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Hybrid internet of things network for energy-efficient video surveillance system

Eyassu Dilla Diratie

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Hybrid Internet of Things Network for Energy-Efficient Video Surveillance System

*Réseau hybride de l'Internet des objets pour un système de
vidéosurveillance économe en énergie*

Thèse de doctorat de l'université Paris-Saclay

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Eyassu Dilla DIRATIE

Composition du jury

Nadjib AIT SAADI Professeur, Université Paris-Saclay / UVSQ Campus	Président
Isabelle GUERIN LASSOUS Professeur, Université Claude Bernard Lyon 1	Rapporteur et Examinatrice
Nathalie MITTON Responsable scientifique (HDR) de l'équipe-projet FUN, Inria Lille-Nord Europe	Rapporteur et Examinatrice
Guy PUJOLLE Professeur, Sorbonne Université	Examineur
Khaldoun AL AGHA Professeur, Université Paris-Saclay	Directeur de thèse

Title: Hybrid Internet of Things Network for Energy-Efficient Video Surveillance System

Keywords: Wireless Multimedia Sensor Network, Low Power Wide Area Networks, Internet of Things Network, Energy Efficiency, Video Surveillance, Quality of Service (QoS), Energy-Efficient Routing

Abstract:

Wireless visual sensor networks based on IEEE 802.11 mesh networks are effective and suitable solutions for video surveillance systems in monitoring intrusions in selected areas. The IEEE 802.11-based visual sensor networks offer high bit rate video transmissions but suffer from energy inefficiency issues. Moreover, the video transmission in the visual sensor networks requires strict quality of service (QoS) in terms of bandwidth and delay. Also, it is challenging to decrease the overall energy consumption of the network while assuring guaranteed QoS in terms of bandwidth and delay in energy-constrained wireless visual sensor networks. The main contribution of this dissertation is to provide an energy-efficient video surveillance network without compromising the QoS requirement of video transmission. First, we propose a new hybrid IoT network architecture for a video surveillance system that detects and tracks an intruder in the monitoring area. The hybrid IoT network integrates the IEEE 802.11-based multi-hop visual sensor networks and LoRa network to provide an autonomous, energy-efficient, high bitrate video surveillance system. Leveraging the LoRa network characteristics, the LoRa network is utilized as an always-active network for preliminary motion detection and tracking. Moreover, the LoRa network also decides which visual sensor nodes to wake up depending on the tracking information. The Kalman filter is investigated to track

the intruder's trajectory from noise measurements of low power motion sensors to activate only the visual sensor nodes along the intruder's trajectory to provide effective video vigilance. We showed through simulation that Kalman filter estimates and predicts intruder trajectory with reasonable accuracy. Moreover, the proposed hybrid IoT network approach reduces energy consumption significantly compared with a traditional, always active continuous monitoring single-tier visual sensor network. Next, the contribution of this dissertation focuses on an energy-aware and QoS routing mechanism for the IEEE 802.11-based multi-hop visual sensor network of the hybrid IoT network. We propose a routing algorithm that routes a set of video streams to the gateway with guaranteed QoS in terms of bandwidth and delay while minimizing the number of visual sensor nodes that are involved in routing. This maximizes the number of nodes that can be turned off completely to optimize the overall energy consumption of the network without compromising QoS performance. The proposed routing problem is formulated as an Integer Linear Program (ILP) and solved using branch-and-bound algorithm. Through computer simulation, the performance of the proposed approach is compared with the existing state-of-the-art routing algorithms from the literature. The results clearly show that the proposed mechanism saves a significant amount of the overall energy consumption while guaranteeing QoS in terms of bandwidth and delay.

Titre: Réseau hybride de l'Internet des objets pour un système de vidéosurveillance économe en énergie

Mots clés: Réseau de capteurs multimédia sans fil, réseaux étendus à faible consommation, réseau Internet des objets, efficacité énergétique, vidéosurveillance, qualité de service (QoS), routage économe en énergie

Résumé:

Les réseaux de capteurs visuels sans fil basés sur les réseaux maillés IEEE 802.11 sont des solutions efficaces et adaptées aux systèmes de vidéosurveillance pour surveiller les intrusions dans des zones sélectionnées. Les réseaux de capteurs visuels basés sur IEEE 802.11 offrent des transmissions vidéo à haut débit mais souffrent de problèmes d'inefficacité énergétique. De plus, la transmission vidéo dans les réseaux de capteurs visuels nécessite une qualité de service (QoS) stricte en termes de bande passante et de délai. En outre, il est difficile de réduire la consommation énergétique globale du réseau tout en garantissant une qualité de service garantie en termes de bande passante et de délai dans les réseaux de capteurs visuels sans fil à énergie limitée. La principale contribution de cette thèse est de fournir un réseau de vidéosurveillance économe en énergie sans compromettre l'exigence de qualité de service de la transmission vidéo. Premièrement, nous proposons une nouvelle architecture de réseau hybride IoT pour un système de vidéosurveillance qui détecte et suit un intrus dans la zone de surveillance. Le réseau IoT hybride intègre les réseaux de capteurs visuels multi-sauts basés sur IEEE 802.11 et le réseau LoRa pour fournir un système de vidéosurveillance autonome, économe en énergie et à haut débit. Tirant parti des caractéristiques du réseau LoRa, le réseau LoRa est utilisé comme un réseau toujours actif pour la détection et le suivi préliminaires des mouvements. De plus, le réseau LoRa décide également quels nœuds de capteurs visuels réveiller en fonction des informations de suivi. Le filtre de Kalman est

étudié pour suivre la trajectoire de l'intrus à partir des mesures de bruit des capteurs de mouvement à faible puissance afin d'activer uniquement les nœuds de capteurs visuels le long de la trajectoire de l'intrus pour fournir une surveillance vidéo efficace. Nous avons montré par simulation que le filtre de Kalman estime et prédit la trajectoire de l'intrus avec une précision raisonnable. De plus, l'approche de réseau hybride IoT proposée réduit considérablement la consommation d'énergie par rapport à un réseau de capteurs visuels à un seul niveau de surveillance continue traditionnelle et toujours active. Ensuite, la contribution de cette thèse se concentre sur un mécanisme de routage sensible à l'énergie et QoS pour le réseau de capteurs visuels multi-sauts basé sur IEEE 802.11 du réseau hybride IoT. Nous proposons un algorithme de routage qui route un ensemble de flux vidéo vers la passerelle avec une QoS garantie en termes de bande passante et de délai tout en minimisant le nombre de nœuds capteurs visuels impliqués dans le routage. Cela maximise le nombre de nœuds pouvant être complètement désactivés pour optimiser la consommation énergétique globale du réseau sans compromettre les performances QoS. Le problème de routage proposé est formulé comme un programme linéaire entier (ILP) et résolu à l'aide d'un algorithme branch-and-bound. Grâce à la simulation informatique, les performances de l'approche proposée sont comparées aux algorithmes de routage de pointe existants dans la littérature. Les résultats montrent clairement que le mécanisme proposé permet d'économiser une quantité significative de la consommation d'énergie globale tout en garantissant la QoS en termes de bande passante et de délai.

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Synthèse

Les réseaux de capteurs visuels sans fil basés sur les réseaux maillés IEEE 802.11 constituent des solutions efficaces et adaptées aux systèmes de vidéosurveillance pour surveiller les intrusions dans certaines zones. Les réseaux de capteurs visuels basés sur IEEE 802.11 offrent des transmissions vidéo à haut débit mais souffrent de problèmes d'inefficacité énergétique. En outre, la transmission vidéo dans les réseaux de capteurs visuels exige une qualité de service (QoS) stricte en termes de bande passante et de délai. Il est donc difficile de réduire la consommation énergétique globale du réseau tout en garantissant la qualité de service en termes de bande passante et de délai de bout en bout dans les réseaux de capteurs visuels sans fil à énergie limitée. La principale contribution de cette thèse est de fournir un réseau de vidéosurveillance économe en énergie sans compromettre l'exigence de qualité de service de la transmission vidéo. Tout d'abord, nous proposons une nouvelle architecture de réseau IoT hybride pour un système de vidéosurveillance qui détecte et suit un intrus dans la zone de surveillance. Le réseau IoT hybride intègre les réseaux de capteurs visuels multi-sauts basés sur IEEE 802.11 et le réseau LoRa pour fournir un système de vidéosurveillance autonome, économe en énergie et à haut débit. Tirant parti des caractéristiques du réseau LoRa, ce dernier est utilisé comme un réseau toujours actif pour la détection et le suivi préliminaires des mouvements. En outre, le réseau LoRa décide également des nœuds de capteurs visuels à réveiller en fonction des informations de suivi. Le filtre de Kalman est étudié pour suivre la trajectoire de l'intrus à partir des mesures de bruit des capteurs de mouvement à faible puissance afin d'activer uniquement les nœuds de capteurs visuels le long de la trajectoire de l'intrus pour fournir une vigilance vidéo efficace. Nous avons montré par simulation que le filtre de Kalman estime et prédit la trajectoire de l'intrus avec une précision raisonnable. En outre, l'approche de réseau hybride IoT proposée réduit considérablement la consommation d'énergie par rapport à un réseau de capteurs visuels traditionnel à un seul niveau, toujours actif et à surveillance continue. Ensuite, la contribution s'appuie sur le mécanisme de routage pour optimiser l'efficacité énergétique globale du réseau tout en satisfaisant à l'exigence de qualité de service de la

transmission vidéo dans le réseau de capteurs visuels multi-sauts basé sur IEEE 802.11 du réseau IoT hybride. La plupart des travaux antérieurs sur les solutions de routage dans les réseaux multi-sauts sans fil généraux qui optimisent la consommation d'énergie distribuent la charge de trafic pour équilibrer la consommation d'énergie et prolonger la durée de vie du réseau. Ces solutions de routage sont toutefois inefficaces en termes de consommation énergétique globale du réseau, car elles exigent que les nœuds restent allumés même s'ils ne transmettent qu'une petite quantité de données, ce qui entraîne une consommation d'énergie importante. Le réseau global peut être économe en énergie en désactivant autant de nœuds que possible tout en maintenant la performance de la qualité de service. Par conséquent, nous avons proposé un mécanisme de routage qui minimise le nombre de nœuds de capteurs visuels impliqués dans l'acheminement d'un ensemble de flux vidéo depuis les nœuds sources jusqu'à la passerelle, tout en garantissant la qualité de service en termes de bande passante et de délai. Nous avons supposé que le retard des paquets de bout en bout est proportionnel au nombre de sauts dans un chemin. En minimisant le nombre de nœuds impliqués dans le routage, il est possible de désactiver autant de nœuds que possible. Ainsi, la consommation d'énergie globale est réduite. Nous avons formulé le problème de routage sous la forme d'un programme linéaire en nombres entiers (ILP) et l'avons résolu à l'aide de l'algorithme branch-and-bound. Par le biais d'une simulation informatique, les performances de l'approche proposée sont comparées aux algorithmes de routage de pointe existants dans la littérature. Les résultats montrent clairement que le mécanisme proposé permet d'économiser une quantité importante d'énergie tout en garantissant la qualité de service en termes de bande passante et de délai.

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Chapter 1

Introduction

This chapter introduces the dissertation's context and motivation. Furthermore, the chapter discusses the significant contributions of the dissertation. Finally, the dissertation's organization is described.

1.1 Context and motivation

Wireless sensor networks (WSN) are rapidly becoming a mature technology after years of intensive research, design, and development efforts worldwide. The primary function of the WSN is to collect and disseminate critical data by characterizing the physical phenomena surrounding the sensors, including but not limited to temperature, motion, humidity, air pollution, and so on [110, 19, 75]. In recent years, technological advances have reduced the cost of complementary metal-oxide-semiconductor (CMOS) camera hardware and microphones, allowing for the development of low-cost wireless multimedia sensor networks (WMSN) capable of capturing, processing and broadcasting multimedia content [101, 99]. WMSN have a wide range of useful applications due to their ability to provide significantly richer data and broader coverage than traditional scalar sensor networks. Some examples of WMSN applications are traffic monitoring,

surveillance, environmental monitoring, industrial automation, and the like [1, 51].

One of the typical applications of WMSN is a video surveillance system, which is composed of numerous visual(video) sensor nodes connected in a mesh multi-hop topology and employed to monitor an intruder in a selected area. The system is known as a wireless visual sensor network. The video surveillance application requires that the captured videos by different visual sensor nodes be transferred to the gateway node so that it is relayed to a monitoring center, where the footage is examined and stored. As a result, it requires a communication technology that can support the high bandwidth demand of video traffic. IEEE 802.11 is the most viable communication technology because it supports high data rate transmission, low implementation costs, and simplicity. As a result, IEEE 802.11 has become the most common and popular communication technology for visual sensor networks. Despite its popularity, the energy inefficiency of the IEEE 802.11 interface remains a challenging problem in such networks.

Moreover, video surveillance applications require Quality of Service (QoS) guarantees in terms of per-flow bandwidth and end-to-end delay. It is difficult to provide guaranteed QoS in an IEEE 802.11-based multi-hop visual sensor network due to wireless interference between visual sensor nodes caused by simultaneous transmissions in a shared medium. Therefore, energy optimization in a wireless multi-hop visual sensor network while providing guaranteed QoS is challenging. This is the problem we try to solve in this dissertation. The dissertation mainly focuses on wireless visual sensor networks, but we also use the broader term wireless multimedia sensor networks (WMSNs).

Thus, energy consumption reduction without compromising wireless visual sensor network performance is critical. There are compelling reasons to reduce wireless visual sensor networks energy consumption. For energy-constrained wireless visual sensor network, energy inefficiency may reduce the network's operational time. There is, however, another critical reason to address the issue of energy inefficiency in general and

wireless visual sensor network in particular. Several studies estimate that CO_2 emissions from information and communication technology (ICT) may account for 2% to 10% of total emissions [23, 77]. This percentage is expected to rise as the number of internet-connected devices consistently grow. This is a serious issue that necessitates energy-efficient solutions. Recognizing the gravity of the situation, significant efforts have been made to reduce needless energy spending; as a result, any solution that reduces the rising energy use of the Internet is appreciated. As a result, whether the visual sensor nodes are battery-powered or not, reducing wireless visual sensor networks's energy consumption is vital.

There have been numerous efforts and attempts to reduce energy consumption in wireless multimedia sensor networks (WMSNs) using a variety of methodologies [100, 30, 53, 71, 26, 83, 63, 48, 33]. Some made significant efforts to reduce energy consumption by designing improved hardware at the device level or by designing efficient network architectures. It is also possible to consider energy reduction at the application level by reducing the complexity of algorithms or at the network level by modifying communication protocols to improve their energy efficiency. Several other options and a combination of one or more of the techniques mentioned can be used to improve energy efficiency. The dissertation is in this context, where it considers designing an energy-efficient network architecture along with energy aware routing. The IEEE-based 802.11-based multi-hop visual sensor network for the video surveillance system consumes significant energy. Low power wide area network (LPWAN) technologies, such as the LoRa network, capable of supporting a wide range of applications, are becoming increasingly popular. These technologies, however, do not provide sufficient bitrate transmission, which is required in video surveillance applications. Therefore, it is challenging for a single wireless technology to offer a high-bitrate video transmission while remaining energy efficient.

Networks providing high bit rate video transmission consume high energy; on the other

hand, low power technologies do not offer enough bitrate. Therefore, the main idea of the study is to make a hybrid IoT network that integrates both technologies to run low power and high bitrate system. The hybrid IoT network architecture for a video surveillance system is used to detect and track an intruder based on the presence of an intruder while keeping the network energy efficient and without compromising the video surveillance network's QoS performance. There are a number of objectives that need to be fulfilled to reach the main goal. First, in this dissertation, we propose a hybrid IoT network architecture consisting of an IEEE 802.11-based wireless mesh multi-hop visual sensor network and LoRa network for a video surveillance system that can activate visual sensor nodes depending on the presence of an intruder. Moreover, we investigate intruder detection and tracking mechanism using the Kalman filter in the hybrid IoT network. Then, we evaluate the performance of the Kalman filter tracker in terms of tracking accuracy and the energy consumption performance of the hybrid IoT network. Finally, we propose an energy-aware and QoS routing algorithm to make the network energy efficient without compromising its performance. Then, we evaluate the performance of the proposed routing algorithm with other algorithms from the literature.

1.2 Contributions

The dissertation mainly focuses on reducing the global energy consumption in IEEE 802.11-based wireless multi-hop visual sensor networks for video surveillance systems while providing guaranteed QoS in terms of bandwidth and end-to-end delay. The application of the video surveillance system considered is for detecting and tracking an intruder. The dissertation's first focus is to propose a hybrid IoT network architecture for a video surveillance system. The dissertation then develops an energy-aware and QoS routing mechanism for the hybrid Internet of Things network to make the network energy efficient while guaranteeing QoS. Thus, the main contributions of the dissertation

are the following:

- The dissertation's first contribution proposes integrating the IEEE 802.11-based wireless multi-hop visual sensor network and the LoRa network in a hybrid mode. The hybridization helps in designing an autonomous, high bit rate, and energy-efficient video surveillance system used to detect and track an intruder. Taking advantage of the LoRa network's low power consumption characteristics, the LoRa network is used as an always-active network for monitoring and preliminary motion detection and deciding the activation of the visual sensor nodes based on the presence of motion detection and its trajectory. We demonstrate single intruder detection and tracking using a Kalman filter. Based on the target detection and tracking information, the LoRa network activates the limited number of visual sensor nodes nearest to the current estimated location of the intruder and the predicted location of the intruder to provide effective video vigilance. Idle nodes that are no longer needed are completely turned off. This reduces the number of high-power-consuming active visual sensor nodes in the network, resulting in lower energy consumption. We demonstrate through simulation that the Kalman filter tracker estimates and predicts the locations of an intruder with acceptable accuracy. Moreover, the proposed IoT network architecture's energy consumption performance is compared with a single-tier visual sensor network baseline scenario where all the network's visual sensor nodes are always active to provide continuous video vigilance of the surveillance region. According to simulation results, the proposed hybrid IoT network saves a significant amount of energy (97.44%).
- The previous contribution did not consider the routing mechanism. As a result, we consider an energy-aware routing algorithm, and it is critical to reducing the network's overall energy consumption while ensuring QoS. The dissertation's final contribution is to propose an energy-aware and QoS routing algorithm in

the presence of wireless interference in the hybrid IoT network to make the network energy efficient without compromising QoS performance. The proposed routing algorithm allows routing a set of video streams with guaranteed bandwidth and delay (assuming that the end-to-end packet delay is proportional to the number of hops in a path) while involving the network's minimum number of visual sensor nodes. The remaining idle visual sensor nodes in the network that are not needed can be completely shut down. This reduces the network's overall energy consumption. We formulate the problem as an integer linear program (ILP) with the goal of finding the minimum number of visual sensor nodes to be used (activated) by imposing bandwidth and delay constraints. We use a branch-and-bound algorithm to solve the Integer Linear Programming optimization model. Finally, the performance of the proposed approach is evaluated using simulation and compared to the existing state-of-the-art approaches from the literature. The simulation results demonstrate that the proposed approach achieves significant overall network energy savings while ensuring QoS in terms of bandwidth and delay.

1.3 Organization of the dissertation

The remaining part of the dissertation is organized as follows:

Chapter 2 describes the state-of-the-art works related to the different strategies used and proposed to tackle energy inefficiency in general multi-hop networks and WMSNs.

Chapter 3 presents the proposed hybrid IoT network solution for energy-efficient video surveillance employed to detect and track an intruder. First, it describes the Low Power Wide Area Network (LPWAN), the basis for the hybrid IoT network. Then, the proposed hybrid IoT network architecture and its energy-saving mechanism are presented. Single intruder detection and tracking using the Kalman filter is then described. Fi-

nally, through computer simulation, the performance of the tracker and IoT network architecture is evaluated.

Chapter 4 describes the energy-aware and QoS routing mechanism to make the network energy efficient while providing guaranteed bandwidth and delay. First, the system and the wireless interference modeling are introduced. Then, the routing problem formulation and mechanism to solve the optimization problem are described. The performance of the proposed routing algorithm is evaluated through simulation with other algorithms from the literature.

Chapter 5 covers the conclusion of the dissertation and indicates the future research directions.

1.4 Publications

The following are the main results of the dissertation that have been published in an international conference and journal:

Conference

1. E. Dilla Diratie and K. Al Agha, “Hybrid Internet of Things Network for Energy Efficient Video Surveillance,” in 2020 IEEE 6th World Forum on Internet of Things (WF-IoT), Jun. 2020, pp. 1–6. doi: 10.1109/WF-IoT48130.2020.9221241.

Journal

2. E. D. Diratie, D. P. Sharma, and K. Al Agha, “Energy Aware and Quality of Service Routing Mechanism for Hybrid Internet of Things Network,” *Computers*, vol. 10, no. 8, Art. no. 8, Aug. 2021, doi: 10.3390/computers10080093.

Chapter 2

State of the Art

This chapter presents an overview of the different strategies used and proposed to tackle energy inefficiency in general multi-hop networks and WMSNs in particular. Moreover, it discusses our proposal specific to the IEEE 802.11-based wireless multi-hop visual sensor network utilized for video surveillance applications.

2.1 Introduction

The enormous amounts of energy consumed by information and communications technology (ICT) have long been a subject of concern. As the number of internet-connected devices grows, so will energy demand, further complicating the situation. In an attempt to address this issue, the scientific community and industry have developed a slew of strategies to reduce the amount of energy consumed by information technology systems. A lot of efforts have been made on wired networks, but the main focus is on multi-hop wireless networks in general and WMSNs in particular. Numerous efforts and attempts to reduce energy consumption have been made in the fields of multi-hop networks and WMSNs in particular, using a variety of methodologies.

Some have made significant efforts to reduce energy consumption by using out-of-band signaling mechanisms in wireless devices and wireless networks. It is an approach that uses out-of-band, low-power radio signaling to turn off the main radio when it is in an idle state. The technique is used in different contexts to increase the lifetime of devices and wireless networks.

There are also mechanisms for saving energy consumption in Wi-Fi-enabled WMSNs or devices. As Wi-Fi is the major source of energy consumption, the IEEE 802.11 standard specifies and employs a strategy known as IEEE 802.11 Power Saving Mode (PSM). The PSM is a sleep scheduling technique that allows the radio interface, which consumes a lot of energy, to enter sleep mode whenever it is idle or not in use. This is a useful strategy since it puts the radio interface, which is the system's primary source of energy consumption, into sleep mode to save energy.

Other research approaches mainly focused on designing energy-efficient network architectures. Sensor network architectures are constructed hierarchically in this approach by grouping heterogeneous sensor nodes in multi-tier network designs. The method employs various sorts of sensor nodes, each with its own set of capabilities and power requirements. This design concept enables lower-tier low-power sensor nodes to be deployed in vast numbers in a specific monitoring region to detect an event of interest and then activate higher-tier high-power and high-performance nodes on demand. This reduces the activity of the high-energy-consuming sensor nodes and increases the network's lifetime.

A substantial number of research works have been conducted to address the energy inefficiency problem at the network layer of multi-hop wireless networks. Energy-efficient routing mechanisms are the most widely used approaches for reducing energy consumption in multi-hop networks in general and WMSN in particular. The majority of the state-of-the-art energy-efficient routing solutions are used to extend network lifetime

by optimizing energy consumption at individual network nodes while providing specific QoS guarantees, but the routing solutions do not reduce the overall energy consumption of the network. However, the routing solution that optimizes the overall energy consumption is essential for networks such as IEEE 802.11-based multi-hop visual sensor networks, where the major source of energy inefficiency is the high consumption of IEEE 802.11 interfaces when the nodes are active. As a result, making the network energy efficient is challenging without reducing the significant energy consumption of the nodes.

Aggregation is another area of research that is being used in multi-hop networks to reduce energy inefficiency. In the context of data aggregation, wireless sensor networks use aggregation to remove data redundancy, reducing the number of data transmissions from the source to the sink. As a result, the network's lifespan is extended. Furthermore, aggregation in the form of flow aggregation is used to reduce the network's overall energy consumption. Flow aggregation is a mechanism for routing different flows generated by sources across a subset of network nodes. To reduce the overall energy consumption of the network, nodes that are not involved or idle can be put to sleep. Most research studies that employ flow aggregation to optimize the network's overall energy consumption do not focus on QoS guarantees in terms of bandwidth and end-to-end delay together, which is essential in delay-sensitive applications like video transmissions in video surveillance networks.

Finally, we introduce our proposal for optimizing the global energy consumption in IEEE 802.11-based wireless multi-hop visual sensor network for video surveillance systems (employed to monitor an intruder in a specific monitoring area) while providing guaranteed QoS in terms of bandwidth and end-to-end delay. To that end, the dissertation contributions focus on proposing a new hybrid IoT network architecture and an energy-efficient and QoS routing mechanism. According to a thorough review of the literature, our approach has never been used before, as we demonstrate in this

dissertation.

The remaining part of the chapter is organized as follows: Section 2.2 discusses the substantial effort to tackle energy inefficiency through the use of out-of-band signaling technology. Section 2.3 discusses the IEEE 802.11 Power Saving Mode, which is a strategy for decreasing energy consumption as a result of the use of Wi-Fi. Following that, in Section 2.4, we discuss the design of energy-efficient network architectures. In Section 2.5, we describe the energy-efficient routing algorithms that are used in general multi-hop networks as well as WMSNs in specific. Section 2.6 discusses the mechanism of aggregation approaches, which are utilized to reduce energy consumption. Finally, Section 2.7 summarizes the different strategies used and presents our specific proposal of the dissertation.

2.2 Out of Band Signaling Solutions

The strategy for employing out-of-band synchronization signals has been proposed numerous times in state of the art, in various ways, and for multiple applications. This section discusses the different solutions proposed and implemented by the research community to improve wireless networks' energy efficiency.

The authors in [94] studied the energy inefficiency of LAN-enabled personal digital assistants (PDAs). These devices consume a great deal of energy during the idle time when they are not in use. This makes the devices quickly drain the limited battery power and decreases the lifetime of the devices. Therefore, the authors proposed a mechanism called the "wake-on-wireless" technique. The mechanism saves energy consumption of the PDAs by shutting down both the device and the wireless network card when they are in an idle state or not in use. It also wakes them up when wake-up control messages are received through a separate low-power channel that is different from the data channel. According to the authors, the mechanism extends the device's lifetime

but is only intended for a single-hop network.

A similar concept of an out-of-band signaling approach to saving energy was proposed in [46]. The strategy in this situation is to reduce the waste of Wi-Fi Access Points (AP) energy consumption while not in use. This approach uses a secondary low-power radio to send out-of-band control messages to activate the access point and maintain connectivity whenever necessary. When there are no connections, the AP radio interface is shut off, resulting in a significant reduction in energy consumption. The authors also provided a detailed description of their approach's hardware and software architecture. Although the mechanism reduces the AP's energy consumption, it is not intended for multi-hop network scenarios.

The authors in [104] proposed a WSN-based out-of-band signaling mechanism to save energy wastage in office environments where internet-connected computing devices (e.g., printers, scanners) are left active all the time even though they are needed occasionally. The mechanism separates data channels and control channels on internet-connected devices. The approach allows for sending a control command through the WSN channel to switch off the devices that are not needed and wake them up as necessary. The approach decreases the devices' energy consumption.

A radio-triggered power management scheme aimed at reducing energy consumption in wireless sensor networks was introduced in [41]. The mechanism integrates a second radio triggered circuit in the sensor nodes, which only activates the sensor node when it receives enough energy from the specific receiving triggering radio signal without using the internal power supply. The sensor nodes will remain asleep after deciding to be in sleep mode, and they are not activated until a specific radio signal is received from other nodes. When the radio-triggered circuit receives a specific radio signal, it gets energized and wakes up the sensor nodes. In this mechanism, the specific signal received should be strong enough to compensate for the attenuation caused by the wireless channel.

This may be difficult for networks with large spacing between nodes. Furthermore, the mechanism does not provide QoS guarantees.

The authors in [105] designed a low-power wake-up radio scheme to minimize energy consumption in wireless sensor networks. The mechanism integrates a secondary radio in the sensor node that is used to continuously listen to a wireless channel and wakes up the primary radio of the node whenever there is a demand for efficient data communication with the sender. The design saves the energy consumption of the primary radio during idle times. The authors presented the prototype of low-power radio operating in the 868 MHz bands that can be used in a wide range of real-world situations. However, it does have a downside with respect to coverage area, as the range of the prototype is short and limited to 2 meters. Moreover, it does not provide QoS guarantees.

The authors of [100, 30] proposed a mechanism that uses an always-on, low-power FM radio as an out-of-band control signal to turn off camera nodes' high-power consuming Wi-Fi radio modules in a WMSN while in an idle state. Figure 2.1 depicts the FM out-of-band signaling mechanism. This method saves the energy consumption of the radio modules during idle time (when not sending, receiving, or relaying data). The mechanism has some limitations, i.e., it only controls the energy consumption of the radio modules, which contribute only a fraction of the total energy consumption of the device. Furthermore, the method requires the FM radio module to be always active, which makes it consume a significant amount of energy even though it is less than the energy consumption of the Wi-Fi radio module.

The authors in [2] proposed a mechanism to save energy consumption in mobile networks. The base station, which is the fundamental component of the Radio Access Network (RAN), consumes a substantial amount of energy even when it is in a standby mode of operation. The authors proposed a mechanism to completely shut down the base station in the mobile network during periods of low traffic in order to reduce energy

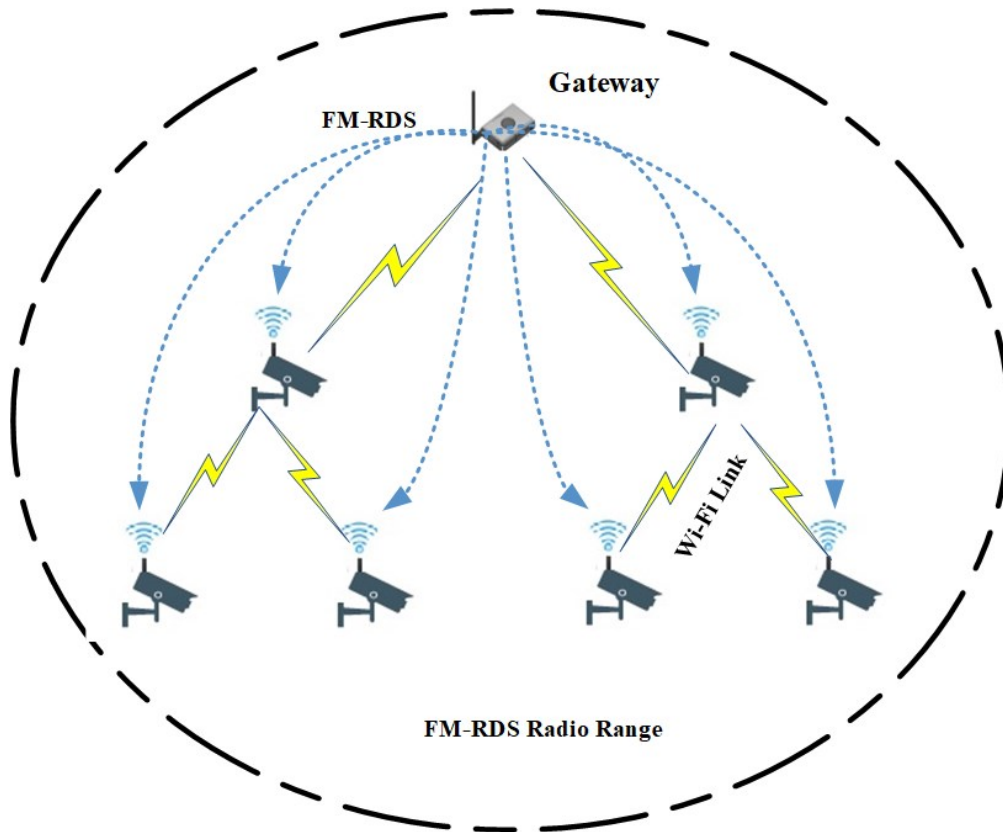


Figure 2.1: FM Out of band signaling [100, 30]

consumption without affecting the QoS performance. In the case of bad QoS detection, the core network in the mobile network then manages the wake-up mechanism utilizing Low Power Wide Area Network (LPWAN). Furthermore, the authors in [3] developed a demo of the system to verify the reduction in energy consumption experimentally. The energy-saving approach is interesting; however, it is only applied to the Radio Access Network.

2.3 IEEE 802.11 Power Saving Mode

IEEE 802.11 is the obvious and preferred choice for high bandwidth communications in mobile devices and networking infrastructures such as WMSN. Despite its widespread use, it has been linked to excessive energy consumption. Power Saving Mode (PSM) is

a feature defined by the IEEE 802.11 standard to help reduce the energy inefficiency issues, and concerns [6]. The PSM is a sleep scheduling technique that allows the radio interface, which consumes a significantly high amount of energy, to enter sleep mode whenever it is idle or not in use. This is a useful strategy since it puts the radio interface, which is the system's primary source of energy consumption, into sleep mode to save energy. The PSM has the potential to save a large amount of energy. However, it has some limitations, i.e., it only manages the energy consumption of the radio modules, which account for a small proportion of the total energy consumption of the device.

2.4 Hierarchical Sensor Network Architecture

Sensor network architectures can be designed using a hierarchical approach by arranging heterogeneous sensor nodes in a multi-tier network architecture. The approach uses different types of sensor nodes, each with unique capabilities and power requirements. The design approach allows lower-tier low-power sensor nodes to be deployed in large numbers in a specific monitoring area to detect an event of interest and then activate higher-tier high-power high-performance nodes on demand. This decreases the activity of high-energy-consuming sensor nodes and minimizes the energy consumption in the network. The hierarchical sensor network strategy saves energy and costs compared to the traditional homogeneous deployment design method.

Multi-tiered sensor network architecture designed for video surveillance applications is presented in [61]. The design approach uses heterogeneous sensor nodes in the network. Each tier in the network uses different types of camera nodes, with characteristics adapted to the tasks to be performed. The authors' employed constrained nodes to perform relatively simple tasks and high-power nodes that are triggered to perform complex operations (such as object recognition and tracking), resulting in efficient energy use. As a result, the design approach is cost-effective and energy-efficient compared to a single-tier homogeneous network. The design approaches extend the network's lifetime.

The authors, however, did not consider ways to improve the network's overall energy consumption or routing mechanisms to provide guaranteed QoS performance.

The authors in [53] proposed a heterogeneous two-tier architecture utilizing wake-up radio receivers to improve the WMSN's life in latency-restricted surveillance scenarios. It is based on a two-tier deployment of low-power scalar sensor nodes and high-power camera nodes. The authors indicated that using information from densely deployed low-power-consuming pyroelectric infrared (PIR) sensor nodes limits the activity of high-power-consuming camera nodes. When there is a human presence, the PIR sensor nodes send a wake-up signal to activate the camera node with the wake-up receiver, allowing the camera node to send alarms or significant images to the gateway or central PC. This increases the system lifetime. Furthermore, the authors demonstrated the advantage of the wake-up radio system over a duty-cycled system in terms of latency reduction.

The authors in [71] proposed a heterogeneous two-tier low-power wireless multimedia sensor network prototype for event-based video surveillance applications. The authors categorized the video surveillance application into preliminary motion detection and real-time video streaming activities. The preliminary motion detection is deployed on constrained motion sensor nodes (tier-1), whereas video surveillance activity is carried out on more computationally capable camera nodes (i.e., sleepyCAM [70])(tier-2). The two tiers communicate via a Bluetooth Low Energy (BLE) radio. When motion is detected in the surveillance area, the motion sensor nodes transmit an alert message to the tier-2 camera node so that it is activated and streams video to a remote computer using a Wi-Fi network. The mechanism reduces energy consumption and extends the battery life of the camera nodes. However, the study does not consider multi-hop network topologies of camera nodes and QoS guarantees in the network.

The authors in [13] presented a heterogeneous two-tier multimedia sensor network for

critical event surveillance. The design approach is based on a combination of high-density deployment of low-cost audio sensor nodes (tier-1) and scattered deployment of high-cost video sensor nodes (tier-2). Lower-tier (tier-1) audio nodes perform continuously to detect events and transmit the detected information to the base station. Then the base station wakes up the video sensor nodes in the event area. According to the authors, the deployment strategy is cost-effective. Furthermore, the authors designed an energy-efficient routing mechanism that increases network lifetime but did not consider QoS guarantees in terms of bandwidth, which is essential in video transmission.

2.5 Energy-Efficient Routing Solutions

Energy-efficient routing approaches are the most widely used mechanisms to reduce energy consumption in multi-hop networks in general and WMSNs in particular. Most of the state-of-the-art energy-efficient routing solutions are used to increase the network's lifetime without compromising QoS performance, but the solutions do not consider reducing the network's overall energy consumption. Researchers use various routing mechanisms to optimize energy consumption in the network.

The authors in [26] proposed energy-aware mechanisms to the Optimized Link State Routing (OLSR) [21] protocol to improve the network's lifetime without compromising performance. It is an extension to the OLSR protocol, and it is clear that the OLSR protocol is a proactive link-state routing protocol. The mechanism involves the Energy-Aware Willingness Setting concept in order to consider energy awareness in the multipoint relay (MPR) selection. Every node computes its energy status in this mechanism and shows its willingness to act as MPR. Heuristic value (default, low, or high) is associated with the willingness of a node. The nodes calculate the heuristic value, demonstrating the node's willingness based on the battery's capacity and expected lifetime. If the node has a high battery value and the expected lifetime is high, the node will have a high willingness heuristic value. If the node's battery value is low, it will

have a low willingness value, making it less likely to be chosen for MPR. Furthermore, the mechanism also allows the reduction of energy consumption due to overhearing without affecting the behavior of OLSR. It reduces energy consumption by turning off network devices when it detects a unicast transmission happening in the neighborhood that is not intended for them. This mechanism improves the energy efficiency of the OLSR protocol. However, it produces a high overhead in the process and does not consider energy awareness in route computations.

There are ad hoc routing mechanisms that extend the lifetime of the network by incorporating energy-based routing metrics. The authors in [88] used a minimum transmission power consumption metric to reduce energy consumption. The authors in [97] employed the battery's remaining capacity as a metric to increase the network's lifetime. The authors in [103] proposed a hybrid mechanism of the concepts used in [97] and [88] as a metric, which is the combination of the remaining capacity of the battery and the total transmission of energy in a route. The authors in [58] use the Minimum Drain Rate (MDR) techniques as a metric in the routing mechanism to extend the network's lifetime. However, the techniques mentioned do not consider reducing the network's overall energy consumption and ensuring QoS guarantees.

The authors in [42] proposed an energy-saving mechanism with Ad hoc On-Demand Distance Vector (AODV)[80, 79] routing protocol. It is clear that AODV is an on-demand routing protocol that determine and maintains routes on a reactive basis, and it does not incorporate energy consideration in the protocol design to improve the network's lifetime. The work in [42] is an energy-aware routing mechanism as an extension to the AODV protocol that utilizes a new cost model that allows routing around nodes that have low battery power for which other routes are available. The mechanism also saves energy usage by switching off the radio interface when the nodes are not in use or an idle state. According to the authors, the proposed mechanism results in a great performance in increasing the lifetime of the network. However, the mechanism does

not consider improving the network's overall energy consumption.

The authors in [37] proposed an energy-aware mechanism extension to the popular DSR [54] protocol. Similar to AODV, the DSR protocol is an on-demand routing protocol that determines and maintains routes whenever needed. This mechanism allows avoiding the use of nodes with low battery power. When the nodes in the network have enough residual energy (e.g., when the remaining energy of the node is above a threshold value), the node behaves like a normal DSR mode. When the remaining energy of the node drops below the threshold value, the node will add delay, which is equivalent to the inverse of the predicted lifetime of the device, before broadcasting the received route request message. The shorter the predicted lifetime of the node, the more delay added before forwarding the received route request message, and the less probable the node involves in relaying data in the network. This way, the mechanism discourages nodes with less residual energy from participating in relaying data in the network. According to the authors, the proposed approach greatly improves the network's lifetime but does not consider improving the network's overall energy consumption.

One of the popular routing protocol designs to make sensor networks energy efficient is the hierarchical routing protocol design. It groups the nodes in the network into groups called clusters. Cluster heads are chosen from among the nodes in each cluster based on their superior processing power. The sensor nodes in the cluster gather information and transmit it to the cluster heads. The cluster heads are responsible for aggregating traffic from the other nodes in each cluster and transmitting it to the gateway. This massively decreases the distance over which individual nodes are required to transmit the data they have collected as the cluster heads are near them. This saves a significant amount of energy. However, as the cluster heads are utilized more often, they may die quickly, decreasing the network's lifetime. The authors in [47] proposed LEACH (Low-Energy Adaptive Clustering Hierarchy) to improve the network's lifetime. LEACH is an adaptive cluster-based protocol that randomly rotates cluster head assignments to

spread the energy consumption across nodes in the network. Due to the fact that data gathering occurs on a periodic basis, LEACH is not ideal for reactive multimedia applications where periodic data transmissions are unnecessary, resulting in inefficient energy consumption.

The authors in [66] proposed power-efficient gathering in sensor information system (PEGASIS) protocol, an upgrade to the LEACH protocol. Unlike the LEACH protocol's cluster-based categorization, this protocol categorizes network nodes as chains. Each sensor node in this chain is aware of its surroundings and only communicates with its closest neighbors. In this protocol, the nodes in the chain make data aggregation and forward the data to the node that communicates directly with the base station. To balance the network's energy consumption, each node in the chain communicates with the base station in turn. This enables the network's operational lifetime to be extended. This protocol selects a single sensor node to forward data to the base station; consequently, it can become a network bottleneck and cause delay.

Optimized energy-delay sub-network routing (OEDSR) [83] is a clustering and an event-driven based routing protocol for wireless sensor networks in which information is transmitted from the cluster heads to the gateway in a multi-hop fashion. The protocol finds the next forwarding node from the cluster heads to the gateway node by considering and calculating the link cost factor. The link cost factor is obtained by dividing the node's remaining energy by the product of the distance from the node to the gateway and the average delay of the link. The potential next forwarding node with the maximum link cost is chosen as the forwarding node. This means that the node with the maximum remaining energy, the shortest delay value, and the shortest distance from the gateway is chosen. In this approach, the protocol makes sure that the path chosen is efficient in terms of energy consumption and has the shortest end-to-end delay possible. Moreover, it increases the network's lifetime as it considers nodes in the paths having higher remaining energy in the network but does not consider improving the

network's overall energy consumption. When compared to the On-Demand Distance Vector (AODV) [80, 79] and Distance Source Routing (DSR) protocol [54], the OEDSR protocol consumes less energy and has a shorter end-to-end delay.

The authors in [68] presented a geographical routing protocol that supports the transmission of multimedia streams in WMSNs. The nodes in the network are aware of their geographical location, and the routing protocol makes packet-forwarding decisions based on the sensor node's position relative to the node's destination. In this protocol, the adaptive compass (also known as an adaptive angle) approach is used to choose the next forwarding nodes. The protocol chooses the next forwarding neighbor nodes within the smallest angular offset from the line of sight towards the destination nodes. The mechanism uses the load balancing technique in a multipath-to-destination to distribute the load and balance the energy consumption in the network. This reduces the frequency of node failures and increases the network's overall lifetime. Similarly, the authors in [55, 64, 7, 102] employ load balancing techniques in their protocol design for increasing the lifetime of a network but make no attempt to improve the network's overall energy consumption.

Directional Geographical Routing (DGR) protocol is proposed in [18] to address the issue of real-time video transmission in WMSNs, where the video transmission is subject to various performance and resource constraints, such as energy, bandwidth and delay. The DGR protocol uses a multi-path routing approach and forward error correction (FEC) coding to address the problem. The DGR protocol divides the video stream into numerous sub-streams that will be transmitted simultaneously by utilizing multiple disjoint pathways to the gateway. The multi-path routing approach allows load balancing, bandwidth aggregation, and quick packet delivery. Reliable data delivery is facilitated with FEC coding in this approach, which is different from most mechanisms that use multi-path routing schemes to increase the reliability of a single flow [36, 27]. The DGR protocol helps extend the network's lifetime, in addition to achieving better

performance in terms of overall delay and better quality of the video at the gateway. Although the DGR protocol increased the network's lifetime, the authors did not consider optimizing the network's overall energy consumption or conclude about it. Moreover, most of the energy-efficient routing mechanisms for WMSN in the literature aim to improve the network's lifetime without compromising some QoS performances, but the routing solutions did not consider optimizing the network's overall energy consumption. For further reference, a more comprehensive survey of energy-efficient routing solutions for WMSN is provided in [31].

2.6 Flow Aggregation

Aggregation has been used extensively and in a variety of ways in wireless multi-hop networks. The authors in [59] used aggregation in the context of data aggregation as an essential mechanism for saving energy in wireless sensor networks. The main idea is to combine data coming from multiple sensor nodes at intermediate nodes before transmitting the merged data to the gateway or sink. The data aggregation mechanism eliminates data redundancy, reducing the number of data transmissions from the source to the sink. As a result, the network's energy consumption is reduced. This is because, depending on the location between the sources, data from nearby sources may have to wait at an intermediary node before being aggregated with data from faraway sources. Similarly, the data aggregation technique was used in [86, 16] to reduce energy consumption in the network.

Another form of aggregation is called flow aggregation, which is utilized in a multi-hop network to reduce the network's overall energy consumption. As most multi-hop networks provide multiple paths between source nodes and destination nodes in the network, this gives an opportunity for using only a subset of nodes for a routing mechanism. Flow aggregation is a mechanism by which routing different flows generated by sources over a subset of nodes in the network. As a result, the nodes that are

not involved or are idle can be put to sleep or completely shut down to save energy consumption.

As an example to demonstrate flow aggregation, we consider a 3X8 grid wireless network as shown in Figure 2.2. The source and destination pairs for each of the three flow demands are (1,8), (9,16), and (17,24) respectively. The demand for each of the flows is 10 units. The flows are routed using the shortest path routing algorithm and flow aggregation mechanism to demonstrate the difference. Both routing mechanisms are based on the assumption that the links have sufficient capacity to handle all of the demands. As can be seen from Figure 2.2a, to route the flows in the shortest path algorithm, all nodes were utilized (i.e., 24 nodes). In the case of flow aggregation (Figure 2.2b), however, only 12 nodes are used to route the flows, and the remaining 12 unused nodes can be put to sleep or completely shut down to save energy.

Different authors in the literature used flow aggregation mechanisms to save the overall energy consumption of the network.

The authors in [111] proposed an energy-aware traffic engineering mechanism, GreenTE, that is used to reduce energy consumption. The mechanism allows diverting traffic to fewer paths, freeing some links from carrying traffic. This enables the network to put such free links to sleep to save the overall energy consumption of the network. The authors formulated the problem as Mixed Integer Programming (MIP), which maximizes the number of links that can be put to sleep mode while maintaining the desired value of network performance. A similar approach was proposed in [38] to reduce overall energy consumption by minimizing the number of active network elements used while routing. The mechanisms in [111] and [38] are interesting for saving the overall energy consumption of the network, but they are focused only on wired networks.

Similarly, flow aggregation approaches were proposed for wireless multi-hop networks. The authors in [25] proposed a throughput and energy-aware routing mechanism for

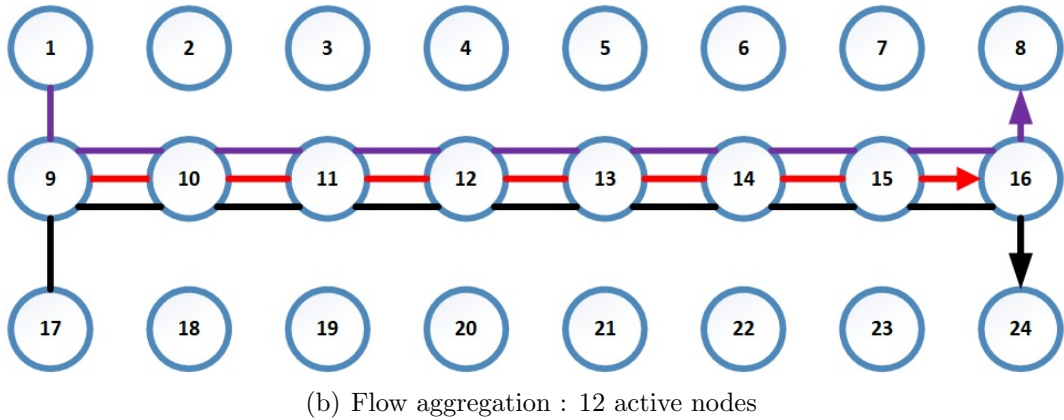
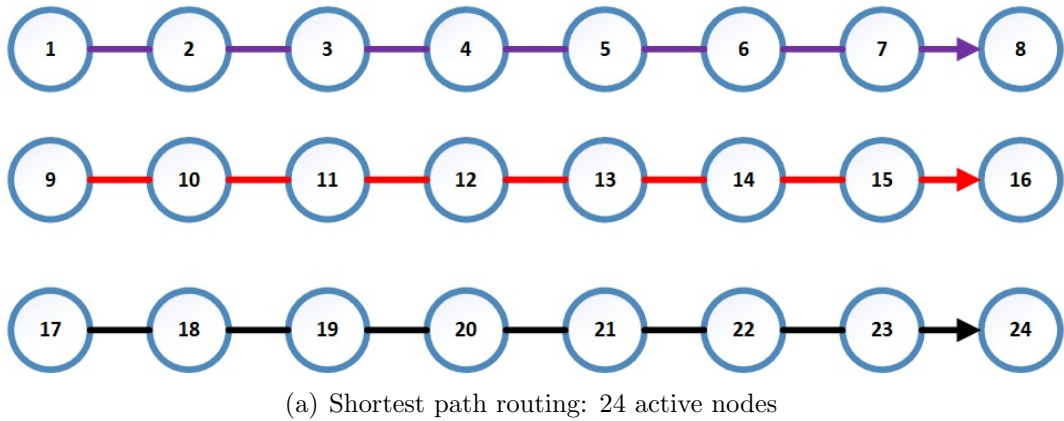


Figure 2.2: Examples of the shortest path algorithm and flow aggregation

IEEE 802.11-based wireless mesh networks. The work has been specifically designed for mesh networks owned by operators, and its intended usage is to give internet access to their customers over these networks. The proposed mechanism is a centralized routing mechanism, which requires a global view of the network. The proposed solution is based on integer linear programming to maximize the number of nodes that can be turned off while guaranteeing throughput. The solution applies an iterative algorithm in order to find the optimum solution that leaves as many routers as possible switched off. This iterative mechanism incurs long delays; therefore, it is ineffective for applications requiring guaranteed delays, like video streaming applications.

The authors in [63] proposed a routing mechanism that allows flows to be aggregated over a minimum number of nodes for any set of source and destination nodes in multi-hop wireless networks. The authors proposed a solution based on integer linear optimization to route flows over a minimum number of nodes while respecting QoS in terms of throughput. Aggregating a set of flows over a minimum number of nodes allows some flows to take a longer path to the destination, which incurs longer delays. Therefore, it significantly impacts delay-sensitive applications like video surveillance, which requires a guaranteed delay.

2.7 Conclusion

A number of techniques for addressing the problem of energy inefficiency in multi-hop networks, and especially in WMSNs, are being researched and tested. The majority of state-of-the-art solutions focus on extending the network's lifetime rather than reducing the overall energy consumption of the network, with only a few focusing on this goal. Furthermore, those focusing on overall energy consumption do not consider QoS guarantees in terms of bandwidth and delay, which is required in video transmissions in multi-hop scenarios of wireless visual sensor networks. Therefore, our goal is to minimize the overall energy consumption of the IEEE 802.11-based multi-hop visual sensor network for video surveillance systems(employed to monitor an intruder in a specific region) while satisfying the QoS in terms of bandwidth and delay requirement of video transmission.

To achieve the goal, we use an energy-efficient network architecture design with an energy-aware routing mechanism. First, we propose a new hybrid IoT network that integrates the IEEE-based wireless multi-hop visual sensor network with a LoRa network in a hybrid configuration to form an autonomous, high-bit-rate, and energy-efficient video surveillance system. Moreover, we propose an energy-aware and QoS routing mechanism for the hybrid IoT network to minimize the overall consumption of the net-

work while providing guaranteed QoS in terms of bandwidth and delay. The routing mechanism provides routing a set of video flow demands using as few visual sensor nodes as possible while ensuring QoS in terms of bandwidth and delay. This enables to selectively turn off as many visual sensor nodes as possible that are not in use used and involved in the routing. Thus, saving the network's overall energy consumption without compromising the network's QoS performance. The uniqueness of our solutions distinguishes it from the vast majority of current state-of-the-art alternative solutions.

Chapter 3

Hybrid Internet of Things Network for Video Surveillance

3.1 Introduction

Recent advancements in wireless communication technologies have paved the way for the construction of low-power multimedia sensor nodes capable of capturing, processing, and broadcasting multimedia content [101]. Wireless Multimedia Sensor Networks (WMSNs) are a collection of small, interconnected multimedia sensor nodes that cover a region of interest and are designed to perform specific functions. Some examples of WMSN applications are traffic monitoring, surveillance, environmental monitoring, and industrial automation [1, 51].

According to worldwide internet traffic forecasts, video traffic can represent an overwhelming majority of the internet traffic. According to a Cisco research, video traffic will represent 82% of global internet traffic by 2022, a significant rise from 75 percent in 2017. Furthermore, the research found that video surveillance traffic, which accounted for 2% of internet video traffic in 2017, is likely to increase to 3% by 2022 [20]. This

increase in video surveillance traffic demonstrates that there will be an increasing demand for video surveillance applications in residential, commercial, military, and other settings in the future. As a result, the technical problems that arise during the deployment of surveillance applications should be studied in order to reduce the likelihood of future technical issues occurring.

This dissertation considers WMSN with only visual (video) sensor nodes (VSNs). These networks consist of a number of small, low-cost, battery-operated visual sensor nodes that can communicate with one another wirelessly across limited transmission distances. The visual sensor nodes can capture visual information and transmit it to the gateway through multi-hop communication. The visual sensor nodes in the mesh network act as both a visual information source as well as a relay for other visual sensor nodes whenever necessary. Figure 3.1 depicts single-tier visual sensor nodes connected in a mesh topology.

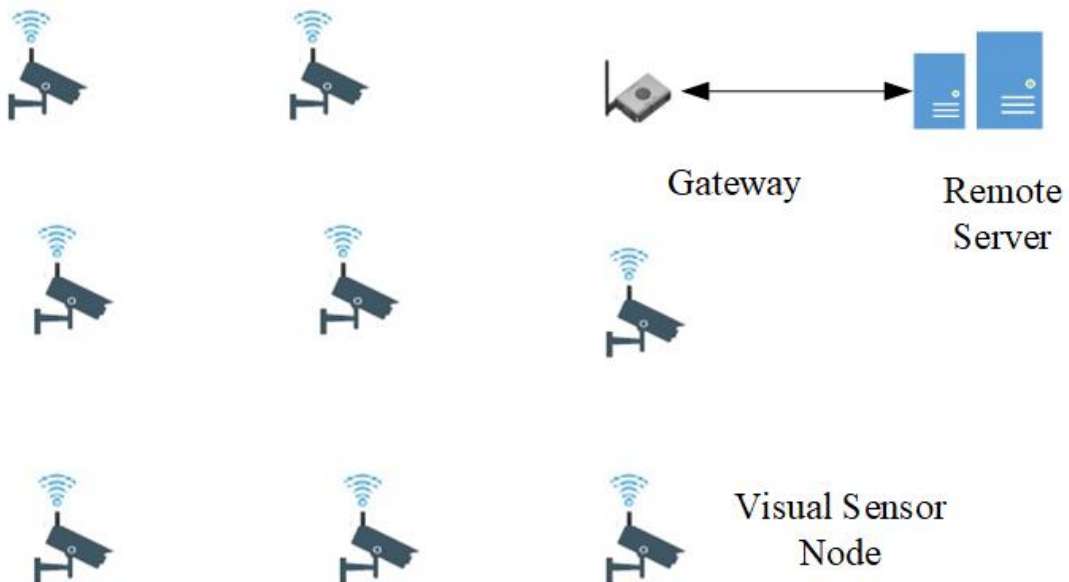


Figure 3.1: IEEE 802.11-based wireless multi-hop visual sensor network

As a matter of facts, the IEEE 802.11 is the most viable communication technology for wirelessly transmitting the video stream between visual sensor nodes as it is low cost and supports high bitrate transmission between nodes. This technology, however, has a challenging problem in that it consumes a great deal of energy. This chapter of the dissertation examines a video surveillance application that is utilized to detect and track a target (an intruder) in a monitoring region. The most prevalent situation in such applications is that visual sensor nodes remain active the whole time to provide continuous monitoring of the surveillance region, even when the time between occurrences of interest is considerable. As a result, a substantial amount of energy is consumed.

A variety of approaches have been utilized in the literature to address the energy inefficiency in such applications. Furthermore, there are low power wide area network (LPWAN) technologies such as LoRa network, which provide increased coverage while consuming less energy and are capable of supporting a wide range of applications, are becoming increasingly popular. These technologies, however, do not provide high data rate transmission, which is essential in video surveillance applications.

On the one hand, networks enabling high bit rate transmission cost a lot of energy, whereas technologies promising low power networks do not provide enough bitrate for video transmission. The main idea is to make a hybrid network that combines both technologies to run low power and high bitrate system. The hybrid architecture combines the IEEE 802.11 based mesh-connected visual sensor nodes and the LoRa network to form an autonomous, high-bitrate, and energy-efficient video surveillance system. The architecture enables switching off idle nodes that are not in use while turning on the visual sensor nodes required for video surveillance and routing a video stream to the gateway. This hybrid architecture may be utilized in various video surveillance application situations; however, this research focuses on intruder detection and tracking in the monitored area. Hence, by leveraging the LoRa network's characteristics (i.e., low

cost, long-range, and low-power consumption), the proposed approach uses the LoRa network as an always-on network for better detection of the presence of motion. Based on the target detection and tracking information, the LoRa network can issue a control instruction to activate only the visual sensor nodes participating in the video vigilance activity and the visual sensor nodes involved in routing the video stream to the gateway. The idle visual sensor nodes can be turned off completely. Thus, it saves the overall energy consumption of the video surveillance network.

The main coverage and contributions of the chapter:

- Proposes a hybrid Internet of Things network integrating IEEE 802.11-based wireless multi-hop visual sensor network and LoRaWAN network to provide an autonomous, high bitrate, energy-efficient video surveillance system.
- Investigates predictive based target (intruder) tracking using Kalman filter in the proposed hybrid Internet of things network.

The remaining sections of the chapter are organized as follows: Section II provides an overview of Low Power Wide Area Network (LPWAN) technologies and introduces the LoRaWAN network architecture, which serves as the foundation for the proposed hybrid internet of things network architecture. Section III describes the proposed hybrid internet of things network architecture for energy-efficient video surveillance. Section IV presents the performance of the proposed hybrid Internet of things architecture in terms of energy efficiency. Finally, Section VI discusses the concluding remarks as well as future works.

3.2 Overview of Low Power Wide Area Network

The Internet of Things (IoT) has enormous potential to revolutionize our way of life. The fast rise of IoT technology is increasing the number of IoT applications in a vari-

ety of industries, including asset tracking, healthcare, agriculture, and manufacturing. These and similar Internet of Things applications require the deployment of vast numbers of IoT devices that cover broad geographic regions, with occasional data transmission, and IoT devices that run for years without the need for their batteries to be replaced on a regular basis. Non-cellular wireless connectivity technologies (e.g., Bluetooth, ZigBee, Wi-Fi) are unreliable for connecting low-power devices spread across broad geographic areas. These technologies have a short range of only a few hundred meters. Cellular-based connectivity solutions (e.g., 2G, 3G, and 4G) have the potential to provide broader coverage. On the other hand, cellular technologies suffer from energy inefficacy and do not provide longer battery life. As a result of the requirements of IoT applications, a new set of wireless communication technologies known as low power wide area network (LPWAN) has emerged.

LPWAN (Long Power Wide Area Network) is a novel communication network for the Internet of Things that has gained significant popularity in the industrial and scientific communities due to a number of distinctive qualities. The following are the LPWAN features that stand out the most: They provide long-range communication or coverage, low power consumption of devices while operating at low data rates, inexpensive deployment or operational costs, simplified network topologies, and scalable and straightforward deployment strategies among other advantages. These distinctive characteristics closely align with the many IoT applications' demands. This makes LPWA technologies better suited for those IoT applications that require a small amount of data to be transmitted over a long-range and that typically require low power consumption previously stated. Figure3.2 shows the positioning of LPWAN in terms of data rate and communication range compared to other radio communication technologies.

LPWAN technologies are being implemented, and their commercial potential is predicted to be enormous. IoT Analytics predicted that LPWAN networks are expected to connect over 1 billion devices to the internet by 2023 [5]. As a result of the vast

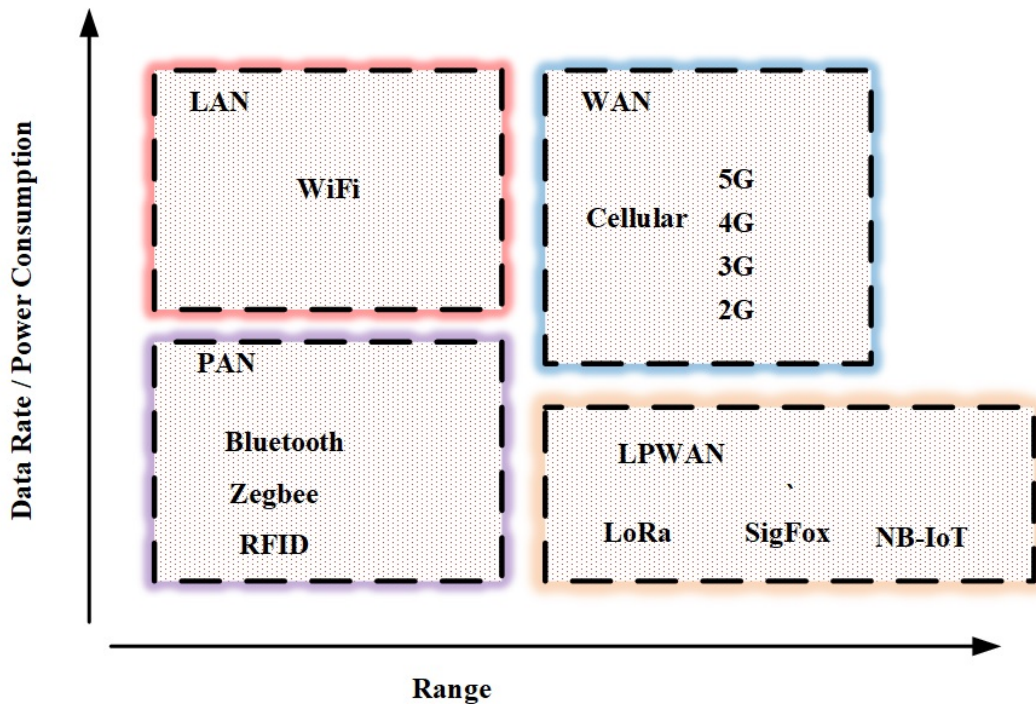


Figure 3.2: Positioning of LPWAN in terms of data rate and communication range in comparison to other radio communication technologies.

range of IoT applications and the increasing market demand, the adoption of various LPWAN technologies has become necessary. There are already a plethora of competing LPWAN systems that utilize a variety of strategies to provide long-range wireless communication, low power consumption, and cheap cost [84]. These diverse LPWAN technologies are divided into two major categories: non-cellular LPWAN networks and cellular LPWAN networks. We highlight and compare the significant players in each category, which include SigFox and LoRaWAN for non-cellular LPWANs and NB-IoT for cellular LPWANs. The comparison of LoRa, SigFox, and No-IoT technologies is summarized in Table 3.1.

3.2.1 SigFox

SigFox [17] is a network developed by the French company in the early 2010s, and it is the leading LPWAN technology for the Internet of things. It employs Ultra Narrow

Table 3.1: Comparison of LPWAN Technologies.

	LoRaWAN	SigFox	NB-IoT
Modulation	CSS	BPSK	QPSK
Frequency	Some really longer text	Unlicensed ISM bands	Licensed LTE frequency
Bandwidth	250 kHz and 125 kHz	100 Hz	200 kHz
Data rate	50 kbps	100bps	200kbps
Estimated Range	5-15km	10-40km	1-10km
Bidirectional communication	Yes/ Half-duplex	Yes/ Half-duplex	Yes/ Half-duplex
Adaptive data rate	Yes	Yes	Yes
Geo-location	Yes	Yes	Yes
Security	Yes	Yes	Yes
Standardization Body	LoRa-Alliance	SigFox	3GPP

Band (UNB) technology and runs at frequencies for which an ISM (Industrial, Scientific, and Medical) license is not required [96]. The exact frequencies vary according to national laws, but generally, Europe uses 868MHz, the United States uses 915MHz, and Asia uses 433MHz. Each SigFox message occupies a narrow bandwidth of 100Hz and is transmitted with a limited data rate of 0.1 kbps. Sigfox employs ultra-narrow band technology to utilize the spectrum efficiently while experiencing extremely low noise levels, allowing it to have higher receiver sensitivity and a long transmission range [84]. The Sigfox gateway can manage as many as needed such as up to one million connected devices and has a transmission range of up to 50 kilometers in rural regions and as low as 3 kilometers in urban areas, where there are generally more obstacles [17]. Sigfox was initially intended to provide just uplink transmission but was later expanded to provide bi-directional communication (uplink as well as downlink communication). The technology allows transmission of up to 140 messages per day through an uplink, with each message having a payload size of 12 bytes. It also enables the reception of four messages in the downlink, each with eight bytes of payload. This limited number of downlink messages indicate that not all messages transmitted in the uplink are acknowledged [95, 84]. SigFox ensures reliability in the uplink transmission by employing the utilization of frequency and time diversity, as well as redundant transmissions. An end device can transmit a single message several times over several frequency channels, and therefore, the redundancy increases the probability of being picked up by the gateway. Due to the gateway's capability of monitoring the spectrum in order to decode messages, the end device can select a frequency channel at random for transmitting a message. This dramatically simplifies the design of end devices and consequently lowers their cost [84, 69]. Sigfox has become popular and widely deployed in more than 72 countries and regions on all five continents, and it presently covers 5.9 million km² and serves 1.3 billion people.

3.2.2 Narrowband Internet of Things (NB-IoT)

NB-IoT [82] is a wireless radio communication technology standard in the low power wide area network category that has been designed to connect a variety of IoT devices and enable different services utilizing cellular telecommunications bands. NB-IoT is a rapidly expanding Narrow Band wireless technology that enables broader coverage with deep indoor penetration, cheap deployment cost, and devices with prolonged battery life. Third Generation Partnership Project (3GPP) introduced and standardized the technology as part of its Release 13 in 2016. NB-IoT is based on enhancing existing LTE (Long-Term Evolution) infrastructure to meet the IoT requirement and capable of coexisting alongside GSM (Global System for Mobile Communications) and LTE mobile network, therefore reducing the deployment cost. It also benefits from all of mobile networks' security and privacy capabilities. NB-IoT runs in the licensed spectrum, which has a significant advantage over other LPWAN technologies that operate in the unlicensed spectrum since it provides more efficient traffic management. Since the licensed spectrum is not shared with other operators, and hence there is less interference, better reliability, and quality of service (QoS) [40]. NB-IoT makes use of the access schemes of the Long Term Evolution network in the uplink and downlink transmissions. In the uplink transmission, it employs the Single Carrier Frequency Division Multiple Access (SC-FDMA) technique, while in the downlink, it utilizes the Orthogonal Frequency Division Multiple Access (OFDMA) technique [106, 12]. NB-IoT may be supported by simply upgrading the software of the existing LTE network. NB-IoT is designed to operate using a narrow bandwidth of 180 kHz in both uplink and downlink, equating to a single physical resource block (PRB) in the LTE network. NB-IoT technology may operate in three different modes: stand-alone in a separate dedicated spectrum, in-band within the standard LTE carrier, and within the guard-band of LTE carrier [72, 106, 12]. These modes of operation enable very flexible deployments for NB-IoT. These different operation modes are illustrated in Figure 3.3.

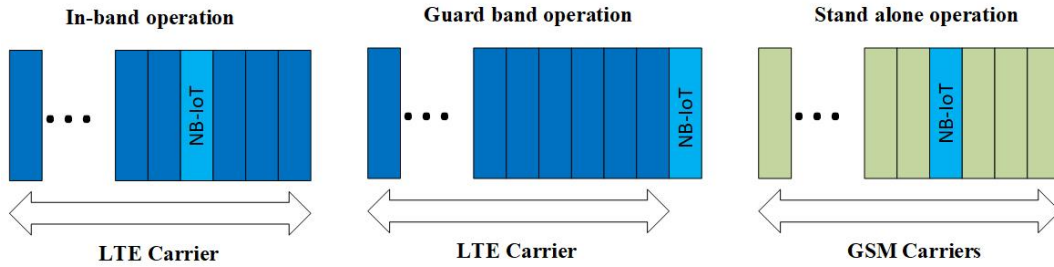


Figure 3.3: The three different operations modes of NB-IoT

NB-IoT can operate independently in stand-alone deployment modes, and one such scenario is the use of one or more GSM channels with 200 kHz bandwidth to transmit IoT traffic. In the in-band operation, it operates within the LTE carrier by allocating one or more PRBs of the LTE carrier. The deployment of NB-IoT within an LTE carrier does not compromise either NB-IoT or LTE performance as they are optimized to coexist without affecting each other. NB-IoT can also be deployed in an LTE carrier guard band utilizing unused resource blocks [106]. The capacity of NB-IoT is enormous. It easily facilitates the connection of over 50K devices per single cell. NB-IoT supports bidirectional transmission at a maximum data rate of 200 kbps in both the uplink and the downlink. Each message can be transmitted with a payload size of 1600 bytes. Moreover, it improves end-device energy efficiency, allowing for more than ten years of battery life [40, 84].

3.2.3 LoRa

LoRa (Long Range) is a wireless modulation scheme for a low-power wide-area network that is responsible for providing low power and long-range communication. It is a proprietary spread spectrum scheme that is based on chirp spread spectrum (CSS) modulation with chirps serving as information carriers [24]. CSS is used in space and military communications applications due to its high communication range, low trans-

mit power, and immunity to interference, but as a matter of facts, LoRa is the first low-cost commercial application. LoRa technology is developed and patented by a company called Semtech. LoRa, like SigFox, uses license-free ISM bands of 915, 868, or 433 MHz, depending on the geographical region in which it is deployed. LoRa utilizes several spreading factors (SF7-SF12) to determine the tradeoff between transmission range and data rate. A lower spreading factor boosts data rate while lowering transmission range and vice versa. LoRa also employs Forward Error Correction (FEC) that allows the recovery of bits of information that have been corrupted as a result of interfering signals. A tiny amount of additional data encoding in the transmitted packet is required to perform it. LoRa provides bidirectional communication and achieves data rates between 0.3 kbps and 50 Kbps depending on the channel bandwidth, coding rate, and spreading factor [69, 84].

LoRa is a physical layer protocol. A layer built on the top of LoRa is LoRaWAN (Long Range Wide Area Network), as illustrated in Figure 3.4, which describes the LoRaWAN network protocol stack. LoRaWAN is an open protocol that specifies the network's communication protocol and network architecture. It is intended to enable low-power end devices to communicate with Internet-connected applications via long-distance wireless links. It also supports secure bidirectional communication, localization service, and mobility support. LoRaWAN is developed and standardized by the LoRa Alliance (a non-profit organization with over five hundred members). The LoRa Alliance is also responsible for overseeing the end devices' certification process to guarantee the operability of certified devices [4].

LoRaWAN network architecture is deployed in a star topology and consists of several elements, as illustrated in Figure 3.5[4, 98, 89]:

- *LoRa Nodes / Endpoints* : An element of the LoRa network that represents sensors or actuators, where the sensing or control takes place. These devices are often

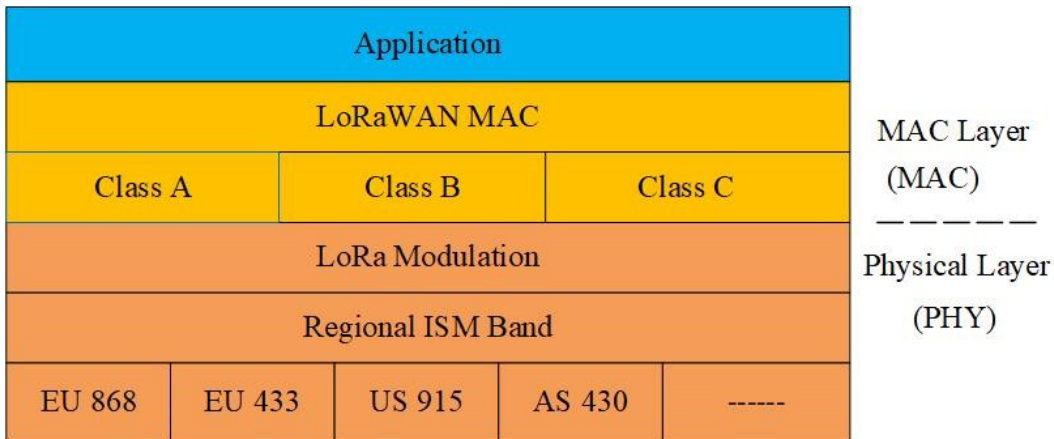


Figure 3.4: LoRaWAN network protocol stack [4]

battery-operated, placed in remote locations, and connected to the LoRaWAN network using a LoRa gateway. These devices are given a number of unique identifiers when manufactured to activate and manage the devices in a secure way and provide safe and encrypted data transfer from the end devices to the network server.

- *LoRa gateway*: A bridge that relays data between end-devices and a network server using an IP backhaul interface. IP traffic can be backhauled using Ethernet, cellular network connection (e.g., 3G or 4G, or Wi-Fi). Furthermore, satellite backhauling is advised for remote places where cellular network coverage is unavailable. A LoRaWAN gateway can serve multiple end devices within a communication range, and there is no specific association between end devices and a particular gateway in the network. As illustrated in the architecture in Figure 3.5, a single end device can be served by multiple gateways within a range. This configuration allows for a reduction in message error rate (i.e., messages transmitted by end devices will have a high probability of being picked up by gateways) as well as the end device’s battery overhead [89]. Having multiple gateway deployments

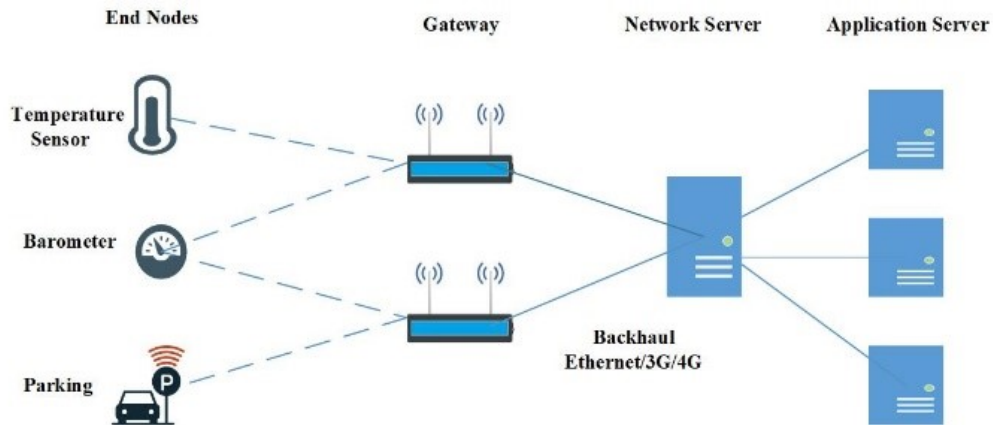


Figure 3.5: LoRa network architecture

in a particular region improves the performance of the network, but on other side it also increases the deployment cost. Therefore, a trade-off between deployment cost and performance must be critically considered when planning a LoRaWAN network [69].

- *Network server*: The intelligent and complex part of the LoRa network that manages the overall network. It dynamically regulates the network settings to adapt the system to constantly changing conditions. It provides secure connections for end-to-end data communication and reliable data routing in the network. The network server is in charge of network management functions such as the following:
 - **Message deduplication**- Removes duplicate messages from an end device that multiple gateways have received.
 - **Message routing**-Transmits downlink messages from any application server to the end device and transmission of uplink payloads to the relevant application server.
 - **Adaptive data rate control**-Transmits adaptive data rate (ADR) com-

mands to optimize the data rate of end devices.

- **Acknowledgment of messages**-Schedules and send an acknowledgment of received data messages and some MAC layer commands.
- **Validating the authenticity of end devices**
- *Application server*: This server is in charge of managing secure application layer communication with end devices. It receives and handles application-specific data messages that are transmitted by the end devices. It also generates application layer messages destined for the end devices and forwards them to the network server [89, 4].

LoRaWAN defines three classes of end devices with different capabilities to address the different needs of IoT applications [4, 98]. The different classes of end devices, which all have bidirectional communication capability, are the following:

- **Class A**: This class of end devices supports bi-directional communication between the end devices and the network server. The devices can send a packet at any time, depending on the communication needs and applications. The devices then open two receive windows after transmitting in the uplink. Compared to other types of end devices, this class of nodes consumes the least power, making them particularly appropriate for applications requiring downlink transmission after transmitting a packet in the uplink.
- **Class B**: These classes of end devices are also the extended version of class A end devices. They use additional scheduled receive windows for downlink message demands from the network server in addition to the default receive windows of class A end devices. Whenever there is a demand for downlink transmission, the gateway notifies the end devices through a time-synchronized beacon when to open the receive windows. This synchronization allows the network server to send

a message to a specific node or a group of nodes simultaneously at the scheduled time. The battery life of this class of nodes is shorter than that of class A due to the increased time spent in active mode during the synchronization and data transmission periods.

- **Class C:** In this class of devices, a receive window is always open except when they are transmitting. This makes them consume more power than class A and class B end devices. However, these classes of devices have the lowest latency among all classes of nodes for the network server to end devices communications [89, 4, 98].

LoRaWAN is a unique wireless communication technology for the Internet of Things, with several deployment and revenue models to address the diverse needs of IoT use cases and applications worldwide. The LoRaWAN technology industry has become increasingly popular LPWAN technology, and it has been widely deployed as either a private or a public network, depending on the application's requirements. Several private and mobile carriers [91] have chosen the LoRaWAN network due to its ability to meet the performance requirements of various IoT applications while also being simple to implement. Furthermore, LoRaWAN network coverage is significant, with deployments across five continents covering 177 countries worldwide [90], as illustrated in Figure 3.6, which depicts the LoRaWAN network deployment map.

The deployment trend and the market potential of the LoRa network is expected to be considerable in the future. According to ABI Research, LoRa will be the leading non-cellular LPWAN network technology by 2026, confirming the existing worldwide industry traction [60]. Furthermore, various LoRa and LoRaWAN-based devices are readily available on the market for installing the network for specific application requirements [92, 81]. Because of these reasons, we chose to use LoRaWAN as the LPWAN technology to integrate with mesh-connected IEEE 802.11 visual sensor nodes to pro-

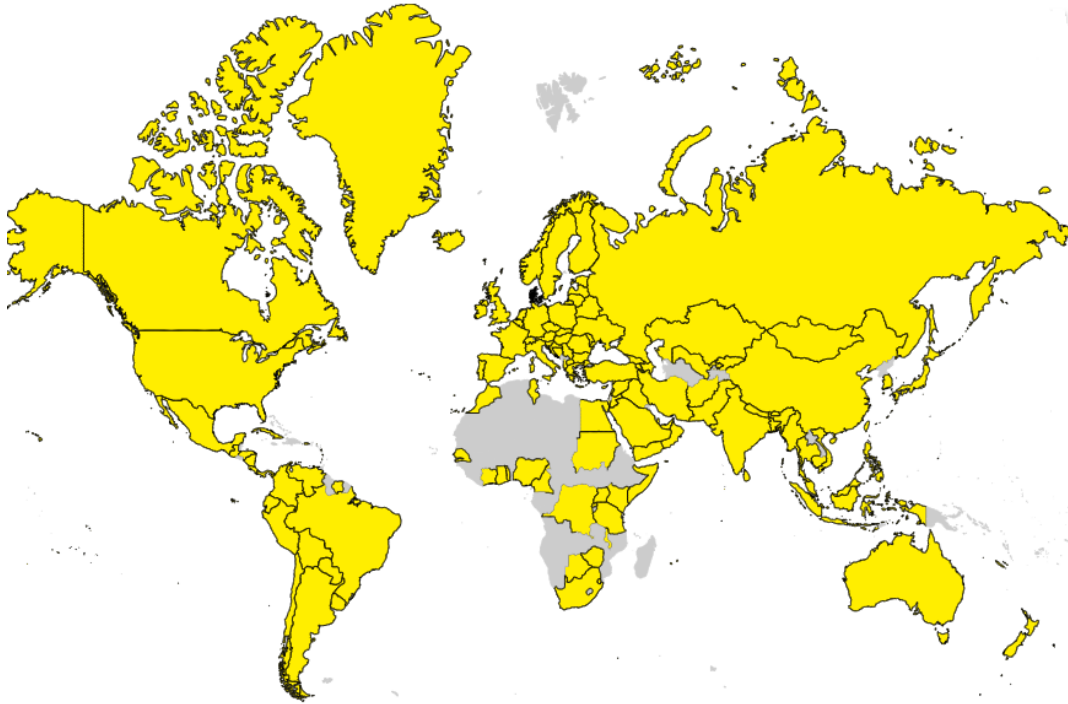


Figure 3.6: The LoRaWAN network deployment map in 2021 [90]

duce autonomous, high bitrate and energy efficient hybrid network, even though other LPWAN technologies such as SigFox and NB-IoT could also support the integration of hybrid network.

3.3 Hybrid Internet of Things Network Architecture for Video Surveillance

It is evident that IEEE 802.11-based mesh-connected visual sensor nodes are an effective and flexible solution for video surveillance systems in detecting and tracking intruders in specific monitored areas. IEEE 802.11-based mesh-connected visual sensor nodes provide high bitrate video transmission but at a very high cost of energy in the network. This indicates that battery-powered visual sensor nodes that are connected in

a mesh topology can quickly exhaust the battery, rendering the network inoperable for the required application until the issue is resolved. As on date, single wireless technology is not capable of providing high bitrate video transmission while still being energy efficient. The popularity of low-power network technologies such as LoRaWAN, which operate in the unlicensed spectrum, leads to the possible integration between the two technologies. The two technologies, IEEE 802.11-based mesh-connected visual sensor nodes and LoRaWAN network, are integrated into a hybrid mode to operate as an autonomous low power, high bitrate video surveillance system utilized for an intruder (target) detection and tracking. In this dissertation, we have chosen LPWAN for integration with the IEEE 802.11-based mesh-connected visual sensor nodes because of the numerous benefits it provides. These are low power consumption, long-range wireless communication, and cheap deployment cost. Because of the increasing growth and advancements in the industry of IoT applications, low-power wide-area networks (LPWANs) have become a prominent wireless communication technology. As a result, LPWAN is projected to be widely used and deployed further in the future. This implies that a broader range of low-cost and energy-efficient video surveillance solutions will be available in the future.

3.3.1 The Proposed Hybrid Internet of Things Network Architecture and Energy Saving Mechanism

In order to solve the energy inefficiency problem in IEEE 802.11-based mesh-connected visual sensor nodes, an energy-efficient hybrid IoT network is proposed in this study. Figure 3.7 presents the proposed IoT network architecture that comprises the core components of the LoRaWAN network, IEEE-based mesh-connected visual sensor nodes, and some of the additional features that are explained in the following section.

- **Motion Sensor Node:** It represents a set of simple ultra-low-energy LoRa enabled scalar nodes that are capable of detecting movement or activity within their

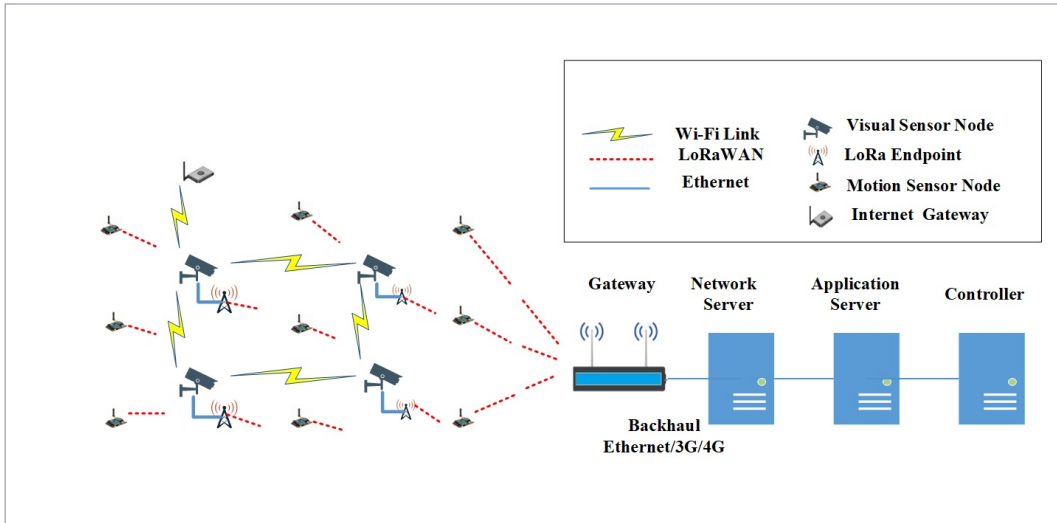


Figure 3.7: The Proposed Hybrid Internet of Things Network Architecture

respective sensing ranges. The sensors transmit the information they have gathered (for example, intruder position information) to the central controller through a LoRa gateway. As the motion sensors are ultra-low power and low cost, they are densely deployed in the monitoring area for better detection of the presence of motion.

- **LoRa End device (Actuator):** It represents a low-power node that communicates with the central controller through the LoRa gateway and is associated with a visual sensor node via an Ethernet cable. Every visual sensor node in the network is associated with specific LoRa end devices (endpoints) via an Ethernet cable as illustrated in Figure 3.7. This node can generate a shutdown message to completely shut down the visual sensor node whenever needed by the central controller. The node can also generate a Magic Packet to carry out a Wake-On-Lan [65] of visual sensor nodes. This would wake up visual sensor nodes that had previously been in a completely shut down mode.

- **Visual Sensor Node:** A high-energy consuming node that is capable of vigilance and video transmission. It consists of a camera node and an interface for connecting Wi-Fi (Wireless Fidelity) and LoRa endpoint connection. As illustrated in Figure 3.7, for the video surveillance application the visual sensor nodes are connected in a mesh, multi-hop fashion for transferring the high bitrate video stream to the gateway.
- **Controller:** This node oversees the overall energy optimization of the network's visual sensor nodes. It is in charge of deciding which visual sensor nodes in the network should be turned on or off depending on the information it gets from the LoRa enabled motion sensors, the tracking information of the intruder, and the routing information. It can send a command to activate only the visual sensor nodes required for video vigilance and the visual sensor nodes engaged in routing video streams to the gateway node. It can also issue a command to completely shut down the visual sensor nodes that are idle and not needed. The central controller calculates the intruder's current and predicted positions and identifies the visual sensor nodes engaged in routing a video stream to the gateway. Afterward, it can activate the nearest visual sensor node to the intruder's current position and the nearest visual sensor node to the predicted intruder's location for better video vigilance. Moreover, it can turn on the visual sensor nodes involved in routing the video stream to the gateway node. The other idle visual sensor nodes in the network could be shut down completely if they had not already been in a showdown mode.

Energy Saving Mechanism

The proposed hybrid IoT network architecture integrates the IEEE 802.11-based visual sensor network with the LoRa network to form an autonomous, high-bitrate, energy-efficient video surveillance system employed to detect and track intruders. The hybrid

IoT architecture provides the detection of the intruder and monitors the intruder's movement in an energy-efficient manner in a specified monitoring area. In the hybrid IoT network architecture, the LoRa network is utilized as an always-active system for monitoring and better detection of the presence of an intruder using the densely placed LoRa-enabled low-power motion sensors in the monitoring region. Based on the sensed information and analysis, the LoRaWAN can execute a control command to activate only a limited number of visual sensor nodes along the pathway of the intruder to provide visual tracking of the intruder. Thus, the high-energy-consuming visual sensor nodes connected in a mesh topology need not be kept active the whole time. Instead, they can be kept in a complete shutdown mode until they are needed for visual tracking as well as routing. This saves the overall energy consumption of the network.

As clearly depicted in Figure 3.7, low-cost, low-power LoRa enabled Pyroelectric InfraRed (PIR) motion sensors are densely deployed in the monitoring area to better detect the presence of motion. The visual sensor nodes are connected in a mesh topology and are deployed to provide video vigilance and tracking. An equal number of LoRa endpoints as the visual sensor nodes are deployed. Each LoRa endpoint is associated with specific visual sensor nodes. They are responsible for waking up or shutting down the visual sensor nodes in response to a command issued from the central controller. The central controller is responsible for managing the visual sensor nodes remotely. It issues a command to ensure the complete shutdown of the visual sensor nodes in the monitoring area when no activity is detected. This ascertains that the visual sensor nodes consume the minimum energy.

The tracking process begins when an intruder enters the monitoring area. The study considers an energy-efficient single target detection and tracking mechanism. When a low-power motion sensor node detects an intruder's presence and movement in the monitored area, it sends the sensed data (e.g., measured intruder position information) to the LoRa gateway. The LoRa gateway relays the data to the central controller for

further processing and decision-making. The central controller uses a Kalman Filter to estimate the intruder's position and predict the intruder's next position. Further details about Kalman Filter estimation and prediction are described in Section 3.3.3. The central controller makes a decision to wake up a visual sensor node nearest to the intruder's position and a visual sensor node nearest to the predicted intruder's position to provide visual vigilance and tracking. Furthermore, the central controller identifies the visual sensor nodes engaged in routing a video stream to the gateway using a routing mechanism and makes a decision to wake them up. Routing mechanism is proposed and described in detail in Chapter 4. Following decision-making, the central controller sends a wake-up command to the LoRa gateway that is localized close to the visual sensor node nearest to the intruder position. The wake-up command contains the unique identifier of the concerned LoRa endpoint associated with the visual sensor node that gets turned on. The LoRa gateway broadcasts the wake-up command. Then, the concerned LoRa endpoint associated with the visual sensor node receives the command and generates a Magic Packet to carry out a Wake-On-Lan of the visual sensor node. This would wake up the visual sensor node that had previously been in a complete shutdown mode.

Similarly, the visual sensor node that is nearest to the predicted subsequent intruders' positions is activated. Moreover, the central controller also issues a command to activate the visual sensor nodes involved in relaying the video streams to the gateway. The remaining active visual sensor nodes that are not needed are shut down completely. This allows the network to save a significant amount of energy.

3.3.2 Deployment Scheme for Sensor Nodes

As discussed in Section 3.3.1, the proposed hybrid IoT architecture for video surveillance is employed for intruder detection and tracking. In order to provide accurate detection and tracking of intruders in the video surveillance network, the sensor nodes should

cover the entire surveillance area. As the sensing range of a single sensor node is limited and cannot cover the surveillance area, a significant number of sensor nodes are needed to provide adequate coverage of the monitoring area. Furthermore, different sensor node types, such as visual sensor nodes and low-power motion sensor nodes, have varying sensing ranges, accuracy, and costs. This implies that the different sensor nodes should be deployed systematically and in an optimal manner to determine the locations and the number of sensors in a monitoring area.

Sensor nodes can be deployed in a random or planned manner. The sensor nodes' positions are randomly placed in the interest area in a random deployment. On the other hand, in a planned or deterministic approach, the sensor nodes are placed in a predetermined position to achieve the performance objective. Most of the time, this deployment option offers an even distribution of sensor nodes in the area of interest. Furthermore, the approach reduces the number of nodes required to achieve the desired coverage [78].

It is clearly mentioned that the study uses two types of sensor nodes in the proposed video surveillance network i.e., visual sensor nodes and low-power motion sensor nodes. These sensor nodes are deployed in a planned manner. It is assumed that the monitored area has a width of W and a length of L . The low power motion sensors have a circular sensing area with radius R_m , and the visual sensor nodes have a 360° angle of view with a radius R_V are deployed in two layers. The first layer is deployed with low-power sensors to detect intruders' presence. In this case, the monitored area is partitioned into equal squares with the square's dimension chosen with respect to the sensing range of the low-power motion sensor node. The low-power motion sensor nodes are deployed at the center of the square in order to avoid overlap of coverage. The number of low-power motion sensors depends on the number of divided squares. Similarly, the second layer is deployed with visual sensor nodes to provide video vigilance, with spacing between two visual sensor nodes equal to the sensing range of a single visual sensor node. The

overall deployment scheme of the network is presented in Figure 3.9. This research assumes that low-power motion sensor nodes and visual sensor nodes are provided with positional information. Each low-power motion sensor node measures the intruder's position in $2D$ Cartesian coordinates.

3.3.3 Target (Intruder) Tracking

Target tracking is one of the most important applications in WSN in which sensor nodes detect and monitor the locations and motion of moving targets in a monitoring area. A target can be any mobile entity such as an enemy vehicle or an intruder. This section deals intruder detection and tracking in the proposed hybrid IoT network in an energy-efficient manner. The intruder tracking scheme is based on the prediction mechanism where the approach uses the current intruder position and the predicted position to select the visual sensor nodes to be activated in order to provide visual tracking.

The intruder tracking scheme is centralized and carried out by the central controller through collaborating the Lora-enabled low-power motion sensor nodes and the visual sensor nodes in the hybrid IoT network. It is clear that Lora-enabled sensor nodes are consuming extremely less energy compared to the energy consumption of the visual sensor nodes. Therefore, LoRa enabled sensor networks are always active to provide better detection of the intruder while the visual sensor nodes remain in a complete shutdown mode.

When an intruder enters a monitoring area, the low power motion sensors detect the intruder and generate an alert containing measurements of the intruder's location. This information is sent via the LoRa gateway and received by the central controller for further processing. Based on the received location measurements of the sensors, the central controller uses the Kalman filter to trace the trajectory of the intruder and predict the next intruder's location within the next predefined period. The visual sensor node nearest to the intruder and the visual sensor nodes nearest to the predicted

intruder position are activated to provide visual tracking. Next, we introduce the operation of Kalman filter that is used to estimate and predict the position of the intruder.

Kalman Filter

A Kalman filter (KF) [57] is an efficient recursive filter that provides the best estimates of unknown variables of interest from a sequence of noisy observations (or measurements). KF can provide estimates of the past and the present. Moreover, it offers the prediction of future states. It can provide the mentioned functions without knowing the specific nature of the system [107, 87]. KF is an optimal estimator that works in a predictor-corrector scheme, which minimizes the estimated error covariance, based on the all-available measurements data at the present time step under linear system [32]. KF is simple to implement, works fast, and needs small computational resources. Furthermore, it occupies a small amount of memory space and only keeps data for one state on the system, rather than a long period of historical data [62]. KF has been widely applied in navigation, target tracking, and prediction algorithms [74].

In this dissertation, we use KF algorithm due to its wide range of applications in target tracking and promising accuracy in estimating the current state and predicting the future states of a moving object from noisy measurement outputs [14, 29, 62, 9]. We use KF to estimate the current position of the intruder from the noisy measurement output of Lora-enabled wireless motion sensors nodes. KF uses the current estimated location to predict the intruder's future location. All the KF operations are performed at the central controller. Following the operation, the central controller can only activate the visual sensor node nearest to the intruder and the visual sensor node nearest to the intruder's predicted position to provide effective video vigilance and tracking.

The KF model is described as a dynamical system model and a measurement model.

System model: The system model represents how the state evolves over time. The KF uses this model to predict the future state of the system, and it is expressed as

$$X_{t+1} = AX_t + W_t \quad (3.1)$$

Where X_t is the state vector at time t , X_{t+1} is the state vector of the system at time $t + 1$ (one time step ahead), A is a state transition matrix that relates the state at time t , without accounting for the system noise, W_t denote the process noise. It is assumed that W_t is uncorrelated, white, Gaussian noise with zero mean and covariance matrices Q_t .

Measurement model: The measurement model describes the relationship between measurements and states, which is expressed as

$$Z_t = HX_t + V_t \quad (3.2)$$

where Z_t denotes the measurement vector, H is the observation transfer matrix which relates the state X_t to the observation Z_t , V_t denote the measurement noise matrix. It is assumed that V_t is uncorrelated, white, Gaussian noise with zero mean and covariance matrices R_t .

As previously stated, the KF is used to estimate the current position of the intruder from the noise measurements as well as to predict the future (one time step ahead) location of the intruder. We consider an intruder moving with a constant velocity in a $2D$ Cartesian coordinate system. The state vector of the intruder consists of the location and the velocity. We define the state vector at time $t + 1$ by :

$$x_{t+1} = \begin{bmatrix} x_{t+1} \\ y_{t+1} \\ v_{xt+1} \\ v_{yt+1} \end{bmatrix} \quad (3.3)$$

where x_{t+1} and y_{t+1} represent the x and y coordinate of the intruder location at time $t + 1$ respectively. Furthermore, v_{xt+1} and v_{yt+1} denote the speed of the intruder at time $t + 1$ along the x -axis and y -axis respectively.

In the monitoring area, it is assumed that each of the Lora-enabled motion sensors measures the absolute position of the intruder in $2D$ Cartesian coordinates as the intruder moves in the monitored area. Therefore, the measurement vector, Z_t , is defined by:

$$Z_t = \begin{bmatrix} x_{m_t} \\ y_{m_t} \end{bmatrix} \quad (3.4)$$

where x_{m_t} and y_{m_t} are measured coordinates of the intruder by the Lora-enabled motion sensors in x and y coordinates.

According to a constant velocity kinematic motion equation and state vector of the intruder, the transition matrix, A , is obtained as :

$$A = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.5)$$

where Δt is the sampling period. The measurement matrix H , which relates the state to the measurement, has the following value:

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad (3.6)$$

KF is an efficient recursive algorithm, consisting of two distinct steps: a prediction step and a correction step, as illustrated in Figure 3.8. The prediction step handles the prediction of a priori state ($\hat{X}_{t+1|t}$) and a priori error covariance ($P_{t+1|t}$). The correction step, on the other hand, deals with the computation of optimal Kalman gain (K_{t+1}), updating a posteriori estimation state ($\hat{X}_{t+1|t+1}$) and a posteriori error covariance ($P_{t+1|t+1}$).

Prediction (Time update):

$$\hat{X}_{t+1|t} = A\hat{X}_{t|t} \quad (3.7)$$

$$P_{t+1|t} = AP_{t|t}A' + Q_t \quad (3.8)$$

Correction (Measurement update):

$$K_{t+1} = P_{t+1|t}H' (HP_{t+1|t}H' + R_t)^{-1} \quad (3.9)$$

$$\hat{X}_{t+1|t+1} = \hat{X}_{t+1|t} + K_{t+1} (Z_{t+1} - H\hat{X}_{t+1|t}) \quad (3.10)$$

$$P_{t+1|t+1} = (I - K_{t+1}H) P_{t+1|t} \quad (3.11)$$

The result of the KF operation is the estimation of the current state of the intruder, $(\hat{X}_{t+1|t+1})$, and the one time-step-ahead prediction of the future state of the intruder, $(\hat{X}_{t+1|t})$. The estimated current locations, $(\hat{x}_{t+1|t+1}, \hat{y}_{t+1|t+1})$ and one time-step ahead predicted locations, $(\hat{x}_{t+1|t}, \hat{y}_{t+1|t})$, are obtained from their corresponding estimated and predicted state vectors. The central controller uses the current estimated and the one time-step ahead predicted intruder locations to wake up the visual sensor node closest to the intruder current estimated location and the visual sensor node closest to the predicted location.

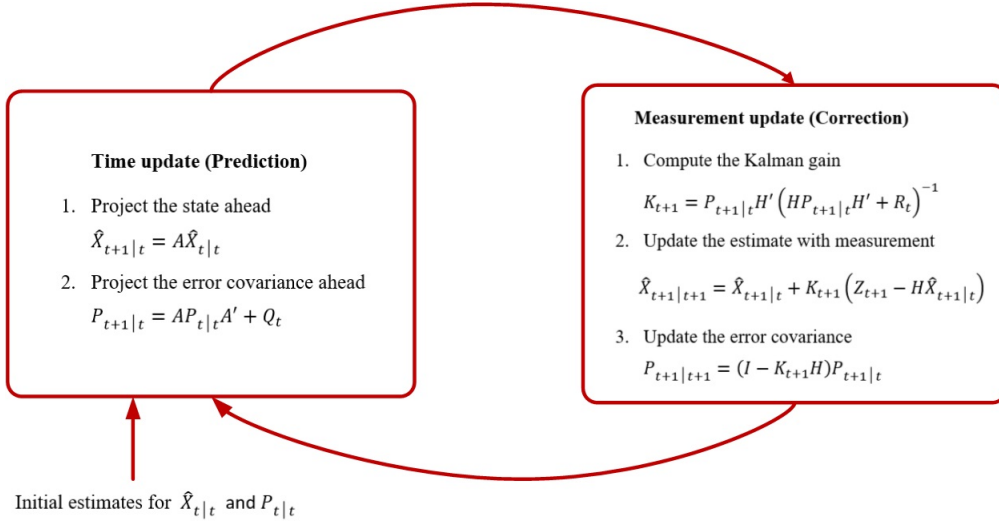


Figure 3.8: The recursive operation of Kalman Filter

3.4 Performance Evaluation

This section of the chapter investigates the performance of the proposed hybrid IoT network architecture. The performance of the proposed strategy is evaluated in terms of the average energy expenditure and target tracking accuracy.

3.4.1 Energy Consumption Model

Energy consumption is one of the metrics used to evaluate the performance of the proposed IoT network architecture. In order to assess the energy consumption, we introduce the energy consumption model of a visual sensor node.

The energy consumption of a visual sensor node in a wireless mesh multi-hop network is the sum of the energy consumption of a node in transmitting mode, receiving mode, overhear mode, and idle mode. It is expressed mathematically as follows [100]:

$$\begin{aligned} E &= E_{tx} + E_{rx} + E_{oh} + E_{idle} \\ &= P_{tx}T_{tx} + P_{rx}T_{rx} + P_{oh}T_{oh} + P_{idle}T_{idle} \end{aligned} \quad (3.12)$$

where E_{tx} and E_{rx} are the transmitting and receiving energy respectively, E_{oh} is the total energy spent by a node when receiving packets that are destined to other nodes, and E_{idle} is the energy that the node spends when transceiver spends in idle mode. Here, P_{tx} , P_{rx} , P_{oh} and P_{idle} represent the corresponding power consumption in each mode. The T_{tx} , T_{rx} , T_{oh} and T_{idle} are the representation of respective times spent in each mode. For simplicity of energy consumption analysis of the network, we consider only evaluating the energy consumption of the visual sensor nodes involved in video vigilance without accounting for the energy consumption of visual sensor nodes involved in relaying the video stream to the gateway. The energy-aware and QoS routing mechanism is studied and described in Chapter 4. Therefore, we consider the visual sensor network as the one-hop network where every visual sensor node reaches the gateway directly for transmitting the video stream to the gateway. The energy consumption model of a visual sensor node in a one-hop network is reduced to the sum of a node's energy consumption in transmitting mode and idle mode, assuming the information

transmitted from the visual sensor nodes to the gateway [71].

3.4.2 Tracking Accuracy

Tracking accuracy is an essential metric for evaluating target predictions and tracking algorithms. As mentioned in Section 3.3.1, KF is used to estimate the intruder's current position and to predict the intruder's future location. Only the visual sensor node is closest to the intruder's current position and the visual sensor node that is closest to the predicted position are activated. Therefore, we use distance error and average distance error metrics to evaluate the tracking accuracy in the one-time step ahead predictions and the current state estimations of the KF.

The prediction distance error, ϵ_d^- , is defined as the distance between the predicted location of the intruder and the actual position of the intruder. Mathematically, it is defined as

$$\epsilon_d^-(t) = \sqrt{(x_{at} - \hat{x}_{pt}^-)^2 + (y_{at} - \hat{y}_{pt}^-)^2} \quad (3.13)$$

Where $\epsilon_d^-(t)$ is the distance error of the prediction, $(\hat{x}_{pt}^-, \hat{y}_{pt}^-)$ is the predicted position, (x_{at}, y_{at}) is the actual position.

The prediction average distance error, ϵ_{ave}^- , is obtained by the average distance between the predicted location of the intruder and the actual location of the intruder. It is calculated as

$$\epsilon_{ave}^- = \frac{1}{N} \sum_{t=1}^N \epsilon_{ave}^- \quad (3.14)$$

Where ϵ_{ave}^- is the prediction average distance error, N is the number of predicted values

Similarly, the current estimation distance error or estimation average distance error

can be obtained. The estimation distance error, ϵ_d , is the distance between the current estimated position of the intruder and the actual position of the intruder. Estimation average distance error, ϵ_{ave} , can be computed by averaging the distance between the current estimated location and the intruder's actual location.

3.4.3 Simulation Parameters and Assumptions

The research study considers a video surveillance network area of $500m$ length and $200m$ width where the heterogeneous sensor nodes are deployed in a planned manner, as illustrated in Figure 3.9, the overall video surveillance topology. 250 Lora-enabled low-power Pyroelectric Infrared (PIR) motion sensor nodes with a sensing range of $R_m = 10m$ are deployed in the monitoring area. A total of 78 visual sensor nodes with a sensing range of $R_{VSN} = 20m$ have been placed to cover the essential monitoring region. The deployed visual sensor nodes transmit video streams in a single-hop transmission through gateways. The average power consumption of the visual sensor nodes is $6.1W$ when it is active (when transmitting video stream to the gateway) and $5.8W$ when it is idle. Furthermore, 78 Lora endpoints associated with the 78 visual sensor nodes through Ethernet cable are deployed to carry out shutdown and wake-up processes. The LoRa enabled motion sensor nodes and the LoRa endpoints are within reach of the LoRa gateway. The distance between Lora-enabled PIR motion sensor nodes is $20m$, whereas the distance between the energy-expensive visual sensor nodes is $40m$. A single intruder enters the monitored area at an average pedestrian speed of $4km/hr$ and follows the trajectory given in Figure 3.10.

In the Kalman Filter's algorithm, the measurement noise and process noise covariance matrices are set at $0.5I2$ and $0.5I4$, respectively, and the sampling period is 18 seconds. In addition to the above parameters, the following assumptions have been made:

- The Lora-enabled low-power motion sensor nodes and visual sensor nodes are provided with positional information.

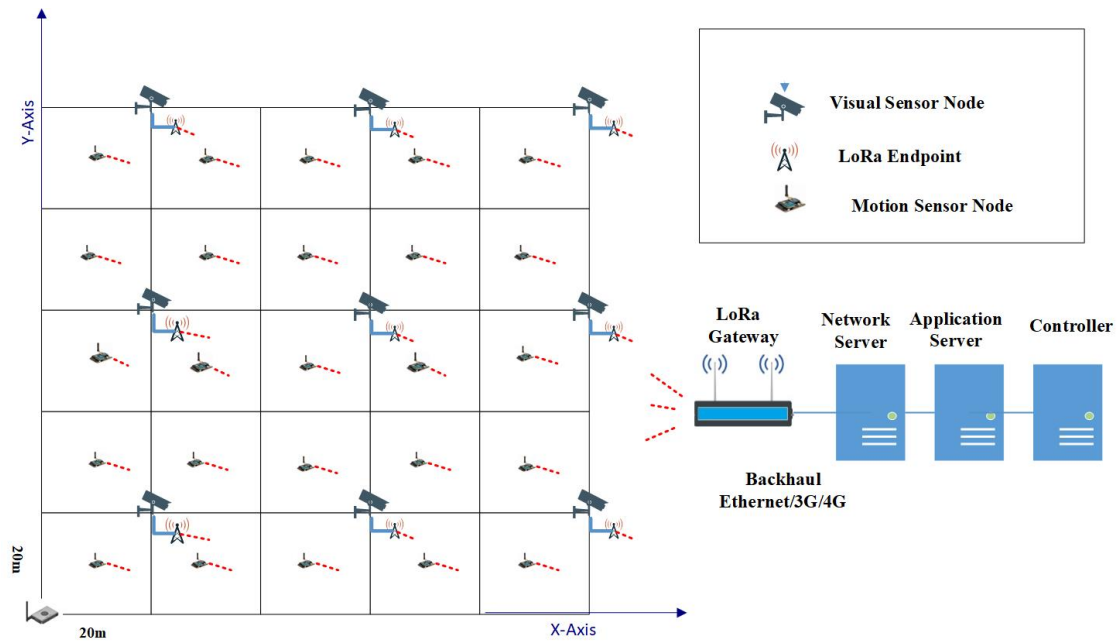


Figure 3.9: Video Surveillance Topology

- Each low-power motion sensor node can detect the intruder instantly when it is in a sensing range and measures the intruder's position in $2D$ Cartesian coordinates.
- The visual sensor nodes can be turned on or off right away when they get a command from the central controller.
- Initially, all the visual sensor nodes are in a complete shutdown mode.
- The low-power motion sensor nodes have a circular detection area, and the visual sensor nodes have 360° angles of view, respectively.
- The power consumption of Lora-enabled low power motion sensors is negligible compared with the energy consumption of the visual sensor nodes.

As previously stated, to evaluate the performance of the proposed IoT network archi-

texture, we use the average energy consumption and the tracking accuracy matrices. Further, we compare the performance of the proposed IoT network architecture with a baseline scenario. We evaluate the performances using *MATLAB* simulations. The following are the simulation scenarios:

- *Baseline Scenario*: This scenario is a single-tier visual sensor network where all the network's visual sensor nodes are always-active to provide continuous video vigilance of the surveillance region. This scenario is used as a baseline to compare the proposed hybrid IoT network.
- *Proposed Approach*: This scenario presents the proposed hybrid IoT network for video surveillance systems.

3.4.4 Simulation Results and Discussions

First, the performance of the proposed approach is evaluated in terms of tracking error. The tracking error metric for assessing the performance of the baseline scenario is not considered since it does not employ predictive tracking algorithms.

Figure 3.10 illustrates the actual and KF predicted trajectory of the intruder as well as the locations of the visual sensor nodes in the monitored area. The KF predicted trajectory distance error is depicted in Figure 3.11 as a function of a time step. As can be seen that the KF predicted trajectory is a good approximation of the actual trajectory when the intruder moves in a straight line. As a result, the predictor has a relatively low level of prediction distance error. The predictor's performance degrades when the intruder makes sudden turns or changes direction. This is noticeable in the occurrence of significant errors. Over the entire path, the KF predictor predicts closer to the actual trajectory, with an average deviation of 3.4 meters.

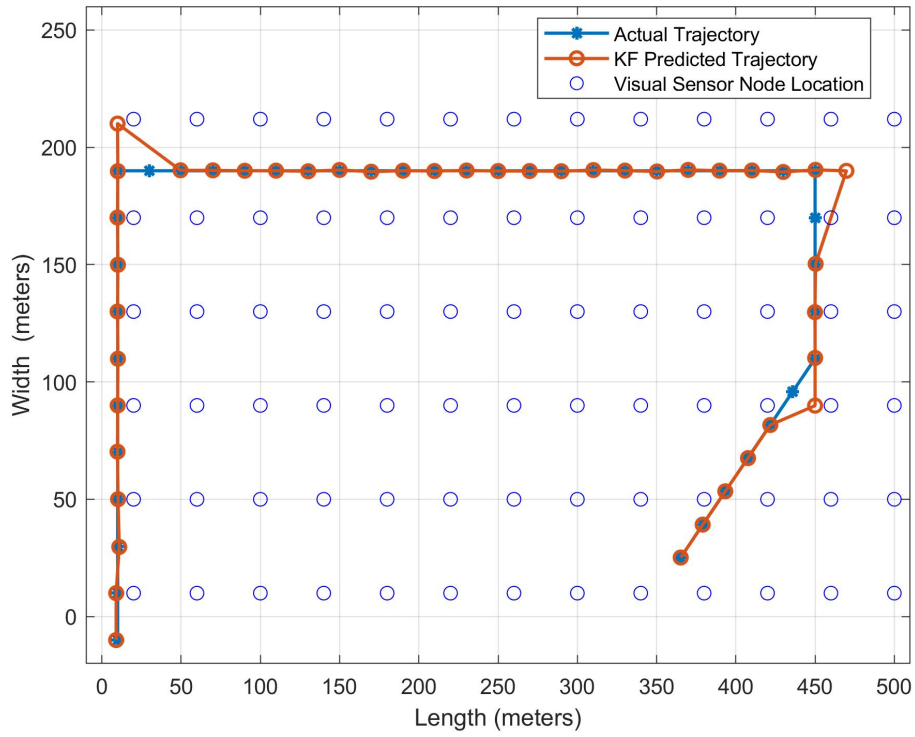


Figure 3.10: Intruder's actual (true) trajectory and KF one time step ahead predicted trajectory

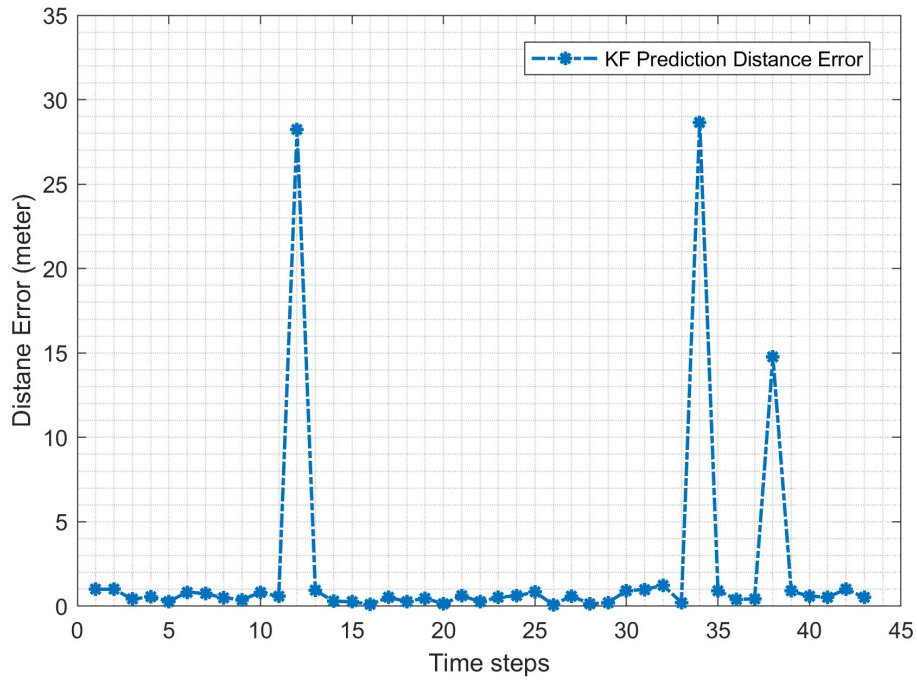


Figure 3.11: KF one time step ahead prediction distance error over time steps. One time step is 18 second.

Figure 3.12 shows the locations of the visual sensor nodes nearest to the predicted trajectory of the intruder and the positions of the visual sensor nodes nearest to the intruder's actual path. It can be observed that the locations of the visual sensor nodes that track the intruder's predicted route and the exact route of the intruder overlap on most of the paths covered by the intruder, except when the intruder makes a turn or changes direction as a result of the good performance of the KF predictor. The KF predictor has 93.02% accuracy (40 exact locations out of the total 43) in locating the nearest visual sensor nodes that track the predicted locations of the intruder with the deployment scenario considered.

Figure 3.13 illustrates the KF estimated trajectory (estimation of the intruder's current position) and the actual trajectory of the intruder, whereas Figure 3.14 shows the KF estimation distance error over time steps. As can be seen, the estimated trajectory is the best approximation of the actual trajectory over the entire path. This is noticed that the KF estimator has a relatively low level of estimation distance error over the whole path. The KF estimator works quite well along the whole path, with an average deviation of 0.84 meters.

Figure 3.15 illustrates the tracking visual sensor nodes that are nearest to the estimated trajectory (estimated trace of the current location) of the intruder and the tracking visual sensor nodes that are nearest to the actual path of the intruder. It can be observed that the locations of the visual sensor nodes that track the intruder's current locations and the actual route of the intruder overlap on most of the locations as a result of the best performance of the KF estimator. The KF estimator has 99% accuracy (42 exact locations out of 43 locations) in locating the nearest visual sensor nodes that track the intruder's estimated (current) locations with the deployment scenario considered.

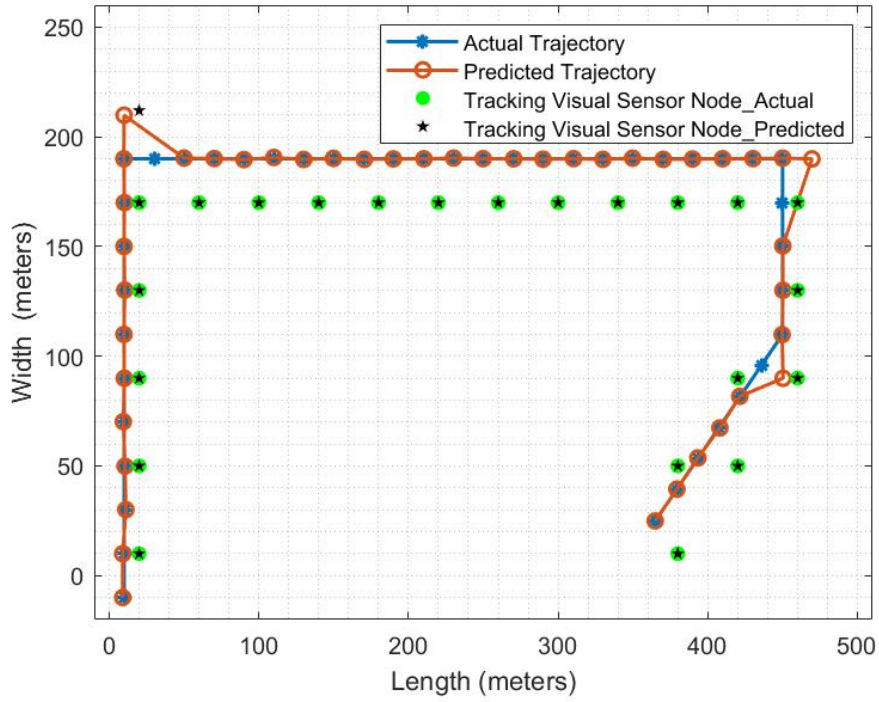


Figure 3.12: The locations of the visual sensor nodes nearest to the predicted trajectory of the intruder and the intruder's actual path.

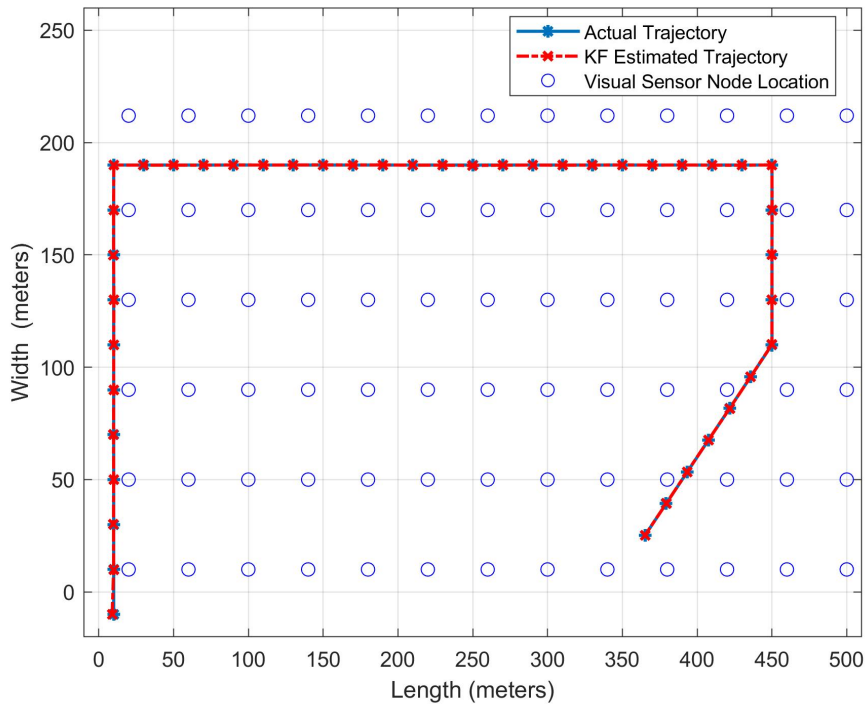


Figure 3.13: KF estimated trajectory (estimation of the intruder's current position), and actual trajectory of the intruder, and the location of the visual sensor nodes.

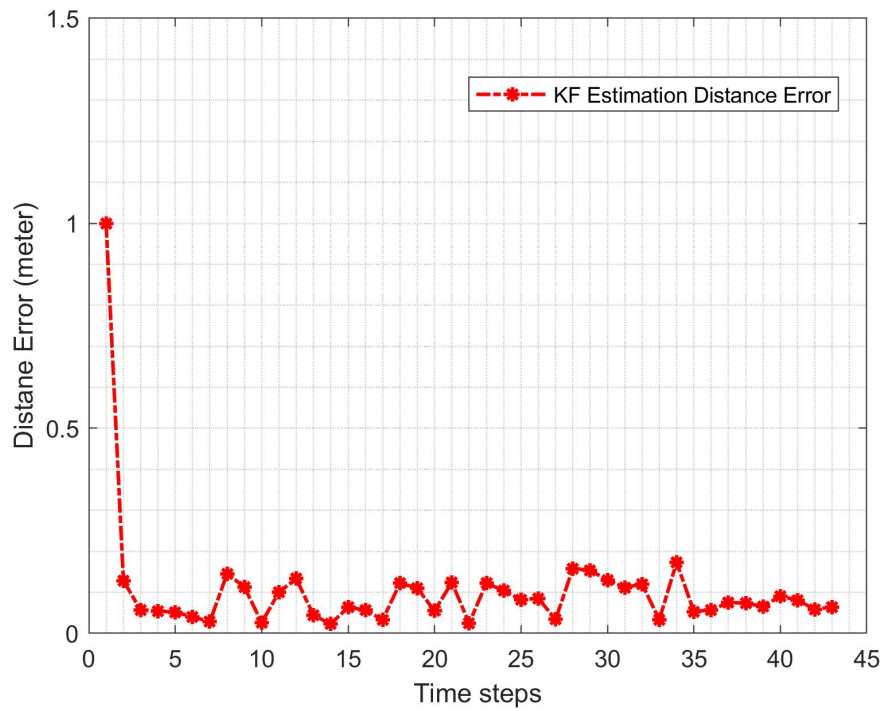


Figure 3.14: KF estimation distance error over time steps. One time step is 18 second.

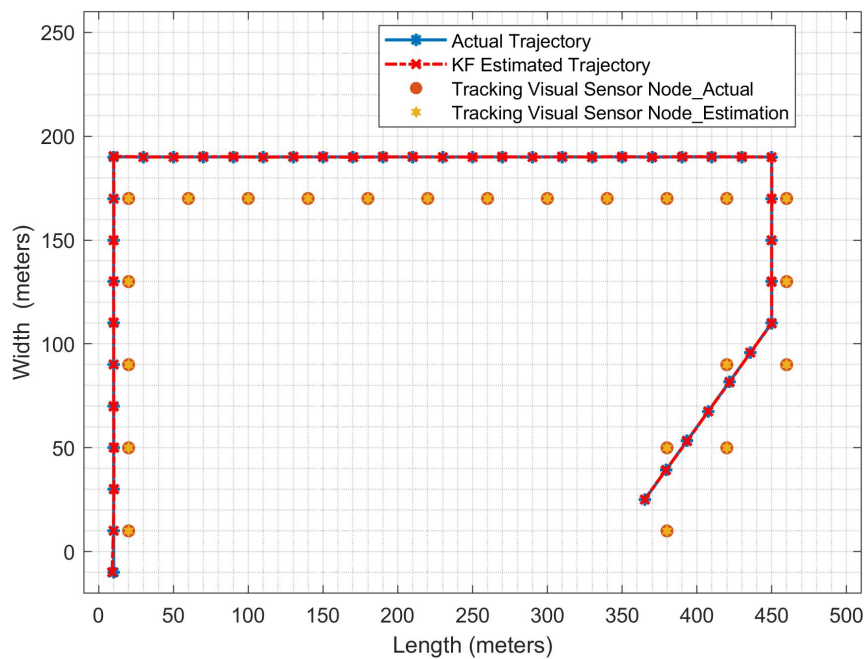


Figure 3.15: The tracking visual sensor nodes that are nearest to the estimated trajectory (estimated current location) of the intruder and the tracking visual sensor nodes that are nearest to the actual path of the intruder.

Further, the performance of the proposed approach is evaluated in terms of the average power consumption over time in comparison to the baseline scenario. Figure 3.16 depicts the average power consumption of the proposed scheme over a total of 12.60 minutes (43-time steps) in comparison to the baseline scenario. As it is clearly shown in Figure 3.16, there is a significant difference in average power consumption, with the proposed approach consuming (0.0122 KW) significantly less than the baseline scenario (0.4758 KW). This is due to the proposed scheme selectively activating only two visual sensor nodes (visual sensor node nearest to the intruder’s current position and the visual sensor node nearest to the intruder’s predicted position) along the intruder’s path every time step to follow the intruder while the other visual sensor nodes remain in a complete shutdown mode. In the baseline scenario, all of the network’s visual sensor nodes are always active, providing continuous monitoring of the surveillance region. Thus, the proposed approach achieved energy efficiency by saving 97.44% of total energy consumption compared to the baseline scenario over 12.60 minutes. This justifies the energy efficiency of the proposed approach through a significant amount of energy savings.

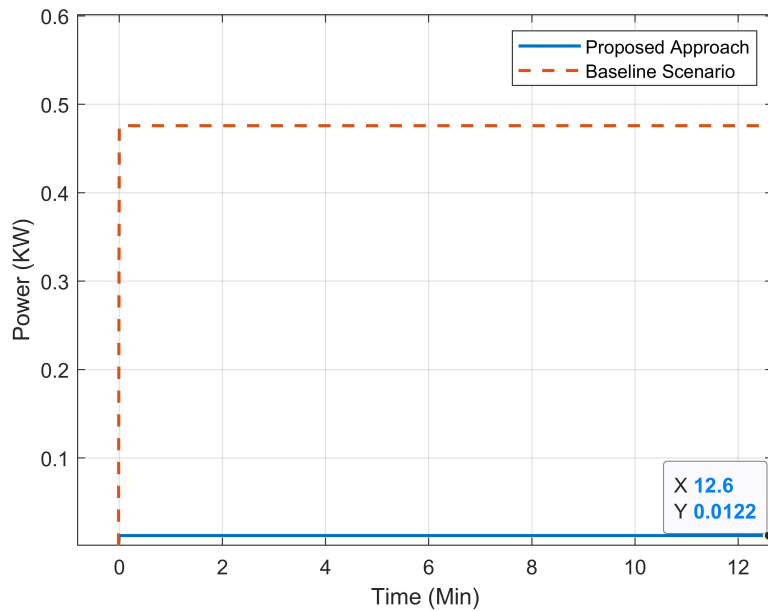


Figure 3.16: The comparison of average power consumption in the proposed approach and the baseline scenario over a total of 12.60 minutes (43-time steps).

3.5 Conclusion

In this chapter, we presented a hybrid IoT network that integrates IEEE 802.11-based wireless multi-hop visual sensor network and LoRaWAN network to form an autonomous, high bitrate, energy-efficient video surveillance system. In addition, we demonstrated intruder (target) detection and tracking mechanism in the hybrid IoT network using the Kalman filter. The hybrid IoT network architecture enables the high-energy-consuming visual sensor nodes to be kept in a complete shutdown mode until they are needed. The LoRa network is utilized as an always-on network in the hybrid IoT network to monitor and better detect the presence of motion. Based on the intruder detection and tracking information, the LoRa network can issue a control instruction to activate only a limited number of visual sensor nodes along the pathway of the intruder, i.e., the visual sensor node nearest to the intruder's current position and the visual sensor node nearest to the intruder's predicted future position. Further, the remaining visual sensor nodes can be kept in a complete shutdown mode or turned off completely. Consequently, the number of visual sensor nodes participating in the video vigilance and tracking activity is reduced. Thus, it saves the overall energy consumption of the video surveillance network.

We conducted a simulation in order to evaluate the performance of the Kalman filter tracking algorithm in the hybrid IoT network in terms of tracking accuracy. The simulation result shows that the Kalman filter algorithm is effective and performs with better accuracy, especially when the intruder moves in a linear trajectory. Furthermore, we compared the energy efficiency of the proposed hybrid IoT network with a traditional baseline scenario. The baseline scenario is a single-tier visual sensor network where all the network's visual sensor nodes are always active to provide continuous video vigilance of the surveillance region. Simulation results indicate that the proposed hybrid IoT network can help reduce a significant amount of energy consumption (97.44%).

In the next chapter, we propose an energy-aware and QoS routing mechanism for the hybrid IoT network.

Chapter 4

Energy-Aware and Quality of Service Routing Mechanism for Hybrid Internet of Things Network

4.1 Introduction

The rapid rise of the Internet of Things (IoT) [76, 35, 85] has led to considerable growth in the demand for video surveillance systems. Wireless Multimedia Sensor Networks (WMSNs) based on IEEE 802.11 multi-hop mesh networks are effective and suitable solutions for video surveillance systems. While IEEE 802.11-based WMSNs support high-bitrate video transmission, they are inefficient in terms of energy consumption. Moreover, video surveillance applications demand more strict Quality of Service (QoS) requirements such as bandwidth, end-to-end delay, and packet loss. In the preceding chapter, we proposed a hybrid Internet of Things network that combines IEEE 802.11 based multi-hop visual sensor network and the LoRa network to provide an autonomous, high-bitrate, and energy-efficient video surveillance system. The hybrid IoT

network architecture simply enables the management of the energy consumption of the visual sensor nodes in the network by switching them on and off as needed. A routing mechanism is needed to transfer the video stream from the sources to the gateway in the multi-hop network. The routing mechanism should be designed to ensure the optimum network's energy consumption while supporting the QoS guarantee requirement of video transmission in the multi-hop visual sensor network. There is, however, a challenge in providing QoS guarantees in multi-hop wireless networks due to the unpredictable nature of the wireless medium and the shared nature of the medium. The interference between the wireless nodes sharing the same wireless medium significantly affects the network performance (such as bandwidth, end-to-end delay, etc.), and accounting for the impacts of interference is critical for QoS provisioning. As a result, providing a guaranteed QoS is a great challenge due to the inherent limitation of the wireless transmissions in multi-hop networks.

Numerous researches in wireless multi-hop networks dealt with energy-aware routing mechanisms that support certain QoS guarantees depending on the application. Among these researches, most of the solutions aimed to extend the network's lifetime/lifespan by utilizing mechanisms that employ load balancing techniques or balance the energy consumption in the network while offering specific QoS guarantees [55, 7, 64, 31]. The mechanisms simply extend the network's life span by reducing the nodes' individual energy consumption; nevertheless, the routing solutions do not make the entire network more energy efficient. This is due to the routing solutions' requirement that nodes remain active even if they only send a small amount of data. The energy consumption of a traffic transmission of an active node has little effect on the total energy consumption of the active node [25, 45]. This demonstrates that a significant amount of energy is consumed to keep the node active, particularly in networks such as IEEE 802.11-based visual sensor networks. As a result, the network's overall energy consumption can be minimized by turning off as many nodes as possible while maintaining the QoS performance. Therefore, this chapter is focused on the overall network energy

consumption savings in the IEEE 802.11-based multi-hop visual sensor network while guaranteeing QoS in terms of bandwidth and delay.

In this chapter of the dissertation, we propose an energy-aware and QoS routing algorithm for the IEEE 802.11-based wireless multi-hop visual sensor network of the hybrid IoT network. The routing algorithm allows routing a set of video streams with guaranteed bandwidth and delay (under the assumption that the end-to-end packet delay is proportional to the number of hops in a path) while minimizing the number of visual sensor nodes involved in the routing. The mechanism maximizes the visual sensor nodes that are not involved in the routing and can be turned off completely. This saves the overall energy consumption of the network without compromising the QoS performance. After evaluating the performance of the proposed routing mechanism through simulation with other algorithms from the literature, the results show that the proposed routing algorithm provides guaranteed bandwidth and delay with a significant reduction in the network's energy consumption.

The key contributions of this chapter are the following:

- Proposing an energy-aware and QoS routing algorithm for the IEEE 802.11 based multi-hop mesh connected visual sensor nodes in a hybrid IoT network.
- Proposing an optimal routing algorithm that provides guaranteed bandwidth and limited delay while minimizing the overall energy consumption of the network. Thus, the energy efficiency is achieved by completely shutting down as many visual sensor nodes as possible without compromising performance.
- Formulating the problem as an integer linear program (ILP) and employing a branch-and-bound algorithm for obtaining the optimum solution.

The remainder of the chapter is laid out as follows. Section 4.2 introduces the models used to represent the multi-hop visual sensor network and network interference, which

form the foundation of the work. Section 4.3 discusses integer linear programming for modeling optimization problems before presenting the branch-and-bound algorithm for problem solving. The proposed energy-aware and QoS routing mechanism is presented in Section 4.4. The mathematical formulation of the routing problem, as well as the optimal solution, are discussed in greater detail. Section 4.5 analyzes the proposed routing algorithm's performance and compares it to that of other algorithms in the literature. Section 4.6 concludes with remarks.

4.2 System Model

This section presents the wireless network model and interference models upon which the dissertation work is based and the assumptions that are considered.

4.2.1 Network Model

We represent the wireless visual sensor network in the hybrid IoT network as a directed graph $G = \{V, E\}$, where V is the set of visual sensor nodes in the network, and E is the set of wireless links between the set of those nodes. We consider a single radio single-channel visual sensor network. For a given pair of nodes i and j in the network, there is a link $(i, j) \in E$ exist if node j is in the node i 's transmission range (i.e. node j can successfully receive data from node i). We consider the same transmission range for all the visual sensor nodes in the network. Therefore, if link (i, j) is element of E , then link (j, i) also element of E . We assume that all the visual sensor nodes in the network are in a static condition. We also assume that the wireless channel is ideal, and therefore, the wireless links are reliable. Figure 4.1 illustrates an example of a wireless network topology having five wireless visual sensor nodes.

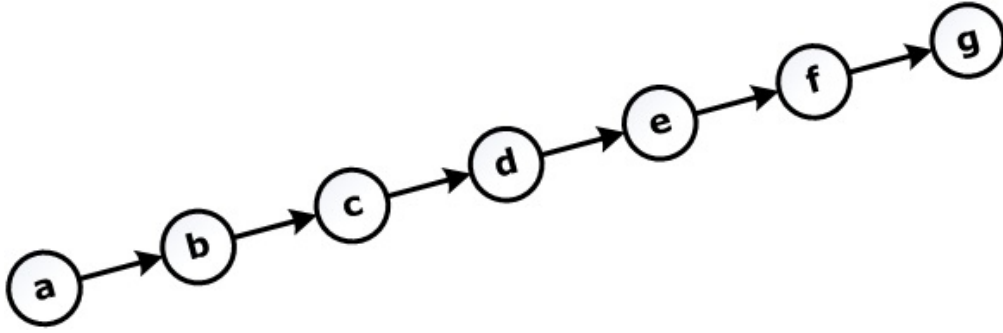


Figure 4.1: Wireless network topology having five wireless visual sensor nodes.

4.2.2 Interference Model

In wireless multi-hop networks, the medium is shared by neighboring links. The flows sharing a set of links in the network are subject to interference as a result of simultaneous transmissions in the shared medium. Intra-flow interference and inter-flow interference are the two categories of interference. Intra-flow interference is caused when a set of links belonging to the same flow interfere with each other. Inter-flow interference, on the other hand, appears when links belonging to different flows interfere with one another [49, 11]. Because both interferences degrade the performance of the wireless multi-hop network, the effect of the interference should be accurately modeled in routing algorithm designs [49].

Interference is often modeled in two ways in the literature: a physical model and a protocol model [52, 43]. The physical model determines whether a transmission is successful by computing the signal-to-interference-and-noise-ratio (SINR) value, which takes into account the received signal strength, interference induced by another concurrently transmissions in the network, and the level of ambient noise [67, 8]. The transmission between node i and j is successful if the SINR at the node j (receiver) exceeds a certain threshold ($SINR_{th}$). This enables the transmitted packet to be decoded with a low bit error probability. If the received SINR is less than the threshold, it is presumed that

an error occurred during transmission, and the packet would not be received. In the protocol model, on the other hand, the successful transmission between node i and j happens if node j is within node i 's transmission range while any other node in the interference range of node j is not transmitting. The interference range is simply the maximum range up to which a wireless node in the receive mode gets interfered with another simultaneous transmission.

In the dissertation, we use the protocol interference model in order to model interference since the research focuses on the network layer. In addition, the protocol model is simple to use and has low computational complexity [93]. Moreover, the model makes it easier to build a conflict graph representing the interference relationships between wireless links in the network [52, 15].

The conflict graph $CG = (V', E')$ is an undirected graph where the vertices indicate the wireless links of the network G , and the edges show the interference relationship between the wireless links in G . If two links in G interfere with one another, there is an edge between the corresponding vertices in the conflict graph, CG . The N -hop interference model (a relaxed model that approximates the protocol mode [109]) is utilized to construct the conflict graph. In this model, a node interferes with its neighbors up to a distance of N -hops. This dissertation uses the 2-hop interference model to construct the conflict graph as in [10], and it has been used widely in the literature. Figure 4.2 shows example of the conflict graphs with a 2-hop interference model of wireless network illustrated in Figure 4.1.

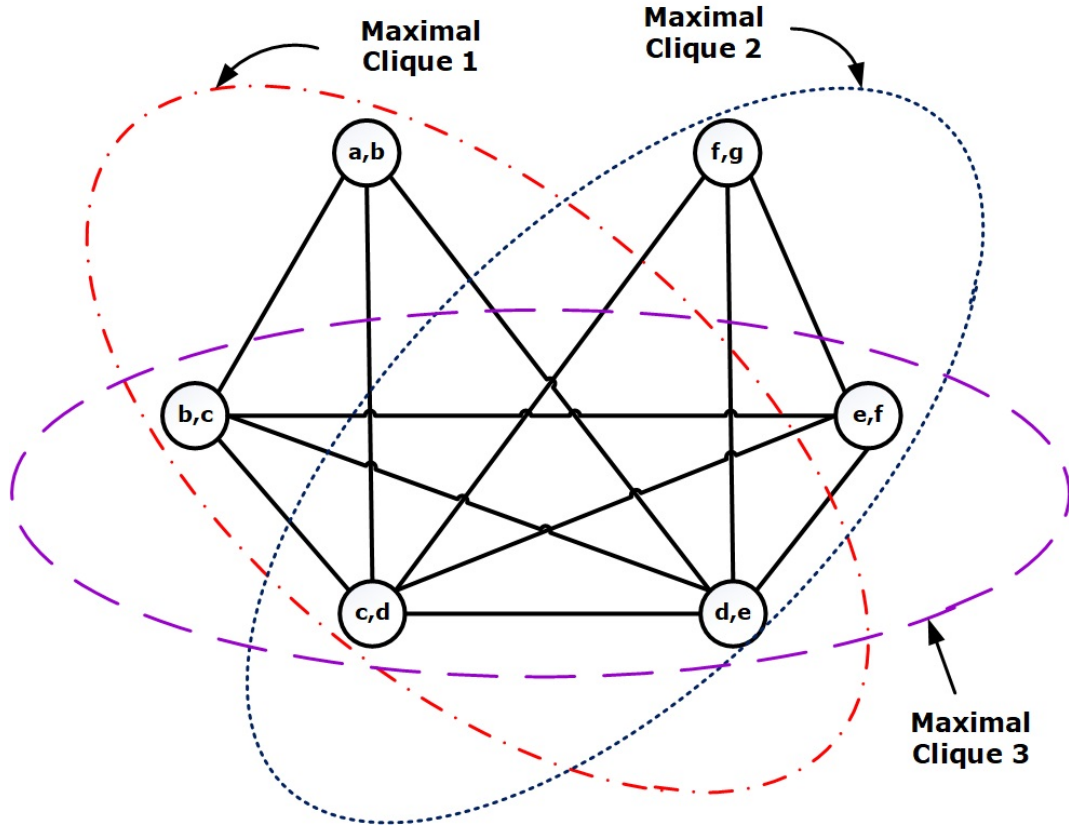


Figure 4.2: Conflict graph.

The maximal clique (i.e., a complete subgraph of CG that is not included in another complete subgraph) can be computed from the conflict graph. For example, in the conflict graph shown in Figure 4.2, the maximal cliques are as follows: $\{(a, b), (b, c), (c, d), (d, e)\}$, $\{(c, d), (d, e), (e, f), (f, g)\}$ and $\{(b, c), (c, d), (d, e), (e, f)\}$. The maximal cliques in the conflict graph represent a set of mutually interfering wireless links in the network that cannot be active simultaneously. As a result, only one conflict graph vertex in a maximal clique (one wireless link in the network G) may be active at once. Accordingly, the sum of the rates of the conflict graph vertices in each maximal clique cannot exceed the channel's capacity. Therefore, cliques can be used to derive necessary and sufficient constraints to accept or reject the flow requests based on the bandwidth available in the multi-hop wireless network.

The clique constraint or the capacity constraint (under interference consideration) as introduced in [44] is given by

$$\sum_{(i,j) \in q} \frac{d_{i,j}}{C_{ai,j}} \leq 1 \quad , \quad \forall q \in Q \quad (4.1)$$

where $d_{i,j}$ represents the total (aggregate) capacity reserved on the link (i, j) , $C_{ai,j}$ is the capacity of the link (i, j) , and Q represents the set of maximal cliques. The constraint makes sure that flows are routed with respect to the available capacity of the cliques.

4.3 Preliminary: Integer Linear Programming

Linear programming (LP) is a popular approach for formulating and solving optimization problems. LP is a mathematical modeling technique that finds the variables' values that optimize (i.e., maximize or minimize) a linear objective function when subject to one or more constraints in linear equations or inequalities. The constraints describe the restrictions on the decision variables. The decision variables in LP models must be continuous, implying that they can take any real value number. However, there are many real-world optimization problems in which using continuous decision variables will be unrealistic. As a result, a wide range of real-world problems can be formulated as integer linear optimization problems. The optimization problem considered in this dissertation is formulated as an integer linear programming problem and is discussed in Section 4.4.

Integer Linear Programming (ILP) enables solving the linear optimization problem with certain integer variables, where the objective function and the constraints are linear [108]. When all the variables are constrained to take only integer values, it is a pure integer-programming problem. When some variables but not all variables take an integer value, it is a Mixed Integer Programming (MIP) problem. Another class of ILP

problem is called Binary Integer Programming (BIP) problem, where the variables are constraints to take only 0 and 1 values [22, 108].

ILP has become a well-established tool to model and solve real-world optimization problems. Moreover, a high-performance and powerful mathematical programming solver, such as IBM ILOG CPLEX [50], can handle Integer linear optimization problems. The availability of linearization techniques for transforming some types of nonlinear integer programming problems into integer linear programming can broaden its applications. ILP has been applied in a wide range of practical optimization problems arising from applications in computer networks, telecommunication, cellular networks, energy, manufacturing, or logistics, to name a few [56]. ILP problems are challenging to solve in a polynomial time. However, different exact mechanisms exist for solving ILP problems, and the most successful mechanism is the branch and bound method [108].

The branch-and-bound algorithm [108, 22, 34] is a technique for finding exact solutions to integer linear programming and combinatorial optimization problems. It is a search strategy for finding the best solution by enumerating a small fraction of the possible solutions in a tree structure. The other remaining solutions are being discarded (pruned) from consideration in the search by applying bounds that prove that the solutions cannot be or lead to an optimal solution. The name branch and bound come from the algorithm's two principles (operations). *Branching* refers to the splitting (dividing) of the solution space into smaller subsets. *Bounding*, on the other hand, refers to the estimation of the bound on the objective function value over the subset of solutions [73, 34].

The branch-and-bound algorithm searches the solution space by recursively partitioning it into smaller subspaces in a tree structure. In the search tree, the root node indicate the given problem to be solved, and each other node represents the subproblems of the original problem. The branch and bound search for the best solution is organized

in a way that the search tree is expanded one by one. The mechanism expands or branches on a node when the node has the potential (or promises) to provide a better solution. This potential can be determined by estimating an upper bound on the objective value of solutions at the node based on the maximization problem's context. We use maximization problem to explain the branch and bound algorithm. The upper bound is often produced by solving the LP relaxation of the problem at the node where the integrality requirement on the variable is dropped. The upper bound is compared with the objective value of the incumbent (the best feasible solution so far), and if the result is worse, then the node is discarded (pruned) as it cannot have the potential to produce better solutions.

At every branch and Bound algorithm level, each node in the search tree represents a subproblem, and it is solved by relaxing the subproblem by dropping the integrality conditions. If the LP relaxation of the subproblem at the node is infeasible, the ILP at the node is also not feasible. If the solution to the LP relaxation of the subproblem results in a feasible integer solution, the solution is feasible to the main problem and optimal for the integer linear program of the subproblem. Suppose the value of the feasible integer solution is better (exceeds) than the value of the current incumbent and in that case, the incumbent will be updated by the new feasible integer solution. The other solution option of the LP relaxation of the subproblem results in at least one of the integer variables being fractional. If the optimum objective value of the LP relaxation is better than the value of the incumbent, branching can take place at the node. There are various alternatives for selecting the branching variable, but the simplest choice is the variable with fractional value [108]. In that case, branching on the fractional variable creates two new subproblems, which exclude the previous fractional solution. It, however, includes all the feasible integer solutions. The two new subproblems represent two child nodes in the search tree. The branching process stops on a node in either of the following conditions: i) when an LP relaxation at the node is not feasible. ii) when the optimum solution of the LP relaxation at the node

satisfies the integrality constraints (i.e., the optimum solution is integer feasible). iii) when the objective function value of the optimum solution to the LP relaxation at the node is worse than (less than) the value of the current the current incumbent. These requirements are often known as the rules for pruning (fathoming) a node. The Branch and Bound algorithm stops when there are no active nodes (i.e., nodes that have not been branched or not pruned) left to consider for further branching. In this case, the incumbent solution is an optimal integer solution for the given problem.

As mentioned earlier, the branch and bound algorithm is general, and numerous components of the algorithm affect its performance. These are the criterion for selecting the next node, the branching strategy (selecting the next variables), and the pruning rule. The policies addressing the components mentioned above must be established to fully describe the branch and Bound algorithm [28]. In order to make this chapter easier to read and comprehend, we use an example to demonstrate the branch and bound algorithm for solving a knapsack problem. A knapsack problem is a combinatorial optimization problem formulated as a BIP problem. The binary integer program is as follows:

$$\begin{aligned}
 &\text{Maximize} && 8x_1 + 11x_2 + 6x_3 + 4x_4 \\
 &\text{subject to} && 5x_1 + 7x_2 + 4x_3 + 3x_4 \leq 14 \\
 &&& x_i \in \{0, 1\}, \text{ for } i = 1 \text{ to } 4
 \end{aligned} \tag{4.2}$$

Figure 4.3 illustrates an example of implementing the branch and bound algorithm to solve the binary integer program provided in Equation (4.2). Obviously, in order to employ the branch and bound method, all of the algorithm's components must be specified. Therefore, we use the best upper bound as the next node selection strategy, the variable with fractional value as branching strategy. Furthermore, we use the same pruning strategy described in the branch and bound algorithm for the maximization

problem.

As it is clearly shown in the Figure 4.3, each node (k) in the branch and bound search tree reflects its associated Linear Program $LP(k)$, where $LP(k)$ is the LP relaxation of K 's subproblem. K denotes the algorithm's iteration number as well as the order in which the nodes in the search tree are evaluated. X_{LP}^k represents the optimum solution, where as Z_{LP}^k is the optimum objective value of the $LP(k)$ (or $node(k)$). X_{in} is the incumbent solution. Z_{in} is the objective value of the incumbent solution.

It is assumed that there is no integer feasible solution at the beginning of the algorithm, hence a value of negative infinity ($-\infty$) is assigned as the incumbent starting value. As it is clear depicted in the Figure 4.3, the brand and bound algorithm starts at $node(1)$ and stops after processing 11 nodes. Therefore, the optimal integer solution for the given problem is the incumbent solution, $X_{in} = X_{LP}^6 = (0, 1, 1, 1)$.

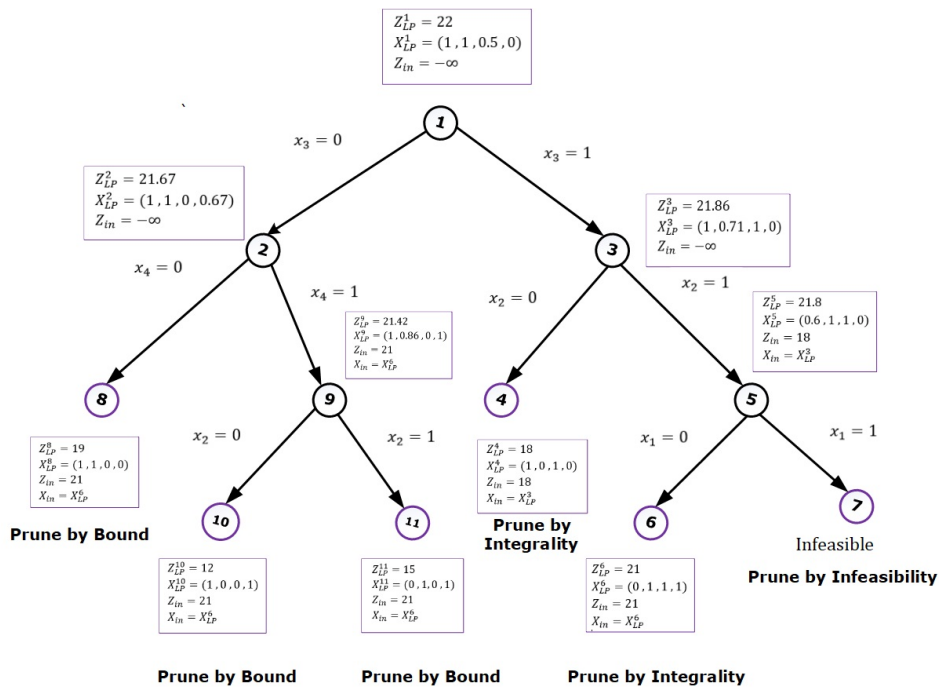


Figure 4.3: The Branch and Bound tree.

4.4 Energy-Aware and QoS Routing Mechanism - Problem Formulation and Optimal Solution

In this chapter of the dissertation, we study how to optimize the energy consumption of the visual sensor network of the hybrid IoT network while guaranteeing QoS in terms of bandwidth and end-to-end delay. We are not concerned with lowering the energy consumption of individual visual sensor nodes in the network but with lowering the network's overall energy consumption while providing guaranteed QoS in terms of bandwidth and end-to-end delay. As a result, a routing mechanism is essential for achieving this goal for the hybrid IoT network.

Therefore, this chapter aims to design an optimal routing mechanism that routes a set of video flows using as few visual sensor nodes as possible while ensuring guaranteed QoS in terms of bandwidth and end-to-end delay. This enables to selectively activate only as few visual sensor nodes as possible that are needed for routing. In other words, the mechanism maximizes the number of nodes that can be turned off completely. This reduces the network's overall energy consumption while guaranteeing QoS in terms of bandwidth and end-to-end delay. The QoS guarantees ensure that each flow with bandwidth and delay requirements finds a path from the source to the gateway with sufficient remaining capacity to meet the bandwidth requirement and that each flow delay is less than the deadline. Otherwise, the flow is not accepted. We assume that each hop in the network causes the same hop delay, so the end-to-end packet delay is proportional to the number of hops in a path.

We formulate the routing problem as an integer linear program (ILP) [108, 22]. The objective is to find the minimum number of visual sensor nodes that must be activated (powered on) under QoS constraints in terms of bandwidth and end-to-end delay.

We use the following notations to describe the model:

E : the set of links

V : the set of visual sensor nodes

Q : the set of cliques

L : the set of flows in the network

$d_{i,j}$: the capacity (the aggregate bandwidth of flows) reserved on link (i, j)

$C_{ai,j}$: the total capacity available on link (i, j)

(S_l, G_l) : the source and the gateway of flow l

B_l : the minimum bandwidth requested by flow l

x_i : equal to 1 if the node is used to route flow, 0 otherwise

$x_{i,j}^l$: equal to 1 if (i, j) is used to route flow l , 0 otherwise

ρ_m : delay deadline or path length limit of each of the flows

The objective function:

$$\text{Minimize } \sum_{i \in V} x_i \quad (4.3)$$

Subject to the following constraints:

$$\sum_{(i,j) \in q} \frac{d_{i,j}}{C_{ai,j}} \leq 1, \quad \forall q \in Q \quad (4.4)$$

$$\sum_{(i,j) \in E} x_{i,j}^l - \sum_{(j,k) \in E} x_{j,k}^l = 0, \quad \forall l \in L, \forall j \in V - \{S_l, G_l\} \quad (4.5)$$

$$\sum_{(i,S_l) \in E} x_{i,S_l}^l = 0, \quad \forall l \in L \quad (4.6)$$

$$\sum_{(S_l,i) \in E} x_{S_l,i}^l = 1, \quad \forall l \in L \quad (4.7)$$

$$\sum_{(G_l,i) \in E} x_{G_l,i}^l = 0, \quad \forall l \in L \quad (4.8)$$

$$\sum_{(i,G_l) \in E} x_{i,G_l}^l = 1, \quad \forall l \in L \quad (4.9)$$

$$\sum_{(i,j) \in E} x_{i,j}^l \leq 1, \quad \forall l \in L, \forall i \in V - \{G_l\} \quad (4.10)$$

$$\sum_{l \in L} x_{i,j}^l \cdot B_l = d_{i,j}, \quad \forall (i,j) \in E \quad (4.11)$$

$$\sum_{(i,j) \in E} x_{i,j}^l \leq \rho_m, \quad \forall l \in L \quad (4.12)$$

$$x_i = \begin{cases} 0, & \text{if } d_{i,j} = d_{j,i} = 0 \\ 1, & \text{otherwise} \end{cases} \quad \forall i \in V, \quad (4.13)$$

$$x_i \in \{0, 1\}, \quad \forall i \in V$$

$$x_{i,j}^l \in \{0, 1\}, \quad \forall (i,j) \in E, \forall l \in L$$

Equation (4.3) is the objective function that minimizes the number of visual sensor nodes that can be used (activated) in the network. Equation (4.4) is the capacity constraint that makes sure that flows are routed with respect to the residual capacity of the cliques. Equation (4.5) ensures the flow conservation rules. Equations (4.6) and (4.8) ensure that a flow should not loop back to its source and leave its destination. Equations (4.7) and (4.9) force the source and the destination to be used. Equation (4.10) shows the single path constraint and that a flow should not split into several paths. Equation (4.11) represents the capacity reserved on a link as the sum of the capacity reserved by each flow on that link. Equation (4.12) puts the delay deadline of ρ_m hops for each of the flows. It ensures that each of the flows is routed within the deadline. Finally, Equation (4.13) ensures a node is used for routing if it receives

or sends traffic. As can be seen from the Equation (4.13), the constraint is not linear. Since most of the linear programming solvers require linear formulations of the objective functions and constraints, it is therefore necessary that the non-linear constraint should be converted to the equivalent linear constraints. Using the techniques as in [39, 63] and assuming constant wireless capacity (C_a) and constant bandwidth request by each flow (B), the linearization of the constraint of Equation (4.13) is the following:

$$C_a \cdot x_i - \sum_{(i,j) \in E} d_{i,j} \geq 0, \quad \forall i \in V \quad (4.14)$$

$$C_a \cdot x_i - \sum_{(j,i) \in E} d_{j,i} \geq 0, \quad \forall i \in V \quad (4.15)$$

$$\sum_{(i,j) \in E} (d_{i,j} + d_{j,i}) - B \cdot x_i \geq 0, \quad \forall i \in V \quad (4.16)$$

Constraints (4.14) make sure that a node is used ($x_i = 1$) if there is a video stream going out of the node. Constraints (4.15) also makes sure that a node is used ($x_i = 1$) if there is a video stream going into the node. Constraints (4.16) ensures the node is not used ($x_i = 0$) if there is no video stream passing through the node.

The CPLEX solver is used to solve the optimization problem, which employs the branch-and-bound method, which is an exact method of solving ILP problems.

The proposed routing mechanism is centralized and runs in the central controller of the hybrid IoT Internet of Things Network. When an intruder is detected in the monitoring area, the central controllers use the Kalman filter tracking algorithm to determine which visual sensor nodes are the video stream sources based on the information from the LoRa-enabled motion sensors. Once the sources of the video streams are known, it uses the proposed routing algorithm to activate the visual sensor nodes involved in routing the video streams from the sources to the gateway.

4.5 Performance Evaluation

In this section, we evaluate the performance of the proposed routing algorithm. First, we assess its energy performance in terms of the number of nodes that can be spared and switched off. Next, we evaluate routing end-to-end delay in terms of the maximum path length taken in hops (assuming that the end-to-end packet delay is proportional to the number of hops in a path). The maximum path length (in terms of hops) considered is the maximum path length taken by a flow from the set of submitted flows. Furthermore, the proposed algorithm is compared with two other algorithms from the literature.

Shortest path algorithm: An algorithm that routes flows (video streams) over the shortest available path between the source and the gateway. The algorithm is defined for a single flow in [10], but it is extended to consider a set of flows in this dissertation.

Flow aggregation algorithm: A routing mechanism that aggregates flows over a minimum number of nodes [63]. Both the aggregation algorithm and shortest path algorithm take into account interference and therefore guarantee the bandwidth requirement of flow demand.

Proposed algorithm: An algorithm that allows flows to be routed over a limited number of nodes while guaranteeing the bandwidth requirement of a flow and without allowing each flow to take a path length longer than the delay deadline value (ρ_m). This limits the path taken by each flow and therefore benefits delay-sensitive applications such as video streaming. We have chosen this path length (ρ_m) to be the diameter of the network, i.e., the length of the shortest path between the farthest node and gateway in the topology.

We consider 6×6 grid network consisting of 36 nodes. The distance between neighboring nodes was 250 m. The nodes had a transmission range of 250 m and an interference range of 500 m. We considered the grid network with one gateway located at one of

the corners of the grid. The shortest path between the farthest node and the gateway was 10 nodes ($\rho_m = 10$). We generated a set of flows from 1 to 10 (1, 2 sets, 3 sets of flows, etc.), and each flow was generated with a randomly selected source, and the bandwidth requirement of each flow was set to $0.5Mbps$. We considered constant capacity between wireless links and varying values of capacities for the simulations ($C_a = 5Mbps$, $C_a = 10Mbps$, $C_a = 15Mbps$). We also considered an ideal wireless link. We used MATLAB for generating and calculating parameters from the network and used CPLEX studio [50] to solve the formulated optimization problem. All computations were performed on a computer equipped with 2.8 GHz Intel Core i7 and 16 GB RAM.

The comparison of the proposed algorithm in terms of energy consumption against the shortest path algorithm and the aggregation algorithm is presented in Figures 4.4–4.6 for varying values of wireless channel capacities ($C_a = 5Mbps$, $C_a = 10Mbps$, $C_a = 15Mbps$).

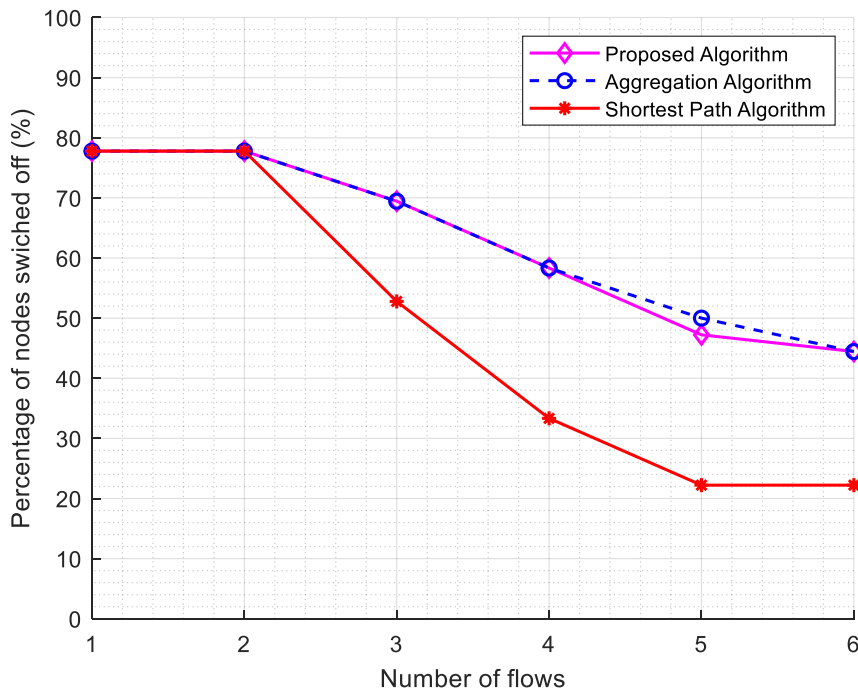


Figure 4.4: The percentage of spared nodes (nodes that can be switched off) variation according to the number of set of flows generated for wireless capacity equal to $C_a = 5Mbps$.

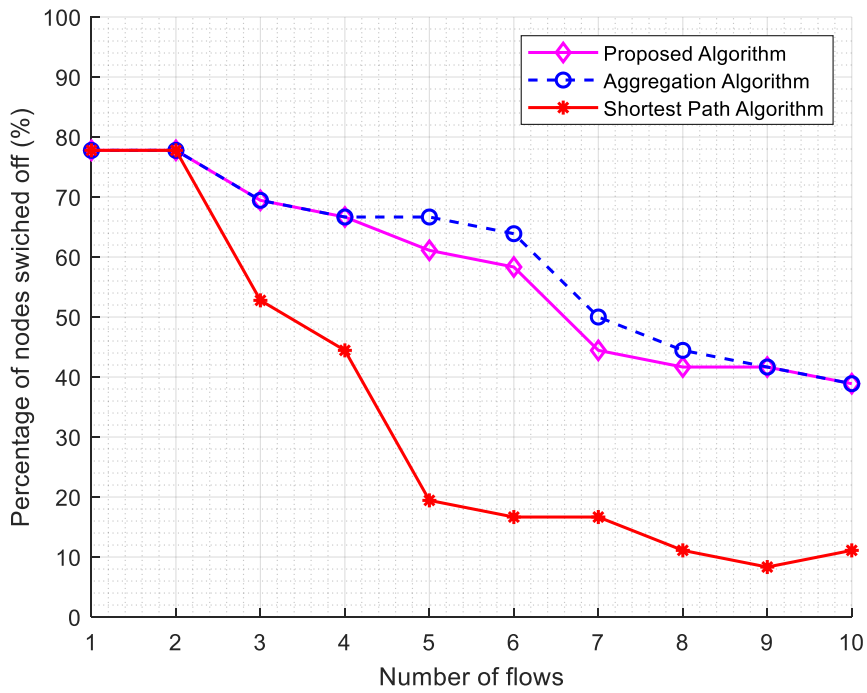


Figure 4.5: The percentage of spared nodes (nodes that can be switched off) variation according to the number of set of flows generated for wireless capacity equal to $C_a = 10Mbps$.

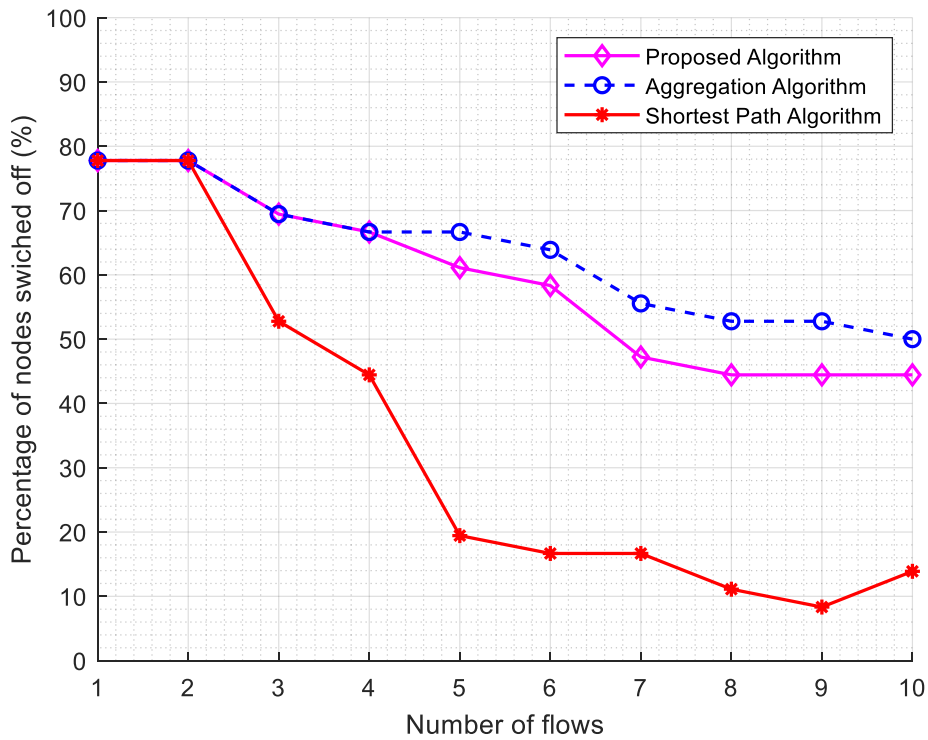


Figure 4.6: The percentage of spared nodes variation according to the number of set of flows generated for wireless capacity equal to $C_a = 15Mbps$.

As can be seen from Figures 4.4–4.6, the proposed algorithm and the aggregation algorithm greatly outperform the shortest path algorithm in terms of energy saving, while the aggregation algorithm performs slightly higher than the proposed algorithm. Taking Figure 4.6 as an example, the shortest path algorithm can use 80% of the nodes in the mesh network to support 10 submitted flows, whereas the proposed algorithm and the aggregation algorithm require 54% and 50% of the nodes in the network, respectively, to provide the same service. The aggregation algorithm slightly outperforms the proposed algorithm in terms of the overall energy consumption reduction, but it provides very poor performance in terms of delay. However, the slight decrease in energy performance in the proposed algorithm is at the expense of guaranteeing and limiting the delay of flows to the gateway (4.7–4.9). Another point, which is noticeable from 4.4, is that we submitted more than six sets of flows, but the algorithms do not accept flows of more than six sets of flows. This shows that the network is overloaded with the given wireless capacity ($C_a = 5Mbps$) as flows are submitted more than six; therefore, there are no feasible paths for the flows to the gateway that guarantee QoS, and therefore it gets rejected.

The comparison of the proposed algorithm in terms of end-to-end delay (i.e., maximum route length in hops) against the shortest path algorithm and the aggregation algorithm is presented in Figures 4.7–4.9 for varying values of wireless channel capacities ($C_a = 5Mbps$, $C_a = 10Mbps$, $C_a = 15Mbps$).

As can also be seen from 4.7–4.9, the aggregation algorithm allows flows to take longer path lengths (in terms of number of hops) to the gateway, which makes it have a longer delay compared with the proposed algorithm and the shortest path algorithm to the gateway. As it is shown in 4.9, the aggregation algorithm uses a maximum path length of 15 nodes to reach to the gateway, whereas the proposed algorithm and the shortest path algorithm use a maximum route length of 10 nodes to reach the gateway.

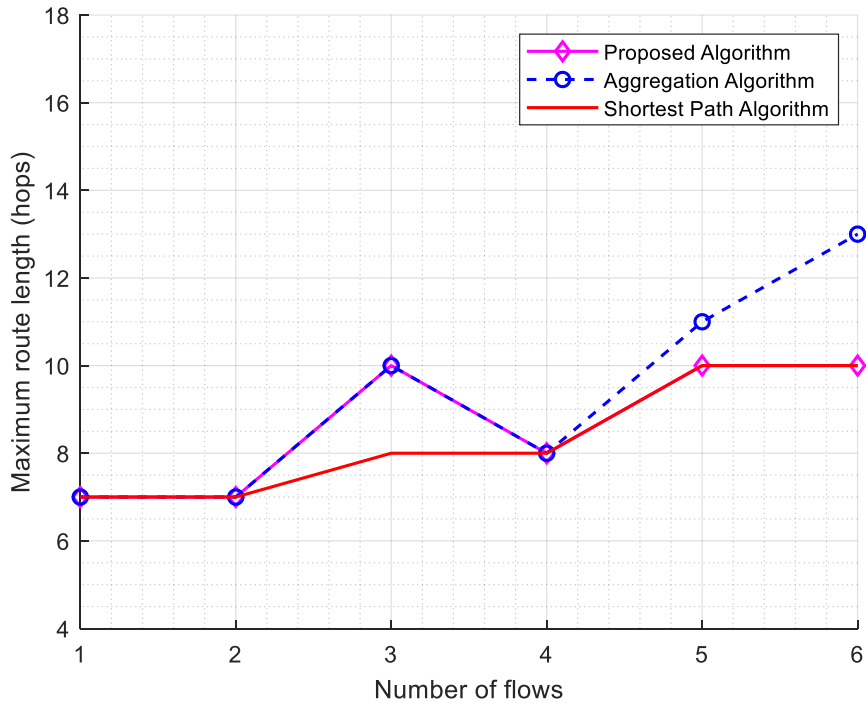


Figure 4.7: The maximum path length variation according to the number of set of flows generated for wireless capacity equal to $C_a = 5Mbps$.

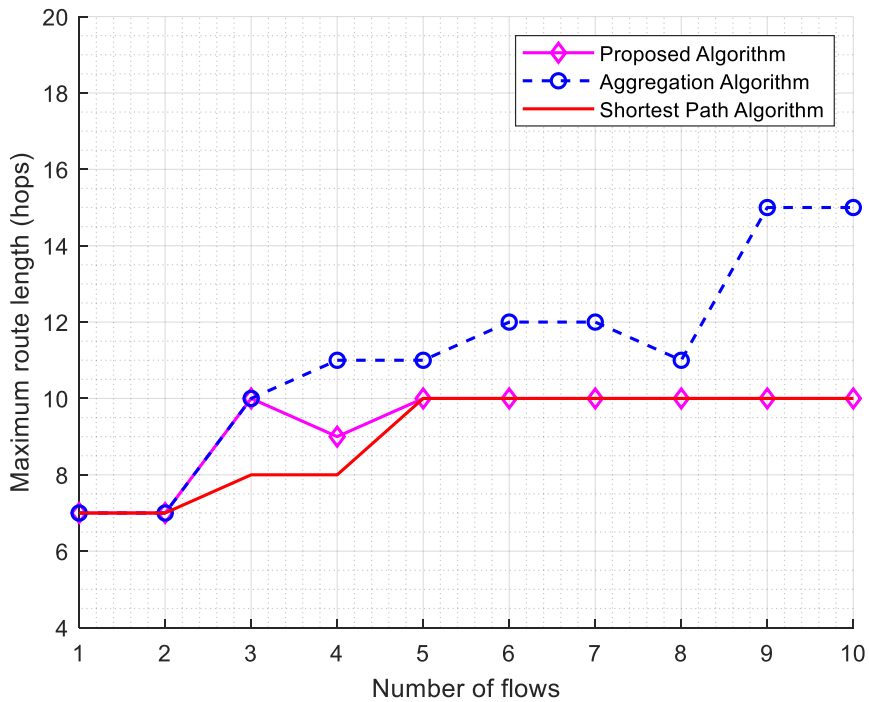


Figure 4.8: The maximum path length variation according to the number of set of flows generated for wireless capacity equal to $C_a = 10Mbps$.

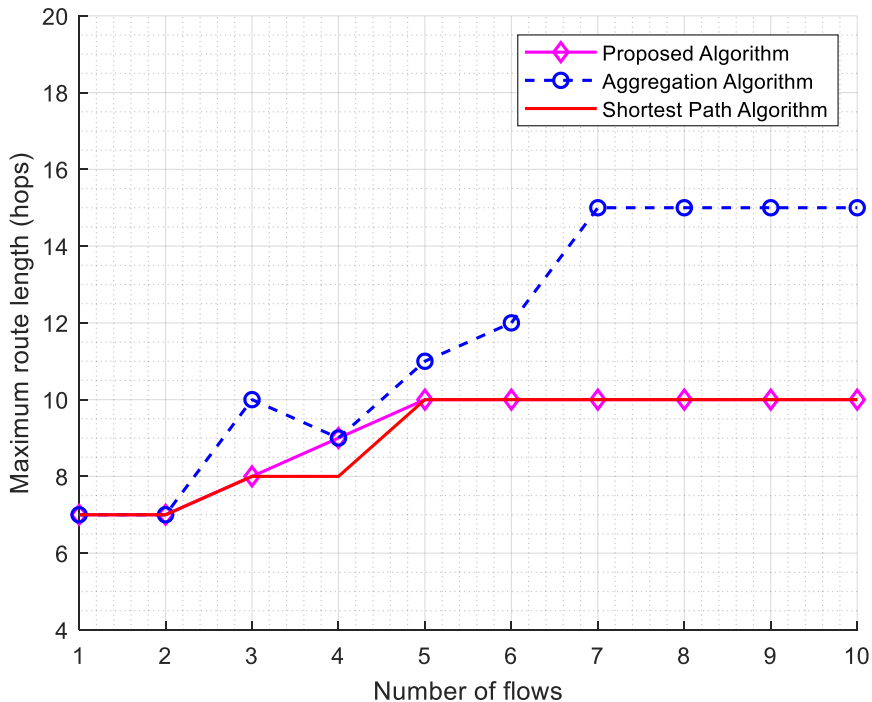


Figure 4.9: The maximum path length variation according to the number of set of flows generated for wireless capacity equal to $C_a = 15Mbps$.

From the above discussion, it can be concluded that there is a clear tradeoff between QoS and energy saving. For video surveillance applications that have strict QoS requirements, the proposed approach reduces a significant amount of global energy consumption while guaranteeing QoS in terms of bandwidth and delay.

4.6 Conclusions

In this chapter, we proposed an energy-aware and QoS routing algorithm for the wireless multi-hop visual sensor network in the hybrid IoT network. The routing algorithm allows the routing of a set of video streams with guaranteed bandwidth and delay (assuming that the end-to-end packet delay is proportional to the number of hops in a path), while involving the minimum number of active visual sensor nodes in the network. We formulated the problem as an integer linear program (ILP) for finding the minimum number of visual sensor nodes to be used (activated) while imposing bandwidth and

delay constraints. We used a branch-and-bound algorithm to solve the integer linear programming optimization model. The proposed approach was evaluated via simulation and compared with previous algorithms from the literature. The simulation results show that the proposed approach achieves considerable overall energy savings while guaranteeing QoS in terms of bandwidth and delay. The proposed routing approach allows as many visual sensor nodes as possible to be completely turned off to reduce the global energy consumption of the network. Putting nodes in a complete shutdown mode has the add-on benefit of reducing wireless interference between wireless nodes.

Chapter 5

Conclusion and Future Works

This section provides the conclusions of the dissertation and indicates the directions for future works.

5.1 Conclusion

Energy inefficiency is a significant issue in IEEE 802.11-based multi-hop visual sensor networks used for video surveillance applications in monitoring intrusions, as the nodes in these networks are energy-constrained. Moreover, video surveillance applications have strict QoS requirements in terms of bandwidth and delay. Provisioning QoS guarantees in the IEEE 802.11-based multi-hop visual sensor network is complex due to the wireless interference. Therefore, minimizing the overall energy consumption of the IEEE 802.11-based multi-hop visual sensor network while satisfying the QoS requirement of video transmission is a challenging problem.

This Ph.D. dissertation first proposed a hybrid IoT network of IEEE 802.11-based multi-hop visual sensor network and LoRaWAN to provide an autonomous, energy-efficient, high bitrate video surveillance system. The video surveillance system detects and tracks

an intruder whenever needed. The proposed hybrid IoT network architecture is centralized. Using the advantages of LoRaWAN (i.e., low power consumption, low cost, and long-range), the proposed approach used the LoRa network as a constantly active network to detect and track an intruder in the monitoring area. Moreover, the LoRa network manages the energy consumption of the visual sensor nodes and decides which visual sensor nodes to wake up depending on the tracking information to provide effective video vigilance. In addition, the Kalman filter is presented to track the trajectory of an intruder. Only the visual sensor nodes nearest to the trajectory are activated based on the tracking information. This reduces the number of nodes involved in the video vigilance. Thus, reducing the energy consumption of the network. We demonstrated through simulation that the Kalman filter tracks intruder trajectory with reasonable accuracy. Moreover, the performance of the proposed IoT network architecture is compared with the traditional always-active continuous monitoring single-tier visual sensor network in terms of energy consumption. The simulation results showed that the proposed IoT network architecture reduces energy consumption significantly (97.85%).

The final contribution relies on the routing mechanism to optimize the network energy efficiency while satisfying the QoS of video transmission requirement in the IEEE 802.11-based multi-hop visual sensor network of the hybrid IoT network. Most prior works on routing solutions in general wireless multi-hop networks that optimize energy consumption distribute the traffic load to balance the energy consumption to extend the network's lifetime. These routing solutions, however, are inefficient in terms of the network's overall energy consumption, as they require nodes to remain turned on even if they are forwarding a small amount of data, resulting in significant energy consumption. The overall network can be energy efficient by turning off as many nodes as possible while maintaining the QoS performance. Therefore, we proposed a centralized routing mechanism that minimizes the number of visual sensor nodes to be involved in routing a set of video streams from the source nodes to the gateway while providing guaranteed QoS in terms of bandwidth and delay. We assumed that the end-to-end packet delay is

proportional to the number of hops in a path. Minimizing the number of nodes involved in the routing makes it possible to turn off as many nodes as possible. Thus, saving the overall energy consumption. We formulated the routing problem as an integer linear program (ILP) and obtained the optimal solution for a small network. Through computer simulation, we showed that the proposed approach saves a great deal of energy when compared with the shortest path algorithm. Moreover, the proposed method significantly outperforms the flow aggregation algorithm in QoS in terms of end-to-end delay. However, guaranteeing QoS in terms of end-to-end delay has little cost in energy consumption as the aggregation algorithm slightly edges the proposed approach in the energy consumption. This demonstrates a trade-off in energy consumption for guaranteeing end-to-end delay. Moreover, for video surveillance applications with strict QoS requirements, the proposed approach significantly reduces global energy consumption while providing guaranteed QoS in terms of bandwidth and delay.

Finally, the study revealed the benefit of a hybrid IoT network in providing low power and guaranteed QoS transmission in a video surveillance system compared with single wireless technology. Furthermore, as the industry of IoT applications grows and advances, LPWAN is expected to be widely used and deployed in the future. This means that a broader range of low-cost, energy-efficient video surveillance solutions will be available in the future.

5.2 Future Works

There are several possible future research directions. From the first contribution, one possible future direction could be developing a real proof of concept for the hybrid IoT network of a small size to study the different performance parameters. Furthermore, we used a Kalman filter to track an intruder, which performs well when the intruder moves in a straight line but degrades otherwise. Therefore, the research could be extended to consider a tracker that handles more realistic target trajectories, such as the Extended

Kalman filter.

In the second contribution, we obtained the optimal solution of the routing proposal using the branch-and-bound algorithm for a small-sized network problem, which provides essential performance bounds for comparison. As a result, the study can be extended to develop feasible, less complex heuristic solutions for networks with a large number of nodes. Furthermore, in the second contribution, we assumed that the end-to-end packet delay is proportional to the number of hops in a path. However, this is not always the case, as shorter routing paths sometimes can have longer delays if the path is congested. As a result, the delay constraint should account for realistic delays (queuing, transmission, and propagation) from the source to the gateway. Moreover, we studied the different performance metrics for the multi-hop visual sensor network of the hybrid IoT network with a single gateway. The set of video flows generated by the source visual sensor nodes are routed in a multi-hop fashion to the single gateway. Therefore, this would cause the network near the gateway to be overloaded quickly and reduce the flow acceptance rate. Thus, the work could be extended to consider a different number of gateways to assess the variation of the various performance metrics. Finally, our video surveillance system can be applied to track poachers who hunt and kill endangered endemic animals in Ethiopian national parks.

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