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<u>Theme</u>

Optimization of MAC mechanisms for energy management in Wireless Sensor Networks

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I dedicate this work:

To my parents.

To my brothers and sisters.

To my wife.

To my children Taki-eddine and Aya.

ABSTRACT

Power consumption is the most important factor to evaluate the performance of Wireless Sensor Networks (WSNs). Most sensor network Medium Access Control (MAC) protocols operate based on a duty cycle mechanism. The asynchronous receiver-initiated MAC duty cycle protocols are popular due to their relatively higher energy efficiency. However, recent advances harnessing the benefits of cooperative communication have become one of the solutions of MAC duty cycle protocol. In this thesis, we improve the RI-MAC protocol by introducing a short frame identifier to notify the sender when the receiver wakes up. This resolution reduces idle listening, which increases energy performance. When the sender node receives a short frame identifier, it cooperates with neighboring senders, which minimizes collisions. Our protocol is called: a Cooperative Short Frame Identifier Receiver Initiated MAC protocol, COSFI-RIMAC is an asynchronous MAC protocol cooperative service cycle initiated by the receiver. The simulation result on the NS2 simulator shows that the COSFI-RIMAC mechanism reduces power consumption, produces minor latency, and increases the rate of packet delivery.

Keywords: MAC, Receiver-initiated, Cooperation, Energy saving, Idle listening, Collision.

RÉSUMÉ

La consommation d'énergie est le facteur le plus important pour évaluer les performances des réseaux de capteurs sans fil (WSN). La plupart des protocoles de contrôle d'accès au support (MAC) des réseaux de capteurs fonctionnent sur la base d'un mécanisme de cycle de service. Les protocoles MAC asynchrones à cycle de service initiés par le récepteur sont populaires en raison de leur efficacité énergétique relativement élevée. Cependant, de récentes avancées exploitant les avantages de la communication coopérative sont devenues l'une des solutions du protocole de cycle de service MAC. Dans cette thèse, nous améliorons le protocole initiés par le récepteur (RI-MAC) en introduisant un identifiant de trame court pour notifier l'émetteur lorsque le récepteur se réveil. Cette résolution réduit l'écoute inactive, ce qui augmente la performance énergétique. Lorsque le nœud émetteur reçoit un identifiant de trame courte, il coopère avec les autres émetteurs voisins, ce qui minimise les collisions. Notre protocole est appelé : a Cooperative Short Frame Identifier Receiver Initiated MAC protocol, COSFI-RIMAC est un protocole MAC duty cycle asynchrone coopératif initié par le récepteur. Les résultats de la simulation sur le simulateur NS2 montrent que le mécanisme COSFI-RIMAC réduit la consommation d'énergie, produit une latence mineure et augmente le taux de livraison des paquets.

Mots clés : MAC, initiés par le récepteur, coopération, économie d'énergie, Idle listening, collision.

ملخص

يعتبر استهلاك الطاقة أهم عامل لتقييم أداء شبكات الاستشعار اللاسلكية .(WSNs) تعمل معظم بروتوكولات التحكم في الوصول المتوسط (MAC) لشبكة الاستشعار على أساس آلية دورة العمل. تحظى بروتوكولات دورة عمل MAC غير المتزامنة التي يبدأ تشغيلها المتلقي بأهمية كبيرة نظرًا لكفاءتها العالية نسبيًا في استخدام الطاقة. ومع ذلك ، فقد أصبحت التطورات الأخيرة في الاستفادة من مزايا الاتصال التعاوني أحد حلول بروتوكول دورة عمل MAC. في هذه الأطروحة ، نقوم بتحسين بروتوكول RI-MAC من خلال إدخال معرف إطار قصير لإخطار المرسل عندما يستيقظ جهاز الاستقبال. تعمل هذه الدقة على تقليل الاستماع في وضع الخمول ، مما يزيد من أداء الطاقة. عندما تتلقى عقدة المرسل معرف إطار قصير ، فإنها تتعاون مع المرسلين المجاورين ، مما يقلل من التصادمات. يسمى بروتوكولنا: بروتوكول MAC التعاوني لمعرف الإطار القصير الذي بدأ تشغيله ، COSFI-RIMAC عبارة عن دورة خدمة تعاونية لبروتوكول MAC غير متزامن بدأها المتلقي. تُظهر نتيجة المحاكاة في محاكي NS2 أن آلية COSFI-RIMAC تقلل من استهلاك الطاقة وتنتج زمن انتقال طفيف وتزيد من معدل تسليم الحزم.

الكلمات المفتاحية : MAC ، بدء المتلقي ، التعاون ، توفير الطاقة ، الاستماع الخمول ، الاصطدام.

CONTENTS

CHAPTER 1: WIRELESS SENSOR NETWORKS AND ENERGY CONSUMPTION

CHAPTER 2: STUDY OF MAC PROTOCOLS

CHAPTER 3 : RECEIVER INITIATED MAC PROTOCOLS

LIST OF FIGURES

LIST OF TABLES

GENERAL INTRODUCTION

Context and Motivation

Nowadays, Wireless Sensor Networks (WSN) show great promise for capturing and processing information in different applications, such as animal tracking, precision farming, environmental monitoring, security and surveillance, military applications, smart buildings, healthcare, etc.

A WSN consists of several sensor stations called sensor nodes used to detect data and transmit it to the base station. Power for each sensor node comes from a battery. Energy efficiency is an important factor in the operation of wireless sensors. A problem with these sensing devices is the limited lifetime due to limited battery power [1].

The MAC sublayer has been widely targeted by researchers to improve the performance of WSNs. Indeed, the MAC layer coordinates directly with the radio of the node and can therefore play an essential role in the management of energy use [2]. The main design goal of a MAC protocol is usually designed to ensure the efficient management of per-channel communications, and this goal can be achieved by sharing a medium with other sensors to minimize power wastage due to communication. listening, over-listening, packet overload, retransmissions, and network collisions.

Problematic

Many MAC protocols with different purposes have been proposed for wireless sensor networks in the literature. Most of these protocols consider energy efficiency as a priority objective. The MAC protocol can be categorized into two main classes, namely, contention-free (scheduled MAC protocols) and contention-based (duty-cycle protocols)[3].

The basic idea of duty cycle protocols is that sensor nodes can turn their radio on or off. In this way, we reduce the time a node is idle or will hear unnecessary activity by putting the node to sleep [4]. As soon as a node wakes up, it listens to the channel to detect any activity before transmitting or receiving packets. If no packet is to be transmitted or received, the node returns to the standby state. A complete cycle consisting of a sleeping period and a listening period is called a sleep/wake period. Indeed, the ideal condition for low-duty cycle protocols is that a node is sleeping most of the time and only wakes up when it transmits or receives packets. Dynamic MAC protocols are contention-based protocols and adapt to changes in topology. In contention-based MAC protocols, dynamic channel allocation is performed by contention algorithms such as CSMA, and CSMA/CA; in which communication resources are dynamically allocated, therefore, the design of a parallel transmission protocol must consider not only the allocation of communication resources but also the process of control information exchange.

Synchronous MAC protocols reduce power consumption by synchronizing the sleeping and waking of sensor nodes. Synchronous MAC protocols such as S-MAC [5] and T-MAC [6], require synchronization of sender and receiver clocks. Synchronous schemes can be either contention-based or reserved time slot based. In either case, part of the active state is used to synchronize all nodes to a global sleep/wake schedule.

Synchronous MAC protocols generate a large number of control messages to ensure the proper functioning of the system as presented in the Speed-MAC [7], MC-LMAC [8], and SEA-MAC [9] protocols by carrying out synchronization before data exchange. Each sending node will create its path to the receiving node before transmission, which limits its usefulness when the duration of node activity is very short, which can also increase the latency of data delivery. Similarly, the implementation of synchronization is complex and difficult to achieve when the number of sensor nodes is large.

In contrast, asynchronous duty-cycle MAC protocols do not require synchronization, which can reduce power consumption. However, asynchronous MAC protocols allow nodes to start their periods of activity and inactivity independently. Asynchronous MAC protocols are distinguished by their short cycle time and low communication cost. Within the asynchronous MAC duty cycle protocols, two main categories of asynchronous protocols are sender-initiated protocols and receiver-initiated protocols.

In Sender-initiated MAC protocols such as B-MAC [10], WiseMAC [11], and X-MAC [12], data transmission and communication are decided and initiated by the sender node. Before sending data packets, the sender transmits a preamble to notify that there is a data communication without knowing the state of the receiver (sleep or awake). When a node wakes up during its regular wakeup period, it detects the preamble and stays awake until it determines if it is the receiving node. This may require a large amount of energy from the sending node. The MAC protocol Receiver-initiated as RI-MAC [13], PW-MAC [14], and EE-RI-MAC [15], exhibits better performance over sender-initiated MAC protocols. In receiver-initiated protocols, receivers wake up independently to indicate their readiness to receive data by sending a beacon. With this mechanism, the receiver beacon does not occupy the channel as long as it does preambles in sender-initiated protocols.

Objectives and Contributions

In this thesis, we present a new receiver-initiated asynchronous duty cycle protocol (COSFI-RIMAC), which is based on two main reasons:

The first reason is idle listening in receiver-initiated MAC protocols, which represents the main source of power consumption, senders have to listen unnecessarily for a significant time (a few seconds), and while a data transaction of the sender may take a few milliseconds (ms). The energy consumption of this unnecessary listening affects the energy performance of the receiver-initiated MAC protocols. Our COSFI-RIMAC protocol minimizes idle listening for nodes (senders and receivers) which we divide by small periods, thus avoiding early wake-up.

The second reason is to minimize overhead in receiver-initiated MAC protocols caused by collision in node communication, which is the reason for communication delay in receiver-initiated protocols. Our COSFI-RIMAC proposal reduces collisions between nodes by using a collision avoidance technique based on cooperation between sending nodes, which minimizes the energy associated with data retransmission.

Organization of the manuscript

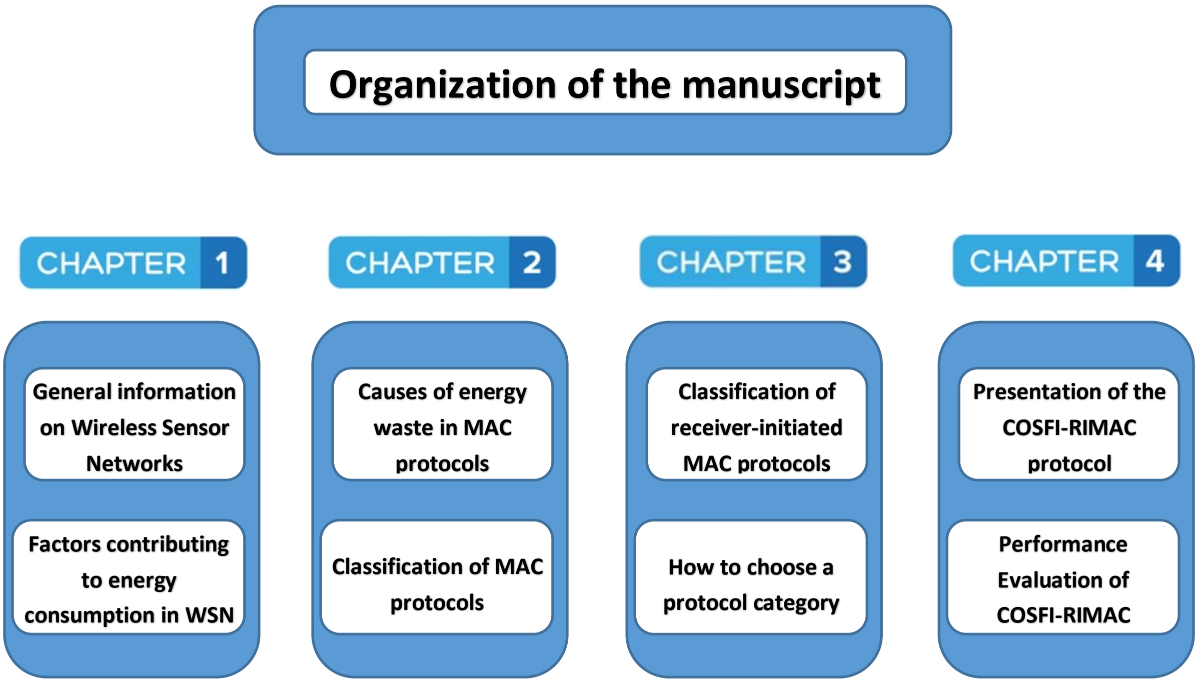
This thesis manuscript is composed of four chapters, an introduction, and a general conclusion.

The first chapter is devoted to the study of the network of wireless sensors, in particular, the main factors and constraints influencing the networks of sensors, as well as the causes of overconsumption of energy. At the end of the first chapter, we will define the MAC "Media Access Control" sub-layer in the protocol stack used for wireless sensor networks.

In the second chapter and after having introduced the MAC layer, we were interested in the analysis of the different classes of MAC protocols: scheduled MAC protocols and MAC Duty-Cycle protocols, so we lemon some MAC protocols for each category.

The third chapter is devoted to the study of the MAC duty cycle asynchronous Receiver-Initiated protocol. An analysis of existing protocols is first presented.

Finally, the fourth chapter describes our contribution and which consists in proposing a new asynchronous duty cycle receiver initiated protocol (COSFI-RIMAC)**[16]**, which contains improvements made to reduce idle listening and collisions to increase its performance, thus evaluating and comparing the performance of the proposed protocol with other protocols.


Organization of the manuscript
CHAPTER 1
General information on Wireless Sensor Networks
Factors contributing to energy consumption in WSN
CHAPTER 2
Causes of energy waste in MAC protocols
Classification of MAC protocols
CHAPTER 3
Classification of receiver-initiated MAC protocols
How to choose a protocol category
CHAPTER 4
Presentation of the COSFI-RIMAC protocol
Performance Evaluation of COSFI-RIMAC

CHAPTER 1

WIRELESS SENSOR NETWORKS AND ENERGY CONSUMPTION FACTORS

1.1 Introduction

Currently, the phenomenon of Wireless Sensor Networks (WSN) is attracting increasing interest due to their simplicity, deployment flexibility, and low cost. The very strong demand in the field of wireless communication networks currently allows the evolution of sensor networks for a wide range of applications such as military, medical, and home automation. Work on sensor networks has shown that most of the energy consumption is due to the use of the radio module in the different communication phases (transmission, reception, sleep phase, wake-up phase, etc).

Therefore, several types of research have focused on the optimization of the different communication protocols, to minimize the consumption of This chapter is composed of two parts, in the first section, we present the characteristics of sensor networks, their basic functions, as well as their various fields of application. Then, we make an overview of the research work on the main factors that have an influence on the energy consumption at each layer as well as the different mechanisms proposed to reduce it and to increase the lifetime of the network.

1.2 Wireless sensor networks

1.2.1 Sensor wireless

Sensor nodes are the fundamental components of WSN. Sensor nodes should provide the following basic functionality [17]:

- Signal conditioning and data acquisition for various sensors;
- The temporary storage of acquired data;
- Data processing ;
- Analysis of the processed data for the diagnosis and, possibly, the generation of alerts;
- Self-testing (eg supply voltage);
- Planning and execution of measurement tasks;
- Management of the sensor node configuration (for example, modification of the sampling rate and reprogramming of the data processing algorithms);
- Reception, transmission, and transfer of data packets;
- Coordination and management of communication and networking.

A wireless sensor is a small electronic device capable of measuring an environmental physical value (temperature, light, pressure, humidity, vibration, etc.), and communicating it to a control center via a base station. Each sensor performs the three main basic functions which are: data acquisition, data processing, and communications to base stations [17]. A sensor node is composed of four basic components as shown in Figure 1.1: a detection unit, a processing unit, a transceiver unit, and a power supply unit [18].

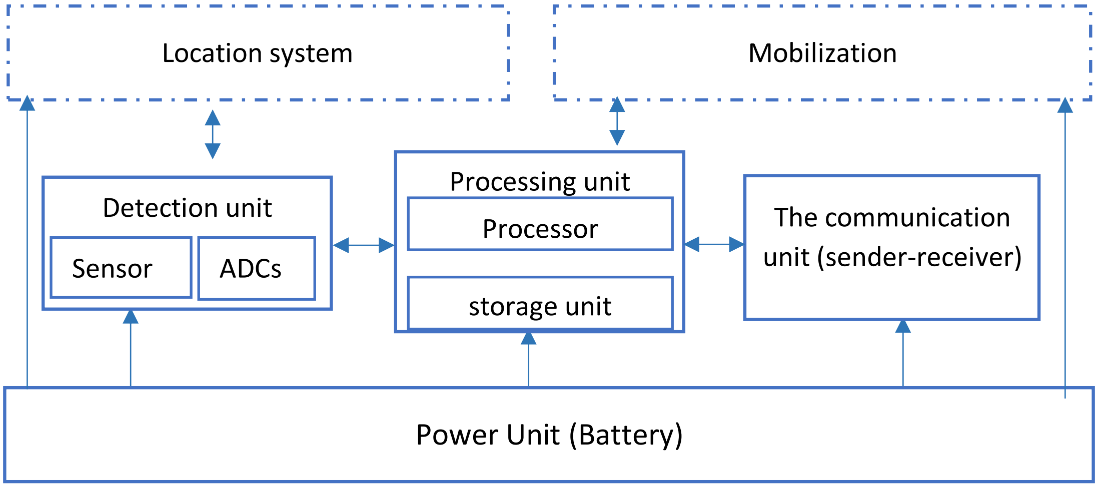


Figure 1.1. Structure wireless sensor [17].

Detection unit

Detection units are generally made up of two sub-units: sensors and ADCs "Analog-Digital Converters". This is the unit responsible for capturing measurements of physical parameters (heat, humidity, vibrations, radiation, etc.) and transforming them into digital signals [16,17].

Processing unit

The processing unit controls the other units and can be considered the sensor's intelligent organ. It is composed of two interfaces, which are an interface associated with the detection unit, and another associated with the communication unit. The processing unit also includes a processor that is generally associated with a small storage unit. It manages procedures for the node to collaborate with other nodes to perform assigned detection tasks and store collected data [18].

The communication unit (sender-receiver)

This unit is responsible for the transmission-reception of data captured and processed via a wireless communication channel. A radio module (sender/receiver) is integrated into the unit that allows communication between different nodes of the network and ensures communication between the different nodes of the network. The radio module is the module that consumes the most energy [18].

Power Unit (Battery)

One of the most important components of the sensor is the power supply unit, which represents a small battery with limited power capacity, which creates an obstacle when designing protocols for sensor networks, since it affects the lifetime of the sensor node and hence the lifetime of the network, in some cases, power units can be supported by the energy collection unit like solar cells [19,20]. There are also sensors with other application-dependent additional components such as the location system [20].

1.2.2 Wireless sensor network

A Wireless Sensor Network (WSN) is a computer network composed of small autonomous devices called sensor nodes fixed or randomly dispersed in a coverage area [17,18] As shown in Figure 1.2, each of these nodes can communicate with each other by radio waves for a specific application (temperature reading, control, surveillance, intrusion detection, home automation, medical field, etc.) [19] and transfer this data to a base station called a sink.

The role of the sink is different from that of other nodes in the network because its task is to collect the data that comes from other nodes and then transmit it through the Internet or by satellite to the data processing center, the sink must be always active because the Data reception is random. The data processing center analyzes this data and makes decisions.

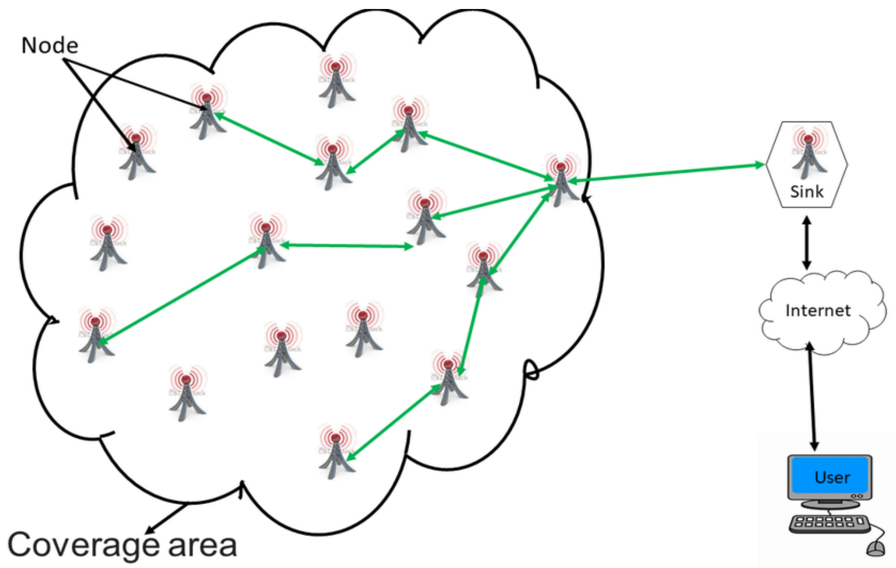


Figure 1.2. Wireless sensor network [20].

1.3 Methods for placing sensor nodes in WSN

The placement of sensor nodes in an area of interest is not necessarily defined upstream in the design and deployment of a given WSN. Thus, the nœuds can every placed randomly in area interest or placed from favas determinist. The node placement methods generally depend on the type of application and the type of environment where they are deployed. There are two methods of node placement in WSNs, which are random placement and deterministic placement.

1.3.1 Random placement

The random deployment method is generally used to disperse sensor nodes in unknown areas, typically without organization or knowledge of the area and difficult to reach or inaccessible (war zone, in the mountains, in the atmosphere, etc.)[21]. In this case, the sensor nodes are deployed from a multitude of means, such as planes, ships, etc. However, these random positioning techniques generally require topological checks and frequent reconfiguration of the nodes to guarantee the stabilization of the networks and the good quality of the data transmission.

1.3.2 Deterministic placement

The study of the positioning of the nodes in a WSN makes it possible to define the number of sensor nodes to be deployed and the location of these in the monitoring area to guarantee all the functionalities of a certain application. In the case where the sensor deployment environment is accessible or known, the nodes are placed deterministically. In this case, the nodes are positioned at determined and known locations.

This way of positioning the nodes is notably used to define the topology of the WSN. The placement modes of the sensor nodes are closely linked to the coverage and connectivity properties of the WSN networks.

1.4 Application of Wireless Sensor Networks

Thanks to the many advantages and new opportunities offered by wireless sensor networks (WSNs), it has been ranked among the most important technologies used today due to their presence in almost every aspect of life. In the following section, we will present some of the main application areas of WSNs:

1.4.1 Military applications

Wireless sensor networks can be an integral part of military command, intelligence, surveillance, and reconnaissance systems. The rapid deployment, self-organization, and fault-tolerance characteristics of sensor networks make them a very promising detection technique in such a field [23]. Monitoring friendly troops, weapons, and ammunition; battlefield surveillance; recognition of opposing forces and terrain; targeting; assessment of war damage; and the identification and observation of nuclear, biological, and chemical threats are part of the armed forces sensor network applications[22,23].

An example of this type of scenario is shown in Figure 1.3. In a battlefield, rapid deployment, self-organization, and network fault tolerance should be required. Devices or sensor nodes should provide the following services:

- Surveillance of friendly forces, equipment, and ammunition;

- Surveillance of battlefields;

- Recognition of enemy forces;

- Targeting ;

- Damage assessment;

- Detection of nuclear, biological, and chemical attacks.

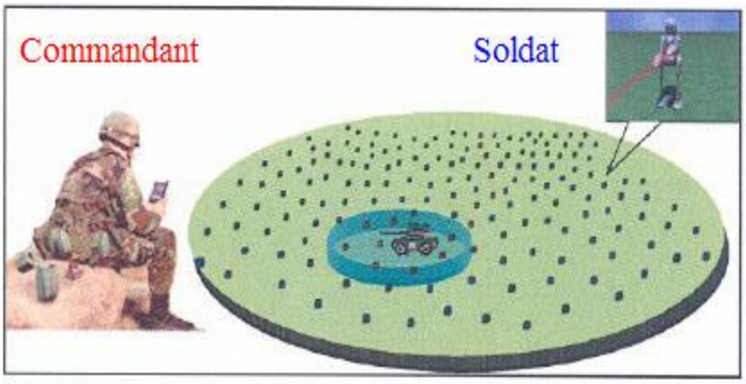


Figure 1.3. Example of interaction between a military leader and his soldiers [23].

1.4.2 Environmental applications

Thanks to sensor networks, it is possible to detect environmental problems such as floods, and forest fires, as well as the possibility of monitoring the level of pesticides in the water. drinking water, the level of air pollution[24]. In this application area, the ability of a wireless sensor node to detect temperature, light, airflow, and indoor air pollution can be used in indoor and outdoor environmental monitoring applications [24, 25, 26] (figure 1.4). Other interior applications may decrease fire and earthquake damage. Fire and smoke detection is something universal nowadays in buildings and most countries, it is enforced by relevant regulations [25].

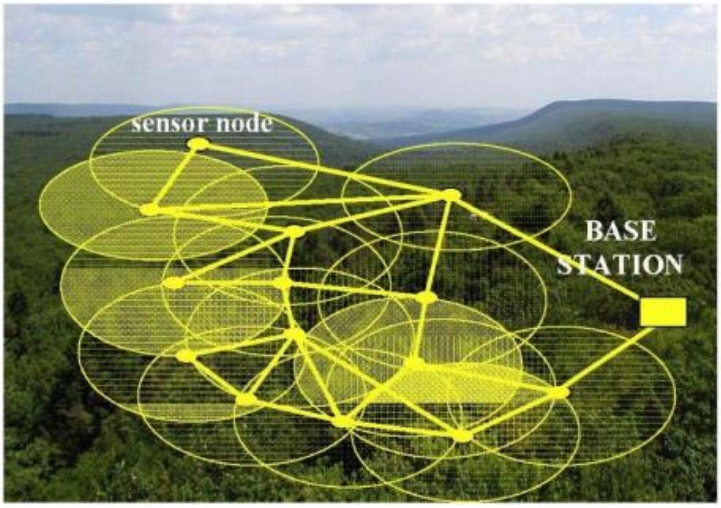


Figure 1.4. An example application of WSN in the environment **[25].**

Sensors can also be deployed in a network to detect on industrial sites, nuclear power plants, or oil sites, leaks of toxic products (chemical products, radioactive elements, oil, gas, etc.) to alert users and help more quickly, and thus allow an effective intervention.

1.4.3 Medical applications

The use of medical sensors that are efficient and fast provides health services in a new and easy way at a low cost for patients. Such information technology enables the improvement of health care, allowing patients to lead normal lives while continuing to maintain health [27, 28,29](figure 1.5). Internet of things technologies in WSN, also enable healthcare and medical institutions to collect medical information through these techniques, and monitor patients' vital signs without stagnation or need for acute care in the hospital, which saves time and money for patients and institutions [28].

There are many requirements in case of the need to periodically measure the patient's vital signs and the most important of these requirements are the nursing healthcare professionals. The medical application based on WSN improves health performance much easier for patients and doctors and also minimizes financial costs for patients and health institutions [29,30,31]. If sensor nodes can be attached to drugs, the risk of obtaining and prescribing the wrong drug to patients can be minimized.

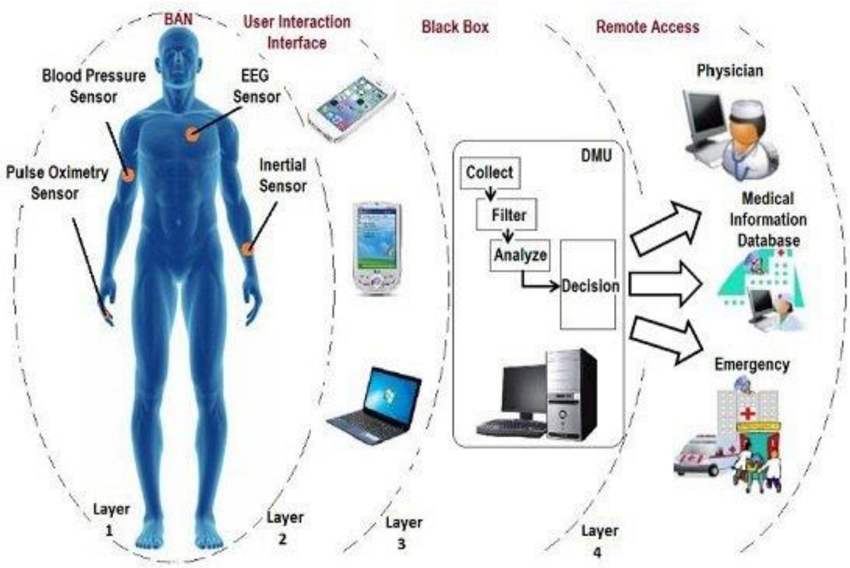


Figure 1.5. Example application of WSN in medical applications [28].

1.4.4 Home automation applications

People want to live in smart living spaces to make their life easier, safer, and more enjoyable. Home automation is a rising trend as the public seeks smart residential homes, apartments, and commercial businesses. Wireless Sensor Networks (WSN) is one of the most essential technologies used in smart home automation. In WSN-based applications, sensors are considered the most important components that collect real-time sensed data from their environment [32,33]. These are distributed networks of tiny and lightweight wireless sensor nodes, which could be extended based on the requirement of physical parameters such as pressure, temperature, and relative humidity[32](Figure 1.6).

As technology advances, sensor nodes can be integrated into devices such as vacuum cleaners, ovens, microwaves, and refrigerators. These sensors integrated with household appliances can communicate with each other and with the external network via the Internet or satellite. Enable end users to easily manage these devices locally and remotely.

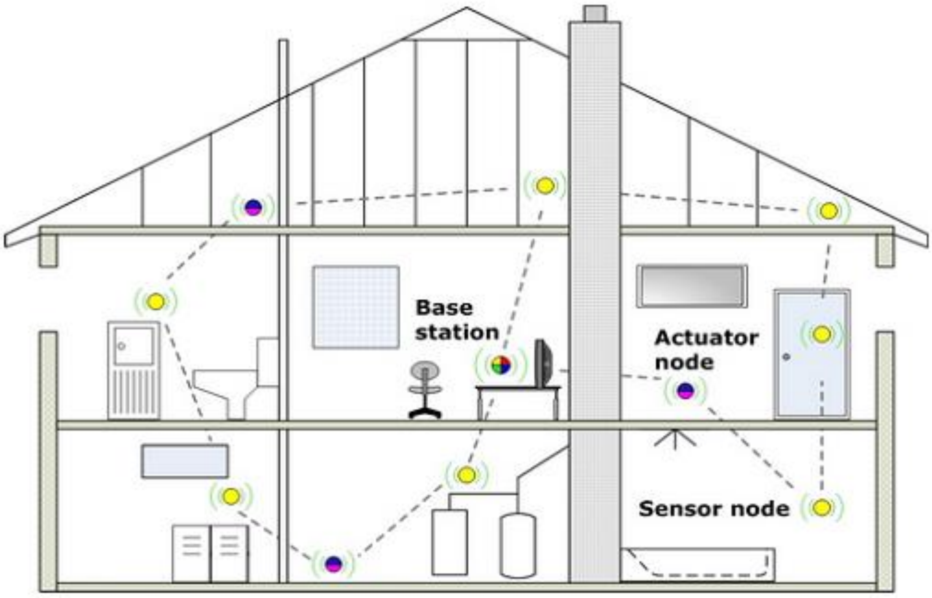


Figure 1.6. Conceptual architecture of the proposed wireless network monitoring system [34].

1.4.5 Other applications of WSN

Other applications of WSN can be cited: industrial application, forest fire detection, ecological supervision, structure supervision, smart agriculture, and also in some additional applications [35]: structural monitoring, construction monitoring, control, automotive monitoring, etc. (Figure 1.7).

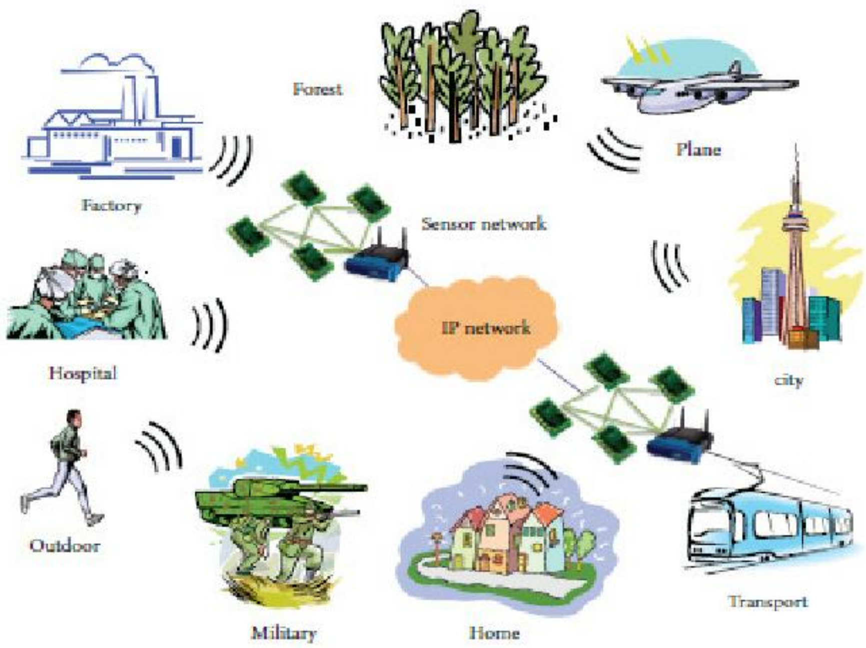


Figure 1.7. Some examples of WSN applications [31,32,33].

1.5 Wireless sensor network protocol stack

Among the seven standard layers defined in the OSI model, communication in the WSN is governed by a multilayer architecture schematized in Figure 1.8. This model describes the different communication layers (application layer, transport layer, network layer, data link layer, and physical layer), as well as the different energy, mobility, and task management planes. Information processed in one layer is transmitted to the adjacent layer [36]. Indeed, each layer has a specific responsibility, therefore uses the services of the lower layers and brings them to the next level. The purpose of the different plants is to coordinate the collection task, minimize energy consumption and drive the data in a mobile network. The operation and role of each layer are detailed in the sections below [37].

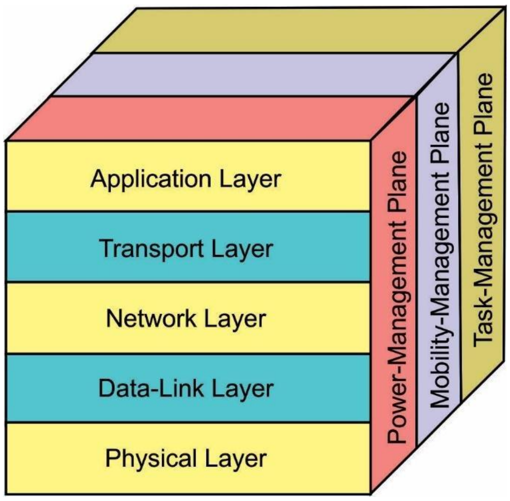


Figure 1.8. Wireless Sensor Network Protocol Stack [36].

1.5.1 Physical layer

The physical layer specifies the hardware characteristics, modulation techniques, carrier detection, and conversion of digital, analog, and optical signals. The physical layer is therefore responsible for the correct transmission and reception of data, the selection of frequencies, and the detection of the signal [36].

1.5.2 Data link layer

The link layer is responsible for controlling access to the physical medium. This layer is also responsible for data multiplexing and transmission error control. It specifies how data is sent between two pairs of sensor nodes with a one-hop distance. The link layer is composed of two sublayers, namely the Medium Access Control (MAC) sublayer and the Logical Link Control (LLC) sublayer [37].

1.5.3 Network layer

The main role of the network layer is to find the path to route the data provided by the transport layer reliably to the base station while trying to best optimize the energy consumption induced by all the nodes. sensors participating in this routing. Given its importance for sensor networks, routing has attracted the attention of a large number of research works [35, 37,38].

1.5.4 Transport layer

The transport layer is responsible for scheduling and transporting data packets without duplication, breaking them into packets, controlling flow, and managing any transmission errors [38].

1.5.5 Application layer

The application layer is the topmost layer. This is the level closest to the user; it provides the interface with the applications. Depending on the detection tasks, different types of applications can be implemented and used on the application layer. The application layer can also manage the aggregation of data before it is transferred to the transport layer [38,39].

1.6 Energy Management Plans

A wireless sensor node requires a power source; its life shows a strong dependence on battery life. The power management plane controls battery usage, it manages how nodes use their power. For example, a node should go to sleep after receiving a message from a neighbor to efficiently use the available energy and thus prolong the lifetime of the network [39].

1.6.1 Mobility management plan

Depending on the type of application, the sensor nodes can be mobile. This plan detects and records the movements of a node and knows its location [39]. Thus, a backtrack to the user is always maintained and the node can keep track of its neighboring nodes.

1.6.2 Task management plan

The task management level ensures the balancing and distribution of tasks on the various nodes of the network. Not all nodes need to perform the capture task at the same time; some nodes perform a task more than others according to their battery level, to ensure cooperative and efficient work in power consumption, which can extend the life of the network [38].

1.7 Design Constraints of Wireless Sensor Networks

The creation and implementation of a wireless sensor network for the different fields of application mentioned above require methods and protocols that take into account the constraints and needs of each type of network. They are also considered performance parameters to assess the results of activities in this area. The main factors and constraints influencing the architecture of sensor networks are coverage, fault tolerance, scaling up, production costs, environment, and change in network topology, hardware constraints, transmission media, connectivity, and energy consumption[40,41,42,43].

1.7.1 Coverage

Area coverage is considered a metric to assess network performance. An area is said to be covered if the surface of this area is effectively monitored. A node can detect any event that occurs in its coverage area. One of the methods used to save energy is the scheduling of the nodes. This change of state must preserve a very important property that is the coverage of the surface.

1.7.2 Fault tolerance

Fault tolerance is the ability to maintain network functionality in the presence of faults. The failure of individual sensor nodes in a wireless sensor network can be caused by various reasons such as lack of power, physical damage, or environmental interference. Fault tolerance aims to minimize the consequences of these faults on the overall operation of the network.

1.7.3 Scaling up

Depending on the type of application, the number of sensor nodes deployed in a network can range from hundreds or thousands of nodes to millions of nodes if the application requires it. It should also be noted that if the number of nodes is large, then it generates many transmissions and may impose difficulties for data transfer. On the other hand, the density of the network must be well exploited to ensure the proper functioning of the network.

1.7.4 Production costs

Sensor networks are often composed of a very large number of sensor nodes. The cost of a single sensor is therefore very important to define the total cost of its network. If it is higher than deploying an array of ordinary sensors, then the cost of WSN is not justified.

1.7.5 Environment

Sensor nodes are typically distributed in a remote, unmonitored geographic area. They are subject to various environmental conditions; they can operate under high pressure on the sea floor, in harsh environments such as battlefields, or even in extremely cold environments.

1.7.6 Changing network topology

Deploying a large number of nodes requires the maintenance of the network topology. This operation includes three phases: deployment, post-deployment (sensors can move, stop working,...), and redeployment of added nodes.

1.7.7 Material constraints

The main material constraint is the size of the sensor with a low manufacturing cost. The other constraints are the energy consumption which must be lower so that the network survives as long as possible and operates at high sensitivities, that it adapts to different environments (high heat, water, etc.), that is autonomous and very resistant because it is often deployed in hostile environments .

1.7.8 Transmission media

In a sensor network, the nodes are connected by a wireless architecture. To enable operations on these networks worldwide, the transmission medium must be standardized. Infrared, Bluetooth, and radio communications are most commonly used. Most sensor networks use radio frequency communication circuits due to their low cost and ease of installation.

1.7.9 Connectivity

Connectivity is a fundamental problem in sensor networks (consisting of fixed or mobile entities). A sensor network is said to be connected if and only if there is at least one connection between each pair of nodes [42]. Each node can thus communicate with any other node in the network, either directly (one-hop connectivity) or by using intermediate nodes (multi-hop communication) [43].

Connectivity depends primarily on the availability of paths and is also affected by changes in topology, which are generally related to node failures, mobility, etc., loss of communication links, separation of nodes, network distribution, etc.

1.7.10 Energy consumption

In most cases, replacing the battery of a sensor is impossible. This means that the lifetime of a sensor node depends essentially on the lifetime of its battery. The various sensor units to perform the tasks of data retrieval (sensing), data processing, and data transfer consume this energy. The transmission of this data is the task that consumes the most energy. This is why the power consumption factor is one of the performance measures that have fundamental importance in sensor networks.

1.8 Limited resources

Sensor nodes, although small in size and low in cost, have many limitations such as very limited power conservation and data processing capabilities, as well as poor sensing and communication capabilities. For example, the MICAz sensor from the manufacturer Crossbow has an 8-bit microcontroller of the Atmel ATMega128L type with a clock frequency of 8 MHz, a flash memory of 512 KB, an EEPROM of 4 KB, and an 'a transceiver whose bit rate is limited to 250 Kbps[44]. These material obligations have determined more and more research issues in this field.

1.9 Wireless Sensor Network Lifetime

Lifetime is a metric etch performance evaluation important in WSN. There are several definitions of this measurement parameter. However, note that its definition is not always trivial. The lifetime of a network is considered the most important metric for evaluating sensor networks. In a resource-constrained environment, the power consumption of each sensor node should be considered. A network can only accomplish its purpose as long as it is "alive", but not beyond that. Expected lifetime is critical in any sensor deployment[44].

Network lifetime is one of the most significant metrics for evaluating sensor networks. In an environment with limited resources, the network can only achieve its objectives as long as it is "alive". The power consumption of each sensor node must therefore be taken into account since the lifetime is essential in any sensor device. There are several distinct definitions of the lifetime of a wireless sensor network[45].

1 .9.1 Lifetime based on connectivity

Connectivity is a major issue in wireless sensor networks. Connectivity depends in particular on the presence of links; in [46], connectivity in a sensor network is defined by the percentage of nodes that have paths to the base station (Sink). In [47] defines the lifetime of the network by the period until the loss of the coverage or the connectivity of the network.

1 .9.2 Lifetime based on the number of live nodes

The lifetime of a WSN as a metric is strongly related to the lifetime of network nodes. It depends on the number of failed nodes draining their battery, in [3,4] the lifetime of the network is defined by the duration until the first node exhausts all its energy. However, in the opinion of other researchers like [48], base stations should be excluded from the calculation of the network lifetime, since they generally operate on direct current. In [49], the lifetime of a network is represented by the time required for all the sensors to consume their energy.

1 .9.3 Lifetime based on Quality of Service (QoS)

A lifetime based on Quality of Service (QoS) in the WSN is often considered a very important performance metric. Therefore, the lifetime is determined by the period during which the network meets the required quality of service [50]. It is implemented by tracking and monitoring the operation of all sensor nodes in the network until an acceptable rate is reached to perform the desired service [51].

1.10 Factors and technologies contributing to energy consumption

1.10.1 Radio module status

The radio module is the component of the sensor node that consumes the most energy since it is it that provides communication between the nodes. The radio module performs in four operating states [52] which are: Sleep, Active (idle), Transmit, and Receive (Figure 1.9).

- Sleep state: the radio is switched off.
- Idle state: the radio is on, and the node is continuously listening to the transmission channel. In other words, the sensor node is neither receiving nor transmitting.
- Transmission state: the radio is transmitting a packet.
- Reception status: the radio receives a packet.

In most radios, the idle mode consumes a significant part of the energy, more or less equal to the consumption in the receive mode after unnecessary listening to the transmission channel [53].

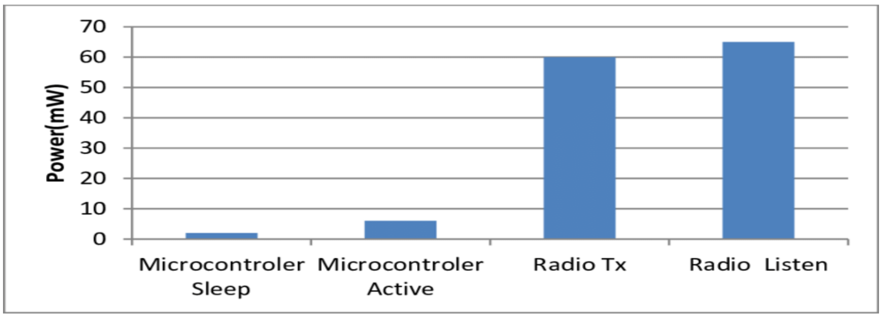


Figure 1.9. Energy consumption by a sensor node [53].

Thus, when it is not necessary to transmit or receive data, it is recommended to turn off the radio completely rather than leave it idle. To reduce the energy consumption of wireless communication, many research works on MAC layer protocols have been oriented, as we have proposed in this thesis, toward the reduction of the listening time of the channel. radio (idle)[54]. Moreover, the transition from one state to another can also be another source of energy consumption due to the activity of electronic circuits.

1.10.2 Radio propagation model

Real-world radio propagation is very complicated because the propagation model is an estimate of the average received power of a radio signal at a given distance from the sender. A free-area radio propagation model can be applied to predict the received signal strength (RSS) between sender and receiver based on a free and unobstructed line-of-sight (LOS) between them [55]. The propagation of a radio signal is generally faced with many factors: diffraction, scattering by various objects, and reflection. On the other hand, the received power defines whether the receiver can correctly receive a packet sent by a sender [56].

1.10.3 Access to the transmission medium (MAC)

In the OSI model, Media Access Control (MAC) is considered part of the data link layer. It is the first layer above the physical layer. The MAC layer defines the channel access rules [34]. It is in charge of access control to the communication medium, synchronization between the different nodes, determination of errors, and retransmission mechanisms in the event of errors [57].

Energy conservation has a very important role in the MAC layer. An energy conservation mechanism plays an important role in the MAC layer. An energy-efficient MAC protocol allows the radio module to be used for as little time as possible, it improves energy efficiency by extending sleep time, reducing idle listening and packet collisions.

1.11 Energy consumption patterns per sensor node

1.11.1 Energy consumed during data capture

A sensor node consists of four main units: a capture unit (detection), a processing unit, a transmit-receive unit (radio), and an energy unit (battery). The capture unit power consumption depends on the specificity of the sensor. It is intended to retrieve data from the environment. Capture energy is dispersed to perform the following actions: sampling, signal processing, analog-to-digital conversion, and triggering of the captured cell [58]. Typically, capture energy is a small percentage of the total energy consumed by a sensor node.

1.11.2 Energy consumed during data transmission

WSNs are also confronted with multiple physical constraints, in particular about the energy capacity for the communication of the sensor, whether it is the reception power or the transmission power. The communication capacity is defined by the amount of data to be communicated, the transmission distance, as well as the physical characteristics of the radio unit, which determines the emission of the signal and its power, determining the value of the energy to be consumed [59]. When the transmission power is high, the signal will have a long-range and the power consumed will be higher, and the communication power accounts for most of the energy consumed by the sensor node.

1.11.3 Energy consumed in the data processing

In most cases, the energy consumption of the capture unit is insignificant compared to the energy consumed by the processing unit. Processing energy is broken down into two parts: switching energy and leakage energy. The voltage source and the total load of the switched capacitor at the software level define the switching energy. For low enough duty cycles or high enough supply voltages, the leakage energy can be greater than the switching energy. For example, when the duty cycle of the SA-1 100 processor is 10%, the leakage energy represents more than 50% of the total energy consumed [60].

On the other hand, leakage energy is the energy consumed when the calculation unit does not carry out any processing. In general, the processing energy is small compared to the energy required for communication.

1.12 Energy saving protocols in WSNs

1.12.1 Dedicated Network Layer Protocols

Routing protocols for efficient energy management represent most of the research work proposed within the network layer. The basic idea of this family of protocols is the realization of efficient routing paths in terms of energy consumption. Many routing strategies have been created for wireless sensor networks. Some are adaptations of strategies that have already existed for other types of networks (especially for wireless networks in the broad sense), while others have been designed specifically for wireless sensor networks. Routing algorithms are divided into three families [61]: data-centric, hierarchical, or geographical routing algorithms.

In data-centric routing protocols, the base station (Sink) sends requests to certain regions and waits for data from sensors located in the chosen regions. the sensor nodes collaborate to accomplish the sensing task. Examples include the propagation protocols proposed in [62], the SPIN negotiation routing protocol [63], and the directed broadcast routing protocol [64]. In location-based (geographic) routing protocols, sensor nodes are addressed based on their locations, which may be available directly by communicating with a satellite using GPS. Node location information is needed to calculate the distance between two particular nodes so that power consumption can be estimated. Among these geographical protocols, we can mention the MECN [65]], GAF [66], and GEAR [61] protocols.

Hierarchical protocols are based on the "standard node – master node" concept where standard nodes route their messages to their master, which then routes them through the entire network via other master nodes to the base station (sink). The main advantage of this type of protocol is the aggregation and fusion of data to minimize the number of messages to be transmitted to the sink, which allows energy savings. Two approaches are derived from this type of protocol, namely:

- Cluster-based approach we can cite LEACH [67].
- Chain-based approach we can cite PEGASIS [68].

1.12.2 Cross-Layer based power saving protocols

The definition of cross-layer architecture corresponds to all exchange of information between layers as defined in [69]:" Protocol design done by the violation of a reference layered communication architecture is cross-layer design for the particular layered architecture". In recent years, researchers have sought to integrate cross-layer design into WSNs to propose protocols based on these cross-layer architectures, including the need to manage network functionality while improving the performance of available resources. However, the majority of proposed protocols focus on energy saving and security issues in WSNs.

Cross-layer protocols dedicated to power saving are classified into three basic categories, namely: the first category includes protocols that exploit the interaction between the network and Mac layers. The second category is composed of protocols based on an inter-layer architecture analyzing the interaction between the Mac and physical layers. Finally, the last category focuses on the interaction between the network and physical layers.

1.12.3 Protocols dedicated to the MAC layer

The challenge of power consumption management can be solved in many ways: it is generally considered that power saving can be achieved by minimizing the communication activity of nodes at the access control layer to the medium (MAC). This layer mainly concerns the use of the radio module, many approaches have been proposed to manage this resource efficiently and thus optimize energy consumption. An energy-efficient MAC protocol must try to reduce the use of the radio module as much as possible. Classification according to the method of access to the medium makes it possible to distinguish between legacy MAC protocols, scheduled MAC protocols, duty cycle protocols, and hybrid protocols [70].

Scheduled MAC protocols provide a media-sharing approach that ensures that only one node has access to the wireless medium at a given time. The latter can be further divided into two subclasses, fixed allocations, and dynamic allocations. With duty-cycle protocols, the nodes are alternately in active and sleep periods depending on the network situation. Decrease the time a node spends in idle listening state, over-listening, and other unnecessary activities by putting the node into a sleep state. Hybrid protocols, as the name suggests, combine the characteristics of the previous two protocol categories (scheduled and duty-cycle) to achieve high performance.

1.13 Conclusion

Sensor networks are mainly deployed in research labs to make advancements in this field, as it is an important technology that is being used more and more day by day, although sensor networks bring many advantages, they present some scientific challenges. However, they correspond to a certain vision of the future and will bring improvements in a large number of areas of daily life, which leads us to believe that sensor networks will soon be an integral part of our lives and will certainly satisfy the biggest projects.

In this chapter, we have introduced general information on the subject of Wireless Sensor Networks (WSN), first, we have described the sensors, WSNs, then the main applications of WSNs, the protocol stack, and the constraints of WSNs. In the following chapter, we present the MAC layer and the energy consumption. Then, we presented the different factors and technologies contributing to energy consumption in WSNs. In the next chapter, we will analyze the main factors that influence directly or indirectly the various classes of MAC protocols on energy consumption and which are related to the transmission phase.

CHAPTER 2

STUDY OF MAC PROTOCOLS

2.1 Introduction

In wireless sensor networks, radio transmission is the primary source of power consumption, and radioactivity is largely controlled by the MAC layer. Therefore, to best save the energy of the battery of a sensor, the radio senders should be switched off for as long as possible. However, this could pose the problem of the synchronization of the sensors and the distribution of the wake-up periods.

2.2 Medium Access Control (MAC)

Medium Access Control (MAC) has been widely studied, due to many interesting applications that involve wireless sensor networks. The MAC layer is generally considered to be a sub-layer of the data link layer in the network protocol stack. The MAC layer is used to define channel access rules. It controls how nodes share the wireless medium. A medium access control protocol (MAC) manages access to the shared medium by specifying rules that allow them to communicate with each other in an orderly and efficient manner. This problem is also known as channel allocation or multiple access problems[71]. It performs several access resolutions when several data frames have to be transmitted and generates the frame check sequences and thus contributing to the protection against transmission errors. It therefore also performs collision resolution and initiates retransmission in the event of collisions. An efficient MAC protocol significantly increases the lifetime of a sensor network, and it can reduce collisions and increase achievable throughput, providing flexibility for various applications.

2.3 Properties of the sensor network related to the MAC layer

A node is forced to receive, process, and respond to messages, which are sometimes unnecessary or redundant due to a large number of adjacent nodes. Maximizing network lifetime is a common topic in most sensor network research. By making a node inactive during certain periods, we can prolong its lifespan. The types of communication patterns seen in sensor network applications are worth investigating, as these patterns define the operation of the sensor network traffic that needs to be controlled by a given sensor network [72].

The classification of possible communication models is described and the necessary characteristics of the MAC protocol for a sensor network environment are. In these perspectives, the proposed MAC protocol must be energy efficient by reducing the potential energy waste. This objective will be achieved by ensuring maximum standby time for the nodes. Sleep rate measures the fragmentation of the time a node spends in sleep mode over the total frame of time.

2.4 Causes of energy waste in MAC Protocols

Energy efficiency is one of the most important characteristics in wireless sensor networks, whatever the network layer studied (MAC, network, or application). The MAC layer makes it possible to determine the access rules to the channel, it has a very important role in the conservation of energy. The MAC protocol dedicated to sensor networks must be energy efficient; it aims to take into account the various factors of energy overconsumption. The major culprits for power wastage in MAC protocols for wireless sensor networks are the following factors **[70] [73] [74]**.

2.4.1 Collisions and Retransmissions

Collisions are the most significant consequence of energy loss. Collisions occur in two cases:

- The simultaneous transmission of data, data packets may be transmitted at the same time by several sensors and interfere, they have become unusable and must be abandoned. Lost information must be retransmitted, which consumes more power.
- The reception by a node at the same time of data that have not necessarily been transmitted at the same time or which have been broadcast by two nodes out of range of each other. These data packets are discarded and must be retransmitted, resulting in high power consumption.

2.4.2 Idle listening

A large number of MAC protocols always listen to the active channel, considering that the user switches off all of his devices if there is no data to send. Idle listening occurs when the radio listens to the channel to receive all traffic that has not been transmitted. The actual cost of listening in idle mode depends on the radios and how they operate. Moreover, several generations of low-speed radios have very high listening costs, of the same order as the reception and transmission costs. Therefore, setting sleep mode, for this reason, the frequency of switching between modes should remain relatively reasonable.

2.4.3 Overhearing

The sensor node can thus receive all the data that has been exchanged between neighboring nodes, even if it was not intended for it. Another common reason for power overconsumption is overhearing, which occurs when a node receives packets not intended for it. Overhearing can result in a large loss of energy when the traffic load is heavy since most FHCNs are deployed on a large scale.

2.4.4 Packet overhead

Exchanging control packets can be another source of wasted power. Many MAC layer protocols require control packets to ensure proper communication between sensor nodes (signaling, connectivity, pathfinding, and collision avoidance). Transmitting, receiving, and listening to control packets consumes power, reducing the effective throughput and lifetime of the network. Mainly if the number of control packets is unnecessarily high, it is called control packet overload.

2.4.5 Overemitting

Overemitting occurs when a sending sensor node broadcasts data packets to a receiver that is not yet ready to receive them. If the sending node is waiting for an acknowledgment, it retransmits the same packet several times, which consumes energy because it is always in active mode and waiting for a possible acknowledgment. The transmitted messages are considered useless and consume additional energy.

2.4.6 Packet size

The energy consumption of the transmitting and receiving sensor nodes is impacted by the size of the packets exchanged in the network. Thus, the size of the packets can neither be too large nor too small. Indeed, if it is small, the number of control packets (acknowledgment) produced will increase the overhead. If it is too large, a large transmission power will be required for larger packets.

2.5 Features of the correct operation of the MAC protocol

The purpose of the MAC protocol in WSN is to build a network of sensors and ensure that the communication medium is shared fairly and efficiently. Thus, some features should be considered for the design of the MAC protocol as follows: [75] [76] [77]:

- **Energy efficiency:** The most important issue when designing a new MAC protocol in WSNs is energy efficiency because the network lifetime is defined by the performance of nodes with limited battery power. The MAC protocol must be designed to conserve its energy to maintain the network lifetime.

- **Scalability and modularity:** The WSN protocol must be able to adapt to changes in network size, node density, and topology, regardless of the number of sensor nodes performing a transaction. Some nodes may stop working due to battery drain, link failure, or other environmental issues. Also, more nodes can be added, as the size of the network must be scalable.

- **Latency:** Latency gives the speed of the network, it is the time required to successfully send a data packet under the MAC layer. When processing network data, if the delay is low, the network connection is considered low latency. While a high latency connection experience results in long delays.

- **Throughput**: The ratio of the quantity of data served by the communication systems is called "throughput". System throughput should be high.

- **Bandwidth Usage**: Bandwidth is limited in the majority of WSN applications, but the base station must receive data equally from all nodes. Channel capacity should be shared equally between nodes without diminishing the operation of the same network. The network should support better bandwidth utilization.

- **Balance between sensor nodes**: The equitable distribution of resources in a network is determined by the principle of equity. This is an important feature of taking resources for communication between nodes in a network, such as selecting the cluster leader in a cluster.

- **Robustness** : is made up of features such as reliability, ease of use, and durability. It indicates to what extent the protocol is resistant to errors and false information.

- **Stability:** The ability of a communication system to manage the phenomenon of traffic congestion in a constantly changing environment is called "Stability". A stable MAC protocol must handle sudden loads that can exceed the maximum channel capacity.

2.6 Classification of MAC protocols

Research at the MAC layer is all about minimizing power consumption in wireless sensor networks. MAC protocols dedicated to wireless sensor networks should be energy efficient, but also stable as the network size increases, and adaptive to changes in network topology and connectivity when sensors stop working or move. The difference between the various categories of MAC protocols that we are going to present is based on the method of communication between the nodes and the way the network will be kept connected.

As shown in Figure 2.1 we have distinguished three categories of protocols at the level of the MAC sub-layer: scheduled protocols, protocols duty cycle, and hybrid protocols, we cite a few MAC protocols for each category [78].

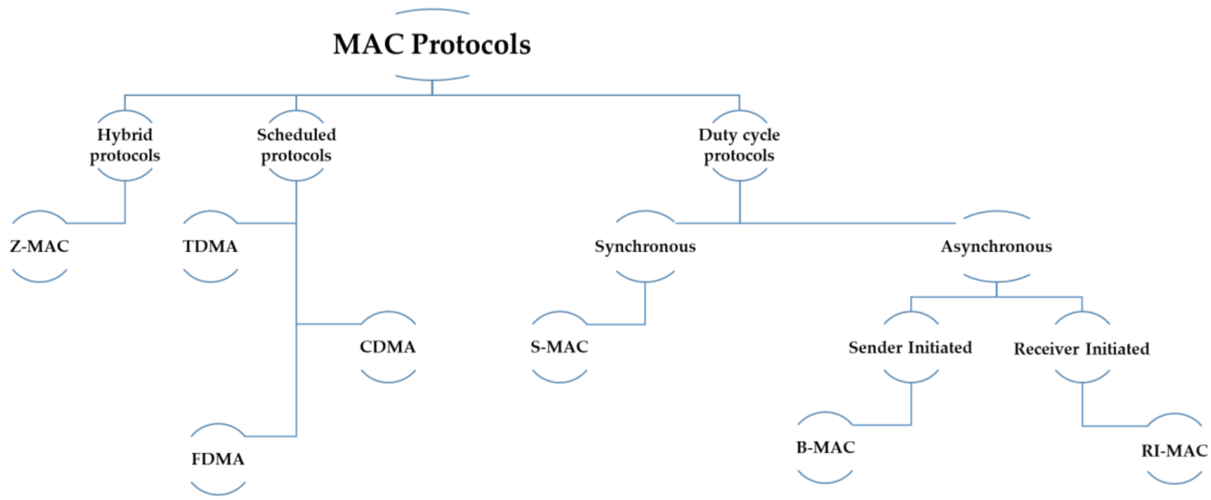


Figure 2.1. Classification of MAC protocols **[3][4][5][6][78]**.

2.6.1 Scheduled MAC protocols

2.6.1.1 TDMA-based Mac protocol

MAC protocols based on TDMA [79] have also been proposed to reduce power consumption in WSNs. For these protocols, each node has a time slot called timeslot where it can access the channel. All of these time slots form a frame whose duration is predetermined. Time is divided into frames and the latter is composed of a certain number of elementary times called time slots. Then a policy of scheduling allowing 'allocate to each sensor node several time slots per frame is implemented. With the allocation of these time slots, each node can thus know the start of its transmission for a given frame and the duration of this transmission to one or more receiver nodes. Each node also uses the allocation of its time slots for receiving the data intended for it. In most cases, a coordinator must be responsible for centralization and coordination in the network. It is thus responsible for distributing the time slots between the different nodes which it handles as shown in Figure 2.2.

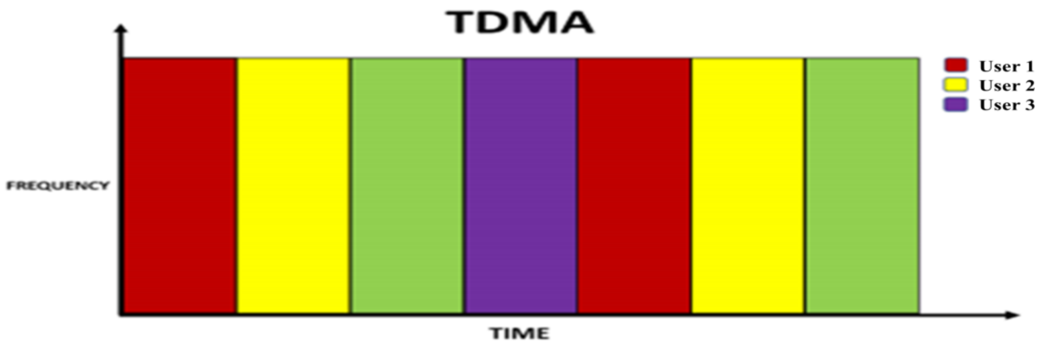


Figure 2.2. TDMA protocol description [79].

These TDMA-based protocols are power-efficient since the radio module of a given node is powered on only during its time slots, and off outside its time slots. They make it possible to avoid collisions but require a good level of synchronization. Therefore, they must implement a slot allocation algorithm on the different network nodes. However, these protocols have some limitations most often due to the dynamic aspects of the WSN such as the temporal variations of the transmission channel, the failures of certain sensor nodes which have exhausted their energy, etc.

Centralized TDMA-based protocols

In the first case, base stations (sink) or cluster managers (in the case of hierarchical networks) are responsible for allocating time slots for the various nodes associated with them. This type of protocol requires some requirements, such as taking into consideration the characteristics of the topology and the synchronization of the different nodes. There are several centralized MAC protocols in the literature, we cite the BMA [80] and the **ED-TDMA[81].**

Distributed TDMA-based protocols

In distributed MAC protocols based on TDMA, the nodes use the local information they contain to implement their scheduling. This kind of protocol does not need a central station to define the scheduling. Among the distributed protocols based on TDMA, we can cite TRAMA [82] and TDMA-CA [83]

2.6.1.2 FDMA-based MAC protocols

In the FDMA approach [84] (Frequency Division Multiple Access), the signals of the different users are disjoint in the frequency domain. The bandwidth is divided into channels and each node can communicate using its channel (Figure 2.3). This allows the nodes to communicate simultaneously. The problem of collisions is minimized since the nodes communicate through separate radio channels. However, the available bandwidth is low and the power consumption increases so unlike TDMA, FDMA eliminates the latency problem. To implement FDMA in sensor networks, nodes must be equipped with a complex radio system capable of receiving signals from multiple channels, which is why the use of FDMA in sensor networks is limited.

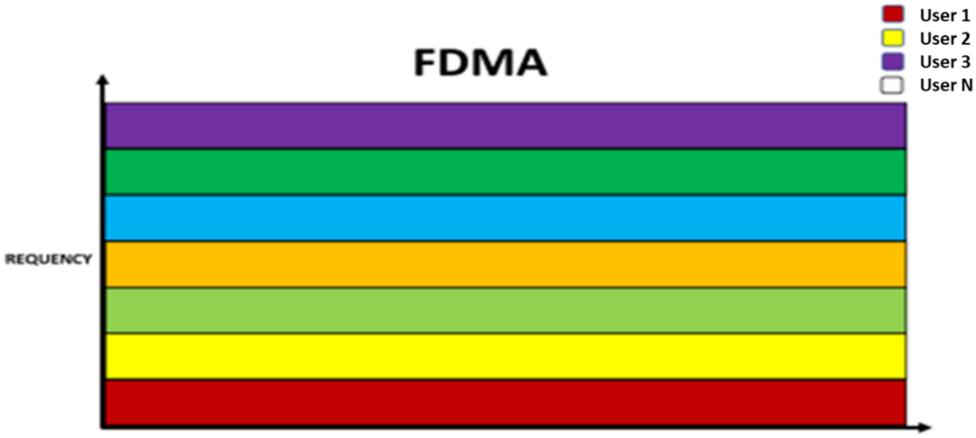


Figure 2.3. FDMA Protocol Description [84].

2.6.1.3 CDMA-based MAC protocols

The CDMA method (Code Division Multiple Access) [85] offers the ability to allocate the entire frequency band. All sensor nodes communicate at the same time. For this, a determined code is assigned to each node, which will use it to transmit the various information that it wishes to communicate in binary form, orthogonally to the other communications. However, a self-interference problem comes into play, which is reinforced when the number of simultaneous communications increases.

These protocols save energy because they avoid collisions and overhearing. They do not support peer-to-peer communication and generally require nodes to form clusters.

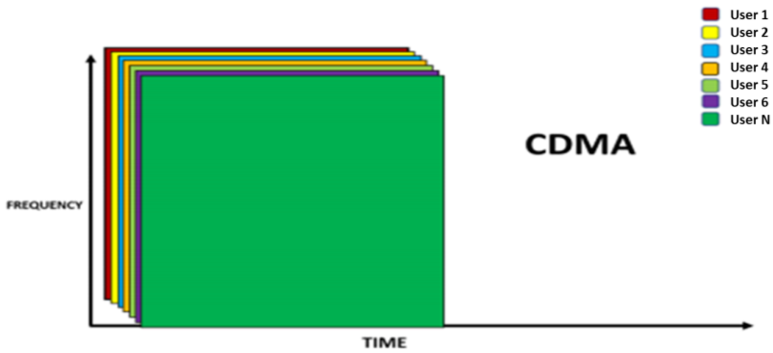


Figure 2.4. CDMA Protocol Description [85].

In the following table (Table 2.1) we will cite the main strengths and limitations of Scheduled Protocols:

Table 2.1 Strengths and limitations of scheduled MAC protocols [79][83][84] [85].

Protocols	Strong points	Limits
FDMA	Used for intra-cluster communications avoids collisions.	Increases sensor power consumption.
CDMA	Avoid collisions.	Calculations consume enough power.
TDMA	Optimizes the slot allocation process to minimize energy consumption.	Scaling up.

Inter-cluster communication is carried out by the approaches: TDMA (Time Division Multiple Access), FDMA (Frequency Division Multiple Access), and CDMA (Code Division Multiple Access). However, these approaches lack scalability and adaptability to topology changes as well as activity scheduling of relay nodes. In addition, they depend on distributed synchronization and their throughput is limited due to unused listening slots.

2.6.2 MAC duty-cycle protocols

The most efficient way to conserve power is to put the Sensor Node radio into sleep (low-power) mode whenever communication is not needed. Ideally, the radio should be turned off as soon as there is no more data to send or receive and should be ready as soon as a new data packet needs to be sent or received. Thus, the nodes alternate between active and sleep periods depending on network activity. The duty cycle [86] is defined as the proportion of the active period over the total duration of a cycle (active period + inactive period). The lower the "duty cycle", the less energy the node consumes. Indeed, nodes operating alternately in active and inactive periods require the synchronization of the active period between a sender and an intermediate receiver, or globally between neighboring nodes. A sending node can only forward a packet to the next hop when the next hop is active. This poses a particular problem of finding a rendezvous point between a sender and a receiver.

MAC protocols adopt a synchronous or asynchronous method to solve this problem. Synchronization is carried out by the frequent transmission of small control frames. Each node broadcasts wake-up frames once it enters its awake period. Thus it wakes up all its neighboring nodes for possible communication. Figure 2.5 illustrates the synchronous and asynchronous approaches of duty cycle protocols [87]. The duty-cycling mechanism reduces the time a node spends in the idle listening state, overhearing, and other unnecessary activities by putting the node into the sleep state.

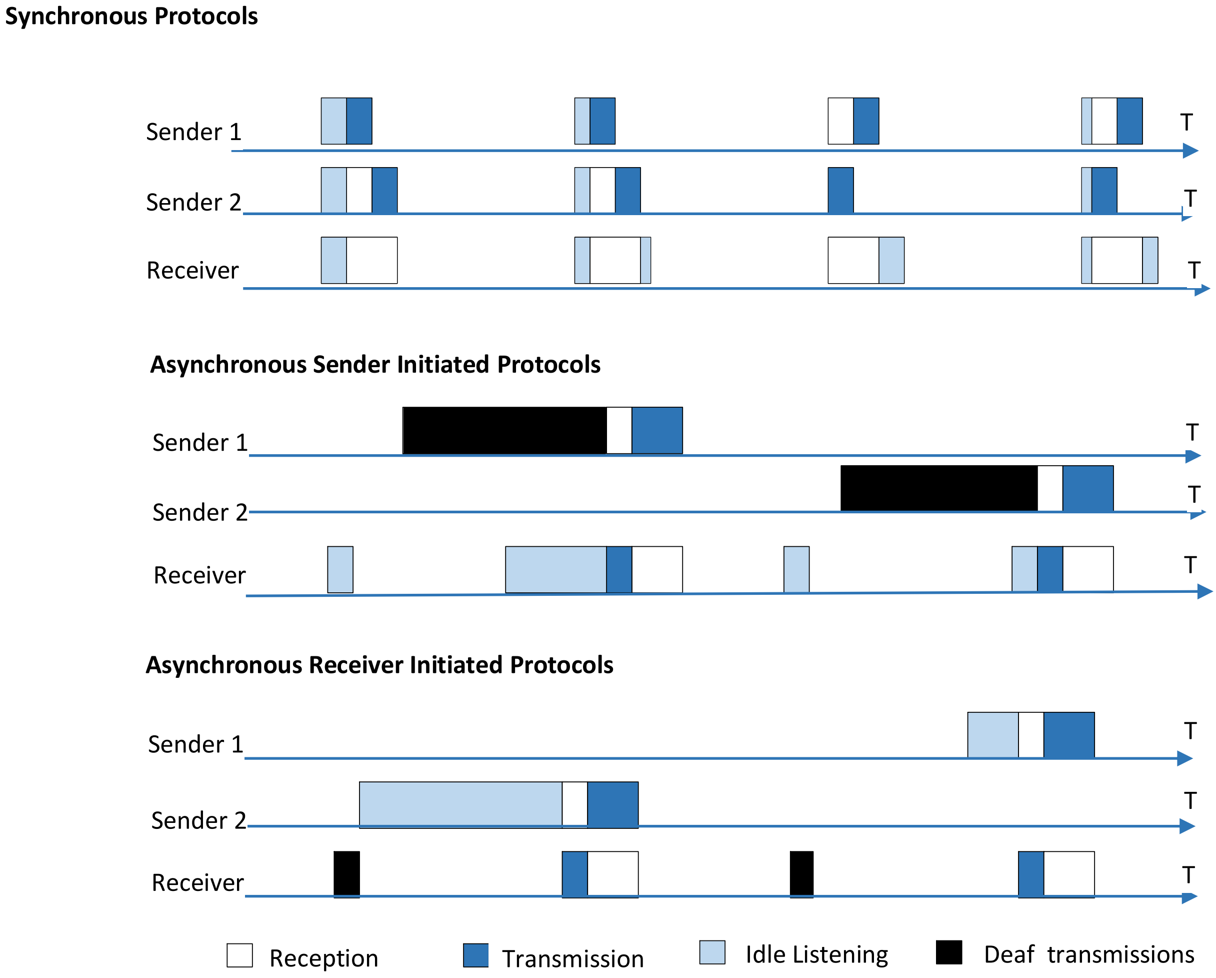


Figure 2.5 –Synchronous and asynchronous approaches to duty cycle protocols [86].

2.6.2.1 MAC Synchronous Protocols

MAC protocols reduce power consumption by synchronizing the sleeping and waking of sensor nodes. Synchronous MAC protocols require synchronization of the sender and receiver clocks. Synchronous schemes can be either contention-based or reserved slot-based. In either case, a portion of the active state is used to synchronize all nodes to a global sleep/wake schedule. Synchronous MAC protocols generate a large number of control messages to achieve synchronization before data exchange. Each sending node will create its path to the receiving node before transmission, which limits its usefulness when the duration of node activity is very short. which can also increase the latency of data delivery. Also, the implementation of synchronization is complex and difficult to achieve when the number of sensor nodes is high. Among the most well-known and widespread synchronous duty-cycle MAC protocols, we can cite S-MAC [5] and T-MAC [6].

S-MAC(*sensor-MAC*)[5]is one of the first duty-cycle MAC protocols designed for multi-hop networks. Each node periodically switches between an active period and an inactive period to save energy. At first, each node is free to choose its duty cycle. For a sending node to find a neighboring router node during its active period, S-MAC adopts the following timing. Each node periodically broadcasts its schedule of active and inactive periods to its neighboring nodes. Thus each node memorizes the schedules of all its neighbors to know when a particular neighbor will enter its active period to transmit its data to it. If several nodes must transmit their data to the same router or receiver node, they use an RTS/CTS type reservation mechanism(Request To Send/Clear To Send) and ACK (Acknowledgement). As shown in Figure 2.6 illustrates the periods of activity and inactivity in S-MAC [5].

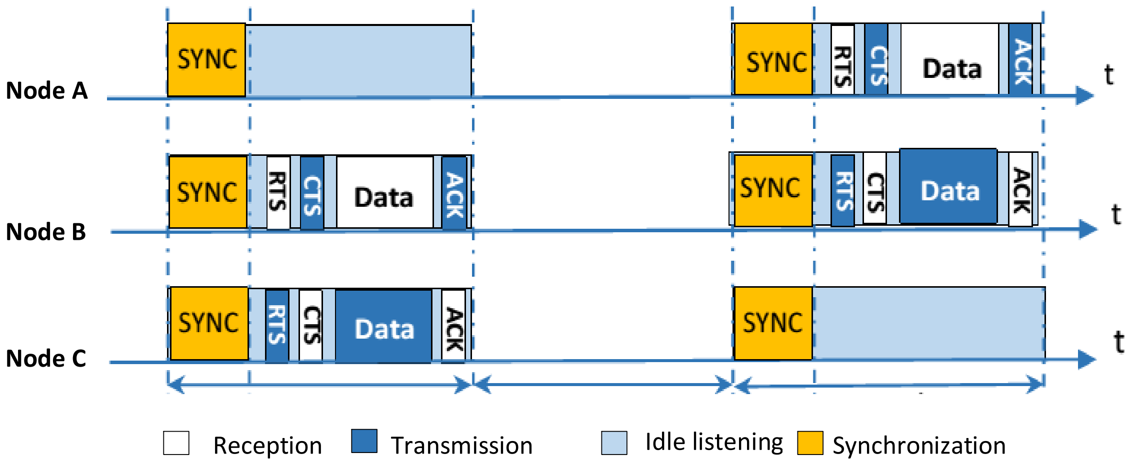


Figure 2.6. Active and inactive periods in S-MAC [5]

Normally in a small network, it is the first node that broadcasts its schedule which imposes its rhythm, because all its neighbors synchronize with it. In general, several nodes may broadcast their different schedules in distinct broadcast zones. A neighboring node having received different schedules then adopts these different rhythms, thus waking up at each different active period.

In S-MAC, the node that broadcasts its schedule first is a synchronizer node and the neighboring nodes are follower nodes. A first remark that we can make is that it is a protocol with a fixed "duty cycle" which does not automatically adapt to the variation in traffic unless a node modifies it explicitly by becoming a new one.

synchronizer (mechanism not provided for in S-MAC). Another note is that the end-to-end delay depends on the period of each node in the path, which can be very long. A third remark is that its control traffic (protocol overhead) represents an important part of the total traffic, because not only does it require the use of RTS/CTS(Request To Send/Clear To Send), but also the broadcasting of synchronization/resynchronization messages. Finally, to tolerate clock drift, the active period must be long enough, which prevents it from being used with an ultra-low duty cycle.

T-MAC(Timeout-MAC) [6] extends S-MAC and provides several improvements. Instead of fixing the active period, T-MAC decreases the active period after a time if it detects no activity on the channel. Another improvement consists in keeping the node in an active state during a time-out to be able to continue transmitting packets in a burst. The active period is also readjusted to adapt to the variation in traffic (the "duty cycle" will be variable in this case). The defect of T-MAC is the problem of over-listening because a node, even if it is not involved in the communication, must remain active during a time-out time.

The performance of T-MAC in monitoring applications is superior to that of S-MAC when there is traffic fluctuation. On the other hand, the dynamic adjustment of the activity time can generate a problem of early falling asleep. For example, in figure 2.7, during the first cycle, the node in T-MAC goes into sleep mode after the time interval TA and just after a frame is available for it. It will therefore have to wait for the next cycle before receiving this frame. This increases the latency time for data delivery.

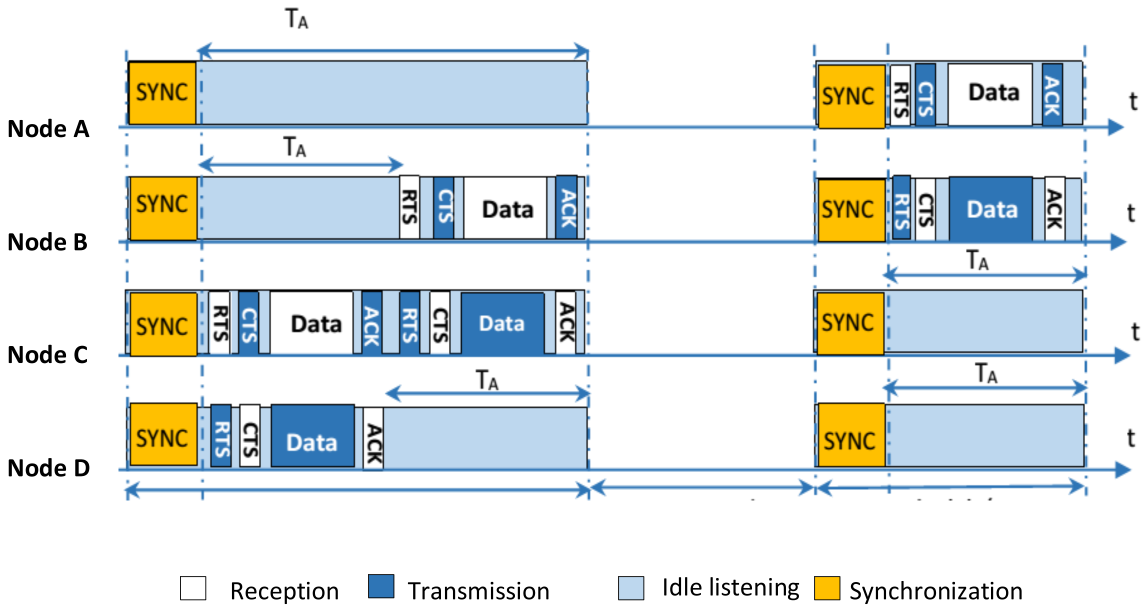


Figure 2.7. Active and inactive periods in T-MAC [6].

2.6.2.2 Asynchronous MAC protocols

Unlike (the previous case), asynchronous duty cycle MAC protocols do not require synchronization, which can reduce power consumption. However, asynchronous MAC protocols allow nodes to start their periods of activity and inactivity independently. Asynchronous MAC protocols are distinguished by their short cycle time and low communication cost. In what follows, we describe the two main categories of asynchronous protocols: Sender Initiated protocols, for example: B-MAC [10], WiseMAC [11], and X-MAC [12], and protocols Receiver Initiated, for example: RI-MAC [13], PW-MAC [14] and EE-RI-MAC [15].

2.6.2.2.1 Asynchronous Sender Initiated MAC protocols

In sender-initiated MAC protocols, the transmission and communication of data are decided and initiated by the sending node. Before sending data packets, a sender transmits a preamble to notify, that there is data communication without knowing the state of the receiver (sleep or awake). When a node wakes up during its regular wakeup period, it detects the preamble and remains in an active state waiting for the receiving node to wake up; this may require a large amount of energy from the sending node. Therefore, in the asynchronous Sender Initiated MAC protocols, most of the communication cost is borne by the senders. Among the best-known and widespread, we can cite B-MAC (Berkeley MAC)[10], WiseMAC [11], and X-MAC [12].

B-MAC(Berkeley MAC)[10]adopts the famous LPL (Low Power Listening) technique. The nodes periodically switch between active and inactive states (radio off). The active state is usually very short-lived, just allowing the node to sample the channel. When a node wakes up, it turns on its radio and checks the channel status (CCA Clear Channel Assessment). If it does not detect activity, it goes back to sleep. Otherwise, it remains active to receive the packet. After receiving, the node returns to idle mode.

On the sender side, each transmission of a packet is preceded by the transmission of a long preamble. The size of the preamble must be longer than the wake-up interval to be sure that a receiver (next hop) can detect it. In this way, the receiver is notified to receive the data packet. BMAC provides good power efficiency and the active period of each receiver node can be extended or shortened depending on the load of the sender. It is therefore with dynamic "duty-cycle" self-adapting to traffic variation.

B-MAC also offers a high-level interface to reconfigure the wake-up interval to find a good compromise between energy and network throughput. B-MAC suffers from the throughput problem during high load due to collisions and the random backoff periods needed to avoid collisions. Another problem is the idle listening of the preamble by neighboring nodes because even if the packet is only destined for a particular node (next hop), all other neighboring nodes still have to listen for the preamble until the end. Figure 2.8 illustrates the long preamble mechanism in B-MAC.

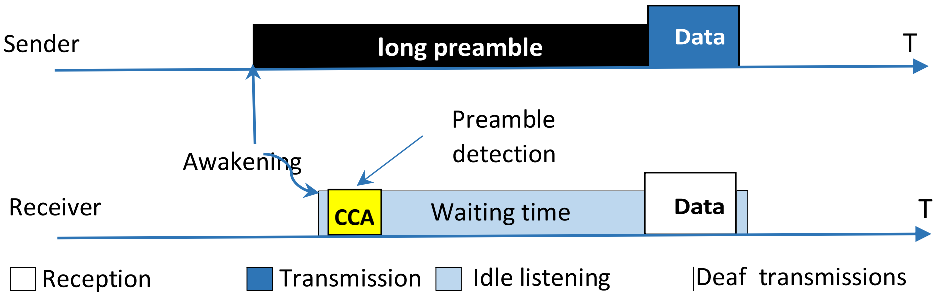


Figure 2.8. Long preamble mechanism in B-MAC[10].

WiseMAC[11], reduces the channel occupancy resulting from sending a long preamble by including in each ACK frame the date of the node's next wake-up. In this way, the sender is aware of the alarm clock of his receiver, if he has other frames to send him he proceeds to send a small preamble frame and quickly begins the transmission of data frames, as shown in Figure 2.9.

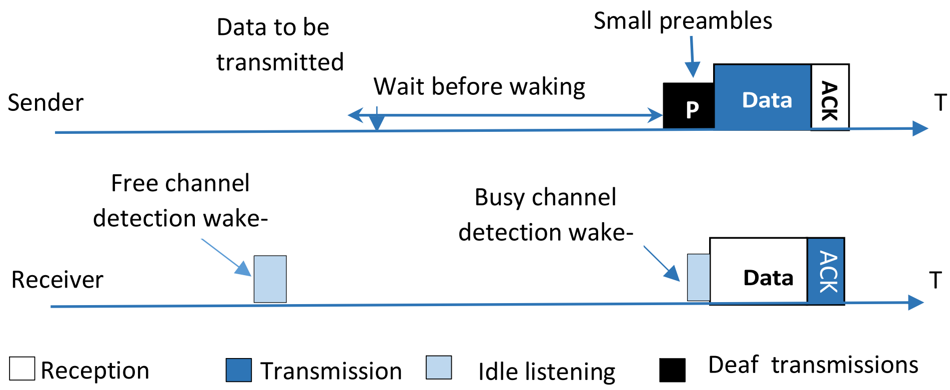


Figure 2.9. Small preamble mechanism in WiseMAC [11].

X-MAC[12] is an improvement of B-MAC to solve the overhearing problem. Instead of transmitting a large preamble, X-MAC divides it into a set of small preamble packets, each containing the address of the recipient of the packet to be transmitted, and transmits it while inserting a time slot between them. These intervals allow the destination node to send an ACK when it receives one of these preamble packets.

Once the sender receives the acknowledgment ACK, it knows that the next hop node is awake and stops sending the following preamble packets, then immediately sends the packet to the receiver. Like B-MAC, X-MAC also offers self-adapting sleep duration based on traffic variation. Compared to B-MAC, X-MAC improves energy efficiency and reduces delay thanks to the shortened preamble, however as explained previously, X-MAC can only choose one router to forward the packet to its destination in a multi-hop network, even if there are multiple paths whose exploitation could have made the end-to-end transmission more robust. Figure 2.10 illustrates the Mechanismsmall preambles in X-MAC.

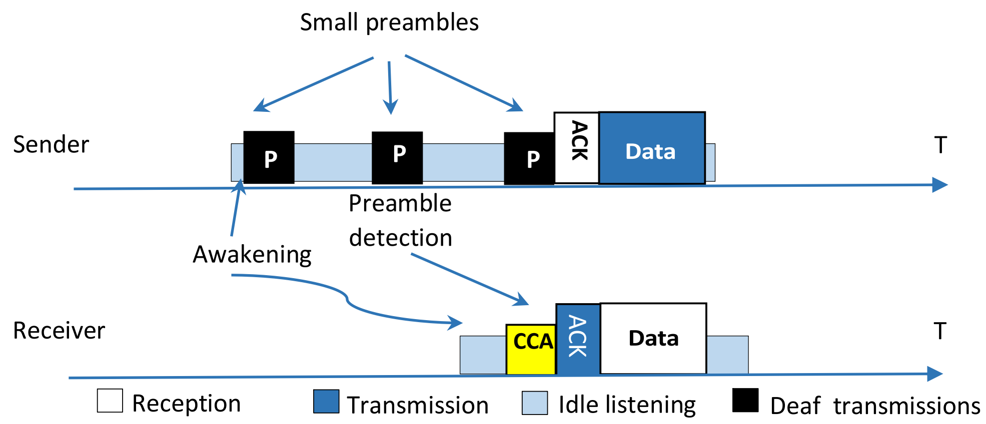


Figure 2.10. Mechanism of small preambles in X-MAC [12].

X-MAC thus ensures a low end-to-end delay, but generates a lot of collisions, because the interval between two preamble sendings can be interpreted as a free channel. In addition, the fact that there is no acknowledgment of receipt for data frames means that the sender does not know the correct reception of the frame sent, which impacts the delivery rate of data. Finally, like most asynchronous sender-initiated MAC protocols, some nodes remain active much longer than others, which poses a problem of fairness in energy consumption.

2.6.2.2.2 Asynchronous Receiver Initiated MAC Protocols

The MAC protocol sender-initiated is more efficient than the MAC receiver-initiated. In receiver-initiated protocols, the receiver wakes up independently to indicate its readiness to receive data by sending a beacon. Now the receiver initiates communication by periodically broadcasting a beacon informing all its neighbors that it is ready to receive. As a sender stays awake when it has a packet to transmit, it will detect this beacon, then transmit its packet. This technique avoids the occupation of the channel during the long duration of the preamble during which the other neighboring nodes cannot access the channel. With this mechanism, the receiver beacon does not occupy the channel as long as it does preambles in sender-initiated protocols [13].

Due to the drawbacks of sender-initiated protocols, researchers have turned their attention to the receiver-initiated approach. In this section, we first describe RI-MAC [13], which is the first receiver-initiated asynchronous MAC protocol. As shown Figure 3.1, in RI-MAC, nodes sleep when not engaged in communication. Periodically, the receiver broadcasts a beacon after it wakes up, announcing that it is awake and ready to receive packets. Upon receiving the beacon, the sender transmits its packet. The sender enters standby mode after completing data transmission. If the sender remains silent after a beacon, the receiving node also goes into sleep mode.

RI-MAC "Receiver Initiated *MAC protocol*" [13] implements the principle of LPP and it is the first protocol based on this mechanism (LPP allows a sender not to occupy the channel until the next wakeup of the receiver. It is now the receiver who initiates the communication by periodically broadcasting a "beacon" informing all its neighbors that it is ready to receive. Since a sender stays awake when it has a packet to transmit, it will detect this "beacon", then transmit its packet). This technique (figure 2.11) avoids the occupation of the channel during the long duration of the preamble used by the Sender Initiated protocols during which the other neighboring nodes cannot access the channel. RI-MAC reduces channel occupancy compared to X-MAC and provides a high data delivery rate with low end-to-end delay.

To avoid the collision between the "beacons", the diffusion period is not a constant but taken randomly between 0.5T and 1.5T (T being the Expected average period). In this way, the sender will only have to wait silently for the receiver to wake up. RI-MAC suffers from a defect nevertheless, when there are several senders, the collision can take place in RI-MAC, but RI-MAC carries out a new broadcast of the beacon of the receiver after each detection of collisions. RI-MAC does not support streaming.

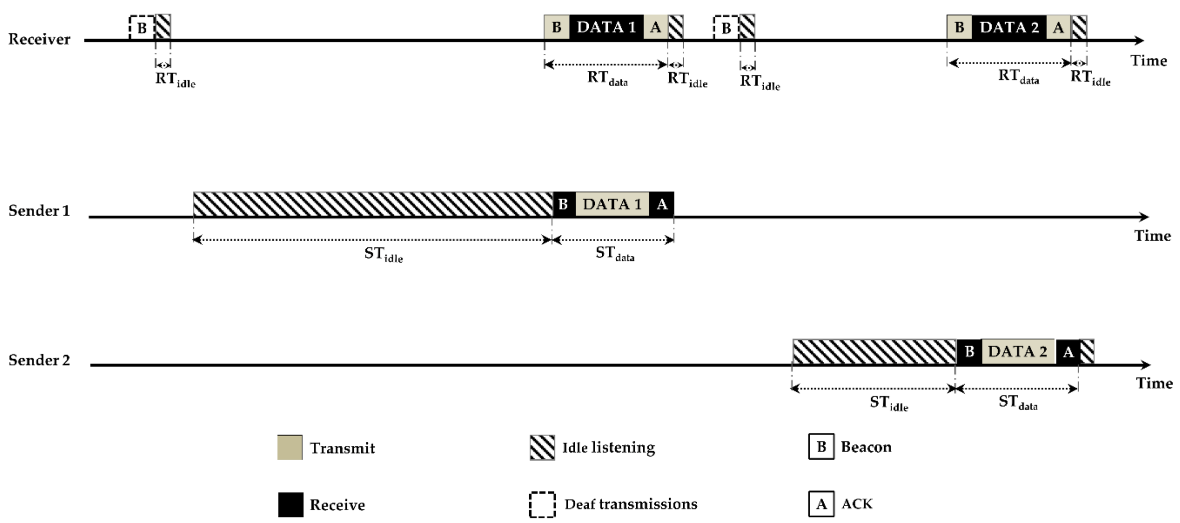


Figure 2.11. RI-MAC Protocol Operation Process [13].

2.6.3 Hybrid MAC protocols

Implementation and performance evaluation of a hybrid MAC protocol for wireless sensor networks that combines the advantages of the TDMA principle and also of the duty cycle principle (CSMA) while implementing their weak points. Like CSMA, hybrid protocols allow for high channel utilization and low latency under low contention and, like TDMA, high channel utilization under high contention and reduced collisions between two-hop neighbors at low cost.

Hybrid protocol performance is robust to timing errors, slot allocation failures, and time-varying channel conditions; in the worst case, its performance always falls on that of the CSMA. However, these latter techniques can prove to be complex to implement in the case of a large deployment of nodes. Compared to the two previous families, the hybrid protocols present great flexibility, good scalability, and good energy saving at the level of the nodes.

Z-MAC [88] dynamically switches between Carrier Sense Multiple Access (CSMA) and TDMA depending on the traffic. The different nodes in the network run a distributed location selection algorithm to obtain a collision-free location. In low contention (LCL) nodes in the network can compete for any slot, but in high contention (HCL) only the owner and one-hop neighbors of the owner compete for this slot to reduce collisions.

The Z-MAC protocol uses the centralized scheduling algorithm and is based on a scalable named pipe reuse DRAND [89]. The TF rule allows nodes to choose their period sizes based on their local two-hop information. This rule makes DRAND adaptive to dynamic period changes (caused by local topology changes) without incurring global changes. Figure 2.12 shows an example of a TDMA program obtained by the TF rule. If the global delay is used, then 6 will be the size of the delay. Then nodes A and B can only use their slots once every 6 slots although their frame sizes are 2 each.

In networks with high contention, the Z-MAC uses congestion notification messages (ECN) to reduce collisions. When a node detects heavy traffic, it propagates the ECN message to its two-hop neighborhood. Z-MAC builds a TDMA structure based on the B-MAC mechanism, Clear Channel Assessment (CCA), and Low Power Listen (LPL). It, therefore, inherits the limits of the B-MAC mechanism. By combining CSMA and TDMA, Z-MAC becomes more robust to timing failures, time-varying channel conditions, slot allocation failures, and topology changes than a standalone TDMA; in the worst case, it always comes back to the CSMA.

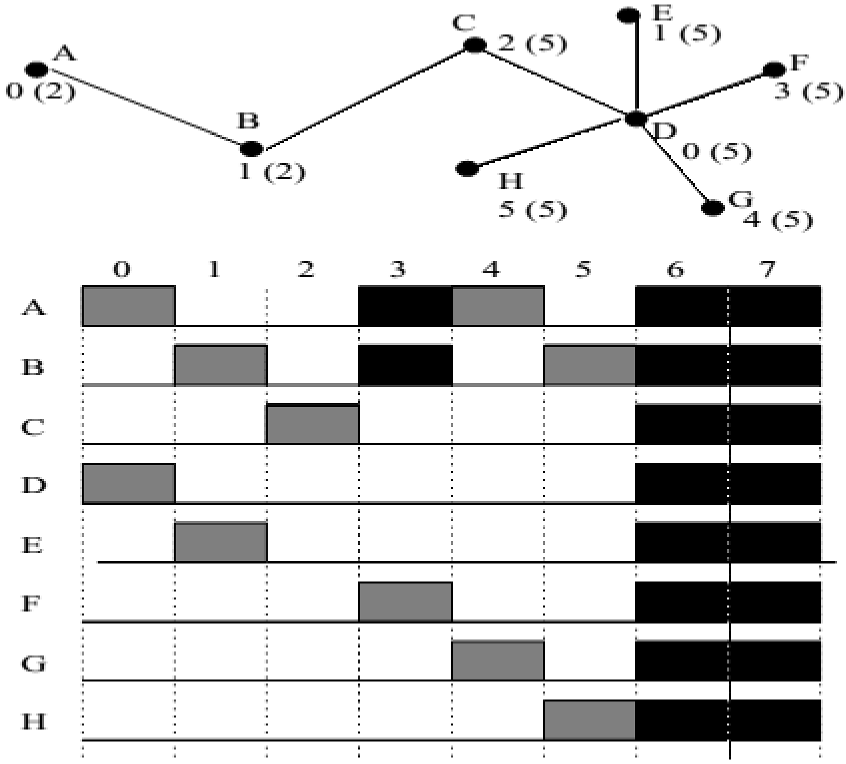


Figure 2.12. An example of the TF rule. The top Figure shows a network topology and the numbers indicate the slot numbers assigned by DRAND and the numbers in parentheses are Fi. The bottom Figure shows the slot schedule of all nodes[89].

ER-MAC[90], is a hybrid MAC protocol for emergency response wireless sensor networks.ERMAC is designed as a hybrid of the TDMA and CSMA approaches, giving it the flexibility to adapt to changes in traffic and topology. It takes a TDMA approach to scheduling collision-free slots (figure 2.13). Nodes wake up for their time slots but otherwise go into a power-saving sleep mode. ER-MAC enables contention in TDMA slots to cope with large volumes of traffic. This system trades power efficiency for a higher delivery rate and lower latency.

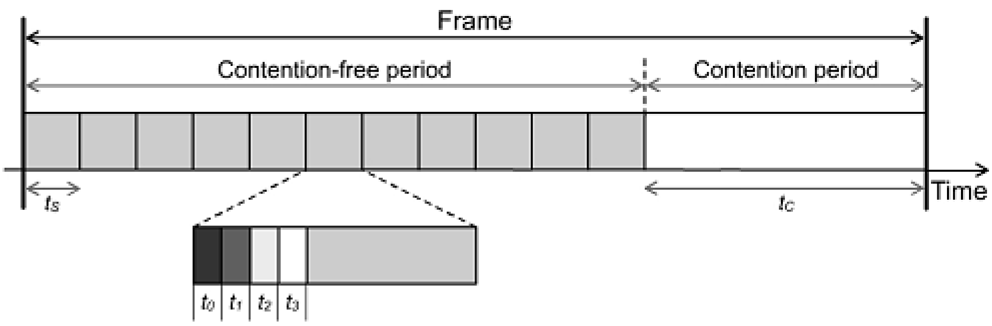


Figure 2.13. ER-MAC's frame structure [90].

ER-MAC maintains two priority queues to separate high-priority packets from low-priority packets. When an emergency occurs, nodes participating in emergency monitoring modify their MAC behavior by allowing contention in slots TDMA to achieve a high delivery rate and low latency. ER-MAC offers a synchronized and loose slot structure, where nodes can change their schedules locally. This allows nodes to easily join or leave the network.

iQueue-MAC[91] allocates slots whose number is variable depending on the traffic, thus forming a vTDMA (variable TDMA) window. Each sending node is allowed to transmit only one packet during CP regardless of the number of pending packets. The number of remaining packets from a sender is embedded in the first packet to tell the receiving node how many slots are needed in the next cycle. The receiver checks this field, if the size of the queue is not empty, the receiver allocates the corresponding number of slots to it during the following cycle. Figure 2.14 shows an example of how the iQueue-MAC protocol works.

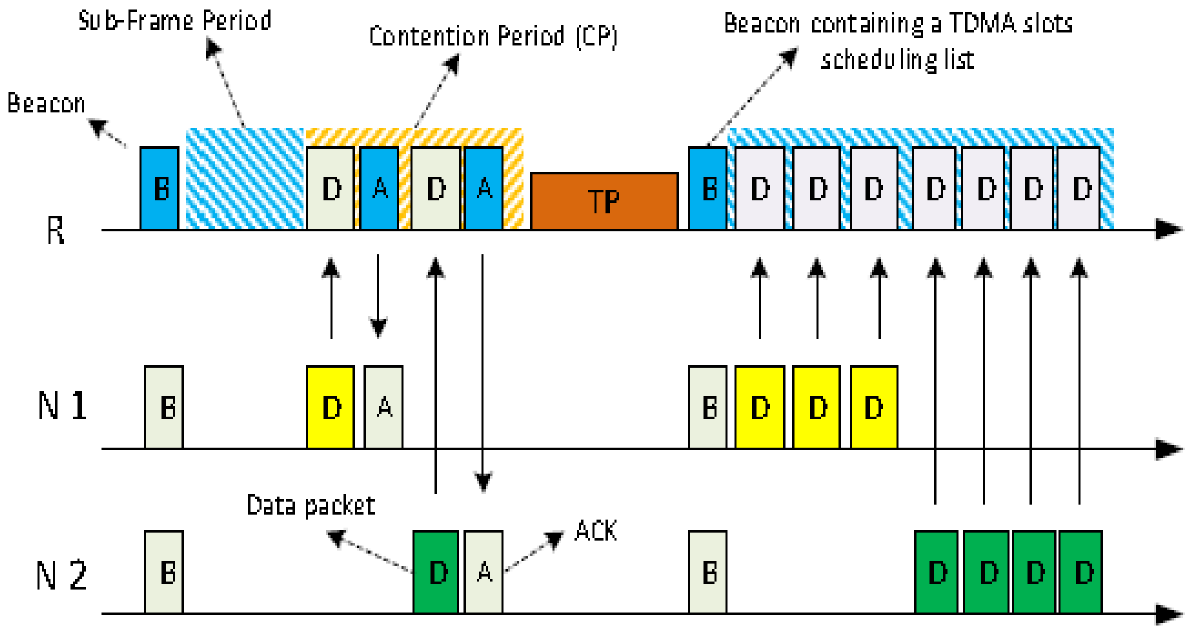


Figure 2.14. Example of operation of IQEUEU-MAC [91].

The sensor nodes N1 and N2 have multiple packets to transmit, after receiving the first beacon, each transmits during CP a single packet by inserting in the queue length indicator field the number of remaining packets (3 and 4 respectively in the example). By checking these two packets received, the receiver then allocates 3 slots for N1 and 4 slots for N2. Then it transmits the two packets to the next receiver. In the next cycle, these remaining packets are transmitted during their slot.

2.7 Conclusion

In this chapter, we have presented some MAC protocols dedicated to wireless sensor networks, among these protocols, we have concentrated our work on the MAC protocols with duty cycle "Duty Cycle", where the nodes synchronize their periods of activity and inactivity to generally ensure fairness in energy consumption and to predict the lifetime of the wireless sensor network, it has been found that their common goal is to improve the performance of WSNs.

In the next chapter, we focus on the category of MAC protocols based on the asynchronous duty cycle Receiver Initiated. By explaining the principles and different techniques, they use to minimize idle listening and collisions.

CHAPTER 3

RECEIVER INITIATED MAC PROTOCOLS

3.1 Introduction

Synchronous duty cycle MAC protocols reduce sensor power consumption by ensuring the synchronization of sensor sleep and wake times. In contrast, asynchronous duty cycle MAC protocols do not require such synchronization. They use preamble sampling instead of additional synchronized control frames. Due to the small number of control frames and the low probability of collision, asynchronous MAC protocols perform better in terms of power consumption. In this chapter, we will present a classification of receiver-initiated MAC protocols. We will analyze and discuss these various protocols, to explain the fundamentals of asynchronous "receiver-initiated" duty cycle protocols, to provide an overview of the state of the art in this category that will allow us to propose a new "receiver initiated" MAC protocol.

3.2 Classification of receiver-initiated MAC protocols

3.2.1 Idle listening minimization

Idle listening occurs when an idle node is ready to receive a packet but currently receives nothing. Because of this, many receiver-initiated MAC protocols have been proposed to reduce the idle listening time of a sensor node, which has been shown to contribute significantly to the total power consumption of the node. . In this section, we present the most interesting receiver-initiated MAC protocols to reduce idle listening.

3.2.1.1 RIVER-MAC

The RIVER-MAC protocol [92] is a receiver-initiated asynchronous duty cycle MAC protocol. The main innovations of the RIVER-MAC protocol are an essential improvement (as shown in the fFigure3.1): a CCA-based rendezvous to reduce empty listening by an order of magnitude (*idle listening*) of the sending node. Instead of listening for a beacon from its intended receiver, a sender STROBES the CCA until it detects activity. CCA here refers to a short physical layer check used to determine the energy on the channel. When some activity is detected, the sender puts its radio into receive mode to receive the next packet.

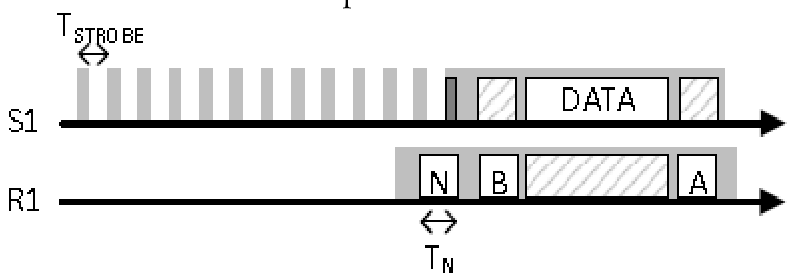


Figure 3.1. Land meet-you RIVER-MAC based on the CCA [92].

The trade-off is that the receiver must send two beacons: one for the sender to detect with a CCA (the beacon, marked "N"), and a second to receive (the regular beacon, marked "B"). To ensure that the CCAs of the sender can detect the first beacon packet, the period of the CCA strobe (STROBE) must not be larger than the transmission time of the beacon packet (TN). The second improvement of RIVER-MAC is a beacon stream-based collision resolution scheme to reduce contention between receiver nodes, a previously overlooked problem in receiver-initiated MAC protocol design.

3.2.1.2 EE-RI-MAC

The MAC protocol (EE-RI-MAC)[15] is an enhancement of the RI-MAC protocol, it introduces an asynchronous duty cycle method, for increased power efficiency, in which the standby and sleep periods of a sender alternate to reduce the standby period. Specifically, the EE-RI-MAC protocol attempts to reduce a sender's duty cycle by adding sleep periods during ideal listening when the sleep period is greater than a certain value. In other words, the standby and sleep periods of another sender to reduce idle time Listen. Figure 3.2 gives an overview of the operation of the EE-RI-MAC sender. Specifically, to further reduce idle listening, senders.

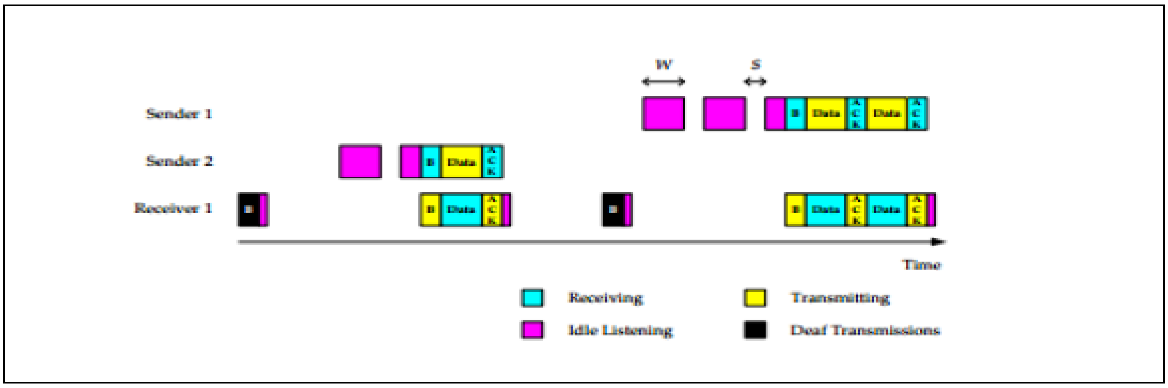


Figure 3.2. EE-RI-MAC introduced the use of cyclic waiting for beacons to reduce idle listening [15].

3.2.1.3 OC-MAC

OC-MAC [93] is a receiver-initiated MAC protocol, neighboring senders can intensively exchange data while waiting for the receiver to wake up. Figure 3.3 shows an example of how OC-MAC works. When a node has data to transmit, it sends an RTR beacon to neighboring senders, if the channel is free. The beacon includes its residual energy, the address of the destination, and a request to other senders to relay the data.

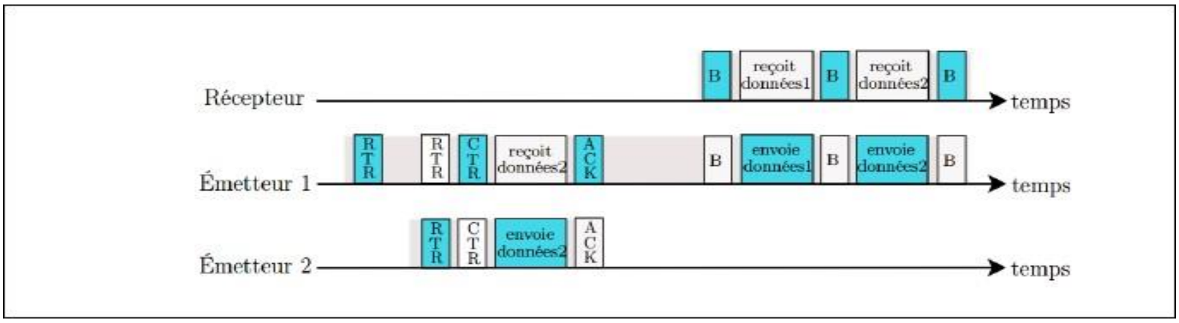


Figure 3.3. Transmission mechanism in OC-MAC [93].

The senders listen to the channel for a certain time and if they do not receive a response during this time, they must go to sleep. If it does not receive a response during this time, it loses its right to cooperate in the communication and continues to wait silently for a beacon from the receiver or another waiting sender. When an awake sender receives an RTS beacon, it compares its residual energy to that of the competing sender. He ignores the request if the latter has more residual energy than him. Otherwise, it transmits a CTS beacon, after a random timeout. The backoff prevents collisions, in case several senders are active.

3.2.2 Wake-up forecast

In the receiver-initiated approach, on the other hand, the sender preambles are replaced by receiver wake-up beacons; since a beacon is significantly shorter than a preamble, wireless bandwidth usage and collisions are reduced. Predictive wake-up of sensor nodes in receiver-initiated MAC network protocols defines node wake-up intervals, allowing a sender to infer the future time of receiver wake-up and send short wake-up beacons shortly. before the receiver wakes up. So several protocols aim to reduce the time a sender waits for a beacon by predicting when the receiver will wake up next.

3.2.2.1 PW-MAC

PW-MAC [14] uses an independently generated pseudo-random signal to control the wake-up times of each node. PW-MAC reduces the power consumption of the sensor node, it introduces an on-demand prediction error correction mechanism that aims to compensate for synchronization problems caused by unpredictable hardware, poor system health, delays, and clock loss. Additionally, as shown in Figure 3.4, predictable wake-up times are used to improve performance in the event of collisions and channel errors. If retransmission is necessary, the RI-MAC's senders stay awake until the receivers wake up again.

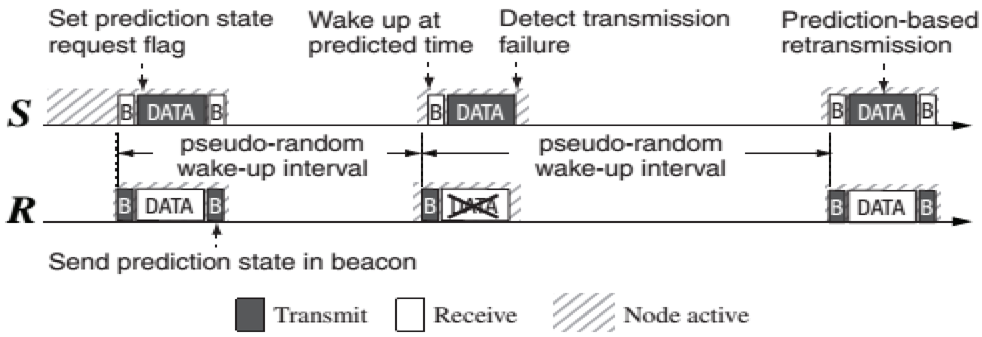


Figure 3.4. The operating mechanism of PW-MAC [14].

By choosing to use a pseudo-random wake-up schedule instead of a fixed wake-up schedule (which would also be predictable, as is the case in Wise-MAC [11]), PW-MAC avoids the presence of neighboring nodes that constantly wake up at the same time, since such events greatly increase the risk of collisions between senders hidden from each other; these collisions are generally more persistent with a wake-up schedule.

3.2.2.2 NW-MAC

In the nW-MAC protocol [94], an asynchronous scheme allows each receiver to wake up n times per cycle. After initialization and selection of schedules, nodes follow wake and sleep schedules. In the basic nWMAC system, a receiver wakes up during a scheduled receive period and sends an RTR to receive data from the senders. In contrast, a sender will only wake up at the receiver's scheduled wake-up time and transmit data upon receiving the RTR.

In addition, to receive multiple packets each wake-up time, the receiver uses a RxOp limit. To meet the demand for an event control network as shown in Figure 3.5, an adaptive version of nW-MAC is also proposed; node A transmits an RTR on each of its four wake-up calls (w0, w1, w2, and w3), for each cycle; at w1, one of the RTRs is received and acknowledged by node B. Therefore, w1 is chosen as the Tx rendezvous for B with receiver A.

Again, nodes C and D receive the RTR at w3 from A. Now, if D sends an ACK first, C pauses the back-off and resumes when node D completes its transmission, and vice versa. Therefore, w3 is selected as the Tx rendezvous for C and D with their receiver A. Finally, in subsequent cycles, node A only wakes up at w1 and w3, since these are the selected Rx rendezvous for HAS.

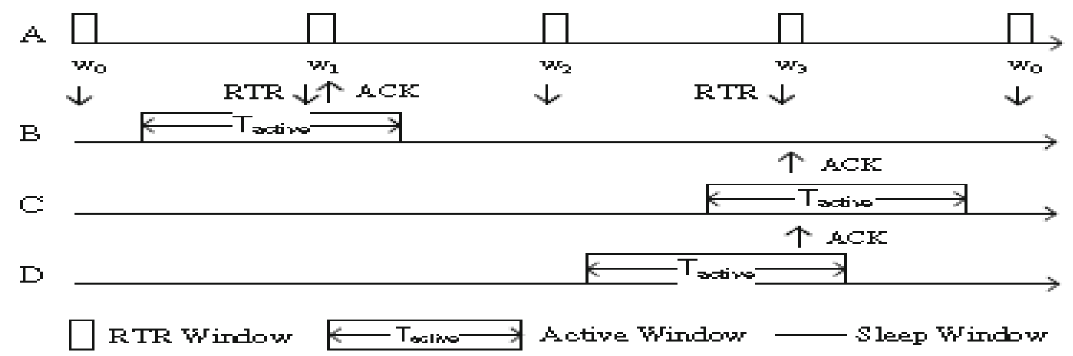


Figure 3.5. The operating mechanism of NW-MAC [94].

3.2.2.3 SNW-MAC

SNW-MAC [95] relies on a receiver-initiated approach (Figure 3.6), it is an asynchronous medium access control protocol proposed for data collection in a star network topology. The protocol leverages state-of-the-art wake-up receivers to minimize the energy needed to transmit a packet and make collisions impossible. The receiver initiates communication by sending a WuB containing the address of a specific sensor node, then listens to the channel to receive the data packet. The targeted sensor node is woken up by its WuRx ULP and begins sending the data packet.

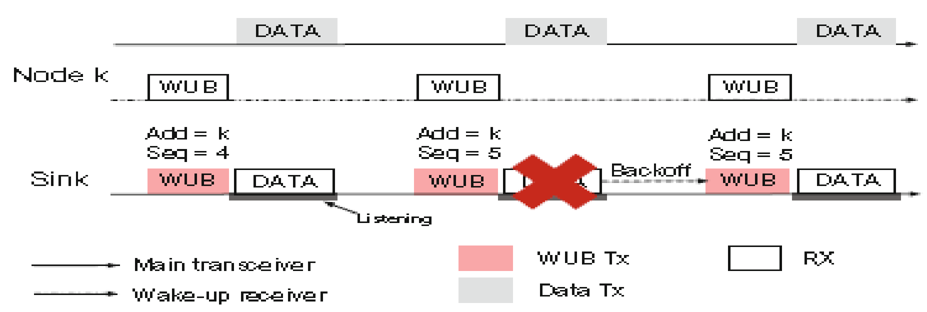


Figure 3.6. Transmission of packets using the **SNW-MAC** [95].

SNW-MAC (Star NetworkWuRx - MAC) has been proposed for energy-harvesting wireless sensor networks. The proposed solution relies on two complementary technologies, energy harvesting and ultra-low-power wake-up receivers, to increase the energy efficiency of wireless sensor networks and to enable energy neutrality. This new scheme is designed to be implemented on real hardware, and therefore only requires residual energy measurement at negligible overhead. Energy efficiency was assessed using a new metric introduced in this work, the energy utilization coefficient.

3.2.3 Adaptive Duty Cycling

Dynamic adaptation of the duty cycle can significantly improve network efficiency. A MAC protocol with adaptive duty cycles, in other words, which takes into account the topological structure and the traffic or resource availability conditions of the nodes, can use the available energy more efficiently. For example, nodes that are closer to the sink generally have more dispatch tasks than nodes that are farther away. Additionally, duty cycle adaptation is critical for wireless networks that are powered by ambient energy, such as solar energy, vibration, or temperature. The system objective for these networks is to operate in a context where the energy consumption is on average equivalent to the energy recovered. In this section, we present the most interesting receptor-initiated MAC protocols for dynamic duty cycle adaptation.

3.2.3.1 ERI-MAC

ERI-MAC [96] proposes a queuing system to modify the activity rate of the nodes according to the rate of energy harvesting because it assumes that the nodes can harvest energy in the environment. Time is divided into cycles and nodes that are receivers immediately broadcast a beacon frame after each wake-up (Figure 3.7), and then listen to the channel for a short time to determine if there is a potential frame.

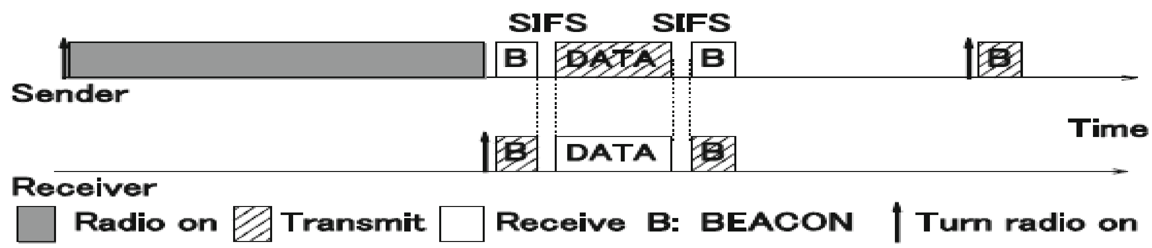


Figure 3.7. ERI-MAC: Mechanism transmission [96].

In addition, the senders listen to the channel to receive the beacon from the expected receiver. When a node receives the beacon from the expected receiver, it sends its pending frame after a short SIFS delay as shown in Figure 4.8. A successful transmission is complete when an acknowledgment beacon (ACK) arrives at the sender. This beacon also serves as a new availability announcement beacon. ERI-MAC also adopts the same collision detection and retransmission schemes as RI-MAC. When a collision occurs on the receiver, the receiver retransmits a new beacon, which includes a backoff. Each sender in a collision situation uses a random backoff period before retransmission to avoid collisions.

3.2.3.2 OD-MAC

With the ODMAC (On-Demand MAC) protocol [97], all sending nodes perform idle listening, waiting for a beacon from the receiver. As soon as a beacon is detected, all senders mine the medium using a CCA contention mechanism, with the duration of the CCA being randomly chosen by each end device. The node with the shortest CCA duration sends its data packet first since the medium is considered to be available. The other nodes wait for the end of this data transfer process (indicated by an ACK packet) before performing a new CCA. With ODMAC as shown in figure 3.8, the receiver does not go into sleep mode immediately after an ACK packet but rather waits for another potential DATA packet from a sender.

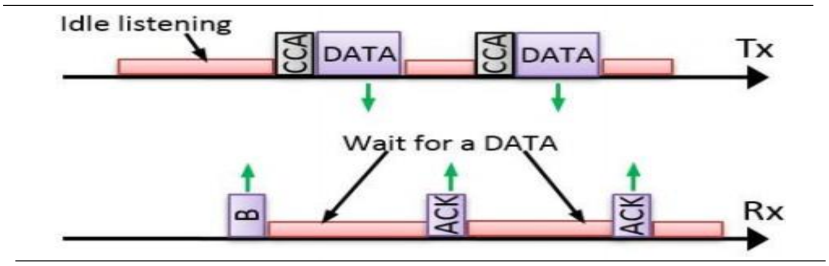


Figure 3.8. Mechanism general of OD-MAC protocol [97].

In contrast, OD-MAC was evaluated on a small-scale network with a redefined traffic model. In addition, OD-MAC does not handle contention or retransmission cases, which are very popular in WSNs. Therefore, there is a lack of reliable evidence in protocol evaluation.

3.2.3.3 LB-MAC

Unlike existing sensor network MAC protocols that typically focus on reducing power consumption and extending the lifetime of individual sensor nodes, LB-MAC [98] aims to extend the lifetime of the network by balancing the lifetime of nodes between neighboring sensors. LB-MAC as shown in figure 3.9 is lightweight and scalable because the required control information is only exchanged locally between neighbors. the receiving node wakes up every Tr interval to interact with potential senders. At the beginning of each wake-up, the sensor node can send a beacon message to the waiting senders to transmit packets. During the wake-up period, the sensor node checks channel activity for incoming messages. If a data packet is received, it responds with an ACK; otherwise, it goes to sleep.

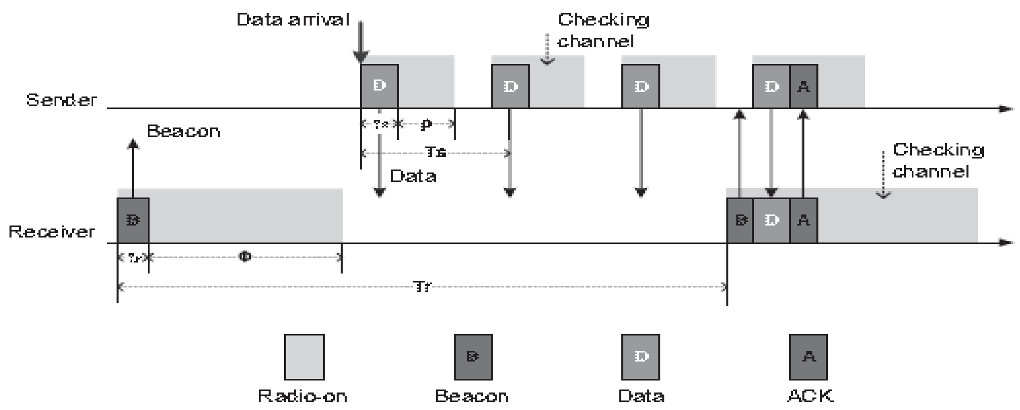


Figure 3.9. LB-MAC Communication Overview [98].

On the other hand, when a sensor node has a data packet to send, it wakes up every Ts interval to interact with the target receiver. At the start of each wake-up, the sensor node can immediately transmit the data packet1 or silently wait for the receiver beacon to start data transmission. During the idle listening period, if an ACK is received, the procedure terminates as the data packet was successfully delivered; if a beacon is received instead, it retransmits the data packet; if neither the ACK nor beacon is received, it goes to sleep and wakes up at the next Ts interval and to repeat the above procedure. Note that a sensor node can participate in network activity as a sender, a receiver, or both at the same time.

3.2.4 Quality of service

For wireless sensor networks, the very nature of the network, with nodes with very limited capacities, a very strong energy constraint, an unreliable radio medium, and a possibility of a node failure, makes the notions of guaranteed service or differentiated impossible to reach. The term QoS (an acronym for "Quality of Service") refers to the ability to provide a service (in particular a means of communication) that meets the requirements for response time and bandwidth [99]. Quality of Service, in the field of WSNs, is therefore usually a guarantee of the "best effort" type. Concerning the important QoS criteria managed at the level of the MAC layers of the WSNs, we are mainly interested in the packet loss rate and transmission delays. Finally, the extremely restrictive nature of the energy limitation makes this obligation to save energy a criterion in its own right of QoS although it is contradictory with the other QoS criteria. The optimization of the QoS thus always comes down to finding the best compromise, the optimal balance. Applied to packet-switched networks (networks based on the use of routers), the protocols that we are going to present in this part are proposals made concerning the ability to guarantee an acceptable level of quality of service.

3.2.4.1 MPQ-MAC

In the MPQ-MAC[100] protocol, a new technique is proposed to reduce the delay and power consumption in the network. It is a MAC protocol based on multi-priority, which provides QoS in WSNs, called MPQ-MAC protocol. The design process of this protocol uses the receiver-initiated approach and minimizes the delay of higher-priority packets while reducing power consumption. In the MPQ-MAC protocol, a new technique is proposed to reduce the delay priority packets and energy consumption in the network. In this technique, the receiving node manages the timeout based on packet priority. During the waiting time, the receiving node receives several beacons from transmission (Tx-Beacons) and selects a sender according to the priority of the packet. These communications are illustrated in figure 3.10, where SIFS (Short Interframe Space) indicates the time required to process a packet and change radio mode.

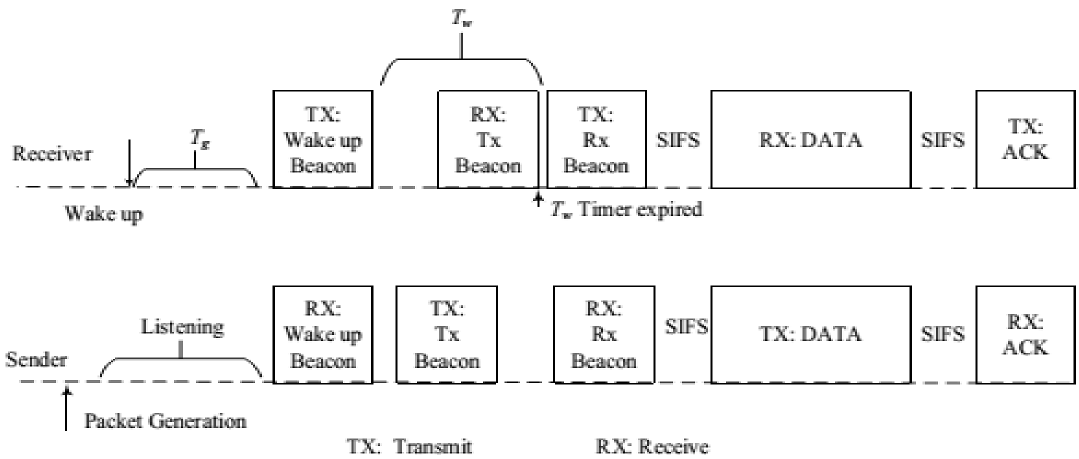


Figure 3.10. QAEE-MAC Communication Overview [100].

In this protocol, the receiving node wakes up periodically to receive the data packets from the sending nodes. After waking up, it listens to the medium for Tg (guarantee time), then it broadcasts a wake-up beacon to inform senders of its availability. After transmitting the wake-up beacon, it waits for Tw (waiting time) to receive all transmit beacons from senders. On the other side, the sending node sends a Tx-Beacon which contains the priority bit of the packet and the NAV (Network Allocation Vector) field. Then it waits for the Rx-Beacon of the receiving node. Meanwhile, the receiver which receives several Tx-Beacons with different priority levels selects a sender according to the highest priority level of the packet. Next, it broadcasts a receiver beacon (Rx-beacon) which contains the address of the selected sender. Upon receipt of the Rx beacon, the selected sending node transmits the data packet.

3.2.4.2 QPPD-MAC

The QPPD-MAC [101] supports multi-priority data packets and uses a new technique to shorten the delay by overriding the wait counter for the highest-priority data packets. In addition to this, it adjusts the receiver's duty cycle based on its current energy level under dynamic energy harvesting conditions to improve performance. The QPPD-MAC uses four priority degrees, but it can be extended to any number of priority degrees. Figure 3.11 provides an overview of QPPD-MAC communication. At the very beginning, the receiving node wakes up and immediately performs a clear channel assessment (CCA) to determine the state of the medium.

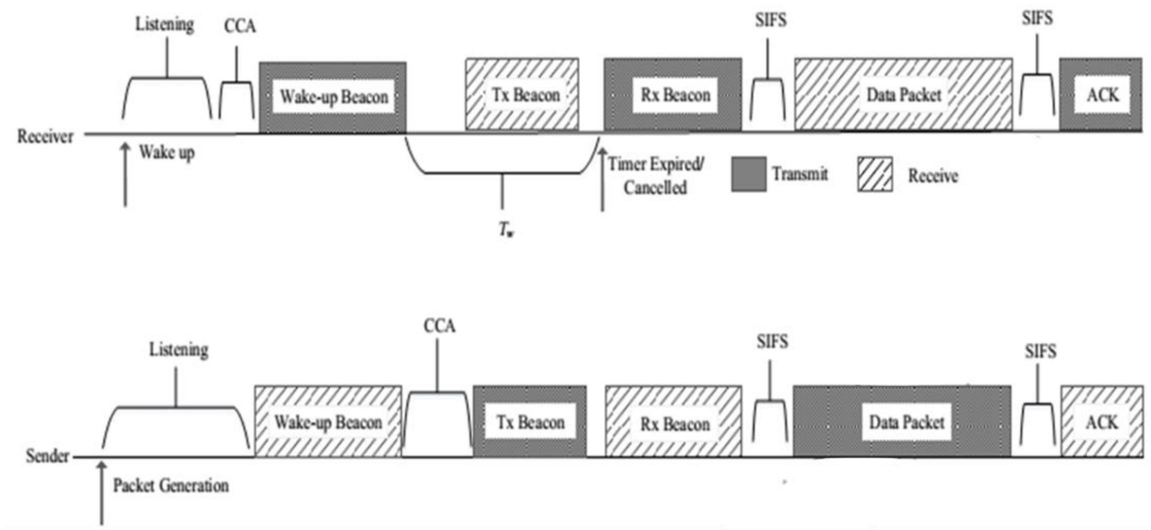


Figure 3.11. QPPD-MAC Communication Overview [101].

If the latter is free, it broadcasts a wake-up beacon, which indicates that it is ready to receive data packets. If the medium is busy, it goes to sleep. The wake-up beacon has two specific fields: a source address (SA) and an energy state (Es). The Es defines whether the receiver has enough energy to receive the data packets or not. In addition, the receiver in the QPPD-MAC protocol uses a technique to reduce the delay of the highest priority data packets, which also improves network energy efficiency.

4.2.4.3 QAEE-MAC

The QAEE-MAC protocol [102] uses the receiver-initiated transmission method and provides Quality of Service (QoS) service. Receiving nodes control their waking period based on their energy state. With this control of the wake-up period, the sending nodes stay in sleep mode longer and save energy. The receiving node determines which sender can send data first, as shown in figure 3.12 broadcasts a beacon frame to all transmitting nodes, in which the sender address and NAV value are contained. After receiving this receiver beacon frame, all the intended sender nodes go to sleep for some time except the sender node selected by the receiver node.

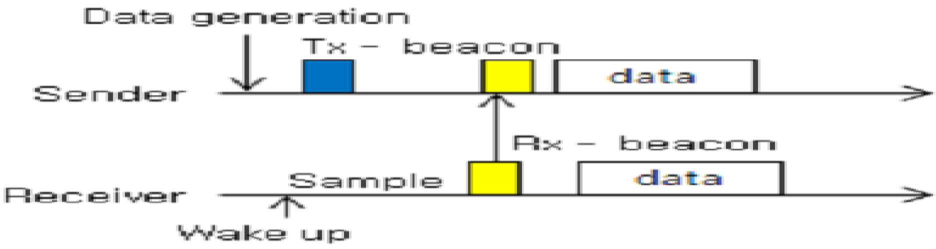


Figure 3.12. QAEE-MAC Communication Overview [102].

Different from RI-MAC, QAEE-MAC places senders in a sleep state for as long as possible until the current DATA sending node finishes sending its data. In addition, priority data can be transmitted faster than normal data. The QAEE-MAC protocol improves throughput and power efficiency under a wide range of traffic loads.

3.2.5 Multi-Channel extensions

The multi-channel context requires another function at the MAC level, which deals with the coordination and all that concerns the distribution of the channels. The use of multiple channels helps to overcome interference as well as improve overall network performance, it can significantly improve network throughput compared to single-channel communication. Thus, the exploitation of several channels increases the capacity of a link. Consequently, fewer collisions and shorter delays in networks with relatively high traffic. In this part, we will introduce the most well-known multi-channel MAC protocols which have been based on the working principle of asynchronous receiver-initiated receiver MAC protocols for wireless sensor networks.

3.2.5.1 DCM-MAC

DCM-MAC [103] was the first MAC protocol to introduce a multi-channel property into the asynchronous duty cycle mechanism. It handles issues such as reducing timing overhead, dynamically allocating multiple channels, and handling multi-channel hidden node issues. DCM-MAC uses a receiver-initiated mechanism and performs a cross-channel handshake to reserve a channel for data transmission. This protocol provides three types of channels: (i) a control channel (CC), (ii) multiple data channels (DC), and (iii) a broadcast channel (BC).

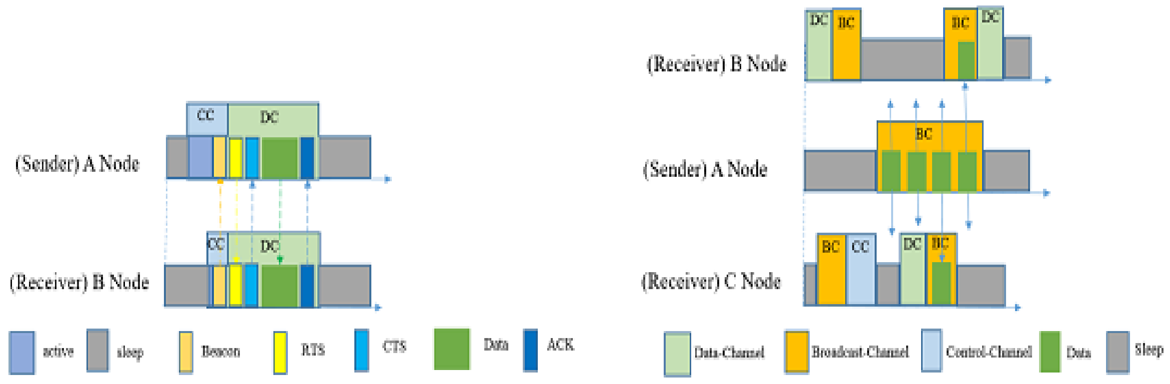


Figure 3.13. Packet transmission procedure of DCM-MAC in unicast (left) and broadcast (right) scenarios [103].

A sender that wants to transmit listens carefully to the CC to detect incoming beacons, called announcements (ANC) as shown in figure 3.13. When it is available, the receiver transmits an ANC on the CC and positions itself on the randomly chosen DC, and listens to an RTS (Ready To Send) frame. The sender, after receiving the ANC, also switches to the advertised channel. The communication then takes place as a typical RTS - CTS - DATA - ACK communication.

3.2.5.2 DURI-MAC

The Receiver Initiated-MAC (RI-MAC) Dual-channel Receiver Initiated MAC (DURI-MAC) [1O4] protocol for WSN used the dual-channel concept with a unique Clear Channel Assessment (CCA) time generator to exposing no hidden problem driver by transmitting an abusive beacon while transmitting data in progress, collision and also many retransmissions. The DURI-MAC protocol operates over two channels (Figure 3.14), one for control and one for data. The control channel performs all control packet transactions.

Figure 3.14. The operating principle of the DURI-MAC [104].

In contrast, the data channel is responsible for exchanging data packets. According to the DURI-MAC protocol, all nodes wake up regularly according to their schedule to check the received data frames intended for it. If a node wakes up, it broadcasts a beacon on the control channel to indicate that it is awake and ready to receive the data packet. Upon receipt of the beacon, the sender has produced a single CCA time and performs a CCA in the control channel to determine if the channel is busy or free. If the channel is free, the sender starts transmitting its data packet on the data channel. When the receiver starts to receive the data packet, it broadcasts its control channel busy beacon to avoid data collision.

3.2.5.3 EM-MAC

The EM-MAC protocol [105] (Efficient Multichannel MAC), addresses these challenges through the introduction of new mechanisms of receiver-initiated adaptive multichannel rendezvous and predictive wake-up scheduling. To reduce wireless collisions caused by nodes waking up at the same time and on the same channel, and to distribute traffic between available channels, a node in EM-MAC switches between channels it selects based on its pseudo-random channel program. Furthermore, each node of the EM-MAC system pseudo-randomly decides its wake-up times; a node's wake-up time is determined from the node's previous wake-up time plus its pseudo-randomly chosen current wake-up interval.

In figure 3.15, S has previously learned the time and information from R's pseudo-random number generator and can predict R's wake-up channels and wake-up times. By sending a message to R, S wakes up on the predicted wake-up channel of R just before the predicted wake-up time of R, thereby achieving power efficiency by minimizing idle listening

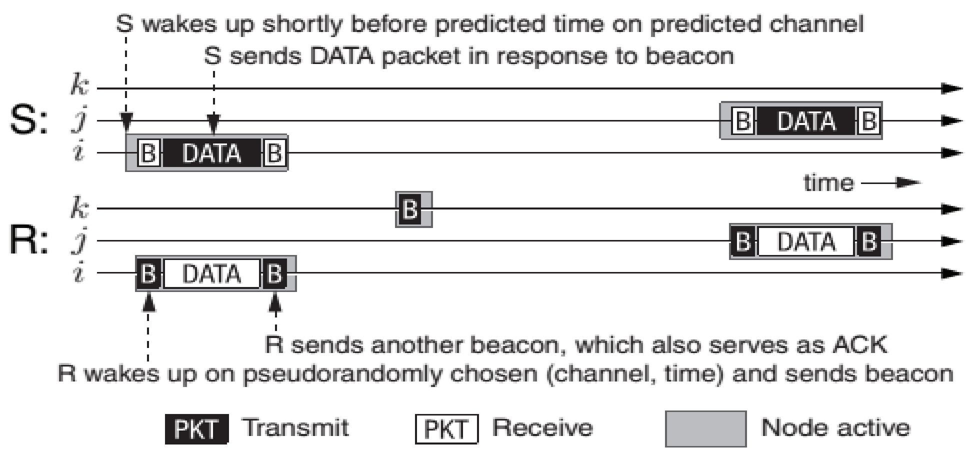


Figure 3.15. Protocol communication principle EM-MAC [105].

EM-MAC significantly improves wireless channel utilization and transmission efficiency while being resistant to wireless interference and jamming by allowing each node to dynamically optimize channel selection cords used based on the channel conditions it detects, without the need for dedicated channel commands.

3.2.6 Cooperative communication

3.2.6.1 EnRI-MAC

EnRI-MAC [106] is a receiver-initiated protocol that has been enhanced to support the different types of traffic in wireless sensing networks. The sender node cooperates with the other senders by producing a short signal to invoke the alert notification before switching to beacon receive mode. Power consumption in transmit mode is generally lower than in receive mode; therefore, the alert notification imposes no additional burden on the sending node. As shown in Figure 3.16, the sending node S2 instantaneously sends an alert notification before switching to beacon reception mode, while no node receives the notification. When the transmitting node S1 wakes up and sends an alert notification, the radio S2 is already in receive mode; in this case, S2 receives an alert notification from S1. The transmitting node (S3) which has not received an alert notification immediately provides data.

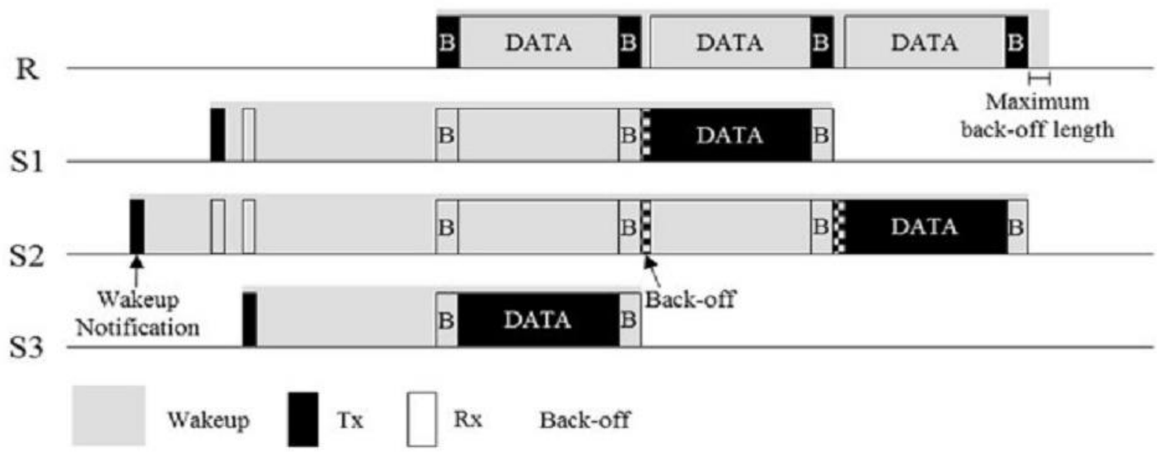


Figure 3.16. EnRI-MAC protocol communication procedure [106].

RI-MAC can significantly reduce the probability of collision compared to RI-MAC, which is especially related to convergent transmission. EnRI-MAC can provide better energy efficiency for each sensor node. This performance improvement should become increasingly important as the amounts and types of data traffic increase, and the number of sensor nodes in the network increases.

3.2.6.2 ASYM-MAC

The ASYM-MAC[107] "Asymmetric MAC" protocol works according to the principle of RI-MAC while taking into account the duty cycle. It combines the two MAC protocols, sender-initiated and receiver-initiated. By default, it operates in receiver-initiated mode. When the sender cannot get the beacon from its receiver, it waits for time "τ" and then enters the sender-initiated mode where it sends its data after a long preamble as shown in figure 3.17(a). ASYM-MAC has two operating modes: R-mode and T-mode. R-mode and T-mode are the two most common operating modes. The site R mode is the default mode in which a receiver-initiated MAC protocol is used. ASYM-MAC switches to T mode when this switching is triggered by a clock that occurs after a certain time "τ" has elapsed without reception of the polling packet. In T mode, the sender sends a preamble to inform the receiver of the current data transmission. The receiver verifies the potential transmission of the sender's preamble packets by a channel occupancy test (CCA clear channel assessment). As soon as it picks up the signal of the current transmission of the preamble packets, it also receives data from the sender.

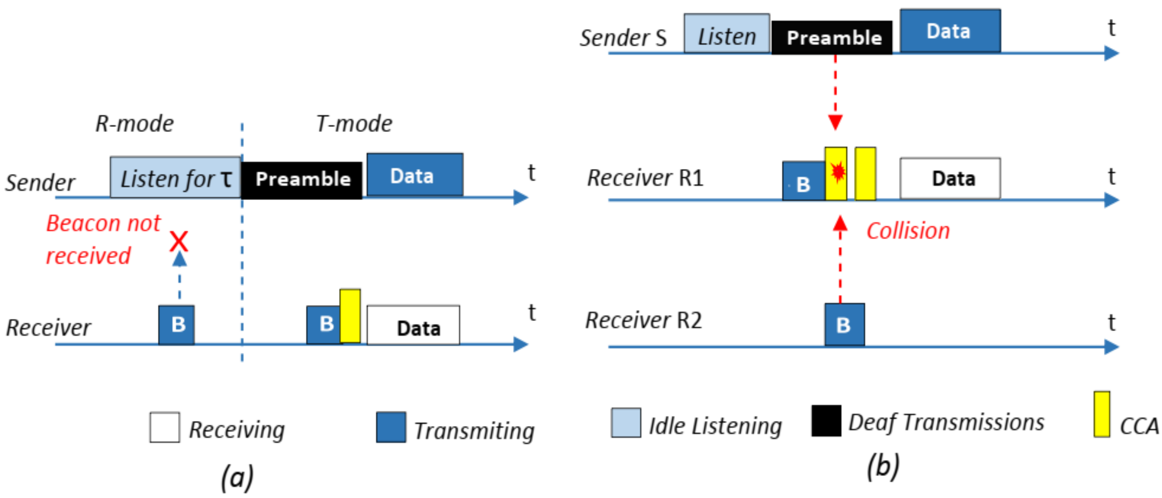


Figure 3.17. ASYM-MAC: (a) Operation, (b) Collision avoidance [107]

ASYM-MAC handles a potential collision between a preamble and a probe packet. As follows: Consider a scenario of three nodes designated by a sender S, receiver R1, and receiver R2 (see Figure 3.17 (b)). If the R2 receiver detects packet is sent just after the sender preamble is transmitted, the receiver R1 will not be able to detect the preamble during the short CCA period due to the collision of the sender preamble packet and the R2 receiver detection packet. To solve this problem, when a collision occurs, a receiver performs another CCA check, increasing the chances of receiving the preamble.

3.2.6.3 COASYM-MAC

COASYM-MAC [108] is a new asynchronous medium access control protocol based on cooperative communication, it is proposed to minimize the negative effects of asymmetric links and meet the quality of service needs. Design of a tree technique [35] to solve the asymmetry of the links between the sender and the receiver, the receiver and the sender, or both. The COASYM-MAC protocol Form their a proposed tree (Figure 3.18), develops an efficient wake-up scheduling algorithm for each node by which the most efficient node among the sender's neighbors wakes up early to send its label to elect an effective helper node.

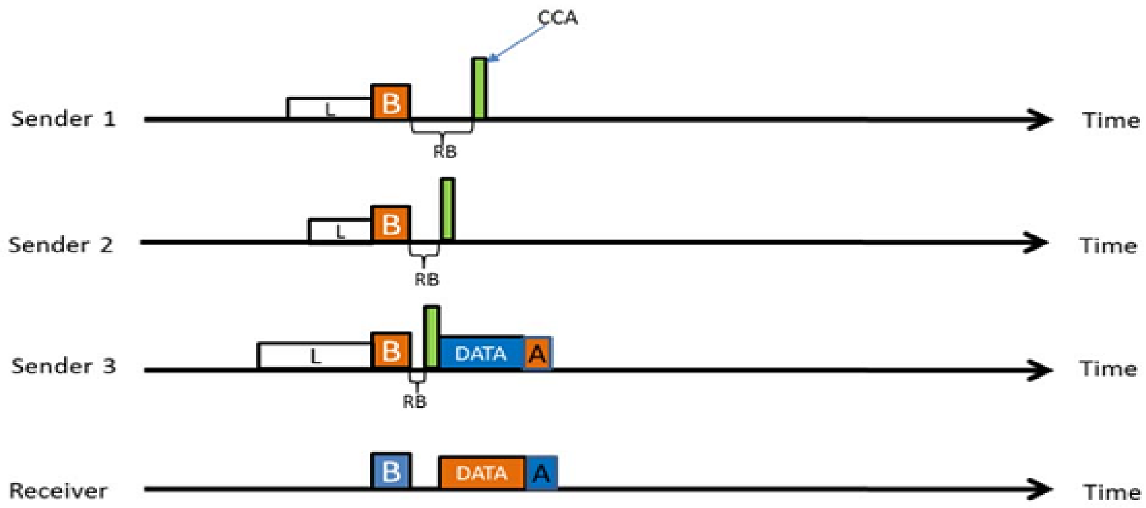


Figure 3.18. COASYM-MAC: Symmetric link situation. [108]

3.3 How to choose a protocol category?

Sensor networks are first characterized by the reduced means available to their nodes. For some applications, wireless sensor network techniques may be inappropriately used due to the limited battery life of the nodes that make up the network. It is therefore essential to bring this life to its maximum while meeting quality of service requirements and minimizing energy consumption to widen the field of application of wireless sensor networks. The MAC protocol must be configured according to the topological structure of the network, the energy-emitting nodes and the characteristics and requirements of the application executed.

The protocols studied in this chapter identify mechanisms and features that can be added to the receiver-initiated MAC protocol to improve its performance, taking into account the functionalities involved, the properties (specificity) of an application can be related to the functions introduced with different protocols to optimize overall network performance.

In general, receiver-initiated MAC protocols save power on the sender side compared to sender-initiated protocols. However, periodic beacon loads add overhead in control messages and increase contention for media access, which increases node power consumption.

3.4 Conclusion

In this chapter, we have presented a classification of receiver-initiated MAC protocols with a common goal of minimizing energy overhead while trying to reduce idle listening time and improve collision avoidance techniques. This overview also reveals the diversity of protocols and the remarkable implementation of different policies in power management schemes. In the last chapter, we will propose a receiver initiated MAC protocol, by comparing its reliability with the RI-MAC protocol through a simulation.

CHAPTER 4

COSFI-RIMAC: A Cooperative Short Frame Identifier Receiver Initiated MAC Protocol

4.1 Introduction

In the previous chapter, a classification of the MAC receiver-initiated protocols allowed us to see the mode of operation of each protocol studied, and to conclude whether these protocols have a huge or weak idle listening when data transmission. Thus, we concluded whether these protocols use a collision avoidance technique or not, and how each protocol manages collisions in case of conflict. Therefore, this study has allowed us to propose in this chapter, a Receiver-Initiated MAC protocol, with very low idle listening, and for collision management, it uses a technique of collision resolution. In what follows, we will present our contribution, which consists in proposing a MAC Receiver Initiated protocol.

4.2 Presentation of the COSFI-RIMAC protocol

In this thesis, we propose a new cooperative asynchronous receiver-initiated MAC protocol called Cooperative Short Frame Identifer Receiver Initiated MAC protocol (COSFI-RIMAC)**[16].** Our main contribution is to reduce collision and idle listening, and thus energy consumption. Our scheme is based on RI-MAC. We ofer two improvements: First, the sender's nodes listen to the channel independently during a short period and wait for a Short Frame Identifer (SFI) from a potential receiver, if it does not receive it goes back to sleep mode in a dynamic interval which minimizes idle listening enormously. The second improvement, introducing cooperation between the sender's nodes, which minimizes collisions. This protocol also introduces a dynamic adaptation mechanism of the service cycle, which aims to converge the waking and waking hours to data trafc conditions.

The objectives of the COSFI-RIMAC protocol are mentioned as follows:

- Minimize idle listening power consumption.
- Cooperation between sender nodes.
- Reduce the number of collisions.
- Reduce the number of transmissions,
- Reduce energy consumption.

4.3 Protocol Design

The COSFI-RIMAC protocol is a contention, asynchronous, duty cycle, and receiver-initiated MAC protocol based on the following main axes:

- The duty cycle is not fixed, but dynamic.
- The receiver does not immediately go into sleep mode after an ACK packet

but rather waits for another.

- Potential DATA packet from a sender.
- The SFI frame contains more information to inform the sender when the receiver wakes up.

Now we describe our proposed protocol COSFI-RIMAC in detail. Table 4.1 describes the notations used in this document.

Table 4.1. Describes the notations used in COSFI-RIMAC.

Notation	Description
SFI	Short frame identifier
RI_{SFI}	Receiver interval to send SFI
RWI_{SFI}	Receiver wakeup interval to send SFI
RT_{sleep}	Receiver time sleep, dynamic sleep time between awakenings of a receiver to send SFI
RT_{sleep1}	RT sleep initial, the time RT between sending SFI_1 and SFI_2
RI_{sleep}	Receiver interval sleep
$RTra_{sleep}$	Random RT_{sleep}
AsynRI	Asynchronous receiver interval
Ω_{sleep}	The sleep duration between sending the last possible SFI and before the receiver wakes up
RT_{idle}	Receiver time idle, receiver idle listening to the channel for short periods
ST_{idle}	Sender time idle
ST_{sleep}	Sender time sleep, the dynamic time between idle of a sender
ST_{sleep1}	STsleep initial, the time ST between ST_{idle1} and ST_{idle2}
$STra_{sleep}$	Random ST_{sleep}
SI_{idle}	Sender interval idle
SI_{sleep}	Sender interval sleep
AsynSI	Asynchronous sender interval
$STra_{sleep}$	Random ST_{sleep}
$STCO_{sleep}$	Sender time cooperation sleep
SWI_{coop}	Receiver wakeup interval cooperation
SW_{syn}	Sender wake-up synch
$AppR_{sleep}$	Appointment receiver sleep
$AppRWI_{data}$	Appointment receiver wakeup interval data
$AppSWI_{data}$	Appointment sender wake-up interval data
$AppS_{sleep}$	Appointment sender sleep
$SynWI_{data}$	Synchronous wake-up interval DATA
T_B	The time required to send a beacon B
T_{data}	The time required to send a data packet
T_{ACK}	The time required to send ACK

4.3.1 Operation of the COSFI-RIMAC protocol

COSFI-RIMAC improves RI-MAC by reducing the energy wastage of the sender when it waits for a receiver to wake up. As seen in Figures 4.1,4.2,4.3 and 4.4 the COSFI-RIMAC, has three phases: Asynchronous cooperation wake-up (Asynch Coop-Wake-up), synchronous wake-up data transmission (Synch Wake-up Data Transmission), and the appointment wake-up data transmission phases.

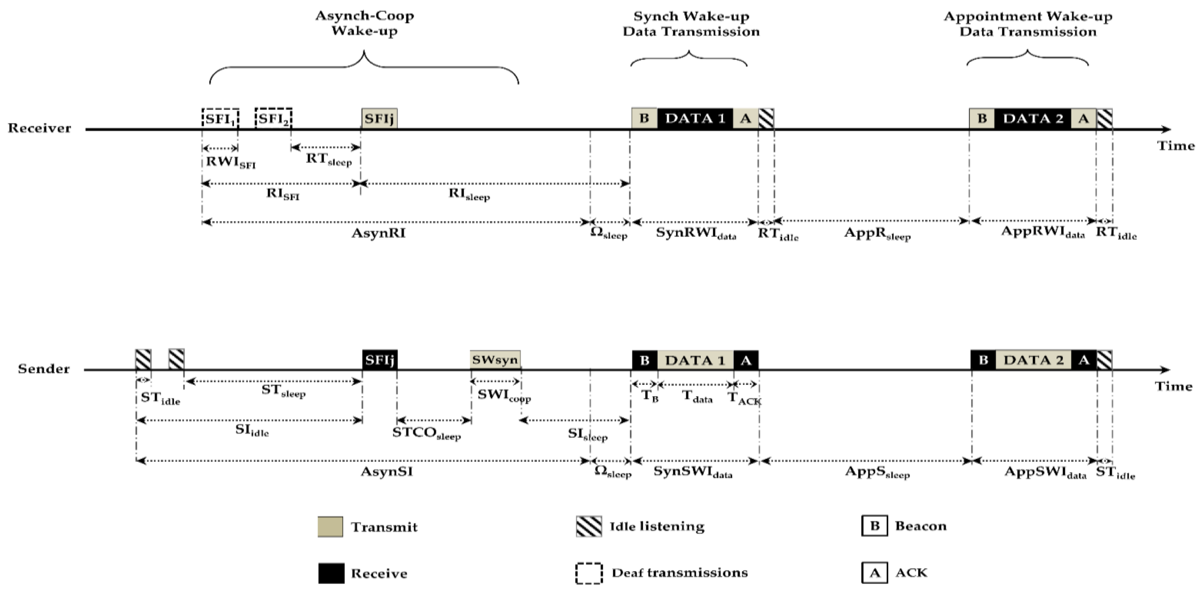


Figure 4 .1. COSFI-RIMAC Protocol Operation Process

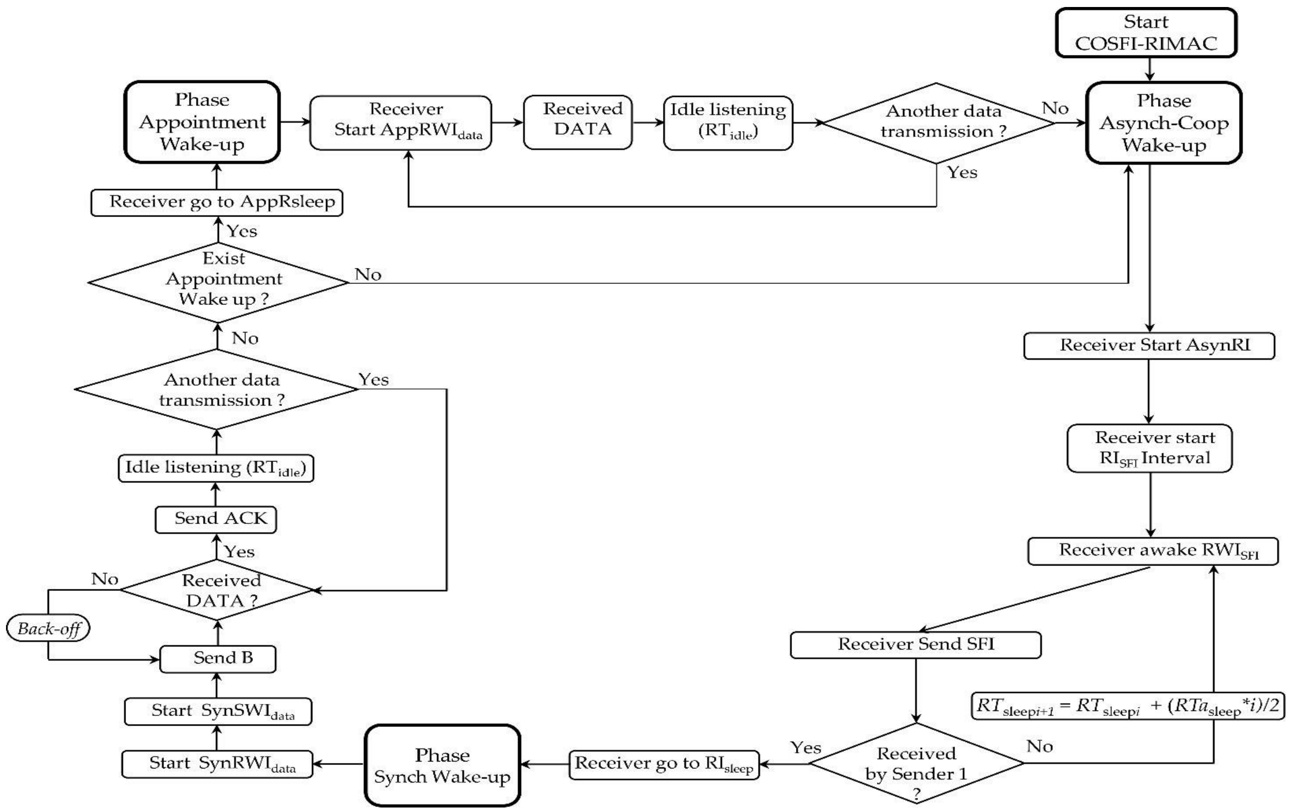


Figure 4.2. COSFI-RIMAC operating diagram, RECEIVER SIDE.

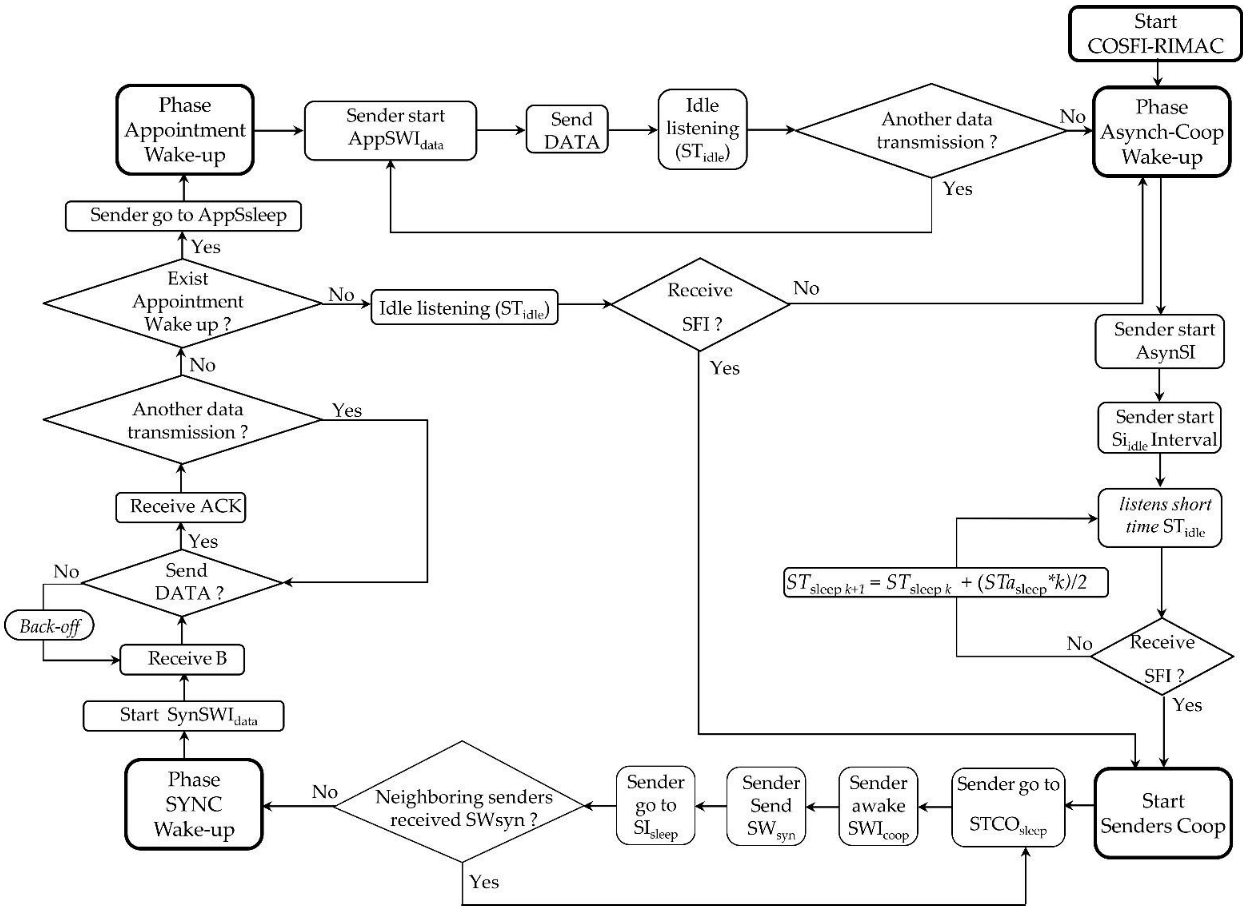


Figure 4.3 COSFI-RIMAC operating diagram, SENDER SIDE.

4.3.1.1 Phase Asynch-Coop Wake-up

In COSFI-RIMAC at the start, each node has its duty cycle, during the asynchronous wake-up period AsynRISFI, the receiver makes small wake-ups RWISFI between the dynamic intervals RTsleep to send short SFI frames, each SFI contains the information: time of receiver wake-up and receiver address.

The sending of the next SFI frame is tied to the previous TRsleep time interval and calculated as shown in the following equation (1):

$$\mathbf{RT_{sleepj+1}} = \mathrm{RT_{sleepj}} + \mathbf{(RTa_{sleep}*j)/2} \qquad \mathbf{(1)}$$

In the Asynch wake-up phase, the receivers perform a small AsynRWI wake-up, then they remain in sleep mode AsynRIsleep most of the time as shown in equations (2.3)

$$\begin{cases} \mathbf{AsynRWI = (\,RWI_{SFI}\,)} & \mathbf{(2)} \\ \mathbf{AsynRI_{sleep} = (\,RT_{sleep}\,) + RI_{sleep}} & \end{cases}$$

$$\mathbf{AsynRI_{sleep} = (AsynRI_{SFI} - AsynRWI) + \Omega_{sleep}} \quad (3)$$

If a sender receives an SFI_j from the expected receiver, it will synchronize its data transmission wake-up. After the receiver goes into RI_{sleep} sleep mode to save power. When a node has a frame to send DATA, it listens to the channel for short time ST_{idle} and waits for an SFIj from a potential receiver, if it does not receive it returns to sleep mode in a dynamic interval STsleep calculated as shown in Equation (4):

$$\begin{cases} \mathbf{k = 1 \text{ a } max=n-1} \\ \mathbf{STsleepk+1= STsleepk + (STasleep*k)/2\ ;} \end{cases} \quad (4)$$

The transmitting node makes a small SWICOOP wake-up to cooperate with their neighboring senders by sending a SWsyn frame after the STCOsleep interval calculate as shown in equation (5), after which it also goes into SIsleep sleep mode, to save energy.

$$\mathbf{STCOsleep= STsleepj\text{-}1 + (STasleep*j)} \quad (5)$$

In this phase as indicated in algorithm 1, the COSFI-RIMAC protocol minimizes the idle listening of the sender nodes (AsynSIidle) which only becomes the sum of the ST_{idle}, as indicated in equations (6), which gives the majority of the senders time to go into sleep mode $AsynSI_{sleep}$ as shown in equation (7).

$$\mathbf{AsynSTidle= (STidle)} \quad (6)$$

$$\mathbf{AsynSIsleep= (STsleep) + STCOsleep +SIsleep} \quad (7)$$

A formal description of the Phase Asynch-Coop Wake-up is presented in Algorithm 1.

Algorithm 1 Asynch-Coop Wake-up

Begin of Asynch-Coop Wake-up receiver
 Begin of ASYNC Wake up of the receiver
  Initialization : i=1 ; k=1 ; $ST_{\mathbf{sleep\ 1}}$;$RT_{\mathbf{sleep\ 1}}$
  Sender launch Asynch wakeup interval AsynSI
  Sender start SI_{idle} *interval*
  Sender S1 listens to the channel for short time STidle
  Receiver R1 launch Asynch wakeup interval AsynRI
  Receiver launch RI_{SFI} *Interval*
  Receiver R1 wakeup RWI_{SFI}
  Receiver R1 send SFI 1
  If *SFI* $_1$ *is not Received by Sender S1* ***then***
  Initial sleep Sender $ST_{sleep\ 1}$ *between* ST_{idle1} *and* ST_{idle2}
  Initial sleep Receiver $Rt_{sleep\ 1}$ *between* $RWI_{SFI\ 1}$ *and* $RWI_{SFI\ 2}$
  Endif
  DO
  $RT_{\mathbf{sleep}i+1} = RT_{\mathbf{sleep}i} + (RTa_{\mathbf{sleep}}*i)/2$
  $ST_{\mathbf{sleep}k+1} = ST_{\mathbf{sleep}k} + (STa_{\mathbf{sleep}}*k)/2$
Receiver sends SFI_i
  UNTIL *(Sender Receive SFI) OR (end of* RI_{SFI}*)*
Sender S1 synchronizes their awake with receiver R1
The receiver goes to sleep RI_{sleep} *Interval*
 End of ASYNC Wake up of the receiver
Begin Coop senders
  *Calculate STCOsleep= STsleep j-1 + (STasleep*j)*
  Sender S1 goes to sleep $STCO_{sleep}$
  while *(sender* S_i *receive Swsyn)and (not the end of* SI_{SFI}*)* ***do***
    Sender S_i *wake up* SWI_{COOP}
    Sender Si Send Swsyni to other neighboring senders
    Sender Si switches to SI_{sleep} *sleep mode,*
  End while
 End coop senders
End of Asynch-Coop Wake-up receiver

4.3.1.2 Phase Synch Wake-up Data Transmission

This phase consists of the synchronization between nodes (transmitter, receiver) for the transmission of data. In this synchronous communication cycle $SynWI_{data}$, the sender node which receives an SFI wakes up (a synchronized wake-up) simultaneously with the receiver node, this time the sender starts sending this data immediately, as soon as the receiver sends the short Beacon signal indicating their awake; The time required to send the data as shown in equation (8).

$$\mathbf{SynWI}_{data} = T_B + T_{data} + T_{ACK} \quad (8)$$

Once the receiver receives the data, it sends an ACK indicating that the data was received successfully. After the transmitted beacon, the receiver R1 waits for another transmission from the sender S1 and then goes into the $AppR_{sleep}$ state. If there is a Wake-up appointment, the sender S1 goes into the $AppS_{sleep}$ state, otherwise, it waits for an SFI from another receiver R2 to synchronize its wake-up and goes into SYNC Wake up data transmission phase.

A formal description of the Phase SYNC Wakes up data transmission is presented in Algorithm 2.

Algorithm 2 SYNC Wake up data transmission

```
Begin of SYNC Wake up data transmission
 Launch of the SynWI_data interval
 Wakeup of receiver R1 and sender S1
 Sender S1 wait in T_B for beacon B
if sender S1 receives a beacon B from receiver R1 then
   Sender S1 sends a DATA in T_data to receiver R1
End if
while collision do
   Receiver R1 Calculate random Back off
   Receiver R1 send beacon B_backoff
   Sender S1 receive B_backoff
   Sender S1 sends a DATA after back off period to receiver R1
end while
if a data packet is received from receiver R1 then
  Send ACK in T_ACK to sender S1
end if
the receiver R1 waits for another transmission of sender S1
while sender S1 there is another data to transmit do
   Sender S1 sends a DATA i in T_data to receiver R1
   Receiver R1 receive DATA i
   Receiver R1 sends ACK in T_ACK to sender S1
end while
The receiver goes to AppRsleep state
if not exist Appointment Wake up then
 Sender S1 waits for an SFI for another receiver R2
 if Sender S1receive SFI for another receiver R2 then
Sender S1 synchronizes their awake with the receiver R2
 Sender S1 go to SYNC Wake up data transmission phase,
 else sender S1 goes to AppSsleep state
end if
end if
End of end of SYNC Wake up data transmission
```

4.3.1.3 Phase Appointment Wake-up Data Transmission

In the previous phase, the response ACK indicates the next wake-up of nodes as an appointment Wake-up. In this phase, the sender S1 sends to DATA after the reception of a beacon from the receiver R1. The sender sends the next DATA (if it exists) after each ACK. If there is the next communication, the nodes pass another appointment Wake-up. Otherwise, the sender S1 waits for an SFI for another receiver R2 to synchronize its wake-up and go to the SYNC wake-up data transmission phase, otherwise go to the Asynch-Coop wake-up phase.

A formal description of the Phase Appointment Wake-up data transmission is presented in Algorithm 3.

Algorithm 3 Appointment Wake up data transmission

Begin of appointment Wake up data transmission
Receiver Launch AppRWI$_{data}$ Interval
Receiver Launch AppRWI$_{data}$ Interval
Sender S1 receives a beacon from the receiver R1
Sender S1 sends a DATA in T_{data} to receiver R1
Receiver R1 receives DATA
Receiver R1 sends ACK
Receiver wait for another data for sender S1
Sender S1 receives ACK
while** sender S1 there is data to be transmitted to R1 **do
    Sender S1 sends a DATA to receiver R1
    Receiver R1 receives DATA
    Receiver R1 sends ACK to sender S1
end while
if** there is another Appointment Wake up data transmission **then
    go to Appointment Wake data transmission phase,
***else** sender S1 **waits for an SFI$_j$ for another** receiver R_j*
    if sender S1** receive SFI$_j$ **then
        sender S1 synchronize their wake-up with the receiver R_j
        sender S1 go to SYNC Wake up data transmission phase
    end if
***else** go to Asynch-Coop Wake-up phase.*
Endif
end of Appointment Wake up data transmission

4.3.2 *Cooperation and Collision settlement*

The RI-MAC protocol is more vulnerable to collisions because the senders immediately transmit the data after receiving a Beacon to the same receiver, which is also a source of wasted energy. As seen in Figure 5, the scenario below shows the collision avoidance technique used by our COSFI-RIMAC protocol.

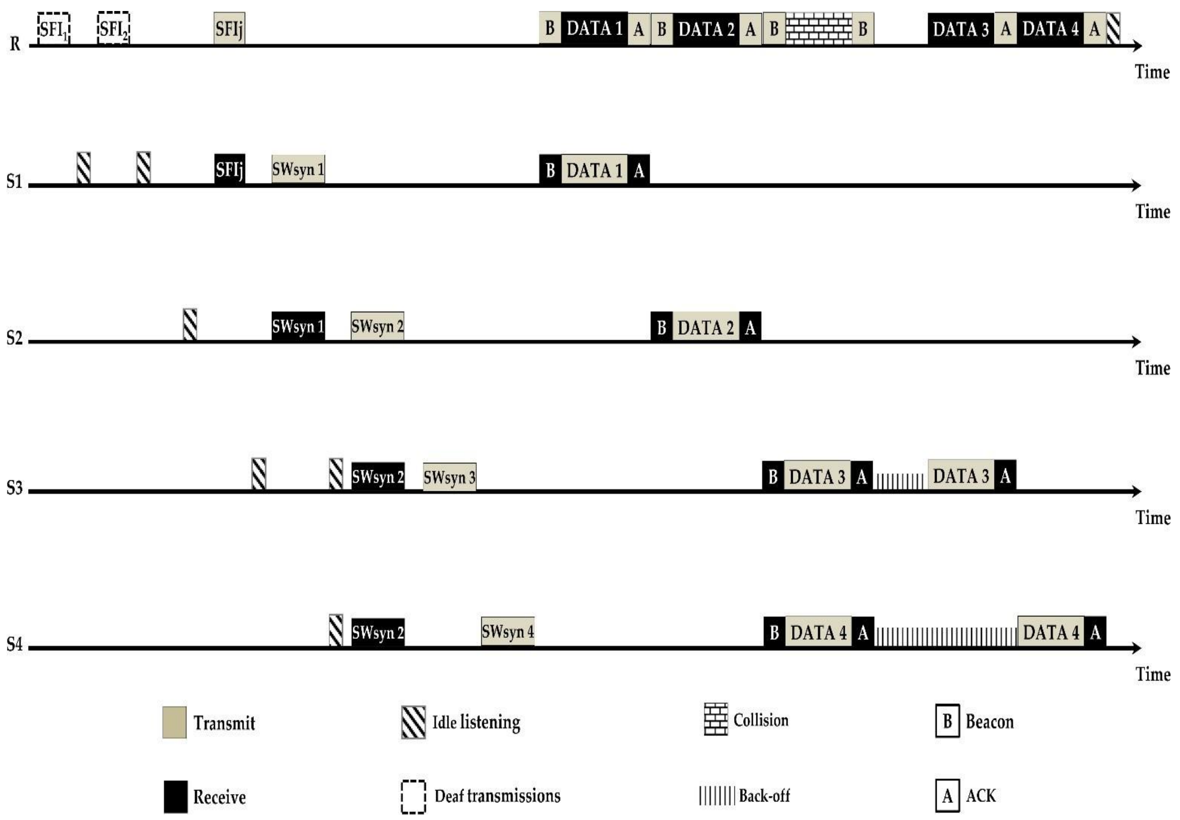


Figure 4.4. COSFI-RIMAC: Cooperation and solving the problem of collisions.

When the sender node S1 receives an SFI, it makes a small SWICOOP wake-up to cooperate with their neighbors after SWsleep by sending a SWsyn 1 frame which contains the information of the SFI and wake-up time and SynWIdata of S1 and it goes into a sleep state. The sender S2 is already in the SWI_{SFI} period, in this case, the S2 receives SWsyn 1, it synchronizes its data transmission after S1, in the same cooperation mechanism S2 informs their neighbors. In our example, the RI-MAC protocol case, all the sending nodes (S1, S2, S3, and S4) perform a back-off, on the other hand in the COSFI -RIMAC only S3 and S4 which perform a back-off which minimizes the number of collisions and therefore data retransmissions, which reduces power consumption and increases the delivery rate of data packets.

4.4 Performance Evaluation of COSFI-RIMAC

4.5.1 Simulation environment

In this section, we evaluate and compare our SFI-RIMAC proposals (our proposal without cooperation) and our final COSFI-RIMAC protocol (SFI-RIMAC plus cooperation) with the RI-MAC. These simulations are carried out using the NS-2 network simulator by performing different scenarios. **Table 4.2** illustrates the simulation parameters for COSFI-RIMAC.

The simulation lasted 200 seconds, during which 10, 20, 30, 40, and 50 nodes were randomly deployed in an area of 550 square meters.

Table 4.2 COSFI-RIMAC parameters for simulation

Simulation Parameter	
parameter	**Value**
MAC Protocol	RIMAC, SFI-RIMAC, COSFI-RIMAC
Node deployment aria	550 m X 550 m
Simulation Time	200s
Number of nodes	10, 20, 30, 40,50
package size	2000 Byte
SFI size	12 Byte
B size	12 Byte
ACK size	12 Byte
Transmission energy	0.0312 w
Receiving energy	0.0222w
The time to send B	T_B =1.0 ms
The time to send ACK.	T_{ACK} =1.0 ms
The time to send SFI	RWI_{SFI}=1.0 ms
The time to send a data	T_{data} = 2.5 ms
Sender Time idle listening	ST_{idle}=0.5 ms
Random Sender Time sleep	$STra_{sleep}$=Random[0.05s , 0.1s]
Random Receiver Time sleep	$RTra_{sleep}$ =Random[0.05s , 0.1s]
Sender Time sleep initially	ST_{sleep1}=0.3s
Receiver Time sleep initially	RT_{sleep1}=0.2s
The sleep duration Ω	Ω=0,5 s

4.5.2 Result and discussion

Energy consumption is often presented in joules/bits and is calculated as the ratio of the total energy consumed by the total number of data bits transmitted. The smaller this value, the more efficient the protocol will be. Figure 4.5 shows the results of energy consumption by the number of nodes. When the number of nodes increases, the power consumption increases in COSFI-RIMAC, SFI-RIMAC, and RI-MAC as the number of retransmission increases. In addition, our proposal has reduced power consumption compared to RI-MAC, as it reduces idle listening time and minimizes the number of collisions.

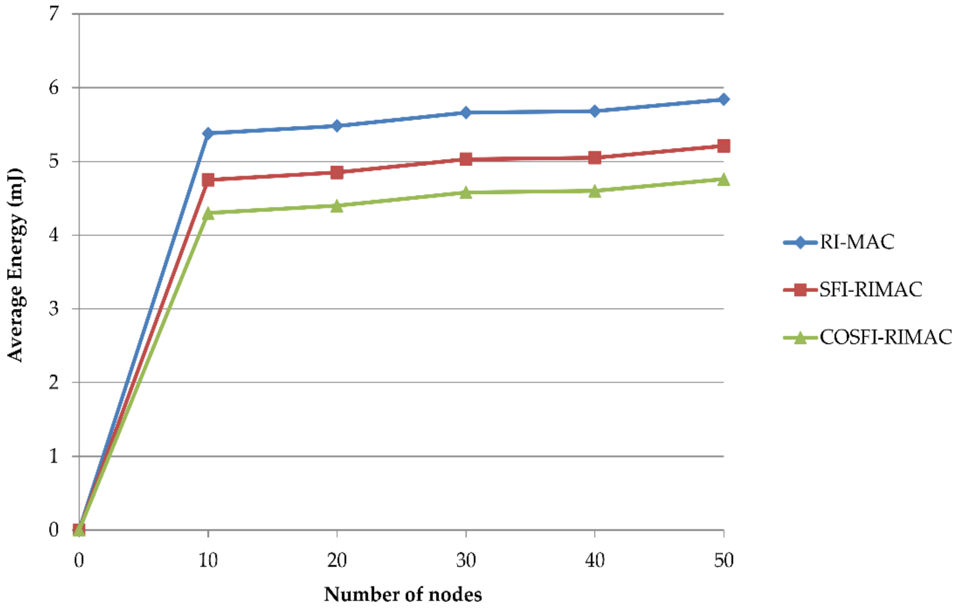


Figure 4.5. Average Energy of different MAC protocols (RI-MAC, SFI-RIMAC, COSFI-RIMAC)

In the RI-MAC protocol, which is the main source of energy consumption, the senders have to listen unnecessarily for a significant amount of time (a few seconds), while a sender's data transaction may take a few milliseconds (ms). The energy consumption of this unnecessary listening affects the energy performance of the RI-MAC protocol. The SFI-RIMAC protocol minimizes idle listening for the nodes (senders and receivers) which we divide by small periods, thus avoiding early wake-up (SFI). Thus, the COSFI-RIMAC protocol minimizes the overhead in receiver-initiated MAC protocols caused by the collision between the nodes, which is the cause of the communication delay in receiver-initiated protocols. Our proposed COSFI-RIMAC reduces collisions between nodes using a collision avoidance mechanism based on cooperation between the sender's nodes, which minimizes the energy associated with data retransmission.

The average end-to-end delay is a measure of the delay between the sending of the message by the source node and its reception by the receiving node. Figure 4.6 shows the end-to-end average delay results. Compared to RI-MAC, synchronization between sender and receiver minimizes average end-to-end delays in SFI-RIMAC and COSFI-RIMAC protocols, and cooperation between senders improves COSFI-RIMAC.

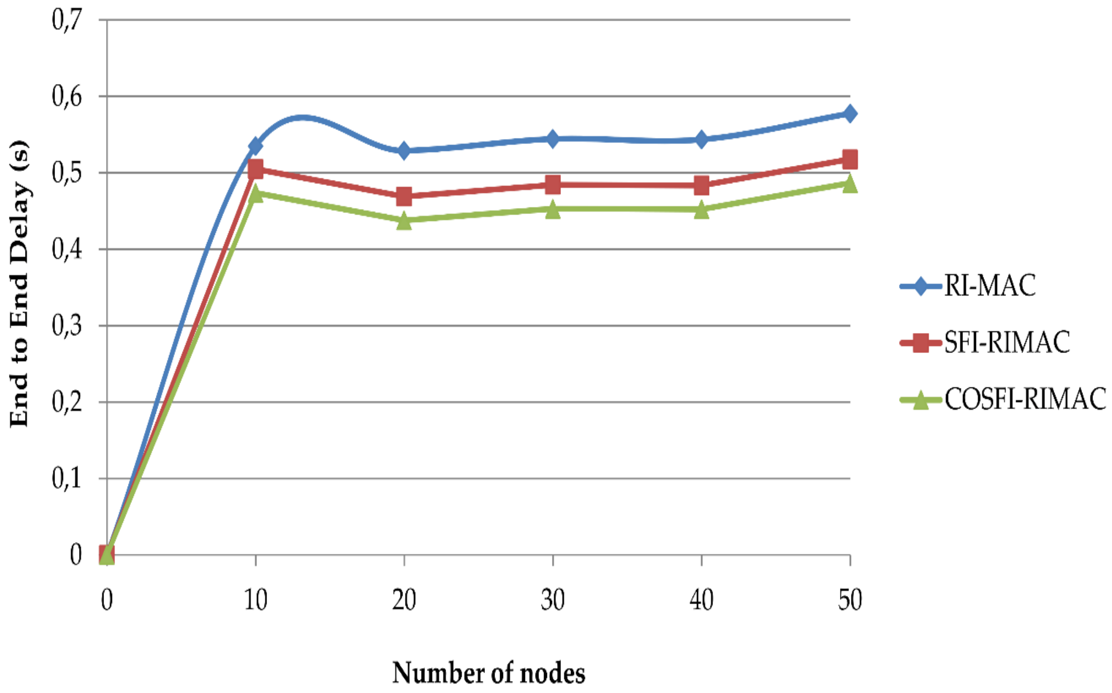


Figure 4.6. End to End Delay of different MAC protocols (RI-MAC, SFI-RIMAC, COSFI-RIMAC).

Compared to RI-MAC, SFI-RIMAC is focused on coordination between the receiver and sender sensor nodes for the benefit of the network as a whole. The basic idea is that neighboring nodes adjust their MAC layer behaviors together only when there is data communication between them via the following adjustable parameters: wake-up period and channel scan period on the receiver side in the asynchronous phase, and transmission period in both phases (*SYNC Wake up data transmission and appointment Wake-up data transmission*) that will also minimize the end-to-end delay. In our COSFI-MAC protocol, the cooperation between sending nodes reduces the number of collisions and therefore minimizes the number of data retransmissions, which reduces the end-to-end delay.

Figure 4.7 shows the number of packets received; our SFI-RIMAC and COSFI-RIMAC proposals minimize the number of collisions that gives more data transformation than in the RIMAC protocol.

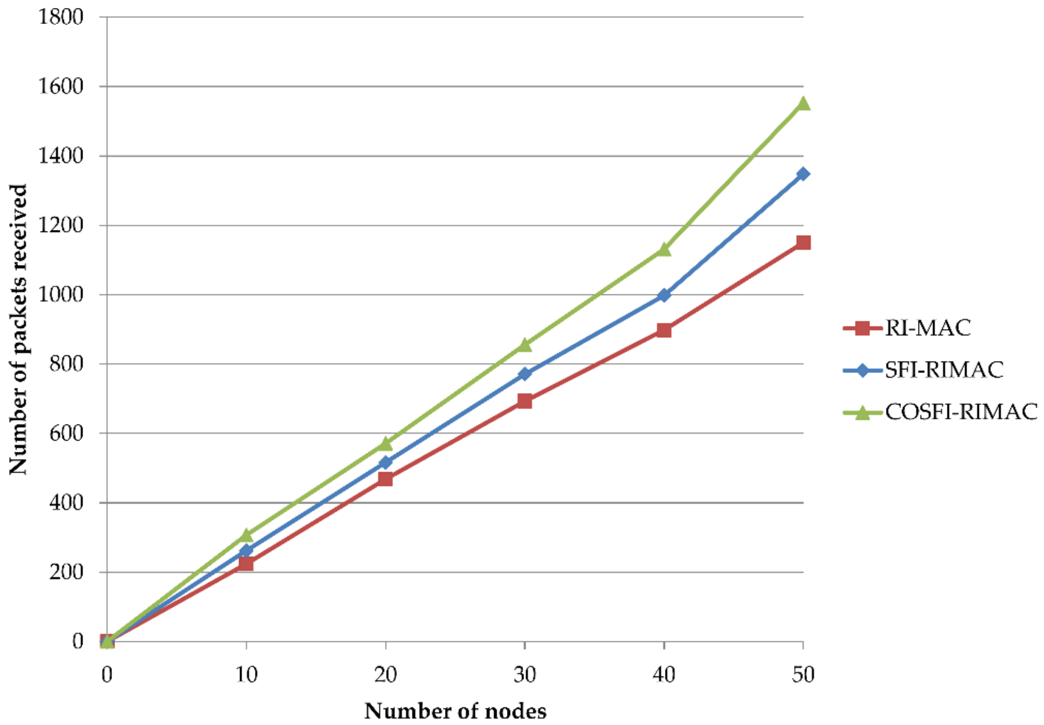


Figure 4.7. The number of packets received from different MAC protocols (RI-MAC, SFI-RIMAC, COSFI-RIMAC).

In SFI-RIMAC, during the asynchronous wake-up phase, receivers perform a small wake-up to send short SFI frames. If a sender receives an SFI from the expected receiver, it will synchronize its data transmission wake-up, which increases the number of packets received. Our COSFI-RIMAC protocol's collision avoidance technology also increases the number of packets received.

The Packet Delivery Rate (PDR) can be defined as the ratio of the data packets effectively received at the receiver end to those originally sent by the sender. Figure 4.8 shows the results for the packet delivery rate for the COSFI-RIMAC, SFI-RIMAC, and RI-MAC protocols. In general, the simulation results show that the SFI-RIMAC protocol has a higher packet delivery rate than RI-MAC due to the insertion of the SFI short frame identifier. In addition, our proposed mechanism COSFI-RIMAC increases the rate of packet delivery.

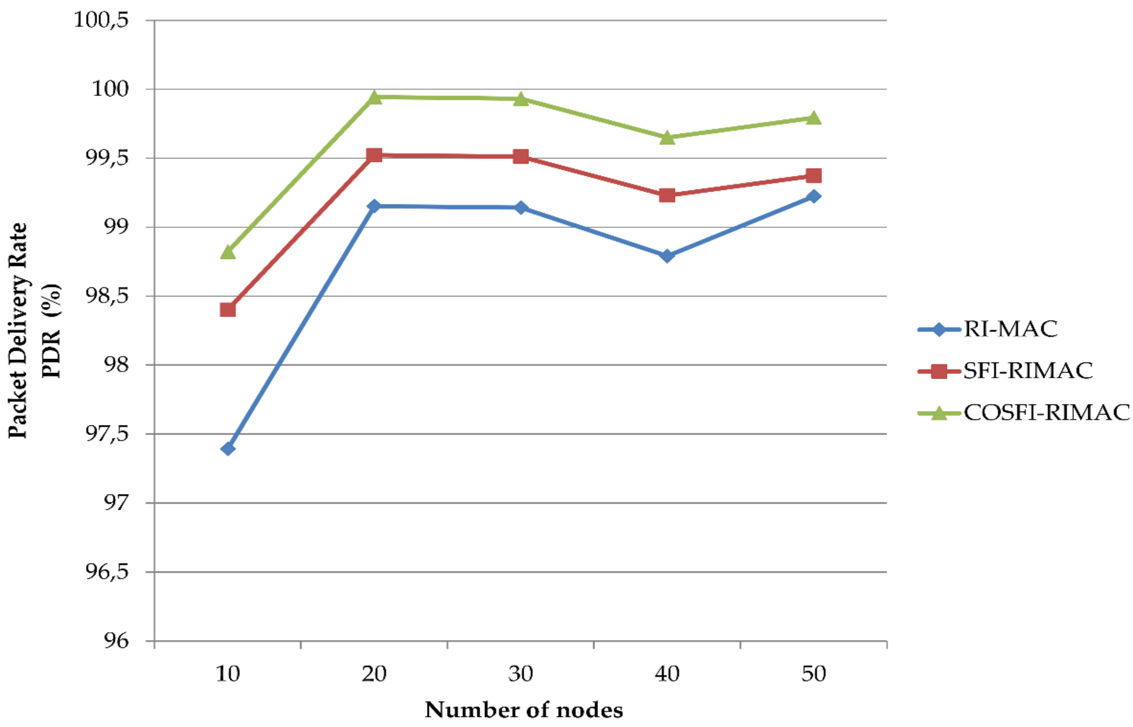


Figure 4.8. Packet Delivery Rate of different MAC protocols (RI-MAC, SFI-RIMAC, COSFI-RIMAC).

In our SFI-RIMAC proposal, short SFI frames synchronize the receiver and the sender nodes, which minimizes the number of lost packets and thus increases the Packet Delivery Rate (PDR). Our COSFI-RIMAC proposal, compared to RI-MAC, reduces collisions between nodes by using a collision avoidance technique based on cooperation between the sender's nodes, which minimizes the number of lost packets associated with data retransmission, thereby increasing the PDR.

Latency is the time it takes for a data packet to travel from a node to the sink. Figure 4.9 shows a comparison of the latency results between our proposals SFI-RIMAC, COSFI-RIMAC, and the RI-MAC protocol. Typically, latency increases as the number of nodes increase for protocols. However, due to the use of all three transmission phases (Asynch-Coop Wake-up, Synch Wake-up Data Transmission, and, Appointment Wake-up Data Transmission), the proposed COSFI-RIMAC protocol exhibited the least latency compared to RI-MAC. The average throughput determines the number of packets transmitted from a source to a destination node per unit t time. To express it, we use the size of the packets in bits, thus the result is in bits/seconds.

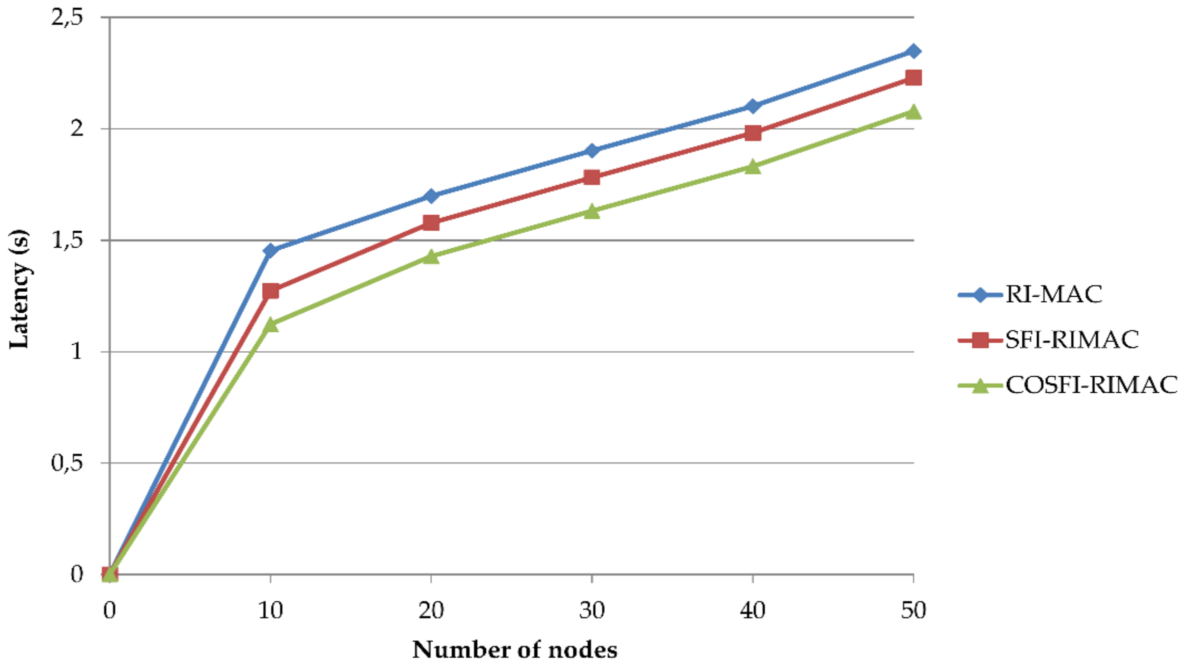


Figure 4.9. Latency of different MAC protocols (RI-MAC, SFI-RIMAC, COSFI-RIMAC).

In the first proposal SFI-RIMAC, the sender node that receives an SFI wakes up (synchronized wake up) simultaneously with the receiver node, this time the sender starts sending this data immediately, as soon as the receiver sends the short beacon signal indicating its wake-up, which minimizes the latency compared to RI-MAC. Introducing the cooperation between the sending nodes in the second COSFI-RIMAC proposal, which also reduces the latency.

Throughput is calculated as the amount of data received by the receiver during the simulation time. Figure 4.10 shows the comparison of the average flow between our proposals SFI-RIMAC, COSFI-RIMAC, and RI-MAC protocol. The average throughput in the three protocols increases linearly with the increase in the number of nodes, the minimization of collisions in our proposals (SFI-RIMAC and COSFI-RIMAC) reduces the average throughput compared to the RI-MAC protocol.

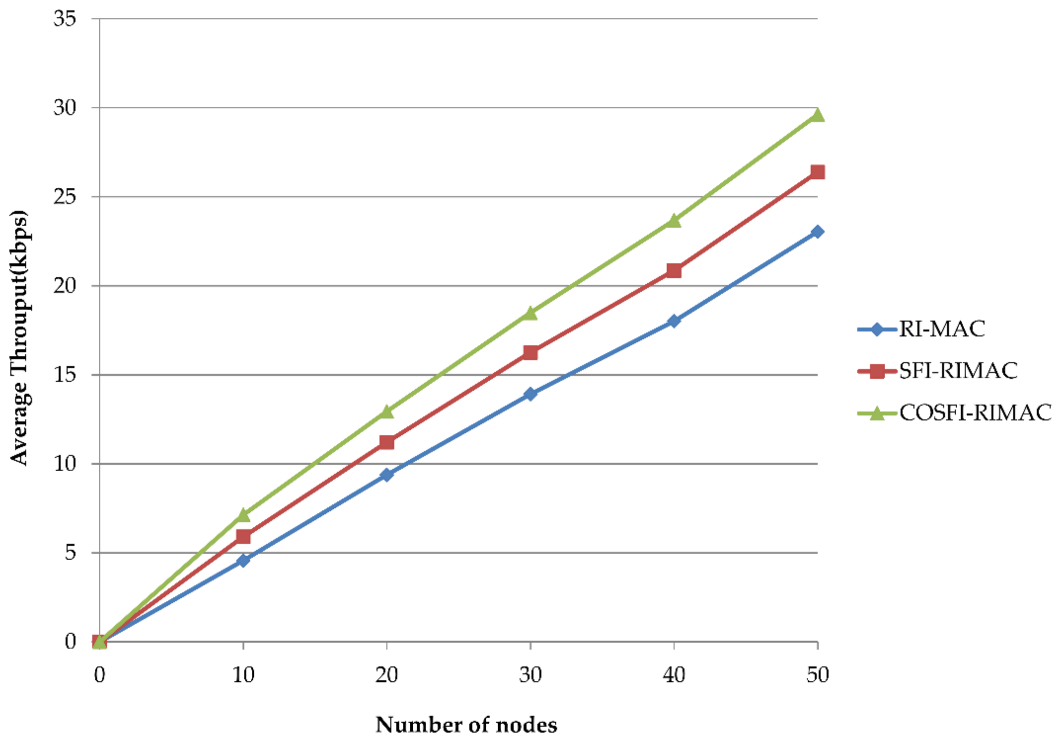


Figure 4.10. Average Throughput of different MAC protocols (RI-MAC, SFI-RIMAC, COSFI-RIMAC)

Collision-oriented retransmissions in RI-MAC minimize throughput and result in a significant delay. Therefore, in the per-cycle wake-up strategy used in SFI-RIMAC, the overhead, and collisions decrease after the use of synchronous and appointments Wake up data transmission between the receiver nodes and the sender nodes, this can provide higher throughput. The additional mechanism proposed in our COSFI-RIMAC proposal to minimize collisions, based on cooperation between the sender nodes, also provides better throughput.

4.5 Conclusion

In this chapter, we have proposed a new asynchronous receiver-initiated cooperative MAC protocol called Cooperative Short Frame Identifier Receiver Initiated MAC protocol (COSFI-RIMAC). Our main contribution is to reduce collisions and idle listening, and therefore power consumption. Our scheme is based on RI-MAC. Simulation, simulation results of our proposal show that COSFI-RIMAC significantly improves power consumption, average throughput, average end-to-end delay, and latency. In addition, COSFI-RIMAC allows more data to be transferred and increases the packet delivery rate.

CONCLUSION AND FUTURE WORK

The success of wireless sensor networks is based on the simplicity of the sensor nodes (low computing power, small battery, radio antenna with limited range, etc.). However, this strong point of WSNs is also their most imposing constraint. The first problem concerns energy consumption. Its inclusion is motivated by several reasons. The first is linked to the autonomy of this type of network: the sensors are often used in isolated or inaccessible environments and their low-power batteries cannot be recharged. The second is linked to the strong dependence of the WSN on the batteries of the various sensors making up the network. Thus, the battery drain of some nodes can lead to a failure of the entire network. Therefore, the consumption of Energy in WSNs is an unavoidable constraint that has changed many considerations for this type of network. Among these considerations, we find the design of the physical layer and the MAC layer which no longer have the same constraints as other wireless networks.

In this work, we are interested in the problem of energy consumption in WSNs. Our objective is to minimize this energy while respecting the constraints posed by the latter. In our proposal, we have given a contention-based MAC protocol relying on a receiver-initiated asynchronous duty cycle approach that relies on random access to the medium in CSMA/CA.

In this thesis, we proposed a high-performance, collision-minimizing, and energy-efficient receiver-initiated cooperative MAC protocol called COSFI-RIMAC for wireless sensor networks. COSFI-RIMAC dynamically minimizes node wake-up and cooperates with neighboring transmitters to synchronize sleep/wake periods to reduce idle listening and minimize collisions. In this protocol, each sensor node follows its own randomly generated schedule. This protocol uses the duty cycle mechanism to minimize the alternation between active and standby mode consumes more energy, adding a collision avoidance mechanism that works in a way that gives an advantage to certain nodes depending on determining factors with the preservation of the random media access aspect that distinguishes contention-based protocols.

To evaluate our COSFI-RIMAC proposals, we used the NS2 simulator. It is one of the most powerful simulators in the field of wireless sensor networks. The results of the simulation show significantly that our objective has been achieved, better management of the energy, that is to say, a maximization of the lifetime of the network compared to the RI-MAC protocol.

Finally, as perspectives, we propose to make an extension of the protocol in a wireless network where it takes into consideration the needs of the application. Also, improve our protocol to support cooperation between receiving nodes, take advantage of the performance of synchronous MAC protocols, and try to combine them to have a more powerful asynchronous protocol.

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