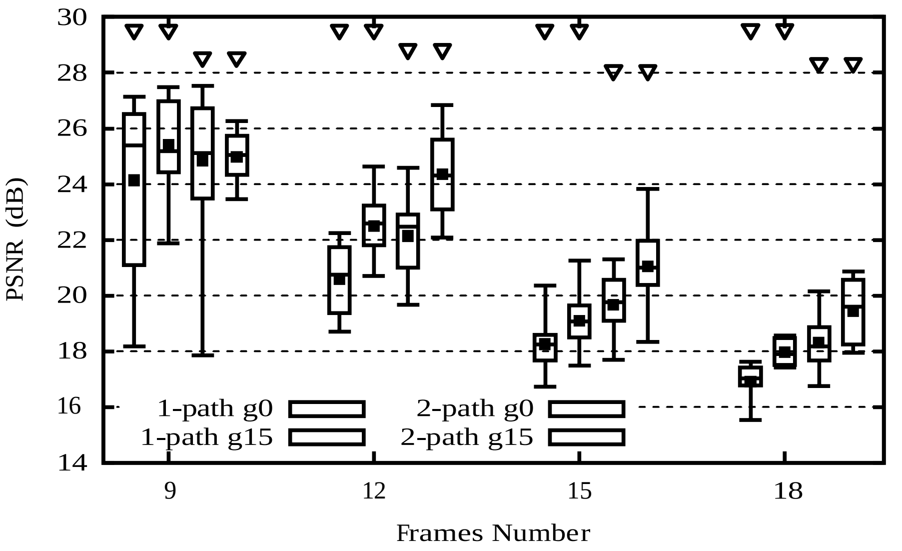


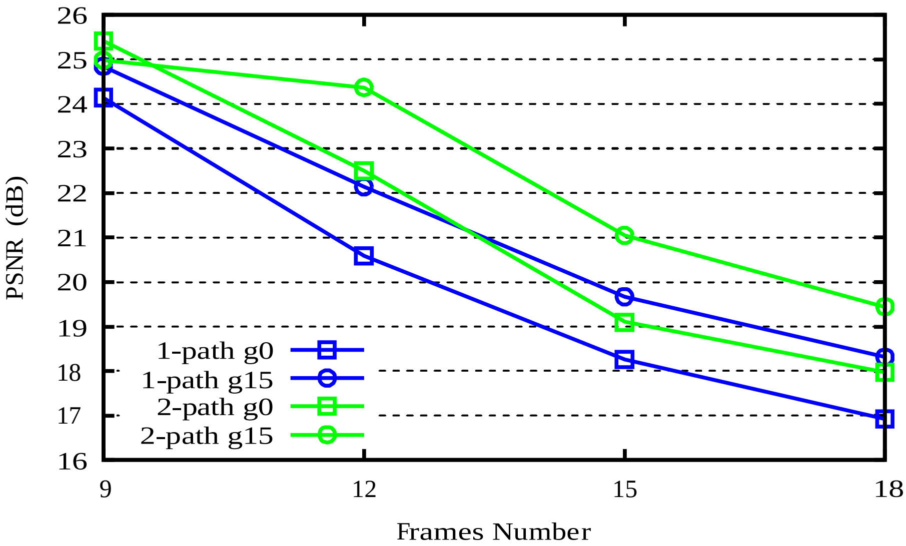
Figure 4.10: IoT-LAB experimental results - Mean power consumption

(2-path, g15) allows an acceptable quality even for the highest transmission rate. Note that thanks to data reduction, received images quality is better when $g = 15$ compared to $g = 0$ even if the corresponding reference values are higher in the latter case.

Figure 4.13 shows the third transmitted frame when 12 images are captured and transmitted with samples of the same frame as received by the Sink for the different evaluated schemes. Observing the pictures confirms that data reduction strategy is profitable mainly when two paths are used where both PSNR and SSIM are improved.

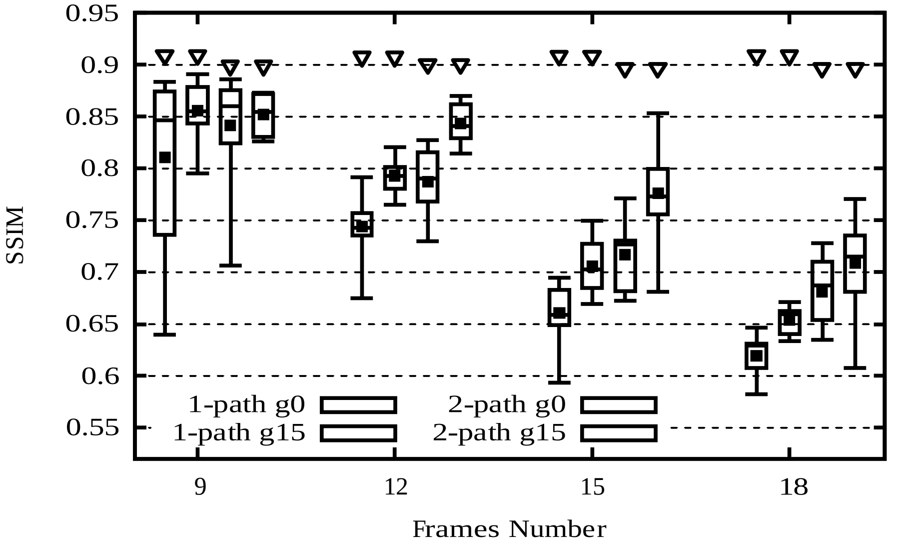


(a) PSNR distribution.

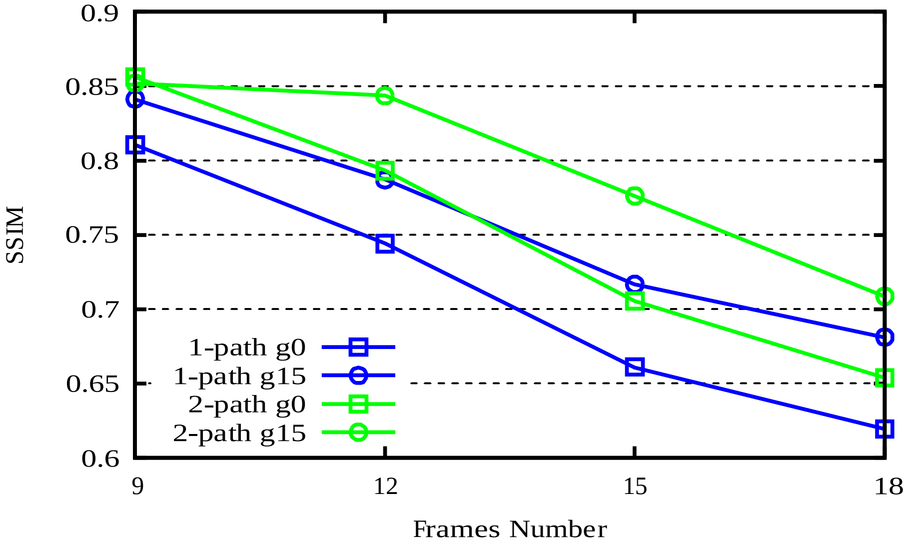


(b) PSNR mean.

Figure 4.11: IoT-LAB experimental results - PSNR



(a) SSIM distribution.



(b) SSIM mean.

Figure 4.12: IoT-LAB experimental results - SSIM

(a) Reference
PSNR 29.530 dB
SSIM 0.907

(b) 1-path, g0
PSNR 20.180 dB
SSIM 0.747

(c) 2-path, g0
PSNR 22.185 dB
SSIM 0.802

(d) 1-path, g15
PSNR 19.819 dB
SSIM 0.767

(e) 2-path, g15
PSNR 24.319 dB
SSIM 0.850

Figure 4.13: Sample images for frame 3 when 12 frames are captured.

4.4 Conclusion

In this chapter, an intra-frame priority mechanism is implemented at the encoding and packetization steps. At the Sink side, an inpainting algorithm is used to allow recovering lost pixels. We carried out experiments using both simulation and real WSN testbed along with real video clip transmission. We considered both QoS (packet delivery ratio and energy) and QoE (PSNR and SSIM) to assess the performance of our proposal mainly compared to standard RPL. We proposed to replicate high priority packets which are sent on two paths. Our results show that using two paths along with the priority mechanism achieves the highest performances. On the one hand, multiple paths allow to gain more bandwidth when compared to one path. On the other hand, highest priority packets delivery ratio is improved which results in reconstructed images with better quality. Energy expenditure is also reduced.

General Conclusion

Routing multimedia data in LLNs is crucial in the development of the IoMT due to unreliable error-prone communication medium and application-specific QoS requirements.

This thesis, first, analyzed RPL to identify some of LLNs potential gaps. We evaluated video transmission using RPL where both QoS and QoE metrics are considered along with a low compression technique more suitable to LLN. The Cooja simulator provided by the Contiki operating system is used to carry out our experiments. We primarily demonstrated that RPL is unable to handle real-time video transmission where it can only transmit at low rates up to 35 frames per minute. As a result, we came to the conclusion that default RPL is far from being able to handle real time video transmission.

To raise the available bandwidth to accommodate high data rate applications, we proposed to simultaneously transmit a flow on multiple disjoint paths. To do so, we proposed to exploit the DODAG structure, already maintained by RPL, to build multiple disjoint paths without incurring extra overhead. We called the newly obtained protocol DM-RPL (Disjoint Multipath RPL).

To reduce the amount of data to send while considering the low computation resources of video sensors, we proposed to apply a priority-based low-complexity encoding scheme on the captured pictures. Highest priority data can be replicated on more than one path. Our conducted experiments using simulations as well as a real testbed showed that the best QoS and QoE are obtained when multiple paths are used along with the replication of highest priority data packets.

As a future work, we expect to improve the rate-distortion efficiency of our compression strategy while remaining low-complex. load balancing objective function to balance traffic among subroot nodes can be used. We expect to design multichannel scheduling method using TSCH (Time Slotted Channel Hopping) protocol to support multimedia traffic, and then evaluate our multipath algorithm using the proposed multichannel mechanism. Finally, the DIS-Trickle mechanism will be leveraged to accelerate the discovery process of additional paths.

List of Tables

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