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Theme

Cross-Layer Routing Protocols in Wireless Sensor Networks

Presented by

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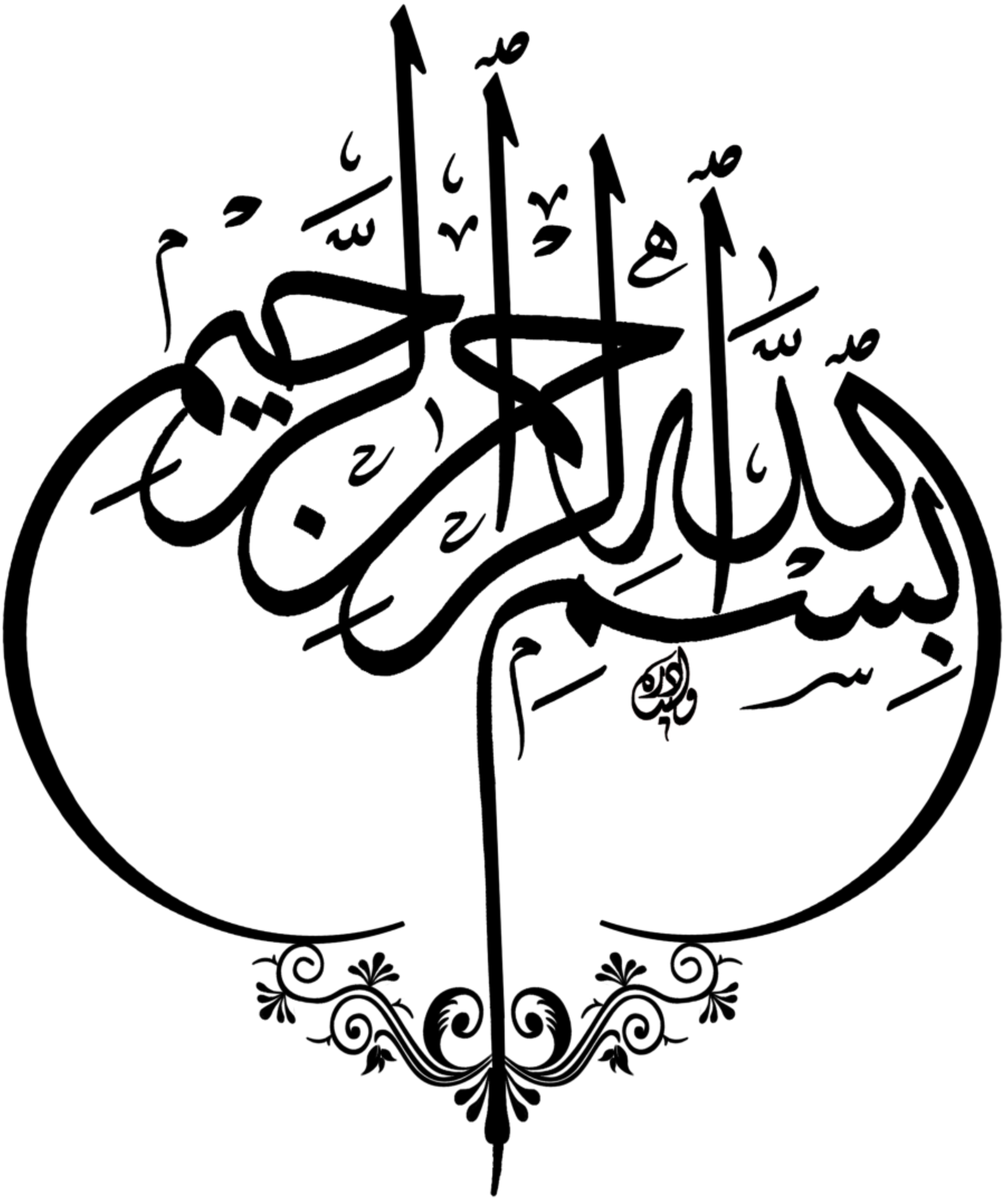
بسم الله الرحمن الرحيم

Dédicates

I would like to dedicate this thesis,
To my loving mother and father,
To my wonderful family for their unconditional love, enormous support and continuous encouragement.

RIAD

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Above all, praise to *Allah* who gave me the strength and the life to accomplish this task.

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Abstract

Wireless sensor networks (WSNs) are considered to be one of the main technologies that are heavily resource-constrained, in constant demand for energy-efficient and effective routing techniques. The so-called hierarchical or equivalently cluster-based routing approaches have shown substantial improvements of the WSNs performance as compared to traditional duty-cycled Medium Access Control (MAC) protocols due to the aggregation process. In addition, the use of the cross-layer approach, based on the cooperation of several layers has proven to be effective in routing data with drastic reduction in energy consumption within WSNs. However, the operation of routing data from the Cluster Heads (CHs) to the Sink remains one of the major sources of wasted node energy. As a remedy, MAC protocols using a wake-up radio (WuR) have been used to address this issue. Based on the idea of letting the CHs and other nodes in the network on a sleep mode for the longest possible period, this thesis proposes the so-called Clustering Multi-Hop Cross-Layer Protocol (CMH-CLP). The various simulation results of the proposed protocol on the basis of some standard network performance metrics show that the proposed protocol improves the WSN performance as compared with some well-known recent protocols.

Keywords: Wireless sensor network, wakeup radio, cross-layer design, energy-efficient networking.

Résumé

Les réseaux de capteurs sans fil (WSN) sont considérés comme l'une des structures qui sont très limitées en ressources d'alimentation, en demande croissante de techniques de routage efficaces et économiques en énergie. De plus, les approches de routage dites hiérarchiques basées sur le regroupement des nœuds en clusters ont montré des améliorations et des performances substantielles des WSNs par rapport aux protocoles traditionnels du contrôle d'accès au support (ou MAC: Media Access Control) en raison du processus de regroupement. L'utilisation de l'approche cross-layer, basée sur la coopération de plusieurs couches de la pile protocolaire s'est avérée efficace dans le routage des données avec une réduction remarquable en consommation d'énergie dans les WSN. Cependant, l'opération d'acheminement des données des chefs de cluster (CH) vers le puits (Sink) reste la source principale de gaspillage d'énergie par les nœuds. Pour résoudre ce problème, une des approches récentes consiste en l'utilisation des protocoles MAC avec une radio de réveil (WuR). Basé sur l'idée de laisser les CHs et les autres nœuds du réseau le plus longtemps possible en mode veille, cette thèse propose la méthode intitulée "Clustering Multi-Hop Cross-Layer Protocol (CMH-CLP)". Les différents résultats de simulation du protocole proposé sur la base de certaines mesures de performances de réseau montrent que le protocole proposé améliore les performances du WSN par rapport à certains protocoles récents bien connus.

Mots clés: : réseau de capteurs sans fil, radio de réveil, conception multicouche, mise en réseau éco-énergétique.

ملخص

تعتبر شبكات الاستشعار اللاسلكية (WSNs) واحدة من البني التي تعاني من قيود شديدة على الموارد، في ظل الطلب المستمر على تقنيات التوجيه الفعالة الموفرة للطاقة. لقد أظهرت ما يسمى بمناهج التوجيه الهرمي، أي المعتمد على تجميع العقد في كتل، تحسينات كبيرة في أداء هذا النوع من الشبكات مقارنة ببروتوكولات تقليدية مبنية على "التحكم في الوصول الى الوسيط" (MAC) و التي يتم تدويرها بسبب عملية التجميع. بالإضافة إلى ذلك، فإنّ استخدام النهج العابر للطبقات، الذي يعتمد على التعاون بين عدة طبقات، قد أثبت فعاليته في توجيه البيانات مع تخفيض كبير في استهلاك الطاقة داخل الشبكات اللاسلكية.

ومع ذلك، فإن عملية توجيه البيانات من رؤوس الكتلة (CH) إلى البئر (بالوعة) لا يزال المصدر الرئيسي لإهدار الطاقة عبر العقد.

استنادًا إلى فكرة ترك رأس الكتلة والعقد الأخرى في الشبكة في وضع السكون لأطول فترة ممكنة، نقترح في هذه الاطروحة ما يسمّى بروتوكول هرمي متعدّد الطبقات والقفزات (CMH–CLP) . تظهر نتائج المحاكاة المختلفة للبروتوكول المقترح على أساس بعض مقاييس المستعملة في اداء الشبكات أن البروتوكول المقترح يحسن الأداء مقارنة ببعض البروتوكولات الحديثة المعروفة.

كلمات البحث:

شبكة استشعار لاسلكية، راديو تنبيه، تصميم متعدد الطبقات، شبكات موفرة للطاقة. .

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Acronyms

ACK	Acknowledgment
ADC	Analogto Digital Converters
ALOHA	Additive Link OnLine Hawaii System
AODV	Ad hoc On demand Distance Vector routing
AOMDV	Adhoc Ondemand Multipath Distance Vector
ARQ	Automatic Repeat reQuest
ASCENT	Adaptive-Self Configuring Sensor Networks Topologies
BER	Bit Error Rate
BMAC	Berkeley MAC
BS	Base Station
C3I	Command Control Communication and Intelligence
CCBE	Cross-layer Cluster Based energy Efficient Routing algorithm
CDMA	Code Division Multiple Access
CH	Cluster Head
CLASS	Cross-Layer Signaling Shortcuts
CLMAC	Cross-Layer MAC
CLPC	Cross-Layer Power Control

CR	Content Routers
CSI	Channel State Information
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
CSMA	Carrier Sense Multiple Access
CTS	Clear To Send
DCF	Distributed Coordination Function
DD	Direct Diffusion
DIFS	Distributed Coordination Function inter-frame
DLL	Data Link Layer
DMAC	Data prediction MAC
DSR	Dynamic Source Routing
ECLP	Enhanced Cross-layer Protocol
EECP	Energy Efficient Cross-layer Protocol
EECS	Energy Efficient Clustering Scheme
EEMC	Energy Efficient Multilevel Clustering algorithm
EFSC	Efficient Flooding Scheme CrossLayer
EHWuR	Energy Harvesting WuR
ERP	Effective Radiated Power
EXMAC	Express MAC
FAMACROW	Fuzzy and Ant colony Optimization MAC CrossLayer Protocol for WSN
FEC	Forward Error Correction
FND	First Node Dead
FTP	File Transfer Protocol

GAF	Geographic Adaptive Fidelity
GPS	Global Positioning System
HCN	Highest Connectivity Networks
HEED	Hybrid Energy Efficient Distributed Clustering
HNA	Half Node Alive
HTTP	Hypertext Transfer Protocol
ICN	Information Centric Networking
IREQ	Interest Request
ISM	Industrial Scientific and Medical
ISO	International Organization for Standardization
LEACH	Low Energy Adaptive Clustering Hierarchy
Leach-CLO	Leach Cross Layer optimisation
LID	Lowest ID
LLC	Logical Link Control
LND	Last Node Dead
LPL	Low Power Listening
LQI	Link Quality Information
MACA	Multiple Access with Collision Avoidance
MAC	Medium Access Control
MACOQCR	Multiobjective Ant Colony Optimization based QoSaware Cross-Layer
MAI	Multiple Access Interference
MEMS	Micro Electro Mechanical Systems
MPF	Most Advanced Forwarder

NAV	Network Allocation Vector
OFDMA	Orthogonal Frequency Division Multiple Access
OSI	Open Systems Interconnection
OSIRM	Open Systems Interconnection Reference Model
PANEL	Positionbased Aggregator Node ELection protocol
PEGASIS	Power Efficient Gathering in Sensor Information Systems
PTC	Power and Time Control
QoS	Quality of Service
RA	Random Access
RSSI	received signal strength indicator
RTS	Request To Send
SCS	Selective Caching Scheme
SEER	Simple Energy Efficient Routing
SIFS	Shortest Inter-frame space
SMAC	Sensor MAC
SMP	Sensor Management Protocol
SMTP	Simple Mail Transfer Protocol
SNR /RP	Simple Mail Transfer Protocol Signal to Noise Ratio /Received Power
SNR	Signal to Noise Ratio
SPIN	Sensor Protocols for Information *via* Negotiation
STEMB	Sparse Topology and Energy Management Beacon
SYNC	Synchronization
TCP	Transmission Control Protocol

TDMA	Time Division Multiple Access
TEEN	Threshold sensitive Energy Efficient sensor Network protocol
TLEACH	Threshold LowEnergy Adaptive Clustering Hierarchy
TMAC	Time out MAC
TRAMA	TRaffic Adaptive Medium Access protocol
TUTWSNR	Tampere University of Technology Wireless Sensor Network Routing
UDP	User Datagram Protocol
WCA	Weighted Clustering Algorithm
WHARP	Wakeup and HARvesting-based energy-Predictive forwarding
WSNs	Wireless Sensor Networks
WuACK	Wakeup Acknowledgment
WuR	Wake up Radio
WuRx	Wakeup receiver
WuS	Wake up signal the message sent by the WuTx
WuTx	Wake up transmitter
ZMAC	Zebra MAC

Introduction

Wireless sensor networks (WSNs) consist of a set of battery-operated computing, sensing and communication devices used to collaborate for a common application. Although WSNs are deployed in many monitoring applications, they still suffer from short lifetime due to the limited energy sources of nodes and the difficulty in replacing their batteries [1]. One of the most stringent constraints resides in the fact that these nodes must always remain in a communication mode [2]. It has been established that Medium Access Control (MAC) protocols substantially improve the energy efficiency of wireless networks. While the use of duty-cycling, *i.e.*, recurrent and periodic activation/sleep of the main radio interface of the wireless sensor node, provides important energy benefits over an always-on approach, MAC protocols for WSNs still suffer from many issues. Indeed, irrespective of their target application, most of the MAC-based schemes are characterized by both the idle listening and the overhearing. Idle listening happens whenever a given node listens to the wireless medium even in the absence of communication. On the other hand, overhearing happens when a node captures unrelated communication, *i.e.*, sent to another node. Moreover, all duty-cycling-based approaches also suffer from additional latency since no information is processed outside the nodes' activation period. Thus, duty-cycling implementations limit the energy efficiency of the MAC protocols, severely affecting the overall network performance [1].

Routing information in WSNs is still a challenge since the objective is to find new protocols for data transmission under the constraints of energy saving, network stability preservation and extended lifetime. The clustering method is one of the solutions proposed to respond to the conceptual constraints of WSN [3]. In such method, the sensor nodes are grouped into clusters and a Cluster Head (CH), *i.e.*, a node elected from members of the cluster, is responsible for collecting the data and sending them to the sink. Forming the cluster and selecting the appropriate cluster head (CH) for data aggregation is considered a promising method to reduce energy consumption and to extend the network lifetime [4].

A new type of cross-layer design has emerged, based on the interaction between the different layers of the Open Systems Interconnection (OSI) model instead of the old single-layer [5]. This new design has opened a new horizon in the field of routing and has led to the advent of several types of protocols. Furthermore, its efficiency has been proved in the transmission of data within the WSNs with reduced energy consumption [6].

Another solution consists of equipping the node with a second low-power wake-up radio (WuR) to wake the node whenever there is a packet to be received. This technique allows the main radio to go into a deep sleep as long as there is no information to be received [7]. While the nodes spend all of their time in a sleep mode, the WuR monitors the channel. In this approach, sensor networks are arranged such that individual nodes remain largely inactive for long periods of time, but switching to active mode whenever an event occurs. If a node wishes to transmit a packet to its neighbor, it simply starts by sending a short wake-up message (WuM) to such neighbor. As soon as the receiver's WuR detects the wake-up signal, it immediately wakes up the main radio, performs the required tasks, and switches on a sleep mode until another event occurs [8]. One of the advantages of this approach is that the WuR is energy saving, characterized by the usage of a short wake-up range [9] as compared with the transmitting radio, and wake-up circuit components relying on power consumption that remains insignificant as compared to that of the main radio [10]. Additionally, the two radios use separate wake-up and transmission channels in order to avoid interference between the data and the wake-up messages [11]. This technique eliminates passive listening and saves energy while increasing the network lifetime along with speeding up the packet forwarding and reducing the latency on each hop. All these sensor novel features motivate for a novel MAC that is different from traditional wireless MACs such as IEEE 802.11.

In this thesis, we present our contribution to reducing this energy dissipation and improving the wireless sensor networks' performance. As a result, we propose the so-called Clustering Multi-Hop Cross-Layer Protocol (CMH-CLP) which is a new protocol in hierarchical WSNs based on the Wakeup radio for routing operation.

This thesis is structured as follows:

Chapter 1 presents the state-of-the-art of wireless sensor networks as well as their characteristics and fields of application. In addition, this chapter discusses the different categories of routing protocols in WSNs, where we focus on the LEACH protocol used in networks with a hierarchical structure.

Chapter 2 presents an explanation of the cross-layer design, with a presentation of some types of protocols based on this design. The chapter explains the protocols that depend on sensors with two radios: one for transmitting and the other for waking up. Emphasis is made on the contribution of the latter in improving the performance of the WSN networks.

In Chapter 3, a new routing protocol in WSNs called Clustering Multi-Hop Cross-Layer Protocol (CMH-CLP) is introduced as our contribution. The various simulation results of the proposed protocol on the basis of some standard network performance metrics are presented with two protocols of the same family. The chapter is an extension of our work [12].

Finally, we end this thesis with a conclusion and future developments.
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Chapter 1

Introduction to Wireless Sensors Networks

1 Introduction

Wireless Sensor Networks have recently become one of the research domains that develop the most. A lot of interest from the scientific community as well as from the industry results in a rapid development of new types of devices, technologies, and protocols. Indeed, the ease of deployment and the large amount of possible uses justify such a great interest.

Wireless Sensor Networks consist of many small nodes communicating through a wireless channel. They can provide some valuable data sensing the environment as well as interact with their surrounding through actuators. The small size and low cost allow sensors to be easily integrated in the environment, providing a nonintrusive way to make our lives easier and improve industrial processes. Intended large scale deployments (we can even read about hundred thousands or millions of devices) will be made possible by a low price of WSN devices [13].

The design and implementation of WSNs face several challenges, mainly due to the limited resources: low-power, low range, low-bandwidth communications, small memory, and finally, a small battery or an energy harvesting device. To accomplish their task, sensor nodes need to communicate with each other and act as intermediate nodes to forward data on behalf of others so that this data can reach the sink or the base station (BS), which is responsible for taking the required decision [14].

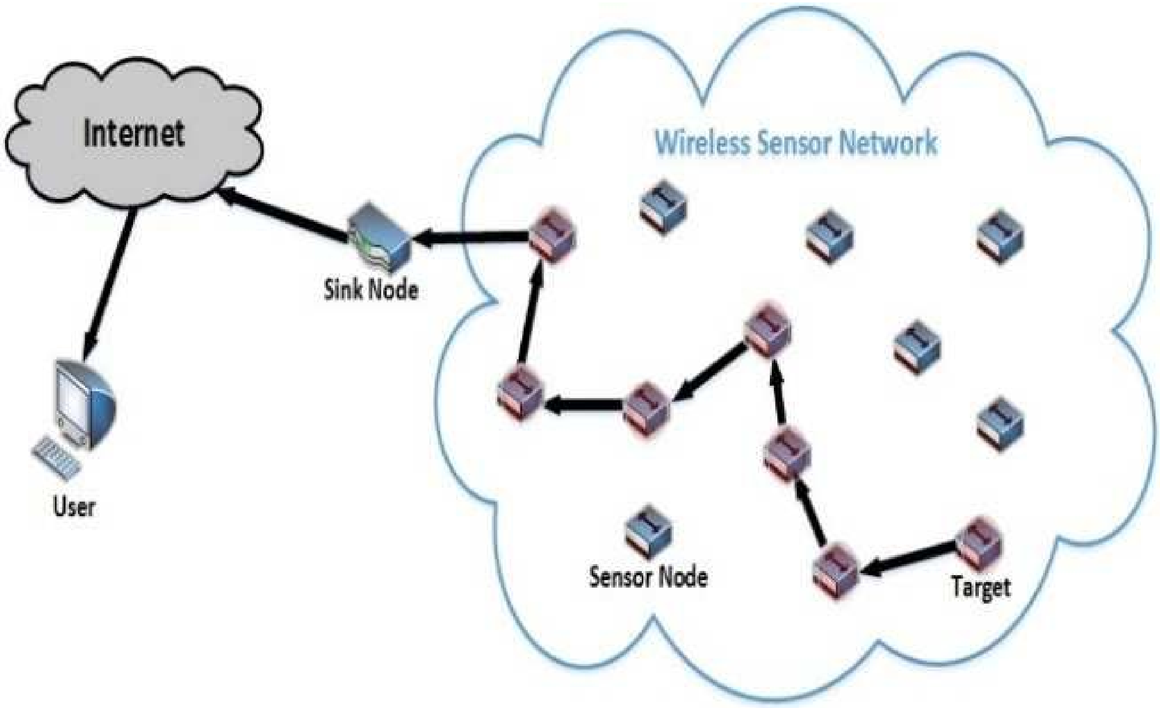

Fig. 1.1 Network Architectures
[16]

2 Wireless Sensor Networks

The recent progress in the field of MEMS (micro electro mechanical systems), wireless communications, and highly integrated digital electronics has led to the development of micro sensors. Such tiny sensors are of low-cost, of low power, and multifunctional and communicate freely over short distances [15]. These sensor nodes are responsible for the sensing, data processing, and data delivery to the BS. They should work together to form a wireless sensor network (WSN). A WSN is composed of a large number of sensor nodes, which are randomly or manually deployed in a given coverage area. These nodes collect local physical information, process them, and send them to a BS called sink.

For the public notice of the phenomenon, the BS is connected to the internet (figure1.1). Another important characteristic of a WSN is the ability of its nodes to cooperate. Instead of sending raw data to the node responsible for data fusion, the sensor nodes can use their processing abilities to locally carry out calculations and fusion operations to transmit only the information required [17]. These characteristics of wireless sensors enable them to be used in many areas especially for surveillance and monitoring [18].

However, the main challenge in the WSNs is the limited power resources of sensor nodes. It is not practical to recharge the nodes batteries or replace them after complete

Fig. 1.2 Wireless Sensor Network Applications

depletion of their energy because, in many scenarios, the nodes are deployed in hostile isolated environments [19]. The sensor network protocols must focus primarily on energy conservation to maximize the network lifetime [20].

3 Network Applications

Sensors can be used to detect or monitor a variety of physical parameters or conditions , for example, light, sound, humility, pressure, temperature, soil composition, air or water quality and attributes of an object such as size, weight, position, speed, and direction [15].

Wireless sensors have significant advantages over conventional wired sensors [21]. They can not only reduce the cost and delay in deployment, but also be applied to any environment, especially those in which conventional wired sensor networks are impossible to be deployed, for example, inhospitable terrains, battlefields, outer space, or deep oceans. On the other hand, the availability of low - cost sensors and wireless communication has promised the development of a wide range of applications in both civilian and military fields. And these are some applications of sensors networks(figure1.2)[22].

3.1 Environmental monitoring

Environmental monitoring is one of the earliest applications of sensor networks. In environmental monitoring, sensors are used to monitor a variety of environmental parameters or conditions. Thus, they are deployed in the forests to detect and signal a possible outbreak of fire. The sensors can also be sown with the seeds, in order to control the watering of the plants. In the industrial field, sensors are generally used to detect leaks of toxic products, or for monitoring critical parameters such as the temperature of a nuclear reactor.

3.2 Military Applications

WSNs are becoming an integral part of military command, control, communication, and intelligence (C3I) systems [15]. Wireless sensors can be rapidly deployed in a battlefield or hostile region without any infrastructure. Due to ease of deployment, self - configurability, untended operation, and fault tolerance, sensor networks will play more important roles in future military C3I systems and make future wars more intelligent with less human involvement.

3.3 Health Care and Medical Applications

WSNs can be used to monitor and track elders and patients for health care purposes, which can significantly relieve the severe shortage of health care personnel and reduce the expenditures in the current health care systems [23]. More it can be used in the monitoring of the vital functions of the human being with micro sensors swallowed or implanted under the skin of patients. Sensors can be implanted inside the human body to treat certain types of diseases (such as the detection of cancers) or to collect physiological information (such as monitoring the level of glucose), or even for monitoring organs [24].

3.4 Home Intelligence

WSNs can be used to provide more convenient and intelligent living environments for human beings. For example, a smart refrigerator connected to a smart stove or microwave oven can prepare a menu based on the inventory of the refrigerator and send relevant cooking parameters to the smart stove or microwave oven, which will set the desired temperature and time for cooking [25]. Wireless sensors can also be used to remotely read utility meters in a home, for example, water, gas, or electricity, and then send the readings to a remote center through wireless communication [26].

In addition to the above applications, self-configurable WSNs can be used in many other areas, for example, disaster relief, traffic control, warehouse management, and civil engineering. However, a number of technical issues must be solved before these exciting applications become a reality.

4 Network architectures and protocol Stack

4.1 Architecture of sensor

A sensor node is made up of four basic components, as shown in Figure1.3: a sensing unit, a processing unit, a transceiver (communication) unit, and a power unit.

1. Sensing units are usually composed of two subunits: sensors and analog-to-digital converters (ADCs). The analog signals produced by the sensors based on the observed phenomenon are converted to digital signals by the ADC, and then fed into the processing unit.

2. The processing unit usually consists of a microcontroller or microprocessor which is generally associated with a small storage unit, manages the procedures that make the sensor node collaborate with the other nodes to carry out the assigned sensing tasks.

3. A transceiver unit connects the node to the network with a short - range radio for performing data transmission and reception over a radio channel.

4. The power unit: The power unit consists of a battery for supplying power to drive all other components in the system, is one of the most important components of a sensor node it's may be supported by power scavenging units such as solar cells.

In addition, a sensor node can also be equipped with some other units, depending on specific applications. For example, a global positioning system (GPS) may be needed in some applications that require location information for network operation. A motor may be needed to move sensor nodes in some sensing tasks. All these units should be built into a small module with low power consumption and low production cost.

4.2 Network Architectures

A sensor network typically consists of a large number of sensor nodes densely deployed in a region of interest, and one or more data sinks or base stations that are located close to or inside the sensing region, as shown in Figure 1.1. The sink(s) sends queries or commands

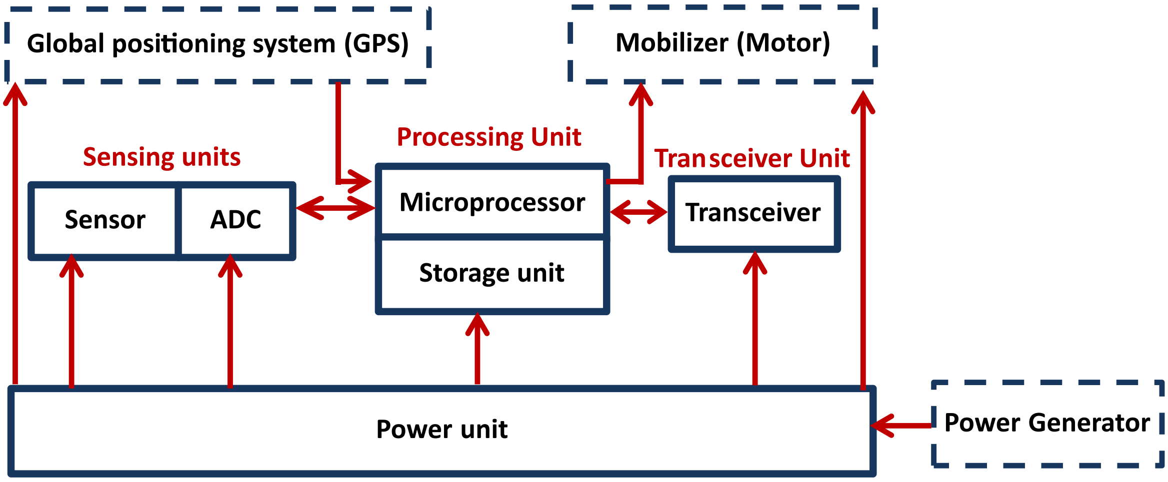

Fig. 1.3 The components of a sensor nodes

to the sensor nodes in the sensing region while the sensor nodes collaborate to accomplish the sensing task and send the sensed data to the sink(s). Meanwhile, the sink(s) also serves as a gateway to outside networks, for example, the Internet. It collects data from the sensor nodes, performs simple processing on the collected data, and then sends relevant information (or the processed data) via the Internet to the users who requested it or use the information.

To send data to the sink, each sensor node can use single-hop (single-hop network architecture) long-distance transmission (figure 1.4(a)), However, long-distance transmission is costly in terms of energy consumption. In sensor networks, the energy consumed for communication is much higher than that for sensing and computation. For this purpose, multi-hop short-distance communication is highly preferred. In most sensor networks, sensor nodes are densely deployed and neighbor nodes are close to each other, which makes it feasible to use short-distance communication In multi-hop communication, a sensor node transmits its sensed data toward the sink via one or more intermediate nodes, which can reduce the energy consumption for communication. The architecture of a multi-hop network can be organized into two types: flat and hierarchical [17], which are described in the next two sections.

4.2.1 Flat Architecture

In a flat network, each node plays the same role in performing a sensing task and all sensor nodes are peers. Due to the large number of sensor nodes, it is not feasible to assign a global identifier to each node in a sensor network. For this reason, data gathering is usually accomplished by using data-centric routing, where the data sink transmits a query to all nodes

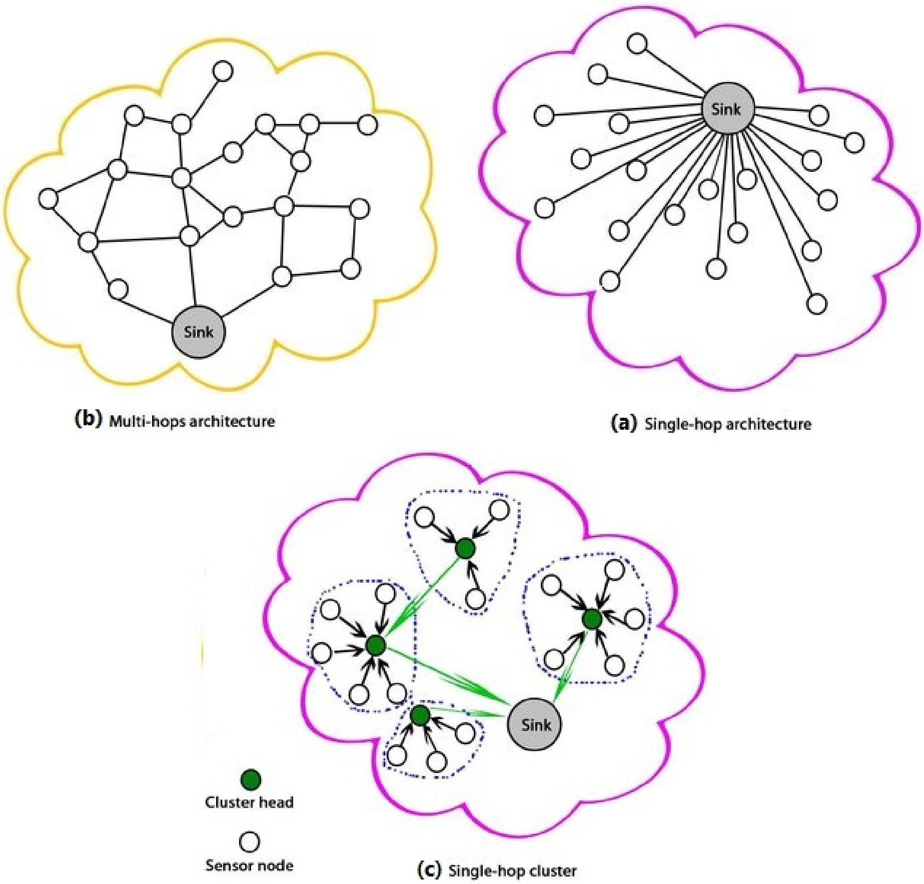

Fig. 1.4 Routing Data to the Sink models

in the sensing region via flooding and only the sensor nodes that have the data matching the query will respond to the sink. Each sensor node communicates with the sink via a multi-hop path and uses its peer nodes as relays. Figure 1.4(b) illustrates the typical architecture of a flat network.

4.2.2 Hierarchical Architecture

In a hierarchical network, sensor nodes are organized into clusters, where the cluster members send their data to the cluster heads while the cluster heads serve as relays for transmitting the data to the sink (Figure 1.4(c)). A node with lower energy can be used to perform the sensing task and send the sensed data to its cluster head at short distance, while a node with higher energy can be selected as a cluster head to process the data from its cluster members and transmit the processed data to the sink. This process can not only reduce the energy consumption for communication but also balance traffic load and improve scalability when the network size grows. Since all sensor nodes have the same transmission capability,

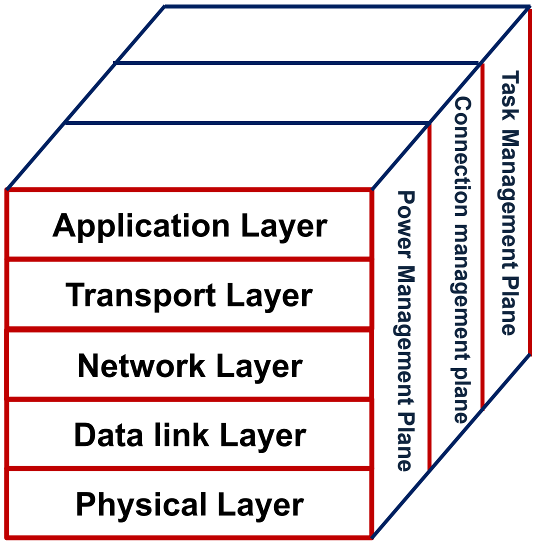

Fig. 1.5 The sensor networks protocol stack

the clustering must be periodically performed in order to balance the traffic load among all sensor nodes. Moreover, data aggregation can be performed at cluster heads to reduce the amount of data transmitted to the sink and improve the energy efficiency of the network [27]. The major problem with clustering is how to select the cluster heads and how to organize the clusters [28].

4.3 Protocol stack for wireless sensor networks

The Open Systems Interconnection (OSI) seven-layer model, proposed by the International Organization for Standardization (ISO), forms the basis for the design of the WSN protocol stack. However, unlike the seven-layer OSI model, that consists of the physical layer, the data link layer, the network layer, the transport layer, the session layer, the presentation layer and, the application layer.

The WSN protocol stack does not adopt all the seven layers of the OSI model. In reality, the seven-layer OSI model has too many layers making it overly complex and difficult to implement. The protocol stack for WSNs consists of five protocol layers: the physical layer, data link layer, network layer, transport layer, and application layer, as shown in Figure 1.5. On the other hand, the protocol stack can be divided into a group of management planes across each layer, including power, connection, and task management planes [29].

4.3.1 Application Layer

The application layer resides close to the users of the system. There are many potential applications implemented at the application layer including, Telnet, Hypertext Transfer Protocol (HTTP), File Transfer Protocol (FTP), or Simple Mail Transfer Protocol (SMTP). In terms of WSN, the application layer programming primarily deals with the processing of sensed information, encryption, the formatting and storage of data. Moreover, the application layer scans the underlying layers to detect if sufficient network resources and services are available to meet the user's network requests. In addition the application layer includes a variety of protocols that perform various sensor network applications. For example, the sensor management protocol (SMP) [15] is an application-layer management protocol that provides software operations to perform a variety of tasks, for example, exchanging location-related data, synchronizing sensor nodes, moving sensor nodes, scheduling sensor nodes, and querying the status of sensor nodes.

4.3.2 Transport Layer

The transport layer is responsible for reliable end-to-end data delivery between sensor nodes and the sink(s). There are varying forms of transport layer protocols; two of the most popular and contrasting are the transmission control protocol (TCP) and the user datagram protocol (UDP). Connection-oriented transport layer protocols, such as TCP, provide a reliable communication service, with extensive error handling, transmission control, and flow control. Whereas, connectionless transport layer protocols, such as UDP, provide an unreliable service but with minimum error handling, transmission, and flow control. Due to the energy, computation, and storage constraints of sensor nodes, traditional transport protocols cannot be applied directly to sensor networks without modification. For example, the conventional end-to-end retransmission-based error control and the window-based congestion control mechanisms used in the transport control protocol (TCP) cannot be used for sensor networks directly because they are not efficient in resource utilization. On the other hand, sensor networks are application-specific. A sensor network is usually deployed for a specific sensing application, for example, habitat monitoring, inventory control, and battlefield surveillance. Different applications may have different reliability requirements, which have a big impact on the design of transport-layer protocols. In addition, data delivery in sensor networks primarily occurs in two directions: upstream and downstream. In the upstream, the sensor nodes transmit their sensed data to the sink(s), while in the downstream the data originated from the sink(s), for example, queries, commands, and programming binaries are sent from the sink(s) to the source sensor nodes. The data flows in the two directions may have different reliability requirements. For example, the data flows in the upstream direction are loss tolerant because the sensed data are usually correlated or redundant to a certain extent. In the downstream, however, the data flows are queries, commands, and programming binaries sent to the sensor nodes, which usually require 100% reliable delivery. Therefore, the unique characteristics of sensor networks and the specific requirements of different applications present many new challenges in the design of transport layer protocols for WSNs.

4.3.3 Network Layer

Is responsible for establishing the communications paths between nodes in a network and successfully routing packets along these paths. The requirements of different routing protocols can vary and the choice will influence the communication paths set up. Some routing protocols will favor communication paths that help the WSN to deliver the best Quality of Service (QoS), other energy-saving protocols may choose the path that enables the WSN to achieve the best life while others will use a hybrid of both objectives. In this context, a large amount of research has been conducted and a variety of routing protocols have been proposed to address various application scenarios of sensor networks. For example, a source node can transmit the sensed data to the sink either directly via single-hop long-range wireless communication or via multi-hop short-range wireless communication. Although it achieves better performance, due to minimizing overhead and minimum delay, due to direct communication long-range wireless communication is costly in terms of energy consumption. In contrast, multi-hop short-range communication can significantly reduce the energy consumption of sensor nodes and is preferred, since sensor nodes are densely deployed and neighbor nodes are close to each other. But the multi-hop routing leads to a significant increase in transit traffic intensity and thus packet congestion, collision, loss, delay, and energy consumption as data move closer toward the sink. Therefore, it is important to take into account the energy constraint of sensor nodes as well as the unique traffic pattern in the design of the network layer and routing protocols [17].

4.3.4 Data Link Layer

The data link layer is responsible for data stream multiplexing, data frame creation and detection, medium access, and error control in order to provide reliable point-to-point and point-to-multipoint transmissions. One of the most important functions of the data link layer is medium access control (MAC). The primary objective of MAC is to fairly and efficiently share the shared communication resources or medium among multiple sensor nodes in order to achieve good network performance in terms of energy consumption, network throughput, and delivery latency. However, MAC protocols for traditional wireless networks cannot be applied directly to sensor networks without modification because they do not take into account the unique characteristics of sensor networks, in particular, the energy constraint. Another important function of the data link layer is error control in data transmission. In many applications, a sensor network is deployed in a harsh environment where wireless communication is error-prone. In this case, error control becomes indispensable and critical for achieving link reliability or reliable data transmission. In general, there are two main error control mechanisms: Forward Error Correction (FEC) and Automatic Repeat reQuest (ARQ). ARQ achieves reliable data transmission by retransmitting lost data packets or frames. Obviously, this incurs significant retransmission overheads and additional energy consumption and therefore is not suitable for sensor networks. FEC achieves link reliability by using error control codes in data transmission, which introduces additional encoding and decoding complexities that require additional processing resources in sensor nodes. However, FEC can significantly reduce the channel bit error rate (BER) for any given transmission power. Given the energy constraint of sensor nodes, FEC is still the most efficient solution to error control in sensor networks. To design a FEC mechanism, the choice of the error control code is very important because a well-chosen error control code can obtain a good coding gain and several orders of magnitude reduction in BER. Meanwhile, the additional processing power consumed for encoding and decoding must also be considered. Therefore, a trade-off should be optimized between the additional processing power and the corresponding coding gain in order to have a powerful, energy-efficient, and low - complexity FEC mechanism.

4.3.5 Physical Layer

The physical layer is responsible for defining and managing the connections between individual devices and their communication medium. The physical layer is responsible for converting bit streams from the data link layer to signals that are suitable for transmission over the communication medium. For this purpose, it must deal with various related issues, for example, transmission medium and frequency selection, carrier frequency generation, signal modulation and detection, and data encryption. In addition, it must also deal with the design of the underlying hardware, and various electrical and mechanical interfaces. Medium and frequency selection is an important problem for communication between sensor nodes. One option is to use radio and the industrial, scientific, and medical (ISM) bands that are license-free in most countries. The main advantages of using the ISM bands include free use, large spectrum, and global availability [30]. On the other hand, sensor networks require a tiny, low-cost, and ultralow power transceiver [31].

Table 1.1 TCP/IP layers Tasks and their primary tasks Layer

Layer	Data	Mission	services
Application	Data	User service: remote log-in, file transfer, web access	(HTTP, FTP, SMTP..)
Transport	Segments	Port addressing, segmentation and re-assembly, flow control, error control, connection control	(TCP, UDP. . . .)
Network	Packets	Logical addressing, routing	IP, ICMP, IGMP. . .
Data link	Frames	Framing, physical addressing, flow control, error control, access control	MAC and LLC (Ethernet 802.15.4. . . .)
Physical	Bits	Physical characteristics of interface and media, representation and synchronization of bits, data rate	Media, signal and binary transmission

4.3.6 A group of management planes across each layer

These planes help the sensor nodes coordinate the sensing task and lower overall power consumption [32].

1. The power management plane: Is responsible for managing the power level of a sensor node for sensing, processing, and transmission, and reception, which can be implemented by employing efficient power management mechanisms at different protocol layers. For example, at the MAC layer, a sensor node can turn off its transceiver when there is no data to transmit and receive. At the network layer, a sensor node may select a neighbor node with the most residual energy as its next hop to the sink.

2. The connection management plane: Is responsible for the configuration and reconfiguration of sensor nodes to establish and maintain the connectivity of a network in the case of node deployment and topology change due to node addition, node failure, node movement, and so on.

3. The task management plane: Is responsible for task distribution among sensor nodes in a sensing region in order to improve energy efficiency and prolong network lifetime. Since sensor nodes are usually densely deployed in a sensing region and are redundant for performing a sensing task, not all sensor nodes in the sensing region are required to perform the same sensing task.

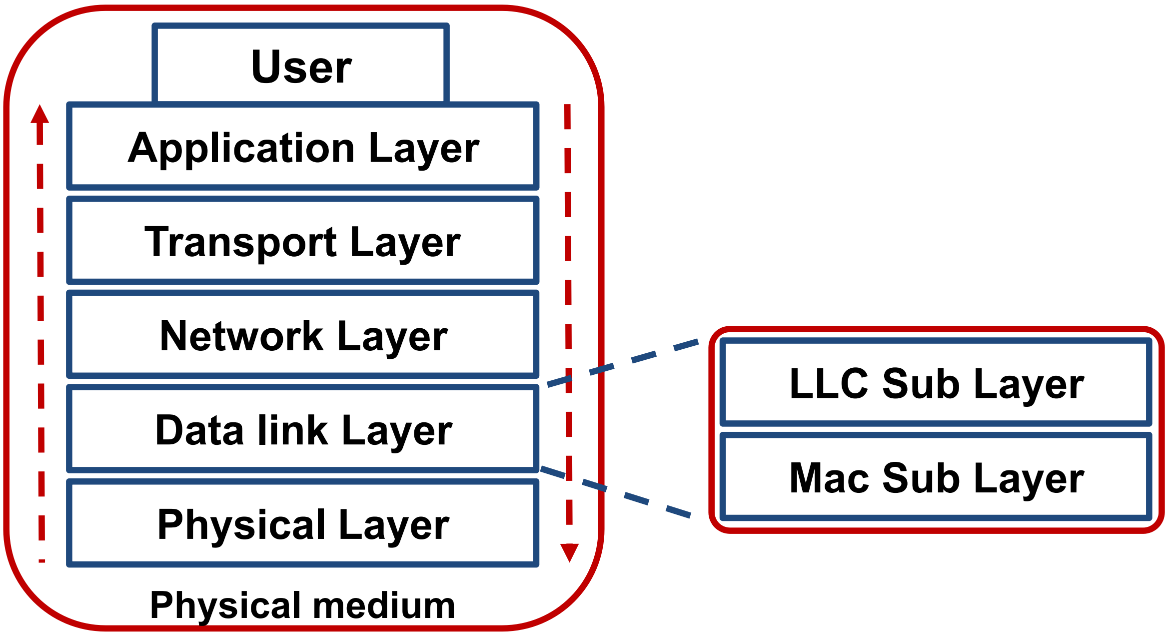

Fig. 1.6 The five-layered Stack and the sub-layers of the Data Link layer in WNs

5 Medium Access Control (MAC)

One of the most important functions of the data link layer is medium access control (MAC). The primary objective of MAC is to fairly and efficiently share the shared communication resources or medium among multiple sensor nodes in order to achieve good network performance in terms of energy consumption.Is one of the critical issues in the design of wireless sensor networks (WSNs) [33]. As in most wireless networks, collision, which is caused by two nodes sending data at the same time over the same transmission medium, is a great concern in WSNs. To address this problem, a sensor network must employ a MAC protocol to arbitrate access to the shared medium in order to avoid data collision from different nodes and at the same time to fairly and efficiently share the bandwidth resources among multiple sensor nodes. From the perspective of the Open Systems Interconnection (OSI) Reference Model (OSIRM), the MAC protocol functionalities are provided by the lower sub layer of the data link layer (DLL). The higher sub layer of the DLL is referred as the logical link control (LLC) layer. The subdivision of the data link layer into two sub layers is necessary to accommodate the logic required to manage access to a shared access communications medium. Furthermore, the presence of the LLC sub layer allows support for several MAC options, depending on the structure and topology of the network, the characteristics of the communication channel, and the quality of service requirements of the supported application. Figure 1.6 depicts the five-layered Stack model and the logical architecture of the DLL for shared medium access in wireless networks. The MAC sub layer resides directly above the physical layer. It supports the following basic functions:

- A header field containing addressing information and a trailer field for error detection.
- The disassembly of a received frame to extract addressing and error control information to perform address recognition and error detection and recovery
- The regulation of access to the shared. transmission medium in a way commensurate with the performance requirements of the supported application.

The LLC sub layer of the DDL provides a direct interface to the upper layer protocols. Its main purpose is to shield the upper layer protocols from the characteristics of the underlying physical network, thereby providing interoperability across different types of networks.

5.1 Objectives of MAC Design

The basic function of a MAC protocol is to arbitrate access to a shared medium in order to avoid collisions from different nodes. In addition to this basic function, a MAC protocol must also take into account other factors in its design in order to improve network performance and provide good network services for different applications. In WSNs, these mainly include energy efficiency, scalability, adaptability, channel utilization, latency, throughput, and fairness [34].

5.1.1 Energy Efficiency

Energy efficiency is one of the most important factors that must be considered in MAC design for sensor networks. It refers to the energy consumed per unit of successful communication. Since sensor nodes are usually battery powered and it is often very difficult or impossible to change or recharge batteries for sensor nodes, a MAC protocol must be energy efficient in order to maximize not only the lifetime of individual sensor nodes but also the lifetime of the entire network.

5.1.2 Scalability

Scalability refers to the ability to accommodate the change in network size. In sensor networks, the number of sensor nodes deployed may be on the order of tens, hundreds, or thousands. A MAC protocol must be scalable to such changes in network size.

5.1.3 Adaptability

Adaptability refers to the ability to accommodate the changes in node density and network topology. In sensor networks, node density can be very high. A node may fail, join, or move, which would result in changes in node density and network topology. A MAC protocol must be adaptive to such changes efficiently.

5.1.4 Channel Utilization

Channel utilization refers to the bandwidth utilization for effective communication. Due to limited bandwidth, a MAC protocol should make use of the bandwidth as efficiently as possible.

5.1.5 Latency

Latency refers to the delay from the time a sender has a packet to send until the time the packet is successfully received by the receiver. In sensor networks, the importance of latency depends on different applications. While it is true that latency is not a critical factor for some applications (e.g., data collection for scientific exploration), many applications may have stringent latency requirements (e.g., real-time monitoring of bush fires).

5.1.6 Throughput

Throughput refers to the amount of data successfully transferred from a sender to a receiver in a given time, usually measured in bits or bytes per second. It is affected by many factors, for example, the efficiency of collision avoidance, control overhead, channel utilization, and latency. Like latency, the importance of throughput depends on different applications.

5.1.7 Fairness

Fairness refers to the ability of different sensor nodes to equally share a common transmission channel. In some traditional networks, it is important to achieve fairness for each user in order to ensure the quality of service for their applications. In sensor networks, however, all nodes cooperate to accomplish a single common task. What is important is not to achieve per-node fairness, but to ensure the quality of service for the whole task.

Among all these factors, energy efficiency, scalability, and adaptability are the most important for the MAC design of sensor networks. In particular, energy consumption is the primary factor affecting the operational lifetime of individual nodes and the entire network.

5.2 Energy Efficiency in MAC Design

Energy efficiency is of primary importance in WSNs. In general, energy consumption occurs in three aspects: sensing, data processing, and data communication, where data communication is a major source of energy consumption. For this reason, it is desired to reduce data communication as much as possible in a sensor network. An efficient MAC protocol can improve energy efficiency in data communication and prolong the lifetime of a sensor network. To design an energy-efficient MAC protocol, it is important to identify the major sources of energy waste in sensor networks from the MAC perspective. According to Ref.[34], energy waste comes from four major sources: collision, overhearing, control overhead, and idle listening.

5.2.1 Collision

A collision occurs when two sensor nodes transmit their packets at the same time. As a result, the packets are corrupted and thus have to be discarded. Retransmissions of the packets increase both energy consumption and delivery latency.

5.2.2 Overhearing

Overhearing occurs when a sensor node receives packets that are destined for other nodes. Overhearing such packets results in unnecessary waste of energy and such waste can be very large when traffic load is heavy and node density is high.

5.2.3 Idle Listening

Idle listening occurs when a sensor node is listening to the radio channel to receive possible data packets while there are actually no data packets sent in the network. In this case, the node will stay in an idle state for a long time, which results in a large amount of energy waste. However, in many MAC protocols, for example, IEEE 802.11 ad hoc mode or CSMA, a node has to listen to the channel to receive possible data packets. There are reports that idle listening consumes 50 – 100% of the energy required for receiving data traffic.

5.2.4 Control packet overhead

An increase in the number and size of control packets results in overhead and unnecessary energy waste for WSNs, especially when only a few bytes of real data are transmitted in each message. Such control signals also decrease the channel capacity. A balanced approach is required so that the required number of control packets can be kept at minimal.

5.2.5 Over-emitting

An over-emitting or deafness occurs due to the transmission of the message when the destination node is not ready to receive it.

5.2.6 Complexity

Computationally expensive algorithms might decrease the time the node spends in the sleep mode. They might limit the processing time available for the application and other functionalities of the protocol. An overly simple MAC algorithm can save higher energy than a complex one, but it may not be able to provide the complex functions such as adaptation to traffic and topology conditions, clustering, or data aggregation.

6 WSN Energy efficient MAC protocols

The objective of the MAC protocol is to regulate access to the shared wireless medium such that the performance requirements of the underlying application are satisfied [35]. Therefore, a MAC protocol plays an important role in enabling normal network operation and achieving good network performance. Based on this, the MAC protocols can be typically classified into two broad categories: contention-based and contention-free.

6.1 Channel Access Methods

Channel access methods are based on multiplexing, where multiple signals are combined into one signal over a shared medium. The aim of multiplexing is the enhanced utilization of a limited bandwidth resource, where sharing is achieved in many ways: space-division, frequency-division, time-division, polarization division, orbital angular momentum and code-division multiplexing or some combination of them. The multiplexing methods can be used to form logical communication media channels, which can be divided for users by means of specific channel access methods known in the literature as multiple access protocols. These protocols are channel allocation schemes that provide desirable performance characteristics. In the OSI reference model, these protocols reside mostly within a special layer called the Medium Access Control (MAC) layer and the protocols are called MAC protocols. At the highest level of the classification, a distinction is made between conflict-free and contention protocols.

6.1.1 Conflict-free protocols

Ensuring a transmission which will not be interfered with another transmission. The conflict-free transmission can be achieved by allocating the channel to the users either statically or dynamically. Static allocation sets up the fixed bandwidth resources for users and dynamic allocation is based on demand so that a user uses only little, if any, of the channel resources, leaving the majority of its share to the other, more active users [36]. The static resource allocation can be done by various reservation schemes, which can be time-based like Time Division Multiple Access (TDMA), frequency-based like Frequency Division Multiple Access (FDMA), code-based like Code Division Multiple Access (CDMA) or hybrid-based like Orthogonal Frequency Division Multiple Access (OFDMA) (see figure 1.7).

1. FDMA is the simplest and oldest form of multiplexing. It divides a specific bandwidth into multiple frequency bands (channels). For data transmission, each of which is used by one or more users. Where each user is allocated a dedicated channel, different in frequency from the channels allocated to other users. The FDMA method is efficient if the user has a steady flow of information to transmit like voice data, but can be very inefficient if the data is sporadic and bursty , another hand in FDMA the channels cannot be very close to one another. A separation in frequency is required, in order to avoid inter-channel interference, as transmitters that transmit on a channel's main frequency band also output some energy on the sidebands of the channel[37].

2. TDMA is a technique that divides a single frequency channel into time slots instead of frequency bands (FDMA) and configures these timeslots into a frame that repeats periodically. Each node is allocated a timeslot and is allowed to transmit only in the allocated timeslot in each frame. The major advantage of TDMA is its energy efficiency because those nodes that do not transmit can be turned off. However, TDMA has some limitations as compared with other MAC protocols. For example, TDMA usually requires nodes to form clusters and it has limited scalability and adaptability to network changes. It requires strict time synchronization for timeslots [38].

3. CDMA divides the shared channel by using orthogonal pseudo-noise codes, rather than timeslots in TDMA and frequency bands in FDMA. All nodes can transmit in the same channel simultaneously, but with different pseudo-noise codes. CDMA can be understood by considering the example of various conversations using different languages taking place in the same room. In such as case, people that understand a certain language listen to that conversation and reject everything else in the other language [39]. The major advantage of CDMA is that it does not require strict time

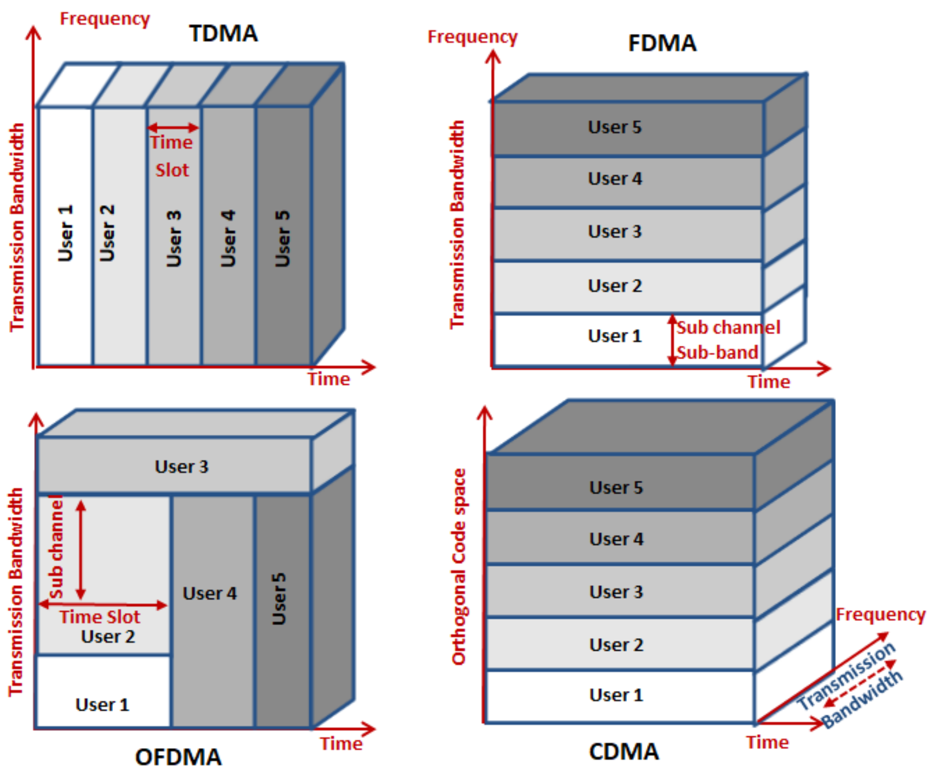

Fig. 1.7 Various Conflict-Free Transmission Schemes

synchronization and avoids the channel allocation problem in FDMA. However, it also has some disadvantages. For example, it introduces the energy consumption for coding and decoding. The capacity of a CDMA system in the presence of noise is usually lower than that of a TDMA system [40].

4. OFDMA divides a channel into multiple narrow orthogonal bands that do not interfere with one another. These methods are widely used in current cellular radio systems with other multiplexing techniques as mixed techniques.

In addition, the dynamic allocation of the channel can be done by various reservation schemes in which the users announce their intent to transmit or a token is passed among the users permitting only the token holder to transmit [36].

6.1.2 In contention-based MAC

All nodes share a common medium and contend for the medium for transmission. Thus, a collision may occur during the contention process. To avoid collision, a MAC protocol can be used to arbitrate access to the shared channel through some probabilistic coordination. Both ALOHA (Additive Link On-Line Hawaii System) and CSMA (Carrier Sense Multiple

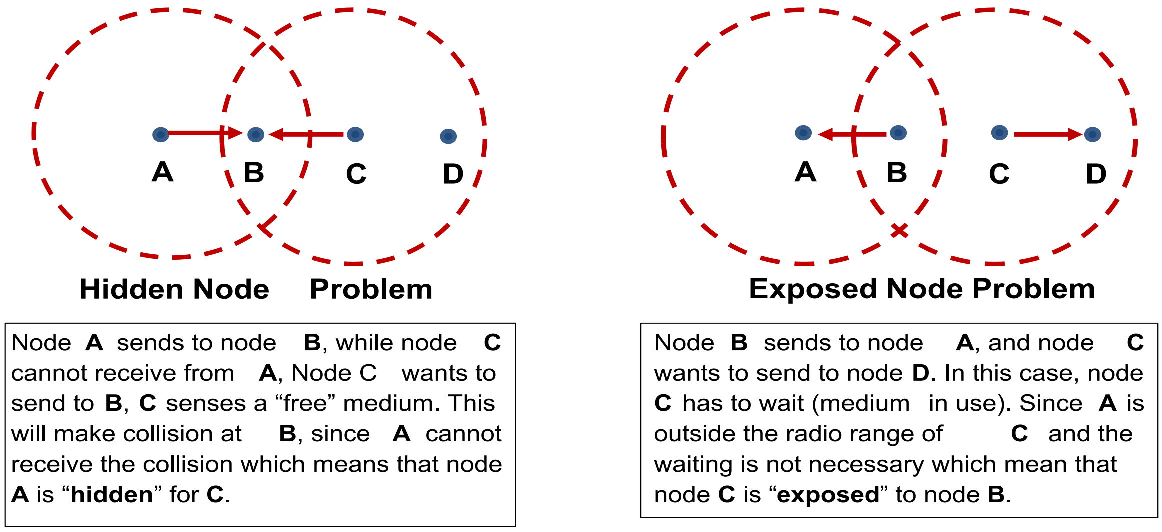

Fig. 1.8 The hidden terminal and exposed terminal problem

Access) are the most typical examples of contention-based MAC protocols. In pure ALOHA, a node simply transmits whenever it has a packet to send. In the event of a collision, the collided packet is discarded. The sender just waits a random period of time and then transmits the packet again. In slotted ALOHA, time is divided into discrete timeslots. Each node is allocated a timeslot. A node is not allowed to transmit until the beginning of the next timeslot. Pure ALOHA is easy to implement. However, its problem is that the channel efficiency is only 10% . Compared with pure ALOHA, slotted ALOHA can double the channel efficiency. However, it requires global time synchronization, which complicates the system implementation[41]. CSMA differs from ALOHA in that it uses carrier sense; that is, it allows a node to listen to the shared medium before transmission, rather than simply transmit immediately or at the beginning of the next timeslot. However, CSMA cannot handle the hidden terminal and Exposed terminal problem [42] (Figure1.8). To address this problem several different versions of CSMA has developed. The most popular is CSMA/CA he was developed and adopted in the IEEE 802.11 wireless LAN standard [43], where CA stands for collision avoidance.

In CSMA/CA, a handshake mechanism is introduced between a sender and a receiver. Before the sender transmits its data, it must establish a handshake with the receiver. The sender starts the handshake by sending a request-to-send (RTS) packet to the receiver. The receiver then acknowledges with a clear-to-send (CTS) packet. The sender starts transmitting data after it receives the CTS packet from the receiver. Through such a handshake process, the neighbors of both the sender and the receiver can know the transmission that is going on and thus back off without transmitting its own data.

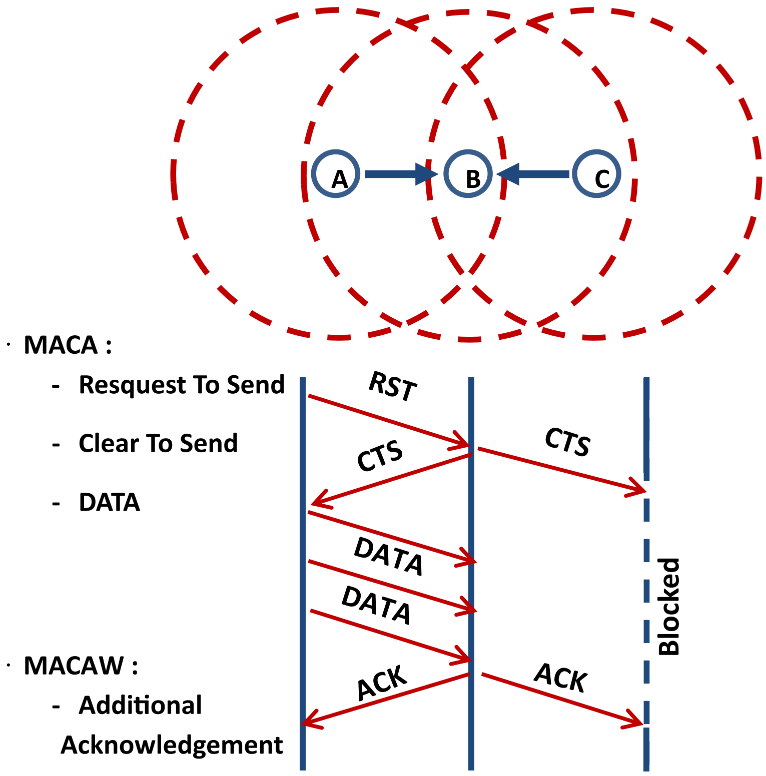

Fig. 1.9 CSMA/CA: Collision Avoidance

Therefore, if a node receives an RTS or CTS to other nodes, it should back off and does not send its own packet. In this case, collisions will mainly happen to RTS packets and can thus be reduced significantly.

To improve the performance of CSMA/CA, a MAC protocol called multiple accesses with collision avoidance (MACA) was developed for wireless local area networks (LANs) [44], which introduces an additional field in both RTS and CTS know how long they should back off. To further improve the performance of MACA, another protocol called MACAW was developed in [45], which makes several enhancements to MACA. For example, after each data packet, an acknowledgment (ACK) packet is used to enable fast link-layer recovery in the event of unsuccessful transmissions. The IEEE 802.11 distributed coordination function (DCF) was mainly based on MACAW and adopted all the features of CSMA/CA, MACA, and MACAW. More details on IEEE 802.11 in [43](Figure1.10).

6.2 WSN Energy efficient MAC protocols

A number of MAC solutions have been proposed aiming at energy efficiency. One efficient method to reduce energy consumption is to reduce duty cycling and extend the

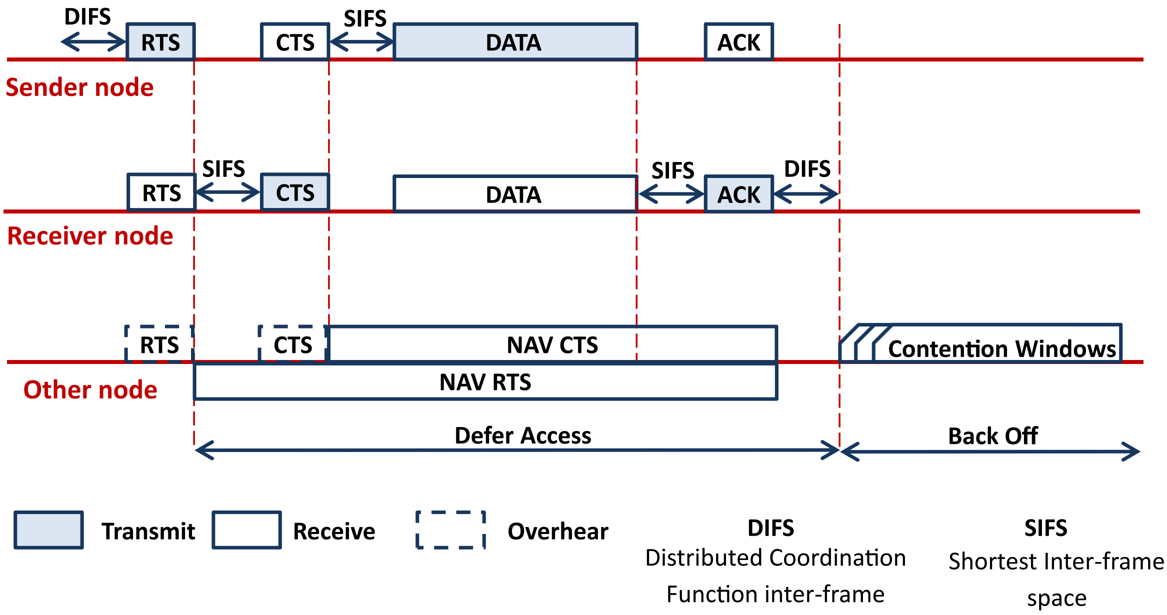

Fig. 1.10 IEEE 802.11 Access control

sleeping time with a suitable MAC protocol design. These solutions can be divided according to the nature of the channel access method: contention-free or contention-based, synchronous or asynchronous and hybrids. Division can be continued according to the multiplexing method used or as an energy-saving approach (collision avoidance, wake-up, redundancy, duty cycling and staggering). see Figure 1.11.

6.3 Contention-free protocols

TDMA-based protocols are time-scheduled systems, where communication takes place in fixed time slots. TDMA-based protocols have a built-in duty cycle that enables collision avoidance and reduces idle listening time [46]. The disadvantage is that they require co-ordination and synchronization for TDMA slot allocation, which consumes extra energy, especially in cases where the network topology changes frequently as in multi-hop ad hoc networks, the maintenance of slot synchronization causes overhead in the form of control traffic. With unstable links and frequent change of topology, it will be hard to maintain synchronization [47]. However, in one-hop or static networks and especially with regular sampling, TDMA-based solutions show good performance [48]. There is no contention between senders and the system provides a deterministic delay/reliability guarantee, which is advantageous in delay-sensitive applications. CDMA and OFDMA are used in cellular networks. The disadvantage of CDMA- and OFDMA-based solutions is that they will need more complex hardware, which rices the cost of the hardware.

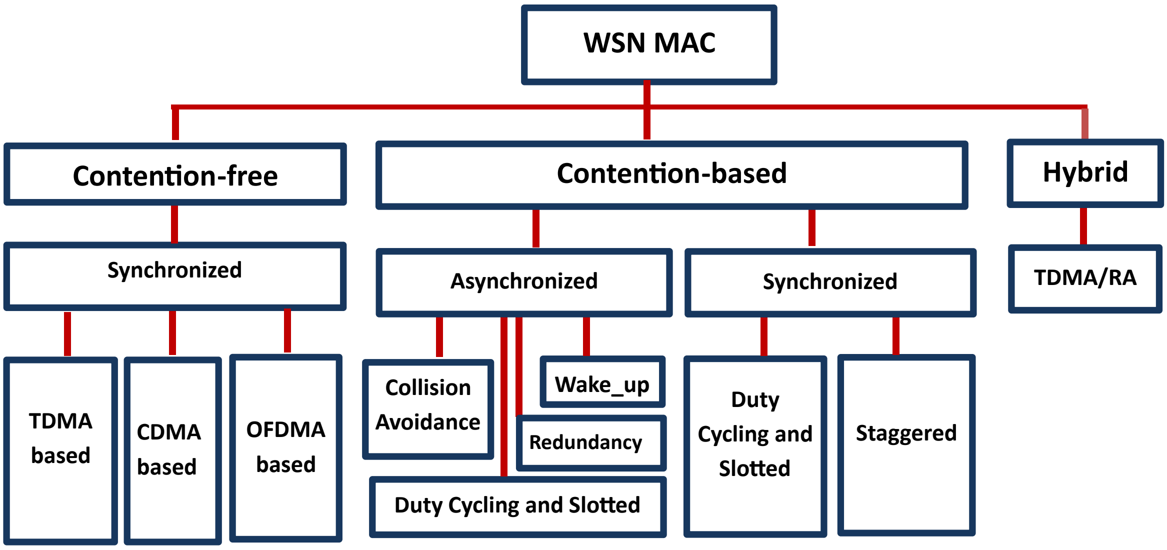

Fig. 1.11 WSN Energy efficient MAC protocols

6.4 Contention-based protocols

In contention-based methods, the bandwidth or channels are not assigned beforehand to any user. In the simplest version (ALOHA), users may transmit whenever they have data to send, i.e. random access (RA). If there are several users transmitting at the same time, collision will take place, which ruins transmissions. Collisions increase as a function of the number of transmitting users and will cause retransmission, which affects performance in delays and energy efficiency [**?**]. Several approaches for MAC that utilize collision avoidance and reduce both contention and idle listening have been proposed to improve energy efficiency. These approaches can be roughly divided into collision avoidance, duty cycling, redundancy, wake-up, slotted and staggering methods, which are to be discussed in the following sections.

6.4.1 Collision avoidance

CSMA-CA (Carrier Sense Multiple Access with Collision Avoidance) protocols listen to a carrier to see if the medium is free for transmission. If it is not, then some collision avoidance mechanism takes place. One such mechanism is a back-off mechanism where users wait for a random back-off time before transmission. The disadvantage of CSMA-CA is that when the network traffic increases, the contention will increase transmission delays [43].

6.4.2 Duty cycling and Slotted (synchronized)

When traffic has some interval patterns, the energy efficiency can be improved by coordinating the listen/sleep schedules according to traffic intervals, like S-MAC (Sensor-MAC) and T-MAC (Timeout-MAC). In order to make the schedules the system is synchronized by periodically exchanging SYNC (synchronization) packets. Depending on how the synchronization is set up, the schedules can be divided into centralized or distributed schemes. In the centralized scheme, the whole network follows the same schedules and thus needs centralized synchronization. If the network has some node or topology changes, the whole network needs to be synchronized. Therefore, the scalability of the system is reduced. To improve scalability and to avoid the synchronization of the whole network, distributed systems with clusters have been proposed. In distributed systems, synchronization is made locally in clusters where listen/sleep scheduling and updating can be done in clusters, as in OLS-MAC (Overlapped Schedules-MAC) [49].

1. S-MAC [50]: Is one of the famous energy-efficient protocols for wireless sensor networks. It is a contention-based random access protocol with a fixed listen/sleep cycle and uses a coordinated sleeping mechanism by using a synchronization packet (SYNC) between neighboring nodes. A time frame in S-MAC is divided into two parts: listen period and sleep period. During the listening period, SYNC and RTS (Request To Send)/CTS(Clear To Send) control packets are transmitted based on the CSMA/CA mechanism for the purpose of synchronization, avoiding collision and an announcement for the following data packet transmission. Any two nodes exchanging RTS/CTS packets in the listen period need to keep in an active state and start an actual data transmission without entering a sleep mode. Otherwise, all other nodes can enter the sleep mode in order to avoid any wasteful idle listening and overhearing problems (Figure1.12). In S-MAC, the duration of a listen period is always fixed and therefore causes unnecessary energy waste. For solving this problem suggests the adaptive listening scheme in Adaptive S-MAC [51] in which, in each transmitted packet there is a duration field that indicates how long the remaining transmission will be, so when a node receives a packet destined for another node, the node records this value in an variable called the network allocation vector (NAV) and sets a timer for it. Every time when the NAV timer fires, the node decrements the NAV value until it reaches zero. When a node has data to send, it first looks at the NAV. If its value is zero, the node determines that the medium is free and then tries to communicate with its neighbors without waiting for the next listen/sleep cycle. Although adaptive S-MAC can provide a solution for the latency problem but produce some disadvantage in the energy-saving

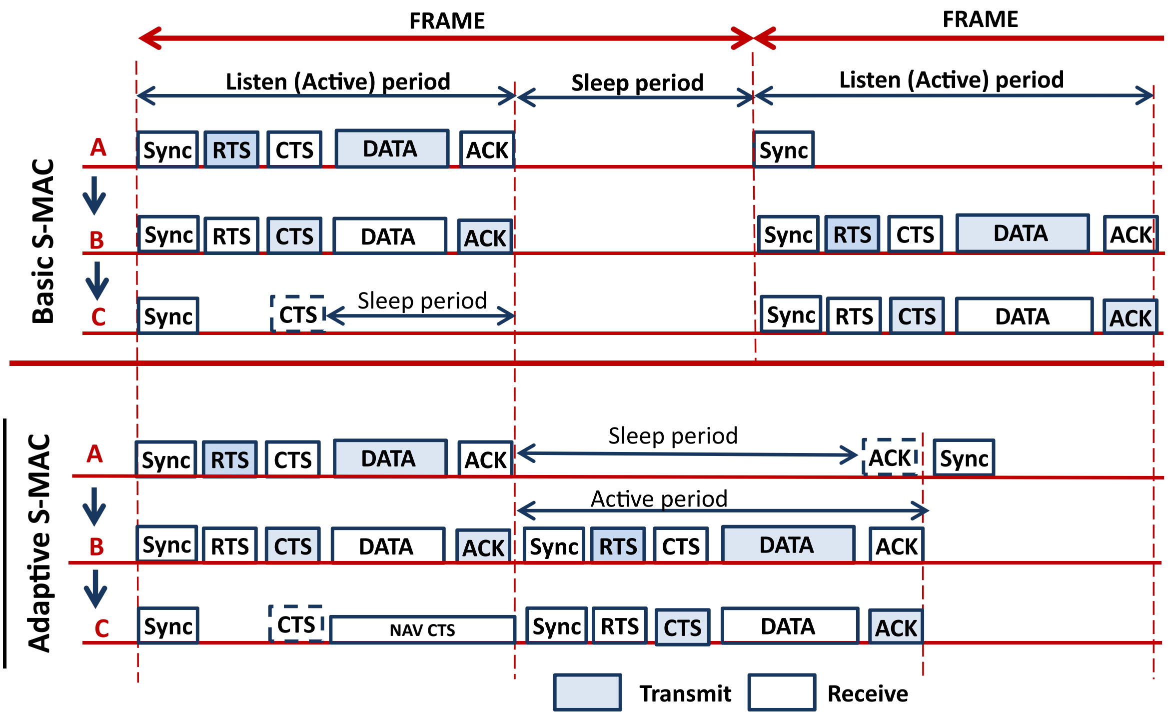

Fig. 1.12 S-MAC protocol duty cycles

because even nodes that do not participate in communication should wake up when their NAV timers expire. this problem is called the "compulsory wake-up problem".

2. Timeout-MAC (T-MAC): Is a successor of S-MAC that has been proposed to enhance the operation of S-MAC under a variable traffic load. T-MAC replace the fixed active time with adaptive active time. The adaptation is based on a monitoring of the activation events (like data reception and transmission) of a node. If no activation event has appeared after the specified time, the node goes to sleep(Figure1.13). Therefore, all the traffic must be buffered between activity periods and sent in bursts at the beginning of the next active period [52]. The advantage of T-MAC is that very low duty cycles can be obtained, but at the expense of high latency and a collapse under high loads[53].

6.4.3 Duty cycling and slotted (asynchronized)

To reduce and avoid collisions, several different methods have been developed such as slotted ALOHA. In slotted ALOHA, the time space is divided into sequenced time slots. If a node wants to send data, it starts transmission at the beginning of the next slot. If transmission is not successful, the node waits for random delay to make a new attempt. One efficient method to save energy with low traffic is duty cycling [54], where nodes go to sleep and wake up in a regular rhythm, which does not depend on the rhythm of other nodes. So, every node

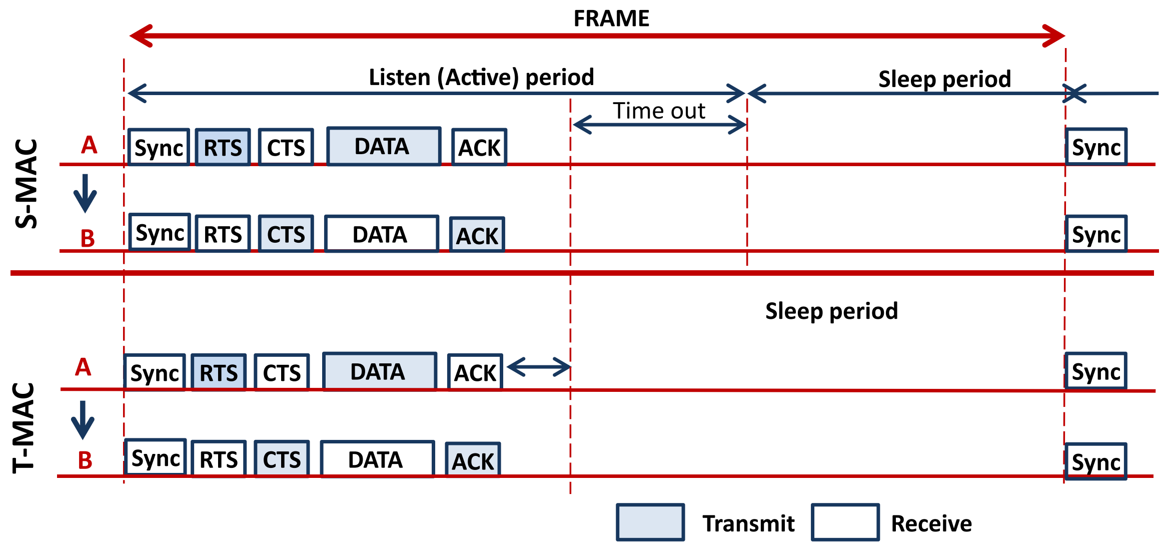

Fig. 1.13 T-MAC protocol duty cycles

has its own duty cycles and there is no need for synchronization between nodes, see B-MAC [55] and X-MAC [56] as examples. B-MAC and X-MAC nodes periodically wake up, i.e. they use low power listening (LPL) to sample the wireless channel to detect activity, i.e. preamble transmission. When the node has data to send, it starts the preamble before actual data transmission. When waking up nodes detect the preamble, they stay awake to receive data transmission or otherwise they go back to sleep. One shortcoming of B-MAC is the long preamble, which consumes transmitter energy and causes overhearing of the nodes that are awake. X-MAC improves energy efficiency by exchanging a long continuous preamble for a shorter train of strobe preambles (Figure1.14).

6.4.4 Redundancy

The basic idea is that the system has redundant nodes, which do not need to perform communication or measuring operations. These nodes can be put to sleep. To decide which nodes may go to sleep and which nodes need to participate, measurement, traffic and routing information etc. can be utilized. When routing information is used, then functionality is implemented in the network layer. One example of redundancy utilization is ASCENT (Adaptive Self-Configuring Sensor Networks Topologies) [57]. Initially, only some nodes are actives. If there is a very high packet loss, the sink node starts to request help from neighboring nodes. When the neighboring nodes receive the help request, they can decide to change from a passive to an active mode and start to help in packet routing.

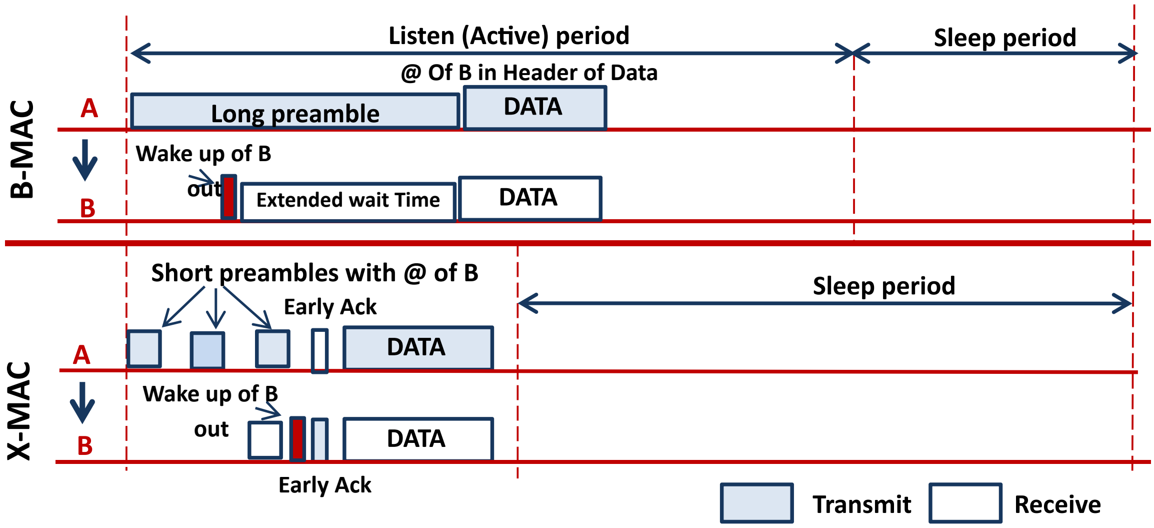

Fig. 1.14 B-MAC & X-MAC protocols

6.4.5 Wake-up

The wake-up approach is utilized in an on-demand communication, where a node, which requests information, can wake up others on demand. These systems are based on a wake-up scheme where nodes have two radios: one low-power radio for waking up and one radio for actual communication. Many studies are concerned with how to make an energy-efficient wake-up radio [58]. The advantage of this kind of system is that it can be scaled for different kinds of sampling rates and methods (event, interval and request) and can achieve low power consumption. However, in terms of cost, the disadvantage is that it needs two radio chips. A more detailed presentation about wake-up radio technology is given later in Chapter 2.

6.4.6 Staggering

The staggering approaches utilize the knowledge that data routes are structured like a tree, where children and parent nodes can be defined. When the relation of the nodes to each other is known, the nodes can be synchronized with each other according to defined, suitable duty cycles. Examples of staggered protocols are DMAC (data prediction is used MAC) and Duo-MAC (two-state asynchronous cascading wake-up scheduled MAC):

- DMAC is designed to allow packets to be forwarded continuously through a WSN from node to sink. This protocol assumes that the data is formed in trees that remain stable for a reasonable period of time. Because the data is gathered in trees, it is possible to stagger the wake-up scheme so that packets flow continuously from a sensor to a sink. The protocol also assumes fixed-length packets. To send multiple packets, more data flags are used to inform other nodes that there will be more packets [59]. The disadvantage of this protocol is that it can only be used in fairly stable networks; otherwise extra control traffic for resetting the routing tree will waste energy.

6.5 Hybrid protocols

The idea of hybrid methods is to combine the best properties of different methods, contention-based and contention-free (or synchronous and asynchronous), while reducing their shortcomings [60]. From the WSN point of view, the disadvantage of these protocols is increased software complexity compared to the basic contention-based or contention-free protocols. Complexity increases the need for data processing and memory usage. It may also lead to additional control traffic. Thus, even though hybrid protocols improve functionalities, they also increase the needs for constrained resources, which may reduce their applicability. In the following, we present examples of hybrids protocols:

- TRAMA (Traffic Adaptive Medium Access protocol) uses the random access method for control traffic and scheduled access for data traffic. The main idea is to determine time slots when the node is needed to communicate and when it can switch to idle mode. The communication slots are defined on the basis of transmission schedule information of two-hop neighborhoods [58].

- Z-MAC: To provide adaptive operation based on the contention level, the ZMAC protocol, takes the advantages of each scheme in hybrid MAC. The communication structure of the Z-MAC protocol depends on the time division scheme similar to TDMA, which allocates time slots for each node. However, different from the TDMA scheme, each time slot of the Z-MAC protocol can be occupied by other nodes when the slot is not used by the owner node. The main feature of Z - MAC is its adaptability to the dynamic contention level in the network. Under low contention, it behaves like CSMA and can achieve high channel utilization and low latency. Under high contention, it behaves like TDMA and can achieve high channel utilization and reduce collisions among 2 - hop neighbors at a low cost. Moreover, it is also robust to time synchronization errors, slot assignment failures, time-varying channel conditions, and dynamic topology changes. The shortcomings are the initial configuration costs and increased complexity [61].

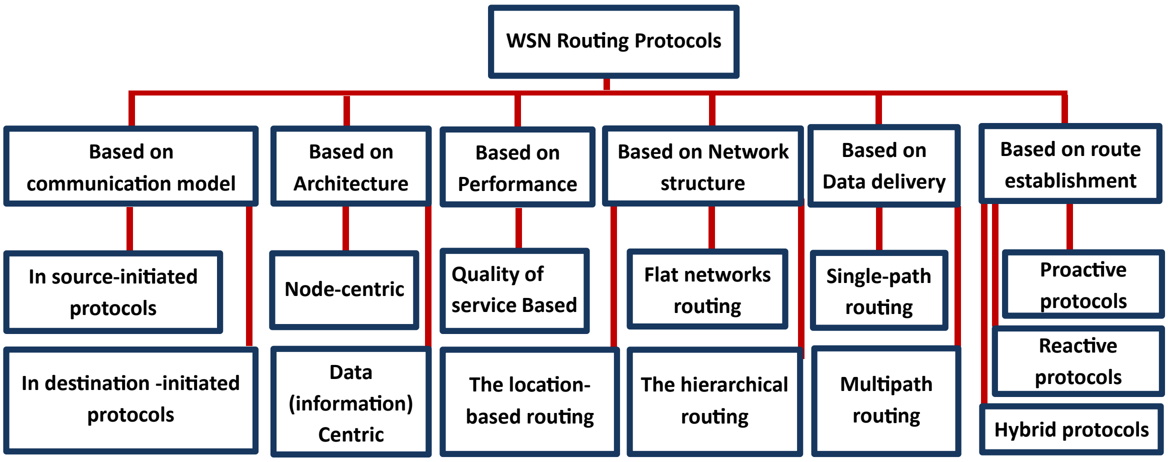

Fig. 1.15 The routing protocols classification

7 Routing Technologies in WSNs

A routing process is needed to select the best path(s) from the source node to the destination node. Routing may also be designed and optimized to support some specific requirements of applications and networks. These requirements include energy and bandwidth efficiency, quality of service, scalability, ad hoc support, throughput, mobility, and reliability. This will cause wide variation in requirements, which cannot be fulfilled by a single routing protocol. Based on the above, the routing protocols can be classified in several ways: network structure, communication model, data delivery, architecture, and performance requirements, see Figure 1.15. In practice, the classification is not strict and the protocol can belong to many classes [62].

7.1 Based on Performance

Sensing applications may have different requirements, which can be expressed in terms of some quality of service (QoS) metrics, such as delay, reliability with good energy efficiency, and fault tolerance.

QoS is an important issue when applications have strict requirements. For example, time-critical applications have delay bounds to meet. For such applications, the sensed data must reach the sink within a certain time. Also, the desired property of sensing applications is fault tolerance which it is meant that a network should remain functional in the event of sensor failures. Another desired property is reliability which it is meant that the sensed data should be received by the sink as correctly as possible to ensure accurate decision-making by the sink. Both fault tolerance and reliability require the deployment of more than necessary sensors so that the network can continue to function properly and deliver accurate sensed data to the sink despite some sensor failures. However, the use of redundant sensors yields additional energy consumption. Therefore, routing and data dissemination protocols should be designed in a way to trade-off between energy, fault tolerance, reliability, and delay. Recall that energy is a constraint that should be met by any routing and data dissemination protocol in order to guarantee efficient usage of the amount of energy available at each sensor.

Numerous routing protocols for ad hoc networks have been proposed that have specific aims such as scalability, robustness, real-time operation, and energy efficiency. Example In [63] A survey of energy-efficient routing in a wireless multimedia sensor network (WMSN) is produced. In the literature, these protocols are often classified according to the route establishment: proactive, reactive, and hybrid protocols.

7.2 Based on route establishment

Routes can be formed either before they are needed “proactively” or when they are needed “reactively”.

7.2.1 Proactive protocols

In proactive protocols, routing information is collected in routing tables and this information is utilized as the routing takes place. When the network structure is quite stable, knowing the possible routes in advance will speed up the routing. When the instability increases, the need for route updates and control traffic increases, which ultimately render the proactive approach inefficient. One example of a simple flat, proactive, source-initiated, ad-hoc protocol is AODV (Ad hoc On demand Distance Vector routing). In AODV, the routing tables are formed at the beginning before actual data delivery. First, all nodes broadcast a "HELLO" message and identify themselves to neighboring nodes. The neighboring nodes save this information in their routing table. When the node needs to transmit, it sends a route request to the neighboring nodes, which forward the message to the destination node. When the destination node receives the route request, it replies. This reply forms a route between the source and the destination. When the node next transmits to the same destination, existing routes can be used [64].

7.2.2 Reactive protocols

The reactive approach avoids the updating problem, but in that case new routes must be established consecutively and all route information included in the transmitted packets, which increases the packet size. Storing these routes for a specified time can help in avoiding unnecessary route establishment. There is a trade-off between route aging and refreshing. Obviously, because the new routes are established on demand this will delay communication compared with the proactive approach. Also, in the case of stable routes, removing the working route as obsolete will cause needless control traffic. Therefore, the reactive approach is preferable for an unstable route environment whereas, in a stable environment, the proactive approach will perform better. One example of a flat, reactive, source-initiated, ad-hoc protocol is DSR (Dynamic Source Routing). When a node wants to transmit, it first sends a route request to its neighboring nodes. The neighboring nodes which receive the route request forward it until it reaches the destination node. The route information is collected during forwarding. The destination returns a copy of this route information in a route reply message to the initiator [65]. [66] proposed a protocols to improve DSR energy efficiency, e.g. approaches similar to AODV, where the energy level of the nodes affects whether they participate in routing or not.

7.2.3 Hybrid protocols

Hybrid protocols aim to combine the advantages of both approaches and to avoid their disadvantages. In many cases, they will be more efficient in routing than proactive or reactive protocols alone, but with the added cost of increased complexity due to increased functionality and source code.

7.3 Based on communication model

A communication model can be source or destination initiated.

7.3.1 In source-initiated protocols

In source-initiated protocols, route discovery is initiated by the source, and routes are built upon the information needed. Reactive protocols are typically source-initiated, as the routes are discovered when the route to the destination is required.

7.3.2 In destination -initiated protocols

In the case of destination-initiated protocols, there is typically a central device (sink), from which a route graph is built. Which approach suits best depends on the overlaying application. One example of a routing protocol that uses both the source and destination methods for setting up routes is TUTWSNR (Tampere University of Technology Wireless Sensor Network Routing). In the set-up phase, sinks use the destination-initiated method to establish the routes to the sink. If some new node joins the network, it can instantly start source-initiated route discovery and does not need to wait for a sink to refresh the route information. In the route set-up phase, sinks present the route advertisement message (RADV), which is flooding the network. The RADV message includes information on sinks, route cost and sink/interest pairs. The route cost value is calculated from information on reliability, energy usage, available bandwidth and end-to-end delay. A node that receives RADV compares the included cost against the old cost. If the cost decreases, the node redirects its gradient and transmits the RADV with updated costs to its neighbours. If the route advertisement contains a sink/interest pair that is previously unknown, the node sends an interest request (IREQ). The IREQ is replied to with an interest advertisement (IADV), which contains the application-specific description of interests, such as the type of data and collection interval. Each node in the network broadcasts its RADV periodically or when a route cost changes significantly in order to maintain routing and interest information [67].

7.4 Based on Architecture

7.4.1 Node-centric

The node-centric approach is used in traditional routing protocols for WSNs, also known as address-centric protocols, the communication is based on node addresses (Equals the current IP networks), where all network nodes have defined addresses, when transmission takes place, the source and destination addresses will be known and routing will take place between them. In addition, each sensor sends its data to the sink independently of all other sensors.

7.4.2 Data (information) centric

An alternative approach is the information-centric networking (ICN) approach, see the survey by [68]. The actor who needs information requests that information from the network. When this information is found, it will be supplied to the actor. Every node that forwards information saves it in its cache memory. If some node needs the same information, it will search for the nearest node which has that information in its cache. Thus, the information-centric approach will enhance information distribution in two ways. No source addresses and routes are needed and the same information will be found in many places around the network. This speeds up information retrieval and balances traffic distribution. The drawback is that information requests flood the network. This will become a costly process if many nodes have to be woken up. Thus, in application cases where the nodes are in sleeping mode most of the time, routes are short and not many nodes/applications need the same information, the traditional node centric approach with known routes will be more energy-efficient.

7.5 Based on Data delivery

Considering data transmission between source sensors and the sink, there are two routing paradigms:

7.5.1 Single-path routing

In single-path routing, each source sensor sends its data to the sink via the shortest path.

7.5.2 Multipath routing

In multipath routing, to improve routing performance, each source sensor finds the first k shortest paths to the sink rather than one route can be created. The Performance can be improved through better throughput, faster routing, QoS support, enhanced load distribution(among these paths), and reliability. Usually, one route is the preferred route, based on the selected policy, and the others are backup routes. When there are multiple routes available, data can also be delivered through multiple parallel routes and in this way, improve the routing performance. The drawback of multiple routes is that the protocols become more complex. When using multiple routers, there is a trade-off between protocol complexity and improved performance. An example of multi-path, event-driven routing is Bee-Sensor-C. This is based on a dynamic cluster and bio-inspired algorithm, imitating the foraging behavior of a swarm of bees. The routing process is divided into three phases: cluster formation, multi-path construction and data transmission. The cluster forms around the event node and the other nodes decide to join the cluster according to the received "claim" signal strength. When an event occurs, every node sends a claim to be the cluster head after a specific delay, which depends on the residual energy of the node. The node which sends the first claim will be the cluster head. When the remaining energy of the cluster head node drops to 60% of the average energy of the cluster nodes, the cluster head is reselected. The route paths explore and report in a similar way as in AODV, except that the route request is called a forward scout and the route reply is called a backward scout. To limit broadcasting, the route request has set up a hop limit and to save energy the intermediate nodes can decide to join or refuse routing, based on their residual energy and the average residual energy of the path. When routes are established, the selection of the route used is based on probability and the quality of the route, which is analogous to the "waggle dance" of the honeybee, meaning that the best performing routes will be selected. To maintain routes, the "swarm" operation is used to determine the validity and update routes. After a specific time, the destination node (sink) will return the last "forager", data packet, to the cluster head "swarm". If no packets are returned, the "forager" will come back within the specific time, the routes will become invalid and a new route discovery process will start [69].

7.6 Based on Network structure

In terms of network structure, all routing protocols are classified in three sub-categories: Flat, Hierarchical, and Location-based routing protocols.

7.6.1 Flat networks

In flat networks, all nodes have the same role, where routing protocols may form and update routes by broadcasting route information through all the nodes in the network. When the network size increases, wide broadcasting becomes inefficient. This means that these protocols do not have good scalability and they are mainly suitable for small networks. Some examples are: SEER (Simple Energy Efficient Routing), SPIN (Sensor Protocols for Information via Negotiation), DD (Direct Diffusion).

SEER uses pre-created routing tables for data transmission, which are created during the initiation process. The source transmits a broadcast message which is flooded through the network in the initiation. The message includes information of the hop count and energy level of the neighboring nodes, and this information is saved in the routing table of each node. When the node wants to send data, it searches for a routing table neighbor which has a smaller hop count than itself and sends the data to that node. If there are many neighbors with a smaller hop count, then the node selects the neighbor which has the highest remaining energy and sends the data to that node. The remaining energy is then decreased before sending the message [70].

SPIN is an information-centric, source-initiated protocol where communication is based on negotiation between communication nodes and there is no need for a central controlling point. When the node has new information, it sends an advertisement message to its neighbors. If some neighbor wants this information, it replies with a request message and the node that has the information sends it to this neighbor. This avoids the flooding of data and ensures that only useful information will be transmitted. Every SPIN node has its own resource manager, which keeps track of resource consumption. If the energy level is low, the node can cut back on activities to increase its lifetime [71].

DD is another information-centric approach, where named Information is stored (cached) in network nodes. When some node wishes to have new information, it sends a request for information, "interest", to the network. In the first place where the information matches the interest, the node replies to the request and the information is "drawn" down towards the node that originated the interest request. Using the stored information will reduce the need for retrieving information from the originator, which reduces the length of routes, especially when many nodes/applications need the same information. Utilization of the stored information will save the transmission energy thanks to shorter routes and a distributed communication load due to multiple sources of information [72].

7.6.2 The location-based routing protocols

The main idea of routing protocols in this category is to utilize the advantage of the locations of the wireless sensor nodes in the routing of the data. The address of each node is determined, based on its physical location. The location of each node may be determined by satellite through the Global Positioning System (GPS) technique or other positioning techniques. The distance to the neighbors can be calculated depending on the signal strength.

The protocol GAF (Geographic Adaptive Fidelity) is concerned primarily with energy awareness without affecting the routing dependability which divides the sensors of the network into a fixed virtual grid zone. The nodes which belong to the same grid are equivalent with respect to routing and decide which will sleep and for how long. Some of these nodes can then be turned off without losing the routing fidelity thus saving more power; but since GAF depends on GPS technique to determine the positions of the wireless sensor nodes, this is not always available, especially for indoor applications. Moreover, this routing protocol places extra overhead on the memory unit in order to save each node's neighbor's address [73].

7.6.3 The hierarchical routing protocols

Hierarchical routing was originally proposed as a method to route data in wired networks. However, it is also suitable for routing data in wireless networks with some enhancement related to network scalability and the efficiency of communication. The main concept of the hierarchical routing protocols depends on dividing the wireless sensor nodes into more than one level. Most hierarchical routing protocols consist of two routing layers, the first one is responsible for selecting the cluster heads, and the second is related to routing decisions. For example, hierarchical routing protocols, that need to achieve very low power consumption, can divide the sensor nodes depending on their energy level. The nodes with a high energy level can be assigned to process and transmit data, while the nodes with a lower energy level can be assigned only to sense events. The formation of clusters within the network nodes can improve the efficiency and the scalability of the sensor nodes. There are many hierarchical routing protocols like LEACH (Low-Energy Adaptive Clustering Hierarchy) [74], which is one of the earliest and has several successors [75]]. A more detail about LEACH is given in next section.

8 Hierarchical Routings Protocols

The collaboration among sensor nodes is very important in WSNs, these sensor nodes periodically monitor or sense the conditions of the targets, and process the data, All of these nodes collaborate together for sensed and transmit reliable data to a base station. Where data collected from multiple sensor nodes can offer valuable inference about the environment. Additionally, The collaboration among sensor nodes can provide trade-offs between communication cost and computation energy. Moreover, it is likely that the data acquired from one sensor node are highly correlated with the data from its neighbors; data aggregation can reduce the redundant information transmitted in the network. Additionally, when the base station is far away, there are significant advantages to using local data aggregation instead of direct communication. Thus, node clustering, which aggregates nodes into groups (clusters), is critical to facilitating the practical deployment and operation of WSNs [15].

Hierarchical routing provides better energy efficiency and scalability due to its architecture. In this type of protocol, the whole network is divided into clusters and some nodes are chosen as special nodes based on certain criteria. These special nodes called cluster heads (CHs) collect, aggregate and compress the information received from neighbor's nodes, and finally transmit the compressed information to the BS.

8.1 Cluster Head Election Algorithms

Properly selecting the cluster heads can lower the rate for refreshing clusters and therefore reduce the overhead in the ad hoc environments. Most node clustering algorithms adopt one of four cluster-head selecting algorithms. According to their specific situations and applications.

8.1.1 Lowest ID Clustering Algorithm

The lowest ID (LID) clustering algorithm is a 2 - hop clustering algorithm [76]. While executing this algorithm, a node periodically broadcasts the list of nodes that it can hear (including itself). A node, which only hears the nodes with IDs higher than itself from the 1 - hop neighborhood, declares itself as the cluster head. It then broadcasts its ID and cluster ID.

A node that can hear two or more cluster heads is a gateway node; otherwise, it is an ordinary node or a cluster head. Simulation results showed that the LID algorithm is more stable in an environment in which the network topology changes frequently [77].

8.1.2 Highest Connectivity Clustering Algorithm

The highest connectivity (HCN) clustering algorithm elects the node with the highest connectivity (degree) in a neighborhood as the cluster head [78]. The connectivity of a node is the number of links to its 1 - hop neighbors. Each node broadcasts the list of nodes that it can hear (including itself). In the case of a tie, the LID node is chosen as the cluster head. A node, which has already elected another node as its cluster head, gives up its role as the cluster head.

8.1.3 Least Cluster Change Algorithm

The least cluster change (LCC) algorithm is proposed to minimize the frequency of cluster - head change, where cluster stability is a major consideration under certain circumstances [79]. In the LCC algorithm, the cluster heads may change only under either one of these two conditions:

- Two cluster heads come within the transmission range of each other.
- A node loses its membership in any other cluster and forms a new cluster.

When it needs to form initial clusters or reselect cluster heads, LCC will use the LID or HCN clustering algorithm. Since the changes of cluster heads are minimized, the cluster structures will not change frequently when nodes join or leave the clusters. The LCC clustering algorithm is robust in an environment in which the network topology changes frequently, and has low routing overhead and latency. However, the load distribution would be unfair for all nodes.

8.1.4 Weighted Clustering Algorithm

The weighted clustering algorithm (WCA) is based on a combined weight metric, which includes one or more parameters, for example, the node degree, distances with respect to a node's neighbors, node speed, and the time spent as a cluster head [80]. Each node broadcasts its weight value to all other nodes. A node is chosen to be a cluster head if its weight is the highest among its neighbors; otherwise, it joins a neighboring cluster. In the event of a tie, the LID algorithm is applied. Basically, a node has to wait for all the responses from its neighbors to make its own decision, and as a result, the latency and the overhead induced by WCA are very heavy. None of the above heuristics algorithms leads to an optimal election of cluster heads because each deals with only a subset of the parameters that can possibly impose constraints on the network. Each of these heuristics is suitable for a specific application rather than for generic wireless networks.

The CHs provides additional services to other nodes in the cluster, it is responsible for coordination among the sensor nodes within their clusters and aggregation of their data (intra-cluster-coordination), and communication with other cluster heads or external observers on behalf of their clusters (inter-cluster communication). As a cluster head needs to perform more load, it may consume energy at a much faster rate as compared to other nodes of the cluster. So cluster rotation is a common method deployed to balance the energy dissipation within a cluster.

The first hierarchical routing protocol was proposed by Heinzelman et al. [81] known as LEACH (low energy adaptive clustering hierarchy). A number of hierarchical clustering protocols have been developed by considering LEACH as the basic protocol and applying different factors over it.

Popular clustering routing algorithms in WSNs include LEACH, HEED [82], PEGASIS[83], EECS [84], EEMC [85], TEEN [86], PANEL [87] and T-LEACH[88].

8.2 LEACH (Low Energy Adaptive Clustering Hierarchy) Protocol

LEACH is a pioneer clustering routing protocol for WSN. The main objective of LEACH is to increase the energy efficiency by rotation-based CH selection using a random number. The LEACH protocol architecture is shown in Figure 1.16. The operation of LEACH consists of several rounds where each round is divided into two phases: the set-up phase and the steady state phase as shown in Figure 1.17.

1. During the setup phase. CH selection, cluster formation and assignment of a TDMA (Time Division Multiple Access) schedule by the CH for member nodes are performed.

    - In CH selection, each node participates in a CH election process by generating a random priority value between 0 and 1. If the generated random number of a sensor node is less than a threshold value T(n) then that node becomes CH. The value of T(n) is calculated using Equation 3.1.

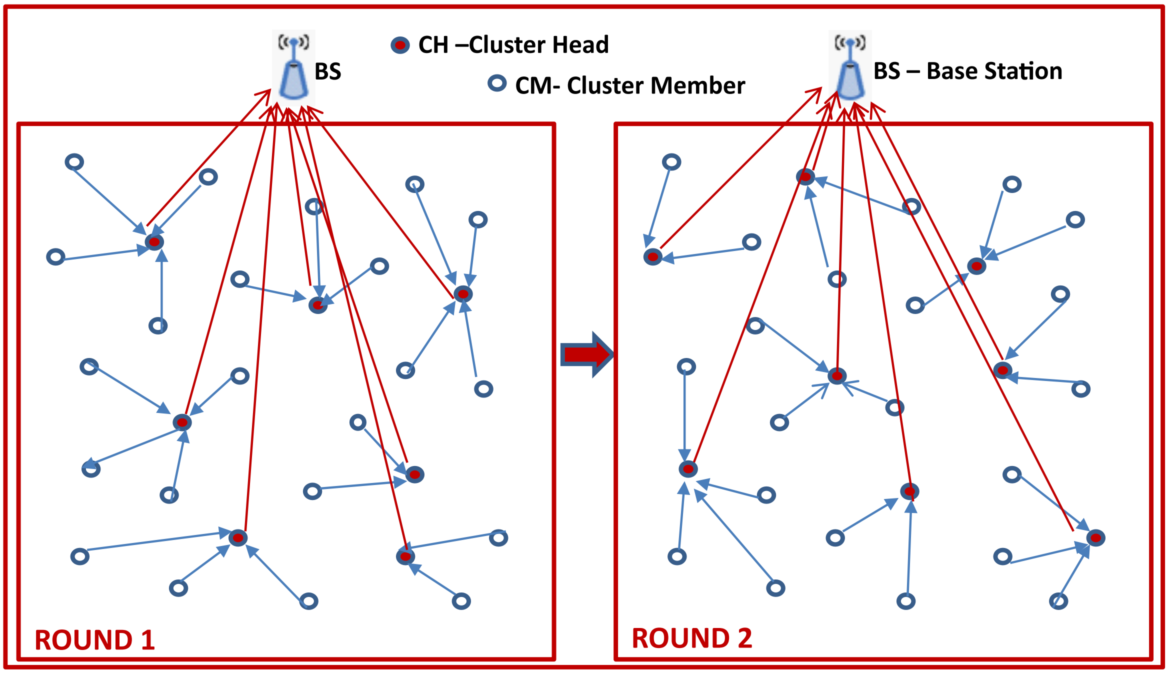

Fig. 1.16 LEACH protocol architecture

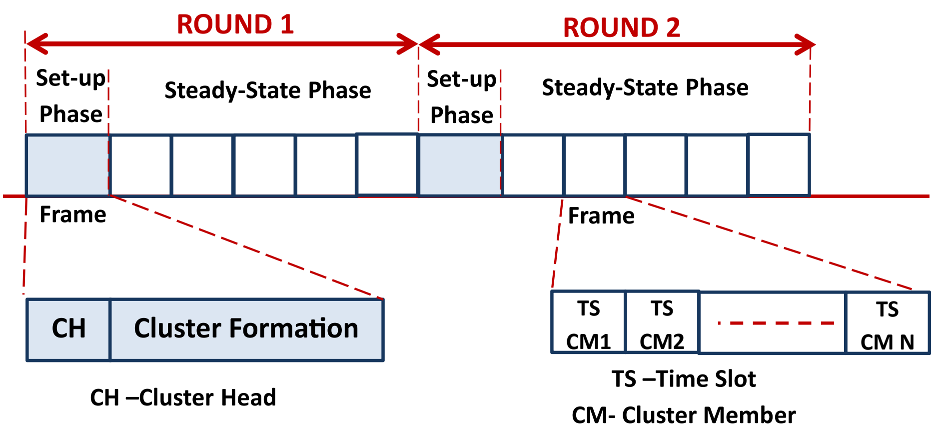

Fig. 1.17 The operation of LEACH

$$T(n) = \begin{cases} \dfrac{P}{1 - P * (r \, mod \, \dfrac{1}{P})} & if \, n \in G. \\ \\ 0 & otherwise \end{cases} \tag{1.1}$$

Where P denotes the desired percentage of sensor nodes to become CHs among all sensor nodes, r denotes the current round and G is the set of sensor nodes that have not participated in CH election in previous 1/P rounds. A node that becomes the CH in round r cannot participate in the next 1/P rounds. In this way every node gets equal chance to become the CH and energy dissipation among the sensor nodes is distributed uniformly.

- Once a node is selected as the CH, it broadcasts an advertisement message to all other nodes. Depending on the received signal strength of the advertisement message, sensor nodes decide to join a CH for the current round and send a join message to this CH. By generating a new advertisement message based on Equation 1, CHs rotate in each round in order to evenly distribute the energy load in the sensor nodes.
- After the formation of the cluster, each CH creates a TDMA schedule and transmits these schedules to their members within the cluster. The TDMA schedule avoids the collision of data sent by member nodes and permits the member nodes to go into sleep mode. The set-up phase is completed if every sensor node knows its TDMA schedule.

2. In the steady state phase, transmission of sensed data from member nodes to the CH and CH to the BS are performed using the TDMA schedule.

   - Member nodes send data to the CH only during their allocated time slot. When any one member node sends data to the CH during its allocated time slot, another member node of that cluster remains in the sleep state. This property of LEACH reduces intra cluster collision and energy dissipation which increases the battery life of all member nodes.
   - Additionally, CHs aggregate data received from their cluster members and send it directly to the BS. Transmission of data from the CH to the BS is also performed with the help of the allotted TDMA schedule. The CH senses the states of the channel for sending its data. If the channel is busy i.e. it is being used by any

other CH then it waits; otherwise it uses the channel to transmit the data to the BS.

8.3 Advantages of LEACH

LEACH is a complete distributed routing protocol in nature. Hence, it does not require global information. The main advantages of LEACH include the following:

1. Concept of clustering used by LEACH protocol enforces less communication between sensor nodes and the BS, which increases the network lifetime.

2. CH reduces correlated data locally by applying data aggregation technique which reduces the significant amount of energy consumption.

3. Allocation of TDMA schedule by the CH to member nodes allows the member nodes to go into sleep mode. This prevents intra cluster collisions and enhances the battery lifetime of sensor nodes.

4. LEACH protocol gives equal chance to every sensor node to become the CH at least once and to become a member node many times throughout its lifetime. This randomized rotation of the CH enhances the network lifetime.

8.4 Disadvantages of LEACH

However, there exist some disadvantages in LEACH which are as follows:

1. In each round the CH is chosen randomly and the probability of becoming the CH is the same for each sensor node. After completion of some rounds, the probability of sensor nodes with high energy as well as low energy becoming the CH is the same. If the sensor node with less energy is chosen as the CH, then it dies quickly. Therefore, robustness of the network is affected and lifetime of the network degrades.

2. LEACH does not guarantee the position and number of CHs in each round. Formation of clusters in basic LEACH is random and leads to unequal distribution of clusters in the network. Further, in some clusters the position of the CH may be in the middle of the clusters, and in some clusters the position of the CH may be near the boundaries of the clusters. As a result, intra cluster communication in such a scenario leads to higher energy dissipation and decreases the overall performance of the sensor network.

3. LEACH follows single hop communication between the CH and the BS. When the sensing area is beyond a certain distance, CHs which are far away from the BS spend more energy compared to CHs which are near to the BS. This leads to uneven energy dissipation which ultimately degrades the lifetime of the sensor network.

LEACH protocol follows single hop communication which plays a major role in achieving better performance. If the network area is not very large, and useful due to minimizing overhead and minimum delay. Due to direct communication, it is not necessary to communicate/set up a path with other relay nodes or the CH, thus minimizing communication cost and network delay and increasing network lifetime. But, When the sensing area is beyond a certain distance, CHs which are far away from the BS spend more energy compared to CHs which are near to the BS. This leads to uneven energy dissipation which ultimately degrades the lifetime of the sensor network. So it has been improved using multi-hop communication, where the CH sends its data via some intermediate nodes to the BS. Intermediate nodes are either some relay nodes or other CHs which forward received data towards the BS, which increases energy efficiency.

The successors of LEACH have mainly focused on improving inter and intra-cluster communication, CH selection, cluster formation, and scalability. These improvements achieve energy efficiency and scalability in WSN. Figure 1.18 summarizes all axis of these improvements.

All the clustering protocols related to LEACH have the same common objective: to reduce energy consumption and extend the network lifetime. However, the major goals for proposing LEACH variants protocols for WSNs are the following:

- Energy-efficient communication in WSN.
- Improvement in scalability.
- Increasing the security in WSN.
- Minimization of network delay.
- Reduction of complexity.
- Assurance of connectivity under various scenarios.
- Equal load distribution over the entire network.
- Improvement of the overall performance in WSN.

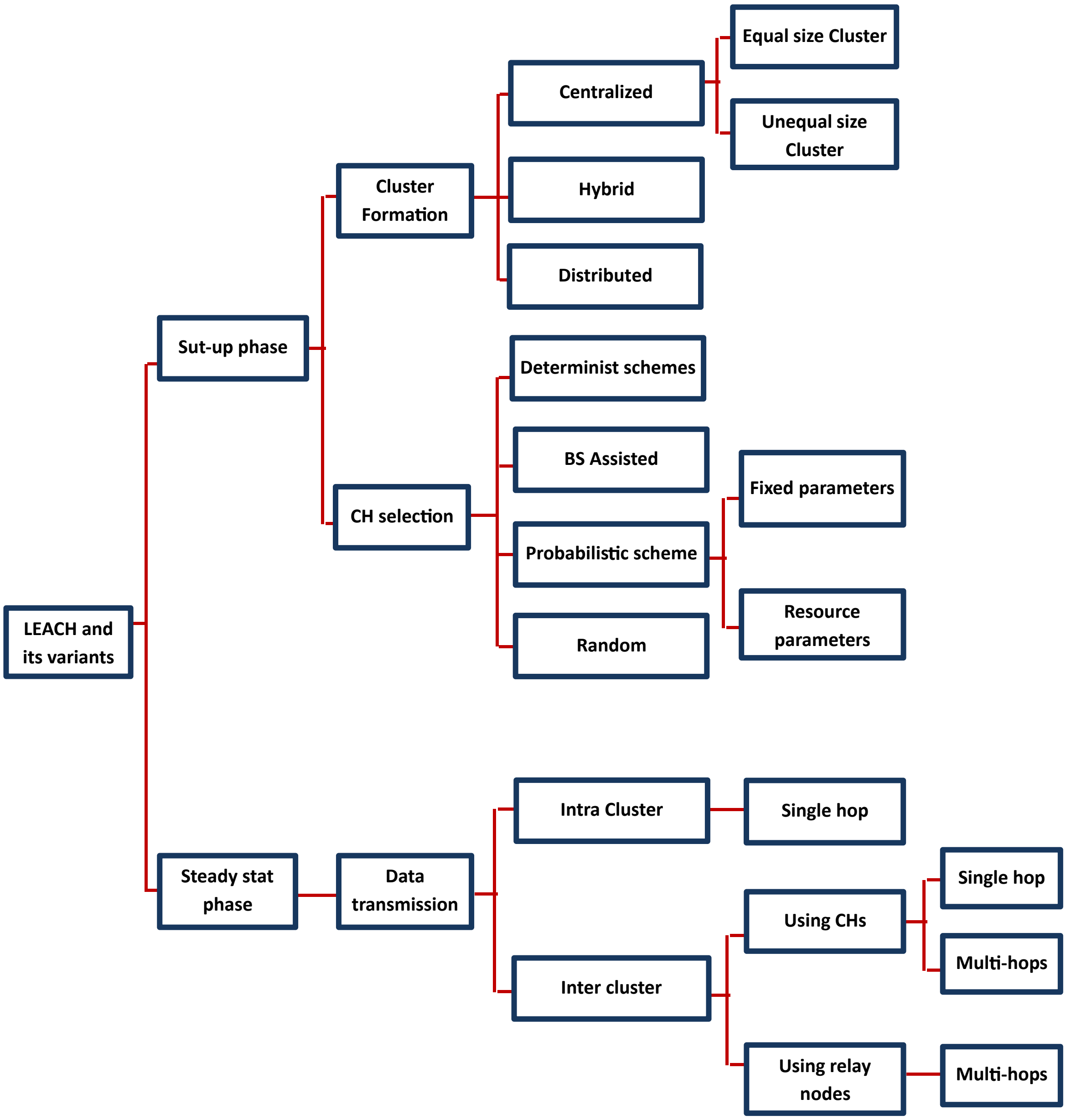

Fig. 1.18 Phases of LEACH and its variants in WSN

The literature indicate that the design of a proper LEACH-related protocol mainly depends on a user's requirements and their applications. Although LEACH has been broadly investigated by researchers in different domains, there still remain a number of issues of LEACH to be explored in the future [75].

9 Conclusion

This chapter gave an introduction to WSNs and described the different architectures, and protocol stacks with an emphasis on the fundamental concepts of the MAC layer. The chapter also discussed the major challenges in MAC and the important role it plays in improving energy efficiency and network performance of WSNs. Additionally, the chapter presented a survey of MAC protocols for WSNs and a sample of existing routing and data dissemination protocols for WSNs. The criteria that were considered were energy and bandwidth efficiency, quality of service, scalability, ad hoc support, throughput, mobility, and reliability. The focus was put on hierarchical protocols and a study LEACH as a sample because this thesis is based on this type, and it can be considered as one of its successors.

Chapter 2

Cross Layer Design in WSNs

1 Introduction

The concept of WSNs has many applications in different areas such as the medical, environmental, civilian and military domains. But always The routing of information, has been a challenge for researchers in this field to find new protocols for data transmission by saving energy and keeping the stability of this type of networks that are characterized by the limited energy of the sensors and the difficulty of replacing their batteries. To overcome these problems, many novel architectures and approaches have been proposed that implicitly and explicitly violate the rules of strictly layered design, cutting across traditional layer boundaries. And this with sharing of information between the different layers of the protocol stacks to improve flexibility and increase inter-layer interactions. These many different solutions and motivations for cross-layer design in WSNs are presented below.

In this chapter, we begin with the definition for cross-layer design, discuss the basic types of cross-layer design and categorize how cross-layer interactions may be implemented with examples drawn from the literature. The emphasis is on the use of protocols across layers on two types of protocols: hierarchical protocols and protocols that you used as a novel solution based on the use of wake-up radio (WuR). We show the different types and features taken into consideration in their respective design.

2 Cross Layer architecture

A layered architecture, like the seven-layer open systems interconnect (OSI) model, divides the overall networking task into layers and defines a hierarchy of services to be provided by the individual layers. The services at the layers are realized by designing protocols for the different layers. The architecture forbids direct communication between nonadjacent layers; communication between adjacent layers is limited to procedure calls and responses. In the framework of a reference layered architecture, protocols can be designed by respecting the rules of the reference architecture. such that a higher-layer protocol makes only use of the services at the lower layers and is not concerned about the details of how the service is being provided. Following the architecture also implies that protocols would not need any interfaces not present in the reference architecture. Alternatively, protocols can be designed by violating the reference architecture, for example, by allowing direct communication between protocols at nonadjacent layers or sharing variables between layers. Such violation of a layered architecture is cross-layer design with respect to the reference architecture.

2.1 Cross Layer Design

The open systems interconnection (OSI) model organizes a networking framework between them. Each layer is responsible for a well-defined function to offer services to the higher layers without revealing the details of how the service was implemented. Although the conventional layered structure offers the benefits of modularity, standardization, and expandability, its firm and strict architecture make the layered structure inefficient to deal with the problems arise due to the random nature of the wireless medium. As a result, the strict boundary between different layers of network in the new designs is blurring and the so-called cross-layer design has received popularity in wireless networks due to its high performance, especially in data routing. In essence, today's wireless networks and applications demand for flexible interactions among different layers of network. As in any other case, these flexible interactions also come at a cost of design complication [89]. Instead of solving the problem in parts at Different layers, Cross-layer design problems extend to a broader region ranging across multiple layers. This makes the process of obtaining global solutions more difficult. A large number of Cross-layer designs have been proposed in the literature [90] [91] Figure 2.1 demonstrates some of these cross- layer design concepts.

A) Backward and forward information flow Cross layer design provides information flow across layers via specialized interfaces. Information received from other layers provides useful knowledge of network status and communication characteristics that may be exploited in better decision making, parameters modification, etc.

B) In design coupling without new interfaces cross-layer method, multiple layers are developed in a collaborative approach. The design of one is conducted by considering another layer functionality, therefore dependency is created at the time of designing.

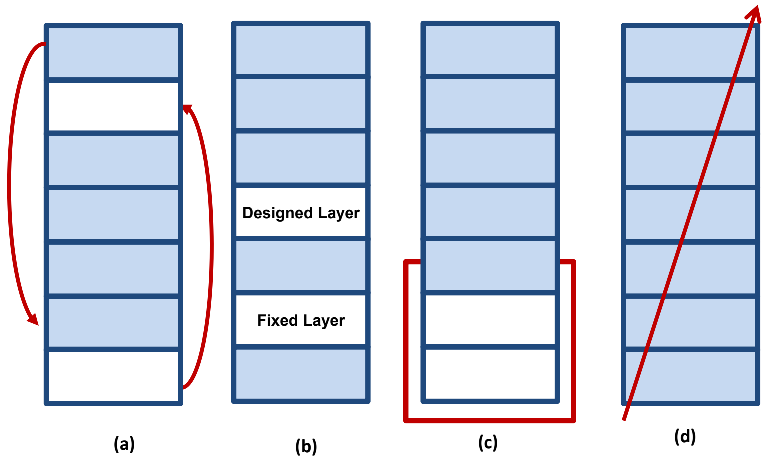

Fig. 2.1 Illustrating the different kinds of cross-layer design proposals. (a) backward and forward information flow cross-layer, (b) design coupling without new interfaces, (c) merging of adjacent layers, (d) vertical calibration

The referenced layer is called fixed layer and the dependent layer is called designed layer. Since the designed layer is developed based on fixed layer, an explicit interface between them is not required.

C) In the merging of adjacent layers method a single super-layer is created by combining the service and functionalities of the adjacent layer. In this method joint optimization can be applied directly to the super-layer. Obviously, this approach does not involve any additional interfaces. However, this method is uncommon due to the complexity it introduces to the network.

D) Vertical calibration across layers. This method refers to parameter adjustment that span across layers. Basically, the application layer performance is a function of the parameters at all the stack layers. Hence, it is reasonable that jointly optimizing all parameters of downstream layers can help to achieve better performance than individual layer configuration.

For example transmission power and data rate are PHY physique layer parameters, whereas delay is a performance measure at the data link layer (DLL) and transmission control protocol (TCP), and packet loss may occur due to bad wireless channel condition (PHY), or congestion (TCP), or queueing (DLL). Moreover, user-specified protocols demands lie in the application layer (APP), therefore other layers need to get some details from the application layer to adapt their parameters accordingly.

2.2 Cross-Layer Interactions

Alongside the cross-layer design proposals discussed earlier, initial proposals on how Cross layer interactions can be implemented are also being made in the literature. These can be put into three categories:

- Direct communication between layers.
- A shared database across the layers.
- Completely new abstractions.

2.2.1 Cross-layer architecture based on direct communication

A straightforward way to allow runtime information sharing between layers is to allow them to communicate with each other, as depicted schematically in Fig. 2.2(a). Practically speaking, direct communication between the layers means making the variables at one layer visible to the other layers at runtime. By contrast, under a strictly layered architecture, every layer manages its own variables, and its variables are of no concern to other layers. There are many ways in which the layers can communicate with one another. For instance, protocol headers may be used to allow flow of information between layers. Alternatively, extra interlayer information could be treated as internal packets. The work in [92] presents a comparative study of several such proposals and goes on to present another such proposal, cross-layer signaling shortcuts (CLASS). CLASS allows any two layers to communicate directly with one another.

These proposals are good where just a few cross-layer information exchanges are to be implemented in systems that were originally designed in conformance with layered architectures. However, in general, when variables and internal states from different layers are to be shared as prescribed by such proposals, a number of implementation issues relating to managing shared memory spaces between layers may need to be resolved.

2.2.2 Cross-layer architecture based on indirect communication

The other class of proposals proposes a common database that can be accessed by all layers, as illustrated in Figure 2.2(b) [93]. In one sense, the common database is like a new layer, providing the service of storage/retrieval of information to all the layers.

The shared database approach is particularly well suited to vertical calibrations across layers. An optimization program can interface with the different layers at once through the shared database. Similarly, new interfaces between the layers can also be realized through

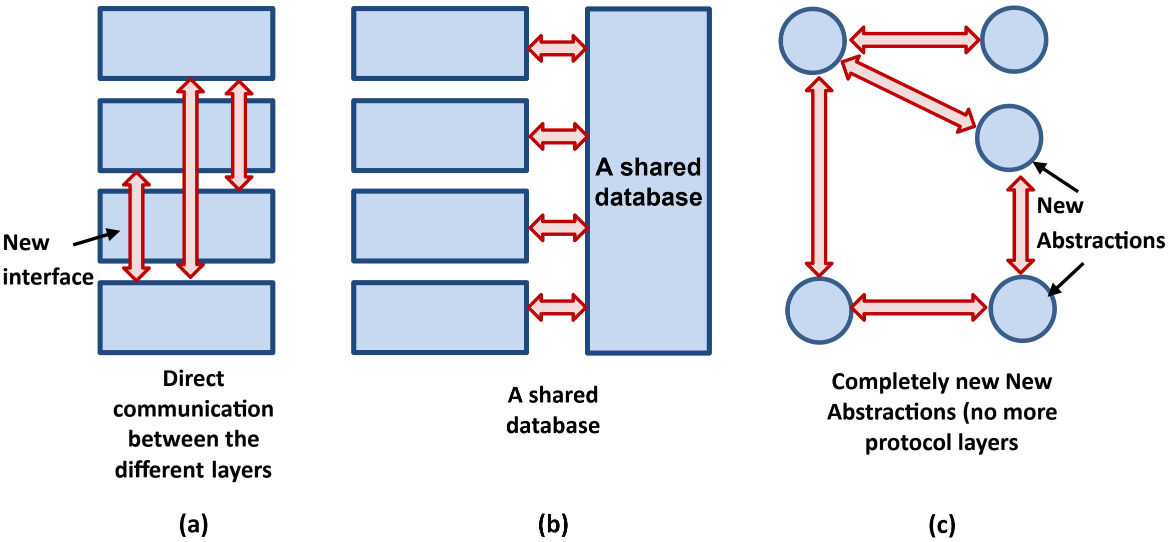

Fig. 2.2 Classification of Cross-Layer architectures

the shared database. The main challenge here is the design of the interactions between the different layers and the shared database.

2.2.3 Cross-layer architecture based on new abstractions

The third set of proposals present completely new abstractions, which we depict schematically in 2.2(c). Consider, for example, the proposal in [94], which presents a new way to organize the protocols: in heaps, not in stacks as done by layering. Such novel organizations of protocols are appealing as they allow rich interactions between the building blocks of the protocols. Hence, potentially they offer great flexibility, both during design as well as at runtime. However, they change the very way protocols have been organized, and hence may require completely new system-level implementations.

3 Cross-Layer optimization

The cross-layer optimization takes advantage of information sharing between the different layers especially the physical layer, link layer, and network layer play an important role for energy-saving optimization in wireless sensor networks, so a cross-layer optimization model in which those three-layer are considered as a whole based on a variety previous of cross-layer protocols is presented as shown in Figure 2.3 [95].

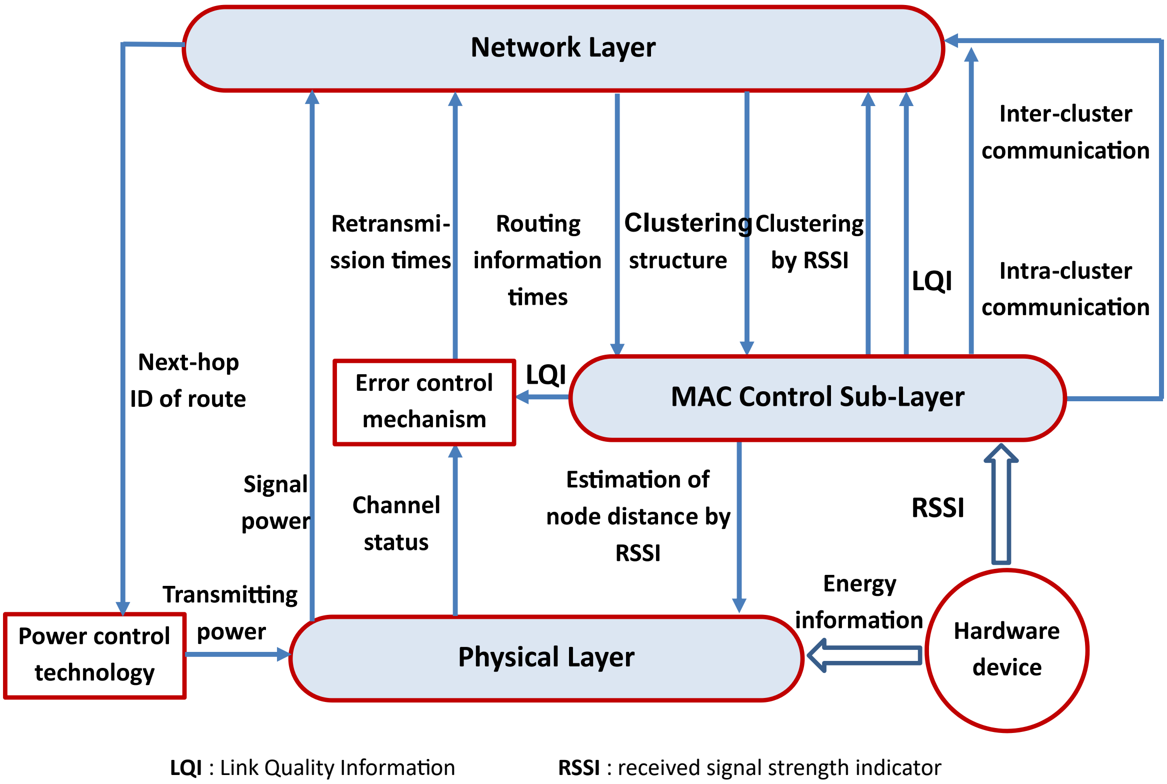

Fig. 2.3 Cross-layer optimization model

3.1 Physical layer optimization

MAC layer is mainly responsible for the accurate reception of data, the system can achieve a higher gain in throughput and power saving by using physical layer information to adjust the MAC layer's control mechanism. The network layer uses information such as channel state information (CSI), residual energy, geographical location, etc., and the transmission power of the physical layer as the basis for its routing. The network layer can transmit different rates and different priorities of data on different channels, according to the channel status information using the routing function to select the best path. Energy consumption in wireless sensor networks mainly involves sending and receiving channel listener data.

3.2 MAC layer optimization

The characteristic of the physical layer can also be improved by the power adjustment information and transmission control from the MAC layer. The error control mechanism of the MAC layer is adjusted according to the state of the current radio channel and the number of the physical layer to reduce the transmission error, and the collision of the data frame is reduced by adjusting the length of the data frame to improve the throughput. The MAC layer can be used as the state of the radio channel reflected by the intermediary. The MAC layer estimate the distance between nodes through received signal strength indicator (RSSI) [96] and the network layer is divided by the distance information, LQI, PRR and other link quality information can also be used as bases for the network layer routing. When the condition of channel is poor, the retransmission mechanism of the MAC layer will introduce a long transmission delay which will cause connection timeout for the transport layer, thus starting the retransmission mechanism and reducing the transmission power.

3.3 Network layer optimization

The physical layer can calculate the optimal transmit power of neighbor nodes according to the neighbor table information in the network layer, can calculate the optimal transmit power for a certain node by routing the next information, and can send data with optimal transmit power to reduce energy consumption. Two-channel usage modes of MAC can be reasonably used through the design structure of network layer clustering. The inter-cluster communication can improve the channel utilization by using competition mode. The intra-cluster communication can use slot allocation mode to use channels and reduce the channel SNR and BER. A reasonable routing protocol can also improve the service quality of the application layer and the efficiency of the transport layer.

4 MAC Cross-Layer protocols

Large number of cross-layer protocols optimizes involving the MAC layer are proposed in the literature. in this subsection these proposals will be briefly discussed, emphasizing the considered technologies used for optimization.

4.1 Cross layer in Contention-free protocols

In [97] the authors propose a cross layer solution to the scheduling problem in clustered wireless sensor networks (WSNs). The objective is to provide network-wide optimized time division multiple access (TDMA) schedules that can achieve high power efficiency, zero conflict, and reduced end-to-end delay. To achieve this objective, the author first build a nonlinear cross-layer optimization model involving the network, medium access control (MAC), and physical layers where a mathematical framework collects information on the traffic load, the retransmission and modulation scheme, and the bit error rates to calculate the optimal transmission powers and the flow rate used for each link. By the analysis of the trend of the calculations with the nonlinear optimization model, an algorithm for minimum delay scheduling has been proposed. The algorithm has been tested on linear, grid, and random topologies, proving to be energy-efficient.

In [98], the authors propose a cross-layer solution considering hybrid TDMA/CDMA medium access method. First, inter-cluster interference is avoided by allocating different super frames (sets of TDMA frames) to interfering clusters, medium access known as spatial TDMA (STDMA). Thus, when nodes transmit in a cluster, adjacent interfering clusters will not transmit at the same time. Second, CDMA scheduling is allocated to sets of sensors inside each cluster according to a power and time control (PTC) in order to reduce power consumption inside the clusters. Through the combination of those techniques, the network lifetime is increased, according to their results.

4.2 Cross-layer ALOHA medium access method

This optimization of the medium access method studied by [99], combined with an infinitely persistent automatic repeat request (ARQ). They have proposed a cross-layer power control (CLPC) algorithm that is capable of calculating the best received power for each node (and thus optimal transmission power can be calculated) by incorporates a physical layer model that uses knowledge of the MAC layer algorithm to accurately model multiple access interference (MAI). Simulation results have shown energy savings of up to 74% when compared to noise CLPC.

4.3 Cross Layer Carrier sense multiple access with collision avoidance (CSMA/CA)

CSMA/CA is the medium access technique used by IEEE 802.15.4. [100] have considered this technology in their cross-layer activity management scheme. The sensors duty cycles (sleep and listen/ transmit time) are calculated in order to achieve a determined event sensing reliability. This is done according to the packet loss probability, calculated with physical layer measurements, and packet collision probability, packet blocking probability, and service time probability distribution, measured at the medium access layer. Two scenarios were considered for duty cycle calculations—centralized and distributed. For the centralized scenario, the sink node determines the duty cycles and transmits them to the other sensor nodes. This method achieves the required reliability, but it can deplete the coordinator node energy faster.

On the distributed case, the coordinator only sends the number of alive nodes to the sensors, and then each of them can calculate its own duty cycle to keep the reliability above the predefined limit. Thus, the coordinator node consumes less energy and the network event sensing reliability is kept at the same level.

4.4 Cross-layer Duty cycling and slotted (asynchronized)

Express MAC (EX-MAC) designed by [101] considers CSMA/CA as multiple access method. When multiple sensors sense an event, event data reservation (EDR) is used to schedule transmissions along the path to the sink with the use of a short length preamble scheme in order to reduce end-to-end delay. EX-MAC has also proven to be more energy-efficient than previous multiple access proposals, achieving up to 15 times less energy consumption than X-MAC.

4.5 Cross-layer Duty cycling and Slotted (synchronized)

In order to overcome the main disadvantage of S-MAC, where all nodes are woken up when their NAV values expire. MAC-CROSS [102] a cross layer protocol exploits the interaction between MAC layers and the routing layer to minimize energy consumption in WSNs. The basic idea is to minimize the number of nodes that are expected to wake up when their NAV value expires, the routing information in the network layer is used for the MAC layer so as to maximize the sleep duration of each node. The set of nodes that are not part of the routing path can remain in their sleep mode until the beginning of the next duty cycle. To decide which node is on the routing path, MAC-CROSS uses the routing information through a Cross-Layer approach. A state can change dynamically each time the data is transmitted and the RTS / CTS control packets are slightly modified from their original formats in the S-MAC protocol family with an address conversion program such as ARP [103], by adding a new field (Final Destination Adress) for the RTS packet, by which the receiver routing agent can look up the address of next hop, and adding a new field (UP Adress) to the CTS packet to inform it which node is to be awakened among these neighbors.

CL-MAC [104] same as MAC-CROSS protocol exploit the interaction between adjacent layers (Mac and Network) to minimize all sources of energy wastage, uses a similar routing table mechanism adopted by the MAC-CROSS, with the difference that MACCROSS protocol acts on three types of consecutive nodes on the other hand CL-MAC acts on all the nodes included in a routing path from the source to the destination. At the beginning of duty cycle the nodes in the CL-Mac protocol exchange the same messages (RTS / CTS), each node receive the CTS message it interprets it as RTS of previous node and forwards it directly to the next node in the routing path at the base of the information of the routing layer until arriving at the destination always in the same duty cycle. CL-Mac forces all other nodes

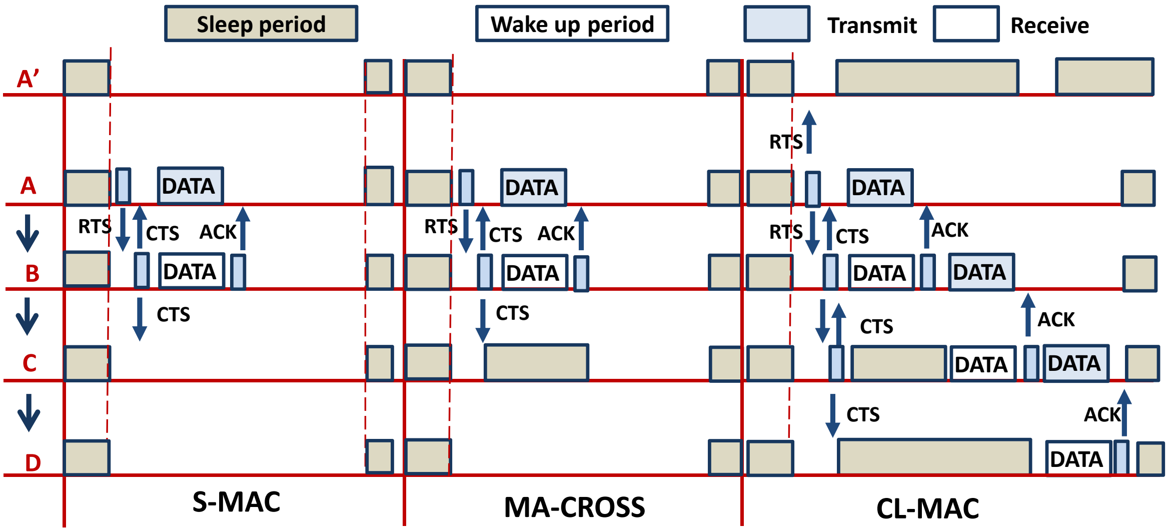

Fig. 2.4 Main features of S-MAC, MAC-CROSS and CL-MAC

that are not selected in the routing path to enter sleep mode, which eliminates all sources of energy wastage (Figure2.4).

4.6 Cross-Layer Staggering protocol

[105] Propose an enhanced cross-layer protocol for energy efficiency (ECLP) by integrating medium access control and routing protocol. ECLP utilizes a synchronous medium access control scheme by using the adaptive duty cycling technique to improve energy efficiency and solve long end-to-end delay problem. The network is presented as a tree-based graph G(V, E), where V is the number of sensor nodes and E is the number of links in the network.

in the setup phase, ECLP uses SYNC and SYNCreply packets,for synchronization and configuration of the routing tree, where the SYNC packet is used to determine the optimal path based on a r_cost function (which is a ratio between the residual node cost and the transmission cost) between two neighboring nodes from Sink to the leaf node. The SYNCreply packet is used to validate the configuration of this path and to determine the total number of hops from a node to the sink on each branch of the network tree (Figure2.5).

Once the routing tree has been built, the node that has data to the end node is just sending it to its parent node, and the data is finally delivered to the end node through the constructed route tree. If the residual energy of a node is below the threshold of its state of danger, it simply ignores the request received and changes its state to danger. Then it sends an SYNCreply packet to Sink telling it that it become a leaf node. Afterward, a recovery algorithm is lanced for creating a new path and retrieving the lost path. The tree-based

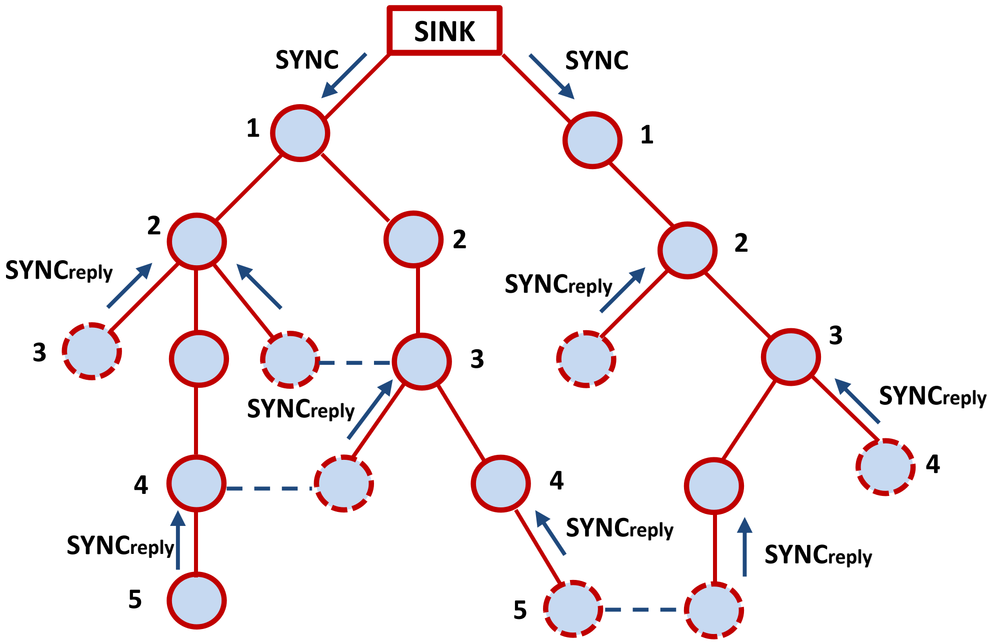

Fig. 2.5 Tree-Based Routing Algorithm in ECLP

energy-aware routing algorithm proposed by ECLP can minimize overhead cost and lengthen the network lifetime (Figure2.6).

4.7 Cross Layer Roactive protocols

In [106], the authors propose SNR/RP cross-layer routing algorithm design to achieve a reliable data transmission and improve end-to-end performance in WSNs, based in DSR (Dynamic Source Routing). SNR/RP present mechanism that allows the network layer to adjust its routing protocol dynamically based on SNR and Received Power along the end-to-end routing path for each transmission link.

In DSR source node generates a route request packet when it has a new route to a destination. The route request is flooded through the network until it reaches some nodes with a route to that destination. When the route request packet arrives at the destination or an intermediate node with a route to the destination, a route reply packet will be generated. This reply packet is then sent back to the source node following the reverse route contained in the route request packet, when current route breaks, destination seeks a new route.

SNR/RP protocol change route selection mechanism. where is define a signal to noise Ratio and received power parameters as new metrics in which those values are added to the route reply packet. Given those features, source node can select the best and more stable

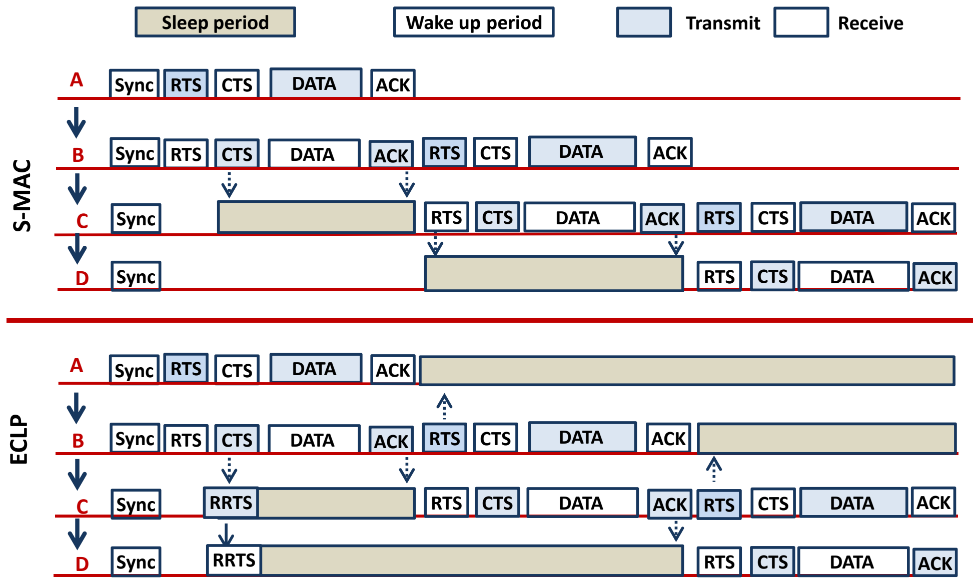

Fig. 2.6 The service cycle in ECLP

route out of various available routes based on Signal to Noise Ratio (SNR) or Received Power (RP).

4.8 EFS-C (efficient flooding scheme with Cross-Layer)

In some circumstances flooding must be used to propagate information or disseminate requests through a wireless sensors network, but due to the high nodes density and stringent constraints on the energy consumption, designing energy efficient flooding scheme with high reachability is critical for the operation and the lifetime of sensor networks. EFS-C [107] a cross-layers approach (between the network layer, MAC layer, and physical layer) is proposed to achieve efficient flooding. EFS-C uses the strength of the received signal to estimate the distance between the transmitter and the receiver, with the use of the free propagation model in space as a reference model [108] and basing at the idea of the most advanced forwarder (MPF) [109], in which the farthest node of the sender retransmits the packet and a novel MAC layer access-deferring scheme based on the received signal power and use of the neighborhood information of the previous senders. Each node can decide how long to defer or if it should retransmit by considering if its retransmission can help the reachability and reduce the collision possibility and broadcast redundancy. Although EFS-C can record redundant broadcasts, it provides good performance in terms of accessibility, and energy efficiency compared to other flood systems.

4.9 Cross Layer Data (information)-centric

To address the energy-efficiency issue in Information Centric Networking (ICN), [110] proposes a novel ICN design, which adapts the power consumption of network nodes to the optimized utilization level proportionally. Learning over the consumers' interactive data traffic pattern/behavior, it introduces a new concept of cross-layer power adaption conducted through dynamically adjusting link rate corresponding to content popularity to reduce the wasteful power consumption of Content Routers (CRs). Also, It develops a controlling policy for each content provider to map its status to the most suitable operating mode to diminish power consumption. Moreover, it proposes a smart Selective Caching Scheme (SCS) so that the caching portion in a CR's cache memory is adjusted according to content popularity and available caching space. This scheme can further decrease the power from caching since it is diminished when the traffic load is reduced via the proposed CRs' adaptive mechanism. The evaluation results with practical insights in several distinct scenarios show that the proposal can provide considerably higher energy efficiency and network performance at the same time.

4.10 Cross Layer with Qos

The goal of QoS provisioning in layered and cross-layer protocols is to provide the desired QoS level to applications and users while maintaining the overall WSN parameters unchanged. The main difference between traditional layered and cross-layered approaches is that traditional approaches investigate the optimization of protocols in individual layers, leading to the achievement of the required QoS provisioning in a specific layer, while cross-layer approaches provide QoS by jointly optimizing the interactions among all layer protocols to achieve an individual objective. In other words, cross-layer approaches for the QoS models in WSNs group resource parameters and performance metrics associated with protocol layers, i.e., the application, transport, network, MAC, and physical (PHY) layers, then maps them to data classes.

The primary advantage of cross-layer approaches is in the optimization of overall performance of the WSNs and providing overall QoS provisioning. The main disadvantage of using cross-layer approaches is the lack of flexibility due to the coupling between layers. If changes in one layer need to be made, all the other layers with which the former has cross-layer interactions also need to be adapted. However, in condition monitoring applications, timeliness and reliability constraints have significant importance thus the necessity of using cross-layer approaches to achieve these goals is reasonable. Most of the published work on QoS provisioning in WSNs focuses on achieving the desired QoS in individual layers.

However, recent work on QoS provisioning in WSNs consider cross-layer interaction to achieve the desired QoS provisioning [111].

In [112], a route protocol called Qos-AOMDV is proposed which considers two criteria. Both the balance of the route and power conservation is considered. Qos-AOMDV is based on cross-layer design, which could cooperate in sharing network-status information in different layers while maintaining the layers' separation to optimize overall network performance. Both the information in network layer and data link layer are combined to make a general criterion, so that it could satisfy the dynamics ofad hoc network. In the path selection phase, the destination nodes do not reply route request (RREQ) immediately. Route reply (RREP) is carried out based on the general cost criterion. In transmission phase, data is transmitted in multiple paths one by one to balance the energy and the traffic loads in multiple paths. It is shown by simulation that QoS-AOMDV could achieve remarkable improvements in terms of end to end delay, throughput and lifetime as compared to AOMDV.

Recent advances in microelectronics have encouraged the implementation of a wireless sensor network (WSN) in Intelligent Monitoring Systems (IMSs). The event data traffic in IMS applications requires timely and reliable delivery in order to react immediately with the appropriate actions. To cope up with the multi-constrained routing problem introduced by event data traffic in IMS, a multi-objective ant-colony-optimization based QoS-aware cross-layer routing (MACO-QCR) [113] protocol has been proposed for inter-cluster communication in WSN-based IMS (The interaction between routing and medium access control (MAC) layers that enables relay node selection by considering node's queue status as the cross-layer parameter). The ACO algorithm is improved to be a multi-objective routing algorithm with considering the energy consumption cost and the end-to-end delay cost of a routing path as two optimization objectives. MACO-QCR determines the optimal routing path for event data transmission with the multi-pheromone information and the multi heuristic information. An external archive method based on fuzzy membership function in MACO-QCR assigns fitness values to non-dominated solutions to obtain Pareto optimal solutions. The consideration of queue length as cross-layer parameter in MACO-QCR balances the traffic load in the network by avoiding paths with high traffic load.

5 Cross-Layer Optimization In Hierchical Protocols

In the majority of hierarchical routing protocols based on a cross-layer architecture, The physical layer, link layer, and network layer play an important role for energy-saving optimization in Wsn, so a cross-layer optimization model in which those three-layer are considered as a whole based on a variety of cross-layer protocols is presented as shown Here, the specific optimization mechanism of the model is as follows:

- The network layer can design the gradient of the monitoring range through the topological information provided by the physical layer, calculate the distance between each gradient, and divide the nodes into ranks in the monitoring range.
- The network layer selects the nodes with higher residual energy and good distribution position as the cluster head nodes according to the residual energy information and the node density information provided by the physical layer.
- The network layer makes the nodes reasonably clustered according to the signal intensity between the nodes provided by the link layer.
- The link layer can reasonably use the link layer protocol according to the node clustering structure information of the network layer. The inter-cluster communication of the nodes uses the link layer protocol based on competition to improve the channel efficiency. The intra-cluster communication of the nodes uses the link layer protocol based on scheduling to reduce competition within the cluster.
- In routing selection, the network layer uses the residual energy information provided by the physical layer and the link quality information provided by the link layer to make the routing choice and select the best path.
- During routing, if the member node is used as the relay node when the link layer is allocated the time slot by the cluster head node, it needs to allocate more time slots to the member node to reduce the delay of the routing.
- The routing information can only be forwarded when the sensor node obtains the time slot or acquired the right to use the channel through competition.
- Before forwarding data, the network layer will inform the physical layer of the next hop node's ID through routing, the physical layer calculates the optimal transmission power through the power-control technology and transmits the data using the minimum transmission power on the basis of ensuring the connectivity of the entire network.
- The link layer uses the error-control technology, which refers to the channel state and link quality to ensure the correctness of transmission.

5.1 CCBE

A clustering cross-layer algorithm, in order to minimize energy consumption in WSNs, CCBE[114] distributes sensor nodes into different groups of hexagonal shapes with equal sides that will help select optimal CHs. Each CH allocates time slots based on the residual energy of CMs with the TDMA method, where the CM having the least energy will get the first transmission slots at the CH, with the same TDMA method the Sink will allocate time slots to the CHs. The sleep states of each CH vary according to the location of the CHs. CHs at the end (far from sink) have more sleep time compared to CHs near Sink. The data aggregated by the CH will be transmitted to the Sink or the neighboring CH node to the Sink according to the hexagonal structure. The CH uses the maximum distance between two adjacent nodes in a hexagonal structure in order to send the neighbors' information to all possible CH candidates in the Sink direction. In addition, the CHs create a route to the Sink and choose a final CH to bring the information to the Sink. The results of the simulations show that the CCBE protocol gives a good energy efficiency and increases the life of network.

5.2 FAMACROW

Fuzzy and Ant Colony Optimization Based Combined MAC, Routing, and Unequal Clustering Cross-Layer Protocol for Wireless Sensor Networks [115]. FAMACROW encompasses the following:

1. A novel cluster head selection algorithm that uses fuzzy logic with residual energy, number of neighboring nodes and quality of communication link as input variables for cluster head selection.

2. An unequal clustering mechanism that avoids hot spots problem by partitioning nodes into clusters of unequal size, with clusters closer to MS having smaller sizes than those farther away from MS.

3. An ACO-based reliable and energy-efficient mechanism for inter-cluster routing from cluster heads to MS. The relay node for inter-cluster routing is selected on the basis of (i) distance from current cluster head and that from MS (which represents energy required for communication) (ii) residual energy (for energy distribution across the network) (iii) queue length (for congestion control) (iv) delivery likelihood (which represents the reliability of communication link).

In FAMACOW Use of LQI for cluster head selection and delivery likelihood for inter-cluster routing increases the reliability of protocol. A comparative analysis of FAMACROW with protocols in the same family shows that FAMACROW is more energy-efficient, network lifetime, and more throughputs.

5.3 LEACH-CLO

[116] Proposed a ring CLO model along with a novel routing framework termed Leach-CLO. This presented work was formulated on the basis of the traditional Leach approach, with cross-layer optimization, combining the design of physical layer, link layer and network layer to construct the cross-layer optimization model of wireless sensor network, and the optimization model of each layer is given. In LEACH-CLO, The ring isomorphism monitoring area is constructed, and the optimal cluster nodes forwarding mechanism is put forward by using the optimized hierarchical strategy, and the research results show that the multiple-hop cluster communication mechanism can save energy more than the single-hop communication under certain conditions. and LEACH-CLO routing algorithm is based on how much of the remaining energy is used to control the priority of the node campaign cluster head, to avoid a large number of cluster heads too concentrated, according to the size of the detection range, the number of nodes and the size of the node communication radius to calculate the number of optimal cluster heads, so that the selection of cluster head and the establishment of cluster is more reasonable. The simulation was carried out that proved the superiority of the presented model in terms of energy saving and adaptability.

6 Ultra Low Power Wake-Up Radios

As we mentioned earlier chapter, "Duty-Cycling" approach includes sleep mode periods, which increases network latency. In fact, when using a lower duty cycle i.e. increasing sleep periods, the energy consumption will be reduced at the cost of an increased latency [117]. On the other hand, increasing duty cycle i.e. decreasing sleep periods leads to idle listening and overhearing problems [118] [119]. Additionally, in distributed scenarios, duty cycling MAC protocols need synchronization to schedule the periodic wake-ups of nodes in the network. This synchronization causes control message overhead, which can affect the energy efficiency In the case of asynchronous duty cycling MAC protocols, to ensure the good reception of a packet, the latter must be transmitted continuously or several times until the crossing of the listening period of the receiver. This process induces energy consumption increasing [120].

In order to ensure low latency and long operating time in WSNs and to overcome the energy/latency trade-off of duty cycling approach, [121] propose an Ultra-Low Power Wake

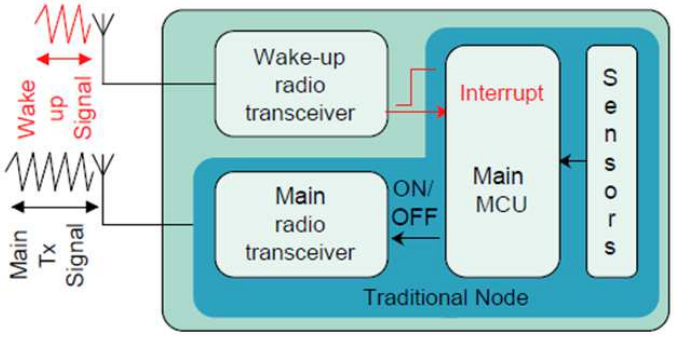

Fig. 2.7 Node with a wake-up radio

Table 2.1 Acronyms for Wake-Up Radio Technology

WuR	wake-up radio
WuRx	wake-up receiver
WuTx	wake-up transmitter
WuS	wake up signal, the message sent by the WuTx

up Radio (WuR) that allow continuous sensing of the radio channel. The principle of WuR consists on activating the main radio only when there is data to communicate.

The introduction of wake-up radios aims to provide a novel hardware solution with listening power consumption orders of magnitude lower than that of low-power radios, promising results towards eliminating the aforementioned problems of idle listening, overhearing, continuous transmissions, and data latency.

In a WuR architecture, as shown in Figure2.7 [8], an ultralow power, secondary radio module with a receiver consuming a few micro watts of power is alongside the primary, low power radio. Since its power consumption is several orders of magnitude lower than that of a traditional low-power radio, the WuR can be kept always-on, leading to a use in contrast to the duty cycling operation descried earlier for the main radio.

The figure 2.8 illustrated comparison of the data transmission using the normal duty cycle and the use of a node with a second radio for wake-up (Wur). In this setting, the main radio is kept in a deep sleep, or off mode, until it is needed. Instead, when a node has a data packet to send, it sends a special packet known as a wake-up signal (WuS) using its wake-up transmitter (WuTx). The always-on wake-up receiver (WuRx) detects this WuS, and generates an interrupt to the main node's micro-controller to switch it from sleep to an active mode. Subsequently, the main micro-controller turns on the main radio transceiver to exchange data packets with the other node in a conventional manner.

Table I summarize the key terminology of the wake-up technology.

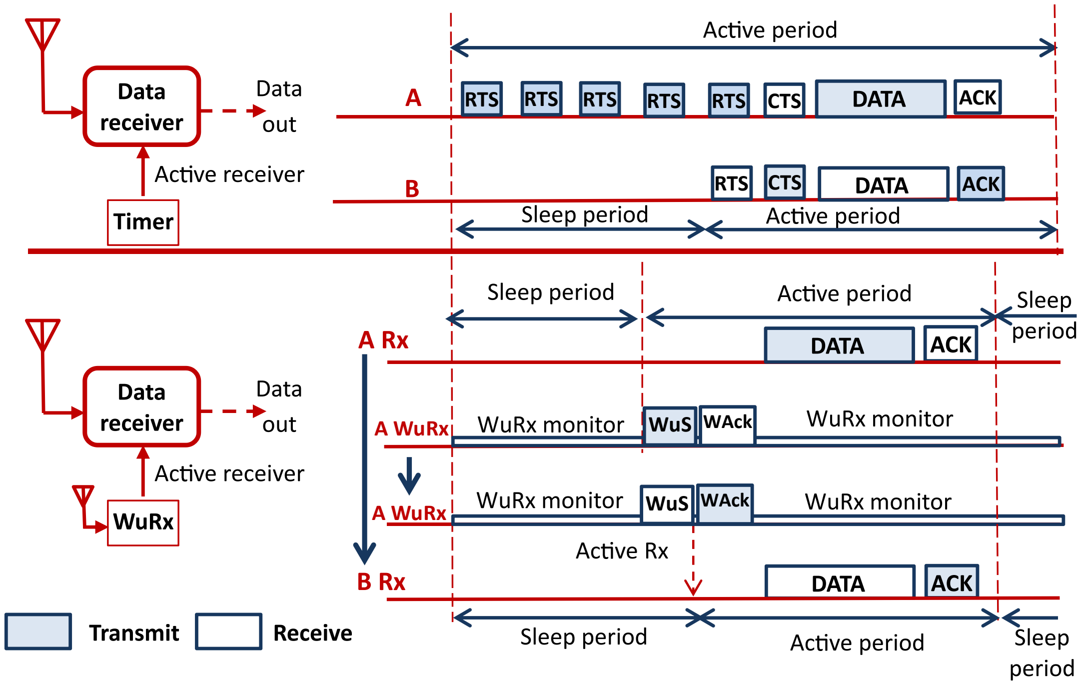

Fig. 2.8 Comparison of protocol-based duty-cycling and wake-up duty-cycling

6.1 Requirements Technologies of WuR

The technology and design considerations for the WuR play a key role in determining the efficiency of low-power sensor networks. For the WuR to operate effectively, it should consider the following design points:

1. Power consumption: The most important feature of the WuR is its low power consumption in active mode. Specifically WuR's active power should be below that of the main radio's sleep power to provide a positive balance between power saved and used.

2. Time to wake-up: The node attached to the WuR must wake-up with minimum latency upon reception of WuS to avoid latency incurred from multi-hops toward the sink and to increase the overall responsiveness of a purely asynchronous network.

3. False wake-ups and interference: If all nodes in a sensor network rely on the same wake-up strategy, when the WuTx tries to wake-up a node, it will trigger all the nodes in the neighborhood causing significant energy waste. This causes unnecessary activation of many nodes that should be avoided. There are two possible sources of false wake-ups:

    - Nodes waking up when receiving a WuS intended for another node.

• Interference from nearby devices operating at the same frequency.

To tackle the first, the WuR can employ a node addressing and decoding capability to trigger only the intended node. This allows the WuRx to avoid generating an interrupt if the WuS was not intended for it, however it introduces complexity and often consumption at the WuRx. Second, interference and background noise that can result in erroneous wake-ups must be filtered. A WuRx must have enough local processing capability to differentiate a WuS from ambient interference, without using the main node's processor. In addition, the WuS must not be missed by the targeted node, as retransmissions are costly in terms of power consumption and latency.

4. Sensitivity and range: In WuR design, receiver sensitivity is an important parameter as it provides the lowest power level at which the receiver can detect a WuS. WuR designs target tens of meters of communication range to support many application scenarios [122]. Very short communication ranges make WuR impractical as high node densities would be required to cover a short distance in a multi-hop fashion increasing node and energy costs. Another side effect of a short communication range is the increase in the hop count messages must traverse to reach the sink, increasing the overall data latency. The wake-up range that can be achieved with most current WuR designs is typically around 30m a value that can be improved by using techniques such as antenna diversity [123] and directional antennas [124].

5. Cost and size: To integrate the WuR into existing sensor nodes, it should be cost effective. To make the WuR feasible [125], the cost of this additional hardware should be in the range of 5-10% of the cost of the complete sensor node. This is, nevertheless, a loos requirement, as some applications can support higher costs if gains are sufficient. Further, standard off-the-shelf components can be used to speed the development and to reduce the overall cost as compared to designing a single chip solution.

6. Frequency regulation: Finally, WuR designs should adhere to frequency regulations in industrial, scientific and medical (ISM) bands. It must also comply with communication standards such as the maximum allowed effective radiated power (ERP) used to transmit WuS.

6.2 Usage and operation of WuR

For using the wake-up radio (how and when it is powered). There are three power management techniques that can be applied: always-ON, duty cycling the WuR, or energy harvesting.

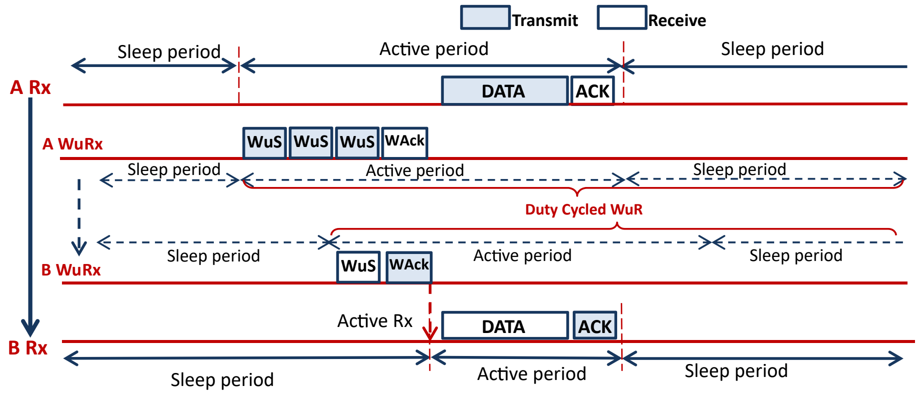

Fig. 2.9 Duty Cycled WuR

1. Always-On WuR: Typically, due to the low consumption of the WuRx technology, it can be constantly powered, waiting for a trigger signal. In a transmitter-initiated scenario, this minimizes the latency, as the receiver is immediately aware of the transmitter's need to initiate communication.

2. Duty Cycled WuR: To further reduce power consumption, the wake-up radio itself can be duty cycled (Figure2.9), meaning the WuRx is periodically put into listen mode to monitor the channel for a wake-up signal. To compensate for the sleeping times of the receiver, the WuTx must send the wake-up signals more than once, until a wake-up acknowledgment (Wu-ACK) is received from the target WuRx. When the WuRx listening period coincides with the wake-up signal transmission, the receiving node switches on its main transmitter and the main data transmission is initiated. If no Wu-ACK is received, the initiator node can re-transmit the wake-up signal. To avoid overhearing by the non-targeted nodes, the wake-up signal carries the destination address.

3. Energy Harvesting WuR: In energy harvesting WuR system (EH-WuR), the WuRx is only woken up when "sufficient" energy is harvested from the wake-up signal. Figure2.10 illustrates the transmitter-initiated scenario where the energy from the WuS is utilized for powering up the trigger circuitry. In this scenario when there is no communication going on, the WuRx is completely switched OFF.

6.3 Wireless spectrum in WuR

There is two cases use of the wireless spectrum:

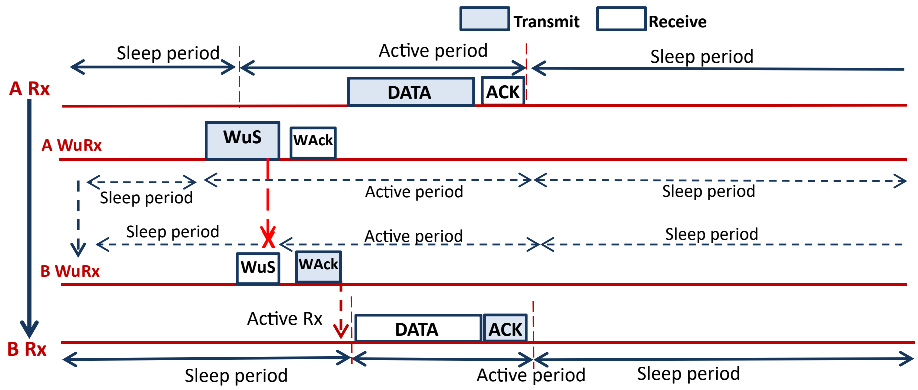

Fig. 2.10 Energy Harvesting WuR System

1. In-Band of data transceiver: Few published MAC protocols address only in-band (single channel) communication i.e, both the trigger and the data are exchanged over the same channel or frequency.

2. Out-of-Band of data transceiver: Multiple channels, can reduce interference and increase bandwidth, but at the expense of additional coordination between senders and receivers both in time, and also across the space of the channels. In most of the WuR-MAC protocols, the bandwidth is divided into two channels: one used for control and the other for wakeup signals. Another is the data channel with higher bandwidth allocated for the main radio. For channel reservation, normally RTS/CTS handshake mechanism is performed over the control channel. The RTS/CTS frame includes a preamble, sender/receiver address, channel information for the main transceiver, and packet length.

Use of out-of-band approach has following advantages. Firstly, using different channels appropriately can lead to higher throughput. Secondly, communication on different channels or frequency does not interfere with each other allowing multiple transmissions simultaneously, leading to fewer collisions.

6.4 Information exchanged over the WuR

Two type of data can be exchanged over the WuR radio:

1. Trigger-only: The most typical use of the WuR is to trigger a higher power radio used for communicating data. This minimizes WuR hardware complexity. The trigger can be broadcast, waking up all neighboring nodes, or unicast, with the trigger containing the address of the intended recipient.

2. WuR as main data radio: As an alternate, the low-power WuR can be responsible for all communication i.e., for sending the wake-up signal and the data packet. However, there is no main high-power transceiver.

6.5 Taxonomy of Wake-up Radio based MAC protocols

We can classify the Wake-up protocol under the conflict-based asynchronous MAC access method (CSMA) that uses WuR as a secondary radio. Instead of MAC protocols using a single radio, ho they suffer from long periods of idle listening and standby times, which increases power consumption and leads to high latency. This is exactly what asynchronous MAC protocols avoid with WuR, as the main radio is activated only when a connection is needed [126]. WuR based MAC protocols can be divided into protocols that address only the MAC layer and protocols that rely on interactions between different layers (cross layer).

- Only MAC: The access decision is done in the MAC layer independently from other layers [127].
- Cross layer: "Cross layer based MAC approach" exploits the interaction between layers to optimize MAC layer performances (energy efficiency, latency, throughput, QoS, etc.). For example, it exploits “routing information” at the network layer, “multimedia and security information” at the application layer [128], "modulation and coding information" at the physical layer [129] to achieve the best Cross layer optimization[130].

Based on the type of their wake-up circuits, these protocols were classified broadly into two categories namely: duty cycled and non-duty cycled.

- Duty cycled: In this category, instead "duty-cycling" the main radio (as in traditional duty cycling MAC protocols), the sensor node use a "duty-cycled" WuR, which is activated periodically to sense the radio channel and send WuS [109].
- Non-duty cycled: In this case, WuR’s circuit can be always-on to continuously control the channel and send a WuS to power on the main radio when needed. The WuR can also be a low-power active circuit or totally passive, which harvest the energy from the WuS.

By identifying the communication initiator, the previous classes were subdivided into three classes: Transmitter Initiated, Receiver Initiated and Bidirectional.

- Transmitter Initiated: In this approach, when there is data to send, the transmitter first sends a WuS to activate the desired node and then sends data.

- Receiver Initiated: In this mode, the receiver starts the communication by sending a WuS to another node in order to get back data from this node.
- Bidirectional: In this category, either the transmitter or the receiver can commence the communication.

By Addressing scheme used to trigger intended nodes. In this case, two classes were found: range-based and identity-based protocols.

- Range-based: In this scheme, the WuS is received by all the neighboring nodes of the sender. Then, each node decodes the received WuS to check whether it is addressed to it; if so, the destination wakes up. In some cases, after waking up all the neighboring nodes, a filter packet will be sent to indicate the intended node and to permit other nodes to return back to sleep.
- Identity-based: In Identity-based wake-up, only the desired next hop node is wakening up. In other words, each node processes only the WuC intended to itself.

6.6 Cross layer Wake-Up Radio based routing protocols

6.6.1 EECP (Energy Efficient Cross-layer Protocol)

wake up based cross-layer routing protocol [131], allow the interaction between the physical, the MAC and the network layers for energy conservation in wireless sensor networks. where addresses many sources of wasted energy: the energy cost of the routing path, the collisions, the idle listening and the overhearing. In Initial phase, EECP broadcasts the RSSI to calculate the distances with her neighbors in neighbors table, in Routing phase EECP selects paths dynamically by wake the best neighbor node taking into account his energy and his distance to the sink, who provides a load balancing for all the network nodes that could participate in the routing (figure 2.11)

6.6.2 STEM-B

(Sparse Topology and Energy Management-Beacon)[132], In this protocol each node is equipped with two radios with two different frequencies f1 for wakeup and f2 for data transmission. In routing phase A stream of beacon messages are sent by the sender on band f1to wake up the desired node. Upon receiving this beacon by the desired node, its main radio is turned on and an ACK packet is sent in band f2 in respond to the sender. The MAC address of both the target and transmitter node is included in the beacon packet. Once the data transmission is ended, the target node turns off its radio in band f2 and the initiator

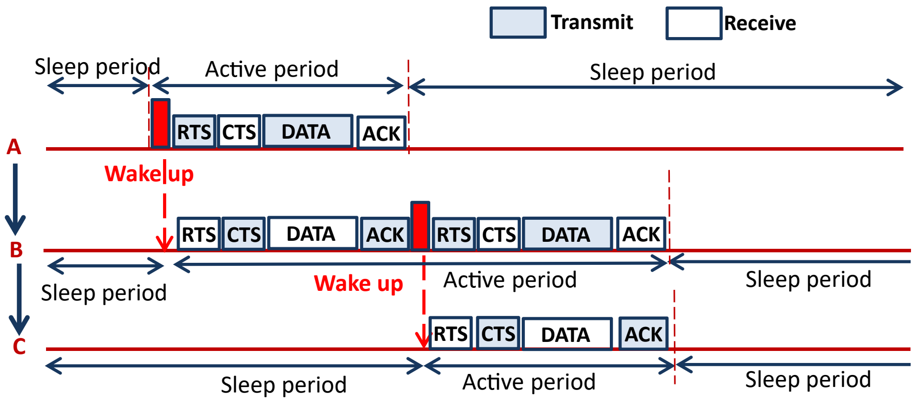

Fig. 2.11 EECP duty-cycling

node still listen the channel periodically to verify if any another node wants to communicate with it. The non-target nodes, that decide to wake up due to beacons collision, returns to the control state if they don't receive data in band f1 after a predefined time.

6.6.3 GREENROUTES

[133] Is a routing protocol that combines WuR with Energy Harvesting solutions. In this protocol, each node executes channel access and next hop relay selection simultaneously for data communication. The cross layer forwarding used by protocol provides with a practically costless way of updating neighboring nodes based on hop count and residual energy. To ensure data transferring, the node diffuses a "wake- up sequence" to activate all its neighbors within one hop. Then, it sends an RTS packet to all the wakeful neighbors and waits to acquire CTS from them. The first node that returns a CTS is picked as the next forwarder. Aiming to reduce the relay selection process delay, and to further improve protocol efficiency, the node i stores the ID of its last successful relay j for a predefined amount of time. All packets that node i needs to transmit within this time will be transmitted directly to j, without any new relay selection phase. In this case, node i will wake up node j directly, i.e., by using its ID as wake-up sequence. The packet is rejected if no ACK is received or if no relay is found.

6.6.4 WHARP

(Wake-up and Harvesting-based energy-Predictive forwarding)[133] is a cross-layer strategy similar to the GREENROUTES protocol, and it performs the same process to forward data packet where the selection of neighboring nodes is based on their distance (in “wake-up radio” hops) from the sink, and on their available energy. However, in WHARP

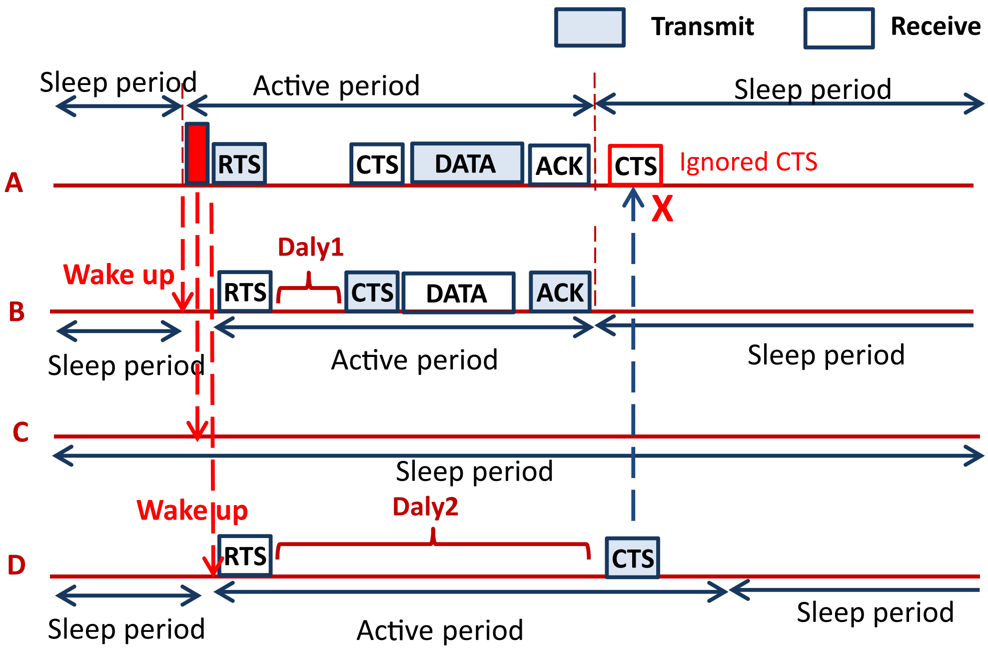

Fig. 2.12 WHARP duty-cycling [105]

protocol, when receiving a WuB, the receiver makes decision about whether to activate or no its main radio based on " Markov Decision Process" . Then, after receiving an RTS packet, the receiver node transmits a CTS to the source. It then calculates a delay used as indicator to determine the performance of the receiver. The data packet is then transmitted to the first node that sends CTS. At the end of data transmission, an ACK is sent to the source. After successfully receiving this ACK, both the sender and the receiver return back into sleep mode. The forwarding principle of the WHARP protocol is shown in Figure2.12.

6.6.5 Zippy

[134]uses an asynchronous rendezvous scheme to perform on demand flooding. In this approach, an initiator node sends a preamble to wake up a node B. Upon detecting this preamble by its always-on ultra-low power WuRx, the node B is activated and it will transmit a wake up preamble to its neighbor node (Figure 2.13). This process will continue until all nodes in the network are awaked. To ensure neighborhood synchronization, the initiator will propagate a bit of synchronization after completing preamble transmissions. For data propagation, Zippy protocol uses a " bit-level" scheme where each bit is relayed through a multi hop network. Using ZIPPY reduces the entire network flooding time while maintaining end-to-end latency of only a few microseconds. ZIPPY does not address the false wake-ups making it susceptible to erroneous network-wide wake-up.

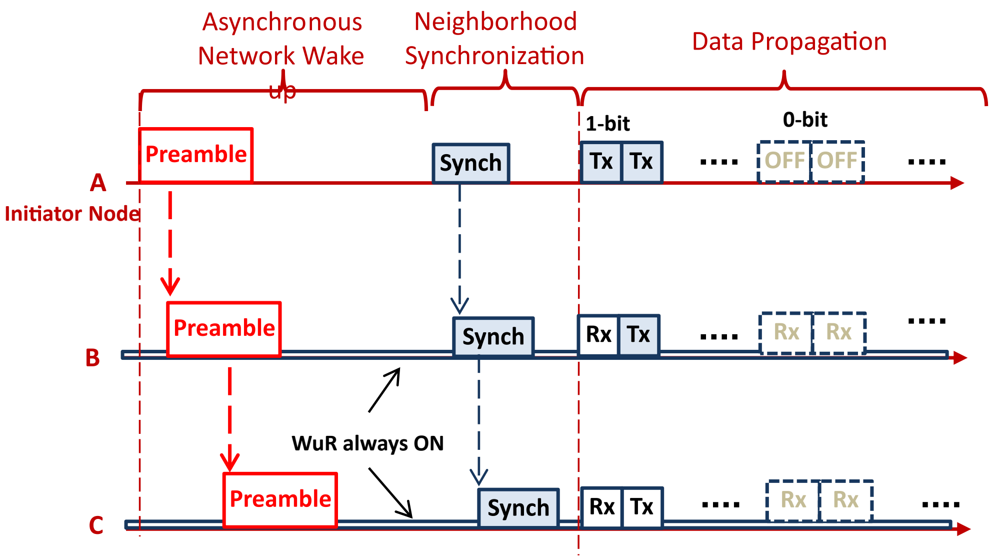

Fig. 2.13 Zippy duty-cycling

7 Conclusion

In this chapter, we addressed protocols based on cross-layer design: a unified scheme that merges common protocol layers functionalities into a cross-layer module through the exchange of information between different layers of protocol stack such as transport, routing, medium access and physical (wireless channel). We showed that it is helpful in improving the efficiency by providing more resistance to data losses which often occur in wireless networks. As a result, the approach increases the network lifetime of WSNs and minimizes the traffic load by exchanging information between non-adjacent layers to satisfy the demands of WSNs applications.

We also discussed the protocols and design features used for the WuR, based on the equipment of the node with a second low-power WuR to wake the node whenever there is data to be received. This is done in order to achieve highly reliable communication with minimal energy consumption, adaptive communication decisions, local congestion avoidance and distributed duty cycle operation.

Chapter 3

Contribution : Clustering Multi-Hop Cross-Layer Protocol (CMH-CLP)

In hierarchical or equivalently cluster-based routing, the operation of routing data from the Cluster Heads (CHs) to the Sink remains the major source of wasted node energy. As a remedy, MAC protocols using a wake-up radio (WuR) have been used to address this issue. Based on the idea of letting the CHs and other nodes in the network on a sleep mode for the longest possible period, in this section we proposes a new protocol the so-called Clustering Multi-Hop Cross-Layer Protocol (CMH-CLP) [12]. The various simulation results of the proposed protocol on the basis of some standard network performance metrics show that the proposed protocol improves the WSN performance as compared with some well-known protocols.

1 Overall description of CMH-CLP

In this Section, we give an overall description of the the proposed protocol. In the architecture, we use two radios and we adopt the cross-layer approach to minimize the nodes' energy consumption, based on some assumptions.

1.1 Assumptions

In our protocol, the following assumptions are considered:

- CMH-CLP is designed for hierarchical network architectures with a single Sink.
- Each node has a unique identifier; here the sequence number or the MAC address.

- Each node is equipped with two radios (as in Figure2.7, in Chapter2); one radio for a wake-up with a small transmission radius r and low energy consumption, and a second radio for data transmission with a large transmission radius R. Radios have two different transmission frequencies in order to avoid messages collision [11].
- The nodes are distributed around the Sink, located in the center. Each node i has at least one neighboring node j in its waking radius. This means that the distance between the two nodes is less than r.
- Each node has a processing unit with low energy consumption that works with the WuR without relying on the main processing unit and the main transmission radio [135].

1.2 Initialization

Initialization phase represents the network configuration step. The objective is to classify all the nodes of the network into clusters. The network configuration steps are described below.

Step 1: The Sink broadcasts a high signal strength message into the network capable of reaching all nodes in the network. Using a two-ray ground radio propagation model, each node i receiving this message calculates its own distance ($dist\_BS(i)$) from the Sink [136].

Step 2 CHs Selection: Nodes make autonomous decisions to become CHs. This is done using the Mamdani-based Fuzzy Inference (FIS) system model [137].

1. The inputs are the following:

   Residual energy: The energy consumption in the node is mainly due to: data acquisition (sensing, analog to digital conversion, preprocessing, storing); transmitting (processing for address determination, encoding, framing, queuing, supply for the baseband and RF circuitry); receiving (low noise amplifier, down converter oscillator, filtering, detection, decoding, error detection, address check); switching from sleep (significant parts of the transceiver are switched off) to idle mode and vice-versa. RES_ENERGY is energy remaining in the node. For a node to take part in any network activity it should have more RES_ENERGY. The node with the maximum energy is elected as CH;

Neighborhood density: (represented by NB_PROX): NB_PROX (i) of a node *i* is defined as

$$NB\_PROX(i) = \frac{1}{N}(\sum_{j=1}^{N} dist(i,j)) \quad (3.1)$$

Where:

- N is the total number of neighboring nodes of node i (can be reached by his R radio).
- $dist(i,j)$ is distance between node i and its neighboring node j.

To become a cluster head, a node should have more neighboring nodes to reduce its intra-cluster communication cost and accordingly should have a lesser value of $NBR\_PROXIMITY$. Each node calculates $NBR\_PROXIMITY$ using equation 3.1.

The link quality indicator (*LQI*): Link Quality Indicator (represented by *LQI*): characterizes quality transmission of a packet through a link. More specifically, measurement studies in [138] show that signal-to-noise ratio (SNR) of a link is roughly linear to its LQI. The minimum and maximum LQI values (0 and 255) are associated with lowest and highest quality signal reception and values in between are distributed between these two limits.

LQI is the average of LQI of links between a node and neighbors in its neighborhood. Deterioration in the quality of reception of the packets is marked by a decrease in LQI. Hence, for a node to become a cluster head it should have a high NBR_LQI.

$Note$: In our simulation, we used values between 0 and 1 for the LQI parameter. To get these values we divide the different values in the range [0,200] by 200 which represents the highest value in real LQI. As a result, 0 represents the lowest value and 1 the highest value of the new LQI values..

2. The Output variable for FIS: It represents the proficiency for becoming a cluster head (represented by $PROFIC$): A large value of $PROFIC$ indicates a large possibility of a node becoming a cluster head. Linguistic variables representing RES_ENR, NB_PROX, and LQI of the node are: Low, Medium, and High. For PROFIC of the node they are: Very Small, Small, Rather Small, Medium, Rather Large, Large, and Very Large.
3. Defining membership functions: Triangle membership functions are used to represent fuzzy input sets Medium, and trapezoid to represent Low and High. Similarly, triangle membership functions are used to represent output sets Small,

Table 3.1 Fuzzy rule base for cluster head selection

N°	RES_ENR	NB_PROX	LQI	PROFIC
1	LOW	LOW	LOW	SMALL
2	LOW	LOW	MEDIUM	RATHER SMALL
3	LOW	LOW	HIGH	MEDIUM
4	LOW	MEDIUM	LOW	SMALL
5	LOW	MEDIUM	MEDIUM	RATHER SMALL
6	LOW	MEDIUM	HIGH	MEDIUM
7	LOW	HIGH	LOW	VERY SMALL
8	LOW	HIGH	MEDIUM	SMALL
9	LOW	HIGH	HIGH	RATHER SMALL
10	MEDIUM	LOW	LOW	RATHER LARGE
11	MEDIUM	LOW	MEDIUM	RATHER LARGE
12	MEDIUM	LOW	HIGH	SMALL
13	MEDIUM	MEDIUM	LOW	SMALL
14	MEDIUM	MEDIUM	MEDIUM	RATHER LARGE
15	MEDIUM	MEDIUM	HIGH	SMALL
16	MEDIUM	HIGH	LOW	RATHER SMALL
17	MEDIUM	HIGH	MEDIUM	MEDIUM
18	MEDIUM	HIGH	HIGH	RATHER LARGE
19	HIGH	LOW	LOW	RATHER LARGE
20	HIGH	LOW	MEDIUM	SMALL
21	HIGH	LOW	HIGH	VERY LARGE
22	HIGH	MEDIUM	LOW	SMALL
23	HIGH	MEDIUM	MEDIUM	RATHER LARGE
24	HIGH	MEDIUM	HIGH	SMALL
25	HIGH	HIGH	LOW	MEDIUM
26	HIGH	HIGH	MEDIUM	RATHER LARGE
27	HIGH	HIGH	HIGH	SMALL

Rather Small, Medium, Rather Large, Large, and Trapezoid Membership functions to represent Very Small and Very Large. Application of fuzzy operators and fuzzy rule evaluation: With three input variables and three levels for each, there are 3^3=27 possible combinations for rule base.

Table 3.1 shows fuzzy rule base for cluster head selection.

The Fuzzy Logic Designer of MATLAB allows the design and test fuzzy inference systems for modeling complex system behaviors. Using this app, we can:

- Design Mamdani and Sugeno fuzzy inference systems.

- Add or remove input and output variables.
- Specify input and output membership functions
- Define fuzzy if-then rules.
- Select fuzzy inference functions for different operations (And, Or, Implication, Aggregation and Defuzzification).
- Adjust input values and view associated fuzzy inference diagrams.
- View output surface maps for fuzzy inference systems.
- Export fuzzy inference systems to the MATLAB workspace.

The FIS output is the node's competence to become a CH; calculated for each node. This latter uses a non-persistent MAC CSMA (Carrier-Sense Multiple Access) protocol to advertise its competence to neighboring nodes within its transmission range.

The node with the greatest competence becomes a CH.

Step 3 Clustering: To reduce the intra-cluster traffic between CHs, no cluster is formed for nodes that are close to the Sink (nodes where $dist\_BS(i) \leq R$). In other words, these nodes react like CHs and pass the data directly to the Sink.

The rest of the CHs advertise their role by broadcasting a message within a transmission range using the non-persistent MAC CSMA protocol [139]. Each node receiving the announcement message, adds its CH identifier, and calculates its distance from the CH based on the Received Signal Strength Indicator (RSSI) [96].

Step 4 Search for neighbors within the wake-up radius r: Let us adopt the following notations.

- Wu_adver: wake-up advert message;
- id_CH: cluster head ID;
- id_node_wkup: ID of the wake-up node;
- nbr_hops: number of hops;

Each node in a cluster searches for neighbors within the wake-up radius r, according to the following steps:

1. First, the CH sends a Wu_adver message containing $(Id\_CH, Id\_node\_wkup, Nbr\_hops = 0)$ to all the neighbors within the wake-up radius r.

2. Second, each node that receives *Wu_adver*, increments the number of hops (*nbr_hops*) and sends *Wu_adver* to neighbors within the radius r.
3. If a node receives several times *Wu_adver* with different *nbr_hops*, it takes the *Wu_adver* with the smallest value of *nbr_hops*.
4. Each node outside the cluster receiving the *Wu_adver*, adds the sending node as a direct neighbor with the number of hops and the identifier of its CH. However, it does not have the right to broadcast this message to its direct neighbors in its own cluster.
5. This process is repeated for all nodes of the cluster.
6. At the end of the detecting step of direct neighbors, each node completes its neighbors' table that serves as relays with the following information:

   $(id\_node, id\_CH, nbr\_hops, comp\_intra, comp\_inter)$;

   where, *comp_intra* and *comp_inter* define the intra-group and inter-group competencies, respectively, as defined below.

   These two parameters are calculated for each node and for each simulation round so as to choose the best node of all direct neighbors as a wake-up relay for intra-group routing (from node to its CH) or for inter-group routing (from CH to the Sink).

   - Intra-group competence is given by the following formula:

     $$comp\_intra = \frac{(enrg\_res)}{((nbr\_hops * dist_{CH}))} \tag{3.2}$$

     Where:
     - *dist_CH* is the node distance from CH;
     - *enrg_res* is the residual energy.

     The node with the greatest energy and smallest distance from CH and the fewest number of hops is chosen to wake up for intra-cluster routing. In the case where the number of hops is equal, the chosen node is the one with the greatest residual energy and with the smallest distance from CH.
   - The inter-group competence is given by the following formula:

     $$comp\_intra = \frac{(enrg\_res * nbr\_hops)}{((dist\_SB * dist\_CH\_SB))} \tag{3.3}$$

     Where:

– *dis_BS* is the distance between the node and the Sink;
– *dis_CH_SB* is the distance between the CH and the Sink.

This choice favors to wake up the nodes far from CH towards the nodes belonging to outer clusters with CH closest to the Sink, to achieve inter cluster routing.

- For nodes near to the Sink, the competence is given by:

$$comp\_CH_{nearSB} = z * \frac{enrg_{res}}{enrg_{init}} + (1-z)\frac{1}{dis\_SB} \qquad With \quad 0 < z < 1 \quad (3.4)$$

To ensure the rationality of the awakening of the selected node, the weighted average is used, which combines the ratio of the energy of the node to the initial energy and the distance to the sink.

7. The nodes which have no direct neighbors within their waking radius are considered isolated nodes despite being within the transmission radius of a CH. Thus, they are considered as CHs.

Step 5 Stabilization of the network: Once the network is stabilized, all the nodes finally know their CH, their direct neighbors (for waking-up) in the cluster and their competences (Figure3.1).

In order to decrease the network energy consumption, all the nodes including the CHs are initially putt on the sleep mode.

2 Cross-layer approach for routing data to the Sink

The cross-layer approach for routing data to Sink begins after the detection of an event by the node. This operation is divided into two stages:

- intra-cluster routing which is used to send the data captured by the CMs to their corresponding CH;
- Inter-cluster routing which is used to send the data aggregated by the CH to the Sink.

2.1 Intra-cluster routing

Figure 3.3 shows how the cluster members send the monitored data to the CH.

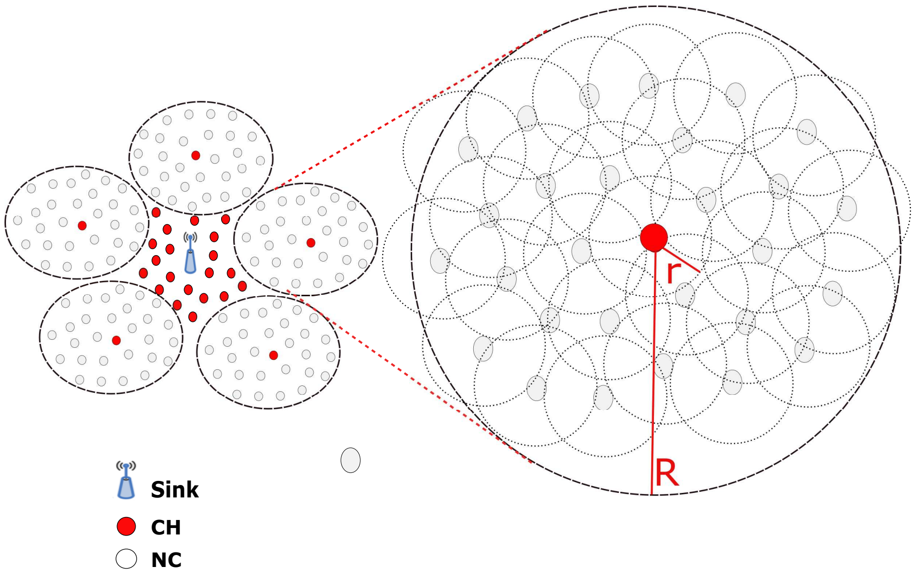

Fig. 3.1 General view of the network

1B	1B	1B	1B	1B	1B
Frame Header	Recipient ID	Id_eme_org	Id_node_wkup	Nbr_hops	FCS (Frame check sequence) CRC (cyclic redundancy code)

Fig. 3.2 Wake-up message format

1. Whenever an event occurs, the node wakes up and sends a wake-up message (WuM) to the direct neighbor with the greatest value of $comp\_intra$, calculated using Equation 3.3. Figure 3.2 shows the modified wake-up message format. This message contains $(id\_eme\_org, id\_node\_wkup, nbr\_hops)$, where:

   - id_eme_org is the identifier of the original sender node (event detector);
   - id_node_wkup as above, is the identifier of the wake-up node. In one case, it is the event detector identifier and in the other case, it is the identifier of the wake-up node (used as a relay).

2. On receipt of this wake-up message by the direct neighbor node, this latter is partially woken up, *i.e.*, without powering the main radio; this being guaranteed by the cross-layer approach between the Application, the MAC and the Physical layers. This latter node wakes up the node with the highest value of $compt\_intra$, calculated using equation3.2 and made available in its neighbors' table.

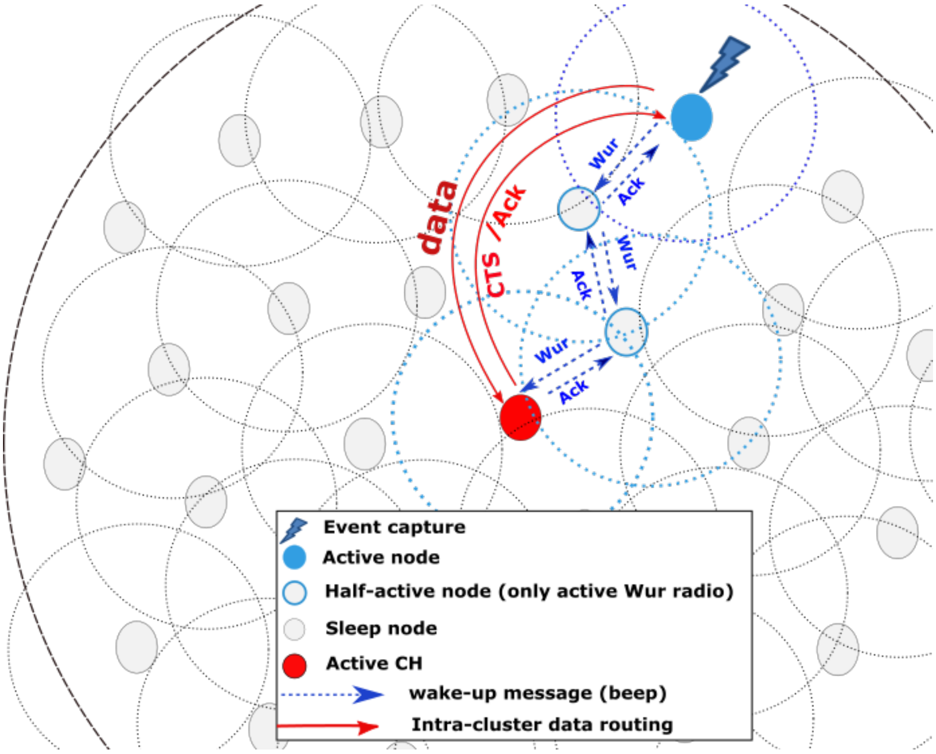

Fig. 3.3 Intra-Cluster Routing

3. If the requested node exists, then it is woken up by the same wake-up message, by changing the *id_node_wkup* in its identifier, and it sends an acknowledgement of the wake-up message (*ACK_Wu*) to the sending node.

4. Otherwise, after a certain time T, the neighbor node is considered faulty and the *nbr_hops* and is assigned the value 255. Wake-up message's sender node moves to the next neighbor in the neighbors' table. This partial wake-up process is repeated until reaching the CH.

5. After receiving the WuM, the CH wakes up completely and sends a CTS (Clear to Send) message to the original sending node, identified in WuM. After receiving CTS, the node sends the data directly to the CH which sends an acknowledge (ACK) message to the original sending node of the message.

   To save the energy and to avoid the CH state transition between active and sleep mode each time it receives a WuM from a CM, the CH remains awake for a time T to send the CTS to these CMs upon the reception of each WuM. This time T is proportional to the size of the cluster, *i.e.* the number of CMs. After removing the redundant data, the CH node aggregates the resulting data and sends it to the Sink with an inter-cluster routing process.

2.2 Inter-Cluster Routing

Since the distance between the CHs and the Sink is usually large, a high energy consumption is needed if the data is sent directly to the Sink. For avoiding this energy consumption, we base on the multi-hop routing between the CHs and the Sink considering the two following steps:

Step1: the nodes are far from the Sink ($dist\_BS(i)$> R) :

- After collecting the data from the CMs, the CH sends a WuM in the same format as the message used in intra-cluster routing but with no hops (Nbr_hops=0). This is done in order to distinguish between the intra- and inter-cluster WuM.
- After the reception of the WuM by the direct neighbor node with the greatest value of $Comp\_inter$, (calculated using Equation 3.3), this node is partially woken up, without powering the main radio. Since Nbr_Hops=0, this is therefore an inter-cluster routing. This node repeats the same process with all direct neighbors.
- If the receiving node is outside the current cluster (known by checking the sender's CH identifier in its direct neighbor table), it wakes up completely and sends a CTS message to the current cluster's CH to receive its data (Figure 3.4).
- After its complete awakening, the relevant node of the neighboring cluster transmits the message received by the CH of this neighboring cluster, to its CH by an intra-cluster routing as seen previously (3.3). This is done by waking up the direct neighbor with the greatest value of $Comp\_intra$ and with the replacement of nbr_hops of the WuM message (which is equal to 0) by the new nbr_hops. Additionally, the identifier of the sender *id_eme_org* is also replaced by the new identifier.
- After receiving the data message by CH - here used as inter-cluster routing relay - and based on the size of this message (the merged data message is larger than the message sent by a node to its CH after the capture of an event), the CH knows that it is an inter-cluster routing. So, it nullifies the number of hops and wakes up the direct neighbor node with the larger $Comp\_inter$ value (the same procedure as for the inter-cluster routing). The identifier of the original CH which ensured the data aggregation is stored in the data message to be sent to the Sink.

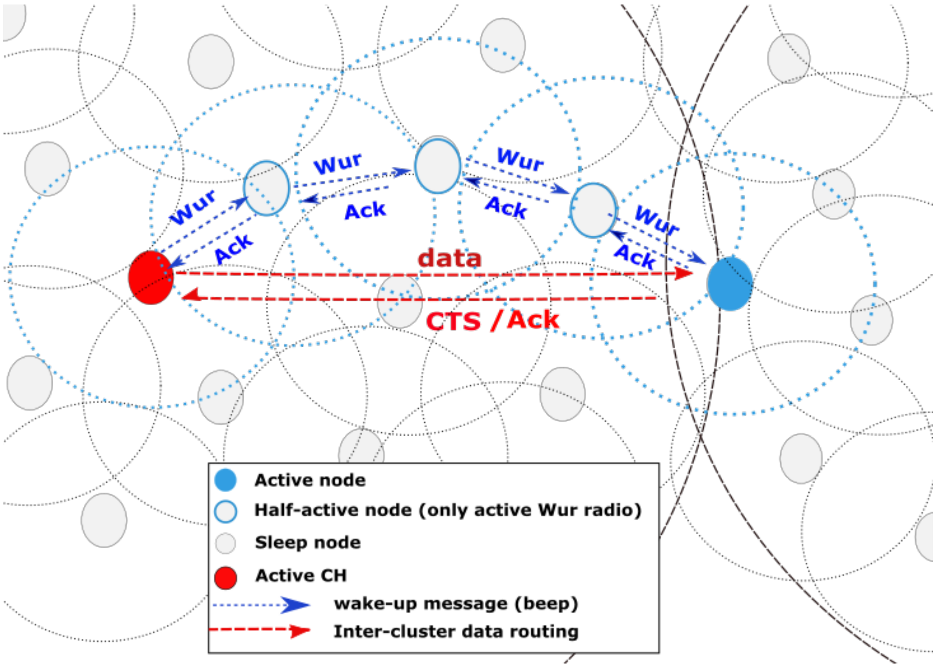

Fig. 3.4 Inter-Cluster Routing (CH far from the Sink)

Step2: the nodes are close to the Sink ($Dist\_BS(i) \leq R$) : All these nodes perform the role of CH, *i.e.*, they transmit the data directly to the Sink. When a node A, for instance (A), receives the data, it compares its inter-cluster competence (given by Equation (3.4)) with direct neighbors (Bi). If their competences values are better, it wakes a node B with the best competence. Otherwise, it transmits the data directly to the Sink.

The neighbor node that will receive the data does the same to route the data to the Sink (Figure 3.5).

The flowchart of Figure 3.6 shows all the communication process of the CH.

When the CH receives a Wakeup message, it switches to the Active mode (turns on the main radio) and sends a CTS message to the original sender. After receiving the data, it can distinguish between the data monitored from CM (intra-cluster routing) and the data sent from other clusters (inter-cluster routing), depending on the size of the packet (the packet sent from external clusters is larger). There are two main scenarios:

1. If the CH receives the data monitored from CM, it waits for a period T to ensure receiving data from a large number of its members in order to remove redundancy, and sends the collected data to the best cluster neighbor to reach the Sink (inter-cluster routing) described in Section 6.4. If the CH does not find a suitable node from the neighboring cluster, it tries to send the collected data directly to the Sink based on its energy. Otherwise, the transmission process fails, and the CH turns to the sleep mode.

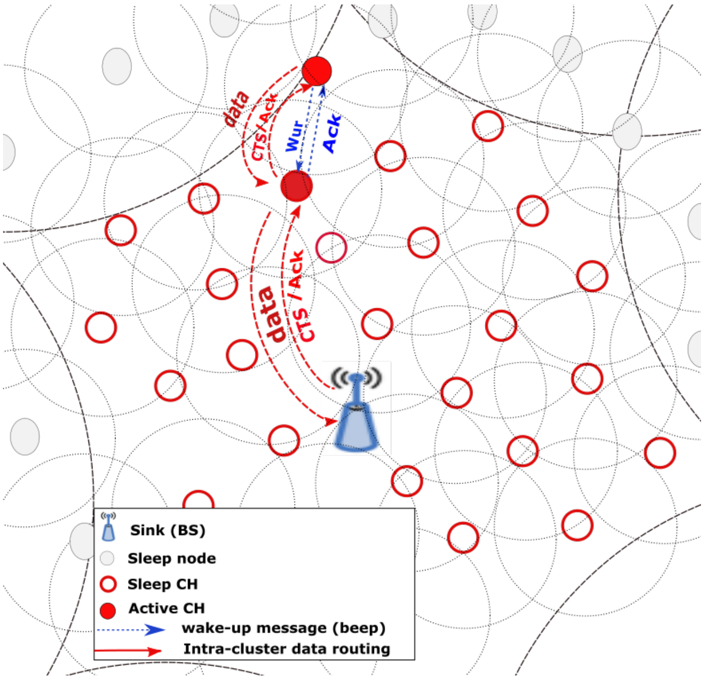

Fig. 3.5 Inter-Cluster Routing (CH near to the Sink)

2. If the data are sent from external clusters, the CH searches for the best neighbor node using the *comp_inter* parameter in the neighbor's table. When finding the node, it sends the Wakeup and waits for an ACK.
    - If the ACK is received, the CH waits for CTS from the relay node of the best neighboring cluster towards Sink and then sends the data to the relay node and turns to the sleep mode: the intermediate node sends the data to the CH of its cluster *via* an intra-cluster routing.
    - If the ACK is not received, the CH chooses the next node in the neighbor's table. If any neighbor node is found or the CH does not receive a CTS, it tries to send the data directly to the Sink based on its energy. Otherwise, the transmission process fails and the CH turns to the sleep mode.

The flowchart of Figure 3.7 shows all the communication process of the CM node. The node wakes up in two scenarios:

1. Monitoring an event: it completes awakening (the main radio is on) and tries to send the data to the cluster CH (intra-cluster routing) by searching the best neighbor node (i.e., the greatest *comp_intra*) in the neighbors' table. The CM waits a CTS from the CH (the Wakeup message is sent hop by hop towards the CH). If the CM doesn't find any neighbor node in the neighbors' table, it is considered an isolated node and it turns

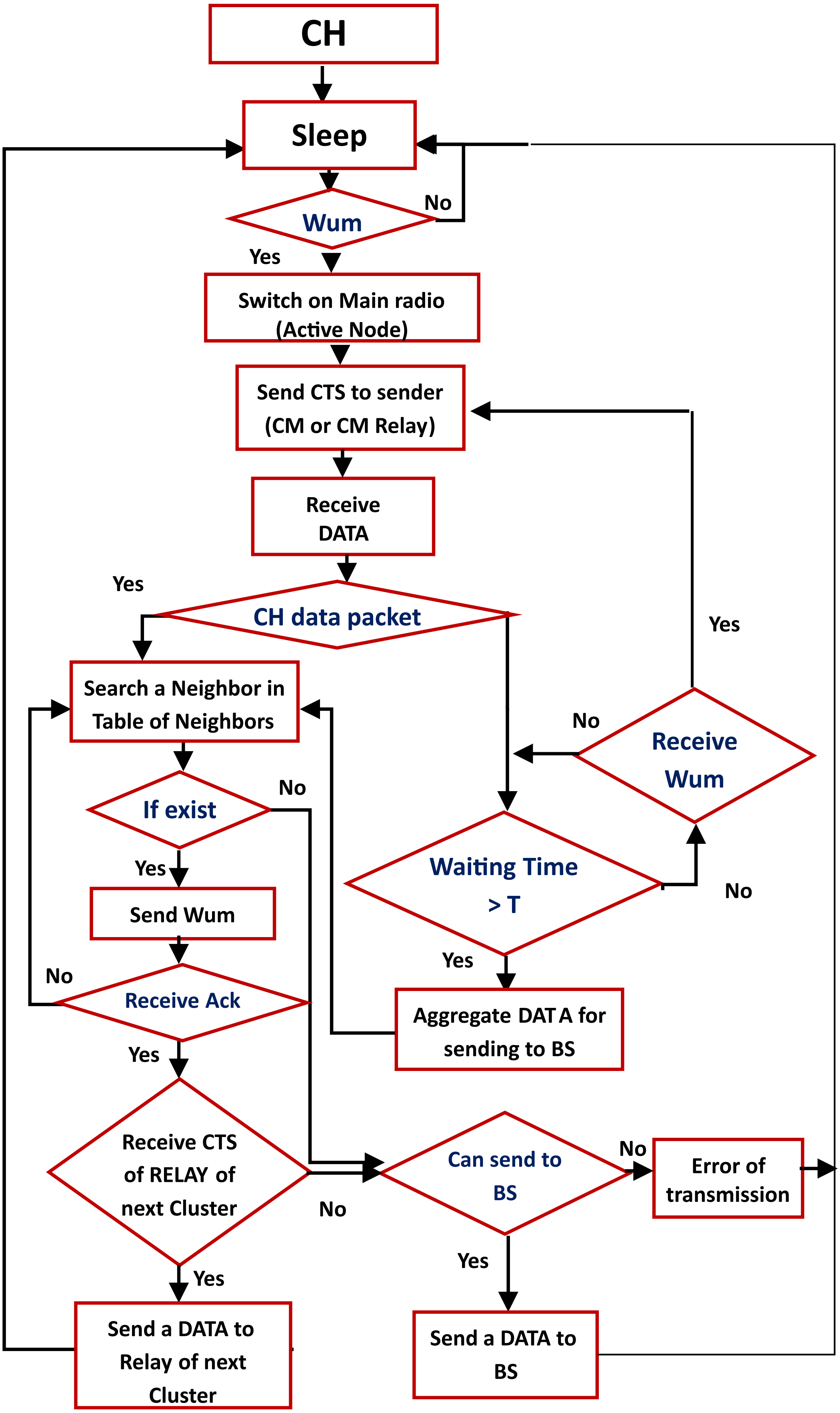

Fig. 3.6 Cluster Head Operation

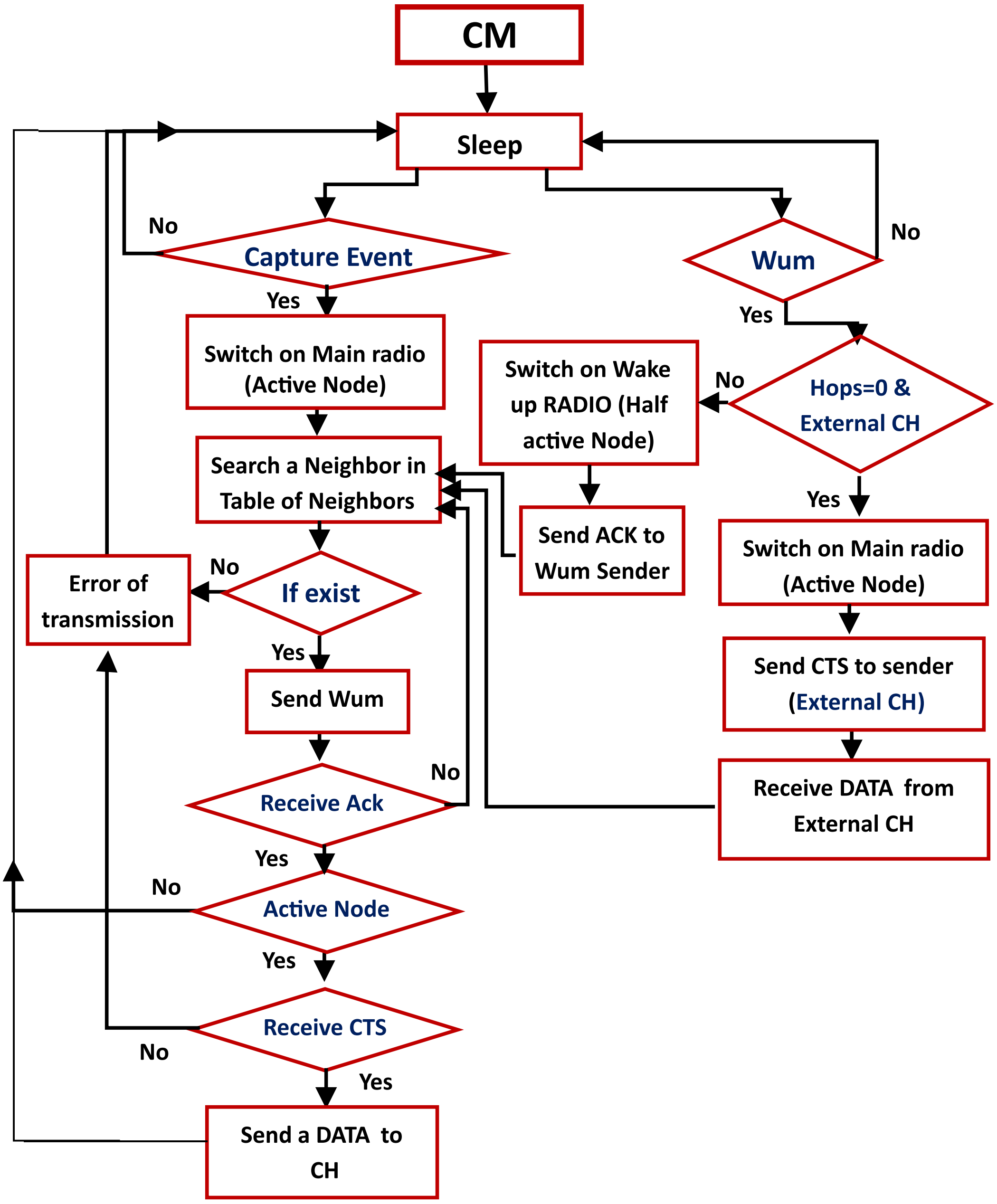

Fig. 3.7 Custer Member Operation Flowchart

Table 3.2 The different cases of awakening a node

Partial awakening of the node	**Complete awakening of the node**
Reception of a WuM by a CM from a node of the same cluster regardless of the number of hops.	Capture an event by the node.
Reception of a WuM by a CM from its CH with no hops.	Reception of a WuM by a CM from a node of another cluster with no hops.
	Reception of a WuM by a CH regardless of the transmitter.

to the sleep mode. When receiving the CTS from the CH, the CM sends the data and turns to the sleep mode.

2. Receiving Wakeup from the neighbor node: we have two cases:

    (a) If the number of hops in the Wakeup message is 0 and the original sender is the CH of an external cluster (inter-cluster routing), then:

    - It wakes up completely: it is considered a relay node between two clusters;
    - It sends the CTS to the external CH and receives the data;
    - It further sends the data to the CH of its cluster using intra cluster routing (Scenario 1);

    (b) If the number of hops in the Wakeup message is different from 0 or the original sender is a node of the cluster, then:

    - It partially wakes up;
    - It sends an ACK to the sender;
    - It resends the Wakeup to its best neighbor node (This partial wake-up process is repeated until reaching its CH using intra-cluster routing or a relay node between two clusters using inter-cluster routing).

3 Simulation and results

We consider a data collection WSN where ’N’ homogeneous sensors are randomly deployed in an area of 1000m × 1000m. We used the $MATLAB^{TM}$ environment to simulate the proposed protocol. For scalability purposes, and in order to allow a more precise

Table 3.3 The simulation parameters

Parameters	Values
BS coordinates	x_BS= 500m, y_BS= 500m
Total number of nodes	200,500 and 1000
Data packet length	512 bits
CH data packet length	2560 bits
Control packet length	120 bits
Wake-up packet length	48 bits
Initial energy of a sensor node	0.5 J
Data packet aggregation energy	5nJ/bit
Energy dispersed per bit(Eelec)	50 nJ/bit
Transmitter amplifier if d>= d0	0.0013 pJ/bit/m2
Transmitter amplifier if d<d0	10 pJ/bit/m2
Power consumption switch on main radio	42.3mW.
d0 break point distance	87 m
Radius of main radio	80 m
Radius of WuR	30 m

comparison of the proposed protocol, we increased the number of sensor nodes from 200, to 500 and 1000. We provide the simulation results with detailed analysis as compared with two state-of-the-art protocols from the same family, namely [115] and [116].

The evaluation of the results is based on parameters such as the sum of the residual energy of all the nodes, the average energy of the CHs in the network, the energy of the CHs close to the Sink, the number of nodes completely exhausting their energy at each round and the number of successfully delivered packets to measure the latency.

We based on the so-called Dynamic Hyper Round Policy (DHRP) as a distributed energy-efficient scheme to cluster a WSN, which schedules clustering-task for extending network lifetime and for reducing energy consumption. Using the DHRP in our simulation, the clustering operation is performed at the begin of each hyper round instead of each round, to reduce the overload of re-clustering. The energy threshold of the CHs for re-clustering is defined by the formula 3.5 [140].

$$enrg\_th\_CH < RF * \overline{E_{CMi}} \tag{3.5}$$

where: $\overline{E_{CMi}}$ is the average energy of cluster members (CMi) and 0 < RF <1.

The parameters used in our simulation are summarized in Table 3.1

3.1 Energy Efficiency

Energy efficiency can equivalently be described by the sum of the energies of all nodes. We can see from Figure 3.8 that our CMH-CLP protocol has the best energy efficiency compared to its competitors. In fact, CMH-CLP outperforms the other two protocols by a maximum factor of two, despite the increase in the number of nodes (up to 1000 nodes). Additionally, CMH-CLP maintains network stability and connectivity throughout the 2000 rounds. This is due to the enhancement of the wake-up system, where each node wakes up only when there is data to be received. In addition, the CHs perform more tasks than the CMs as shown in Figure 3.9 representing the average energy of the CHs at each round.

Thus, we notice that the hot spot problem is greatly reduced in our protocol. The hot spot problem occurs since the nodes closer to the Sink quickly consume their energy ; which is a major drawback in hierarchical routing. On the basis of the enhanced wake-up system used, we also notice that the nodes which are close to the Sink still keep their energies for approximately up to 200% as compared to the other two protocols (Figure3.10).

3.2 Dead nodes over rounds

The number of dead nodes at each round is shown in Figure 3.11.

- The node death is reduced by 78% compared with LEACH_CLO and by 50% compared with FAMACOW for 200 nodes simulation.
- This node death is reduced by 90% compared with LEACH_CLO by 60% compared with FAMACOW for 500 and 1000 nodes simulation.

Once again, this is so, because all the nodes spend most of their time in sleep mode.

3.3 Network Lifetime

To make an fair comparison between protocols in terms of network lifetime, base our experiments on standard metrics such as:

- First Node Dead (FND), describing the round when the first node dies;
- Half Node Alive (HNA), describing the round when half of nodes are still alive (or, equivalently, dead);
- Last Node Dead (LND) specifying when the last node dies.

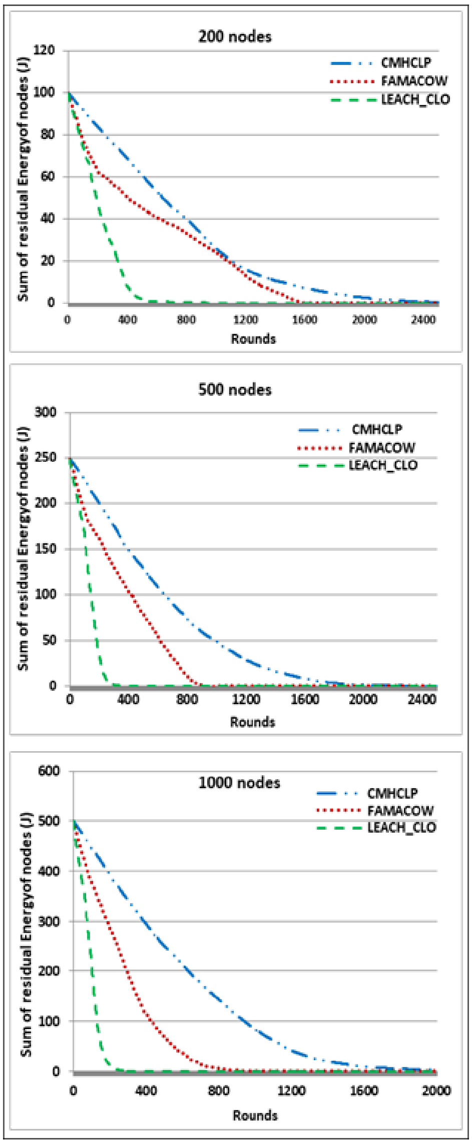

Fig. 3.8 Nodes energy consumption

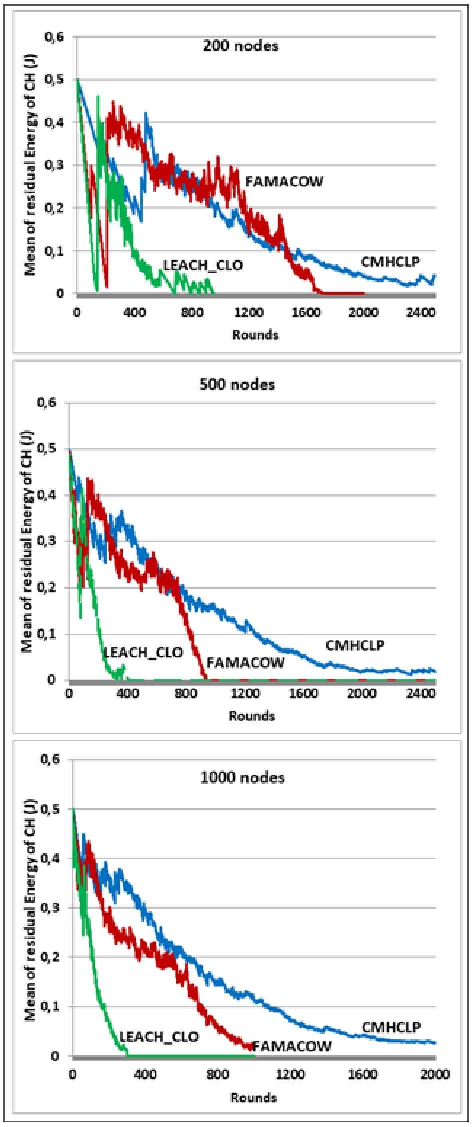

Fig. 3.9 Average energy of CHs

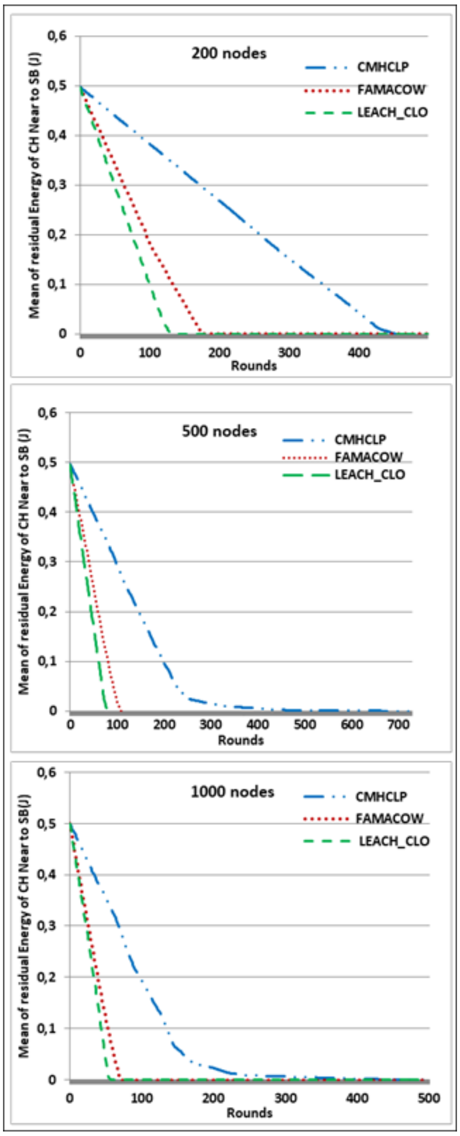

Fig. 3.10 The energy average of the CHs near to the SB

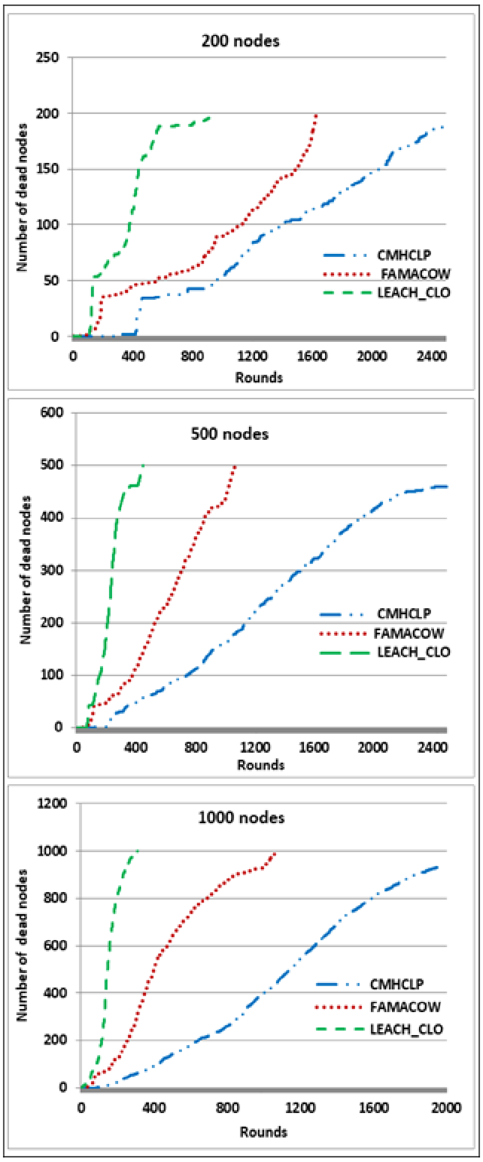

Fig. 3.11 Number of dead nodes

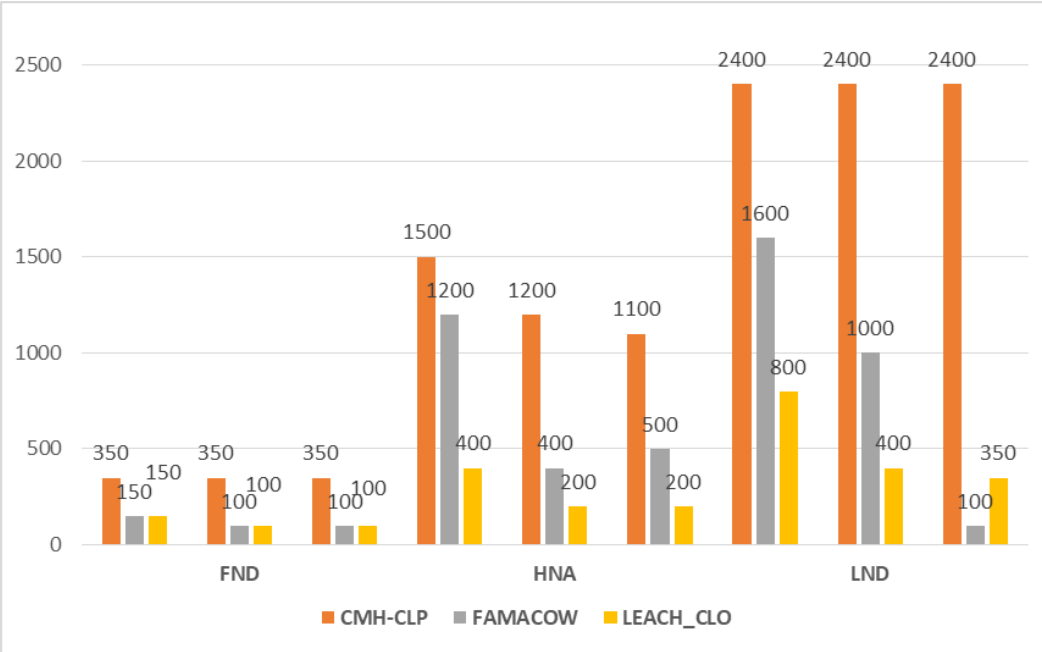

Fig. 3.12 Network lifetime metrics of the 3 protocols for 200, 500 and 1000 nodes

Figure 3.13 shows that our protocol provides a network lifetime better than the competitor for 200 nodes case. When increasing the number of nodes (500 and 1000 nodes), CMH-CLP achieves even better results in terms of network lifetime.

Table 3.4 summarizes the chosen metrics and their values for all the three protocols. It is required that all metrics have maximum values for better network lifetime performance. It is clear that CMH-CLP gives better results, as shown in Figure 3.12.

Table 3.4 Lifetime network metrics

Metric	**#Nodes**	**CMH-CLP**	**FAMACOW**	**LEACH_CLO**
FND	200	350	150	150
	500	350	100	100
	1000	350	100	100
HNA	200	1500	1200	400
	500	1200	400	200
	1000	1100	500	200
LND	200	2400	1600	800
	500	2400	1000	400
	1000	2400	100	350

3.4 Data transmitted to the Sink

Figure 3.14 shows the total number of data packets transmitted to the Sink over time. We clearly see that the CMH-CLP protocol ensures an efficient packet transmission.

- For 200 nodes, CMH-CLP protocol successfully delivers at least 100% more packets than FAMACOW and 400% more than LEACH-CLO.
- For 500 nodes, CMH-CLP protocol successfully delivers 200% more than FAMACOW and 600% more packets than LEACH-CLO.
- For 1000 nodes, the successful packet delivery of CMH-CLP is even better than the two previous cases. Indeed, CMH-CLP delivers 400% more than FAMACOW and 900% more than LEACH-CLO.

The obtained results are due to the stability and the connectivity that the CMH-CLP protocol provides. In addition, the formulas used for choosing which nodes to wake-up in the routing process always ensure that at least one valid routing path exists. This minimizes packet loss and increases the number of packets successfully received by the Sink.

4 Conclusion

In this chapter, a new hierarchical routing protocol based on the cross-layer architecture has been designed to enhance existing systems in many ways. The performance evaluation of our WuR-based protocol has been compared to two state-of-the-art protocols under three real-world network deployments, with increasing degree of complexity and using network standard metrics, such as first node death, half node death, and last node death.

The proposed protocol presents many benefits and provides an essential contribution to WuR-based protocols. Using the advantage of the wake-up radio, the proposed protocol has shown clear advantages over similar protocols in terms of increasing network lifetime, reducing energy consumption; in particular, by improving the solution of the hot spot problem, as well as the number of successfully delivered packets.

Moreover, the energy efficiency of CMH-CLP improves the other two protocols by 200-300%, despite the increase in the number of nodes (up to 1000 nodes). Additionally, CMH-CLP maintains network stability and connectivity throughout experiments. The node death rate of our protocol is 50 to 78% less than that of its competitors. As for successful packet delivery, our protocol allows 200-900% more successful packets than its competitors.

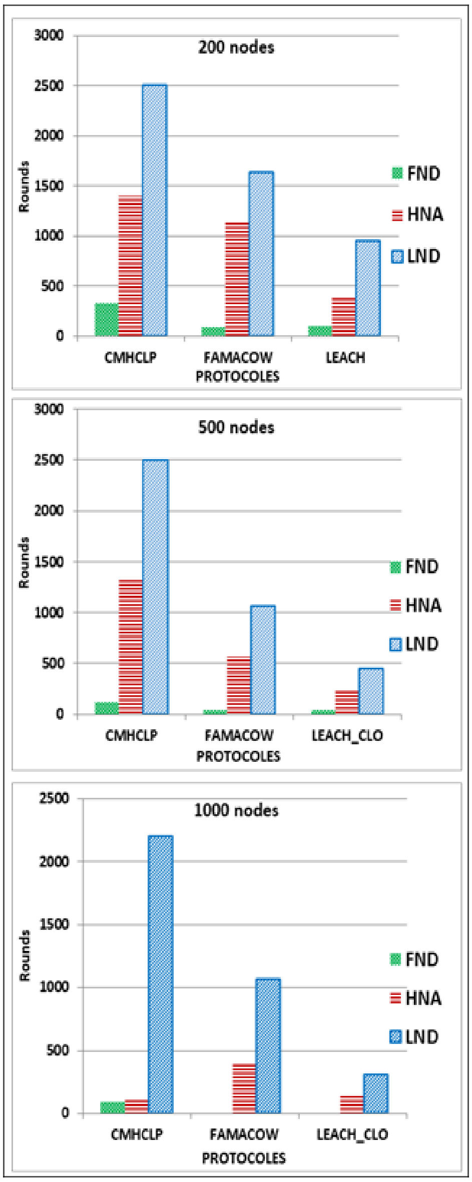

Fig. 3.13 Time for FND, HNA, and LND

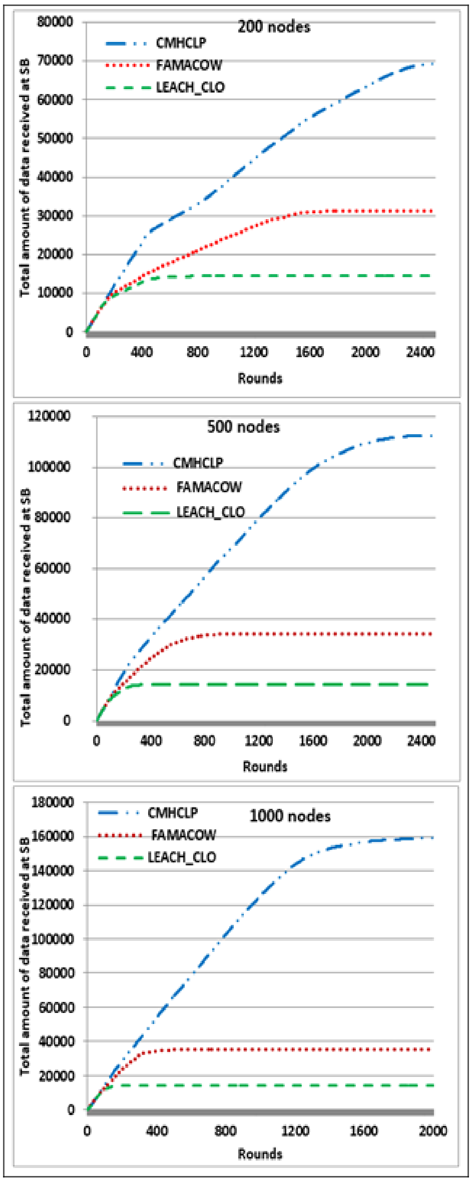

Fig. 3.14 Number of successfully delivered data

Conclusion and future work

This thesis focused on cross-layer routing protocols analysis in WSNs. An introduction to WSNs was provided, and a number of relevant works on radio frequency communication energy efficiency improvement were reviewed, concentrating on hierarchical protocols, taking LEACH as a model. An explanation was given for the cross-layer design, with a presentation of some types of protocols highlighting their advantages and drawbacks. Special attention was made on the protocols with wake-up radio and the contribution of the latter in the performance of the WSNs.

In particular, this thesis presented a contribution to the area of energy-efficient routing protocols based on cross-layer design WSN. The so-called called Clustering Multi-Hop Cross-Layer Protocol (CMH-CLP) was proposed as a new routing protocol. Our contribution took advantage of the wake-up radio of the sensor and the cross-layers design to improve the hierarchical routing protocols in WSNs as it would enable CHs and other nodes in the network to remain in sleep mode for as long time as possible. Two levels of routing were considered:

- Intra-cluster routing: after sensing an event by a particular node, the protocol relies on wake-up radio to wake the CH using wake-up message and wake neighboring nodes as relays; the latter partially wakes up to transmit the wake-up message to their best neighbor towards the CH. This procedure contributes to saving cluster energy using time slots instead of classic hierarchical protocols that forces nodes to wake up even if there is no information to send.

- Inter-cluster routing : the CH uses a multi-hop wake up to wake the relay node of the neighboring cluster towards the Sink. This node sends information to the CH in the same way as intra-routing, allowing the CM and CHs return to sleep as soon as data is sent.

We concluded that CMH-CLP presents many benefits and provides an essential contribution to WuR-based protocols. Using the advantage of the wake-up radio, the proposed protocol has shown clear advantages over similar protocols in terms of increasing network lifetime, reducing energy consumption; in particular, by improving the solution of the hot spot problem, as well as the number of successfully delivered packets.

Besides the described contributions, we believe that this thesis opened new vistas for future works that can possibly enhance and extend the actual proposal, and provides more energy-efficient solutions for WSNs. The following lines of research would be useful:

- Another study of the effectiveness of this protocol can be carried out in terms of delay time.
- The density of wakeup neighbors can also be used as parameter to select the CH.
- This contribution can be implemented on mobile sensors and drone networks.
- Use of type-2 fuzzy methods and study trade-offs between complexity and potential improvements.

References

[1] SH Gajjar, SN Pradhan, and KS Dasgupta. Wireless sensor network: Application led research perspective. In *2011 IEEE Recent Advances in Intelligent Computational Systems*, pages 025–030. IEEE, 2011.

[2] Guangjie Han, Xuan Yang, Li Liu, Wenbo Zhang, and Mohsen Guizani. A disaster management-oriented path planning for mobile anchor node-based localization in wireless sensor networks. *IEEE Transactions on Emerging Topics in Computing*, 8(1):115–125, 2017.

[3] Sarang Dagajirao Patil and Pravin Sahebrao Patil. A theoretical review of topological organization for wireless sensor network. *International Journal of Electronics and Telecommunications*, 67, 2021.

[4] Shilpa Mahajan and Pushpender Kumar Dhiman. Clustering in wireless sensor networks: A review. *International Journal of Advanced Research in Computer Science*, 7(3), 2016.

[5] Quoc-Tuan Vien, Wanqing Tu, Huan X Nguyen, and Ramona Trestian. Cross-layer optimisation for topology design of wireless multicast networks via network coding. In *39th Annual IEEE Conference on Local Computer Networks*, pages 466–469. IEEE, 2014.

[6] Tommaso Melodia, Mehmet C Vuran, and Dario Pompili. The state of the art in cross-layer design for wireless sensor networks. In *International workshop of the EuroNGI network of excellence*, pages 78–92. Springer, 2005.

[7] Joaquim Oller, Ilker Demirkol, Jordi Casademont, Josep Paradells, Gerd Ulrich Gamm, and Leonhard Reindl. Has time come to switch from duty-cycled mac protocols to wakeup radio for wireless sensor networks. *IEEE/ACM Transactions on Networking*, 24(2):674–687, 2015.

[8] Maarten Lont, Dusan Milosevic, Peter GM Baltus, Arthur HM Van Roermund, and Guido Dolmans. Analytical models for the wake-up receiver power budget for wireless sensor networks. In *GLOBECOM 2009-2009 IEEE Global Telecommunications Conference*, pages 1–6. IEEE, 2009.

[9] Stefano Basagni, Federico Ceccarelli, Chiara Petrioli, Nithila Raman, and Abhimanyu V Sheshashayee. Wake-up radio ranges: A performance study. In *2019 IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1–6. IEEE, 2019.

[10] Rajeev Piyare, Amy L Murphy, Csaba Kiraly, Pietro Tosato, and Davide Brunelli. Ultra low power wake-up radios: A hardware and networking survey. *IEEE Communications Surveys & Tutorials*, 19(4):2117–2157, 2017.

[11] Fatima Zahra Djiroun and Djamel Djenouri. Mac protocols with wake-up radio for wireless sensor networks: A review. *IEEE Communications surveys & tutorials*, 19(1):587–618, 2016.

[12] Riad Aouabed, Fouzi Semchedine, and Aboubekeur Hamdi-Cherif. A wake-up radio-based energy-efficient multi-hop clustering protocol for wsns. *Wireless Personal Communications*, 127(4):3321–3346, 2022.

[13] Wint Yi Poe and Jens B Schmitt. Node deployment in large wireless sensor networks: coverage, energy consumption, and worst-case delay. In *Asian internet engineering conference*, pages 77–84, 2009.

[14] M Atto and C Guy. Wireless sensor networks: Mac protocols and mobility management module for real-time applications. In *The Ninth International Conference on Wireless and Mobile Communications (ICWMC 2013), Nice, France*, pages 1–6, 2013.

[15] Ian F Akyildiz, Weilian Su, Yogesh Sankarasubramaniam, and Erdal Cayirci. A survey on sensor networks. *IEEE Communications magazine*, 40(8):102–114, 2002.

[16] Mohd Fauzi Othman and Khairunnisa Shazali. Wireless sensor network applications: A study in environment monitoring system. *Procedia Engineering*, 41:1204–1210, 2012.

[17] Jamal N Al-Karaki and Ahmed E Kamal. Routing techniques in wireless sensor networks: a survey. *IEEE wireless communications*, 11(6):6–28, 2004.

[18] SH Gajjar, SN Pradhan, and KS Dasgupta. Wireless sensor network: Application led research perspective. In *2011 IEEE Recent Advances in Intelligent Computational Systems*, pages 025–030. IEEE, 2011.

[19] Deborah Estrin, Lewis Girod, Greg Pottie, and Mani Srivastava. Instrumenting the world with wireless sensor networks. In *2001 IEEE International Conference on Acoustics, Speech, and Signal Processing. Proceedings (Cat. No. 01CH37221)*, volume 4, pages 2033–2036. IEEE, 2001.

[20] Giuseppe Anastasi, Marco Conti, Mario Di Francesco, and Andrea Passarella. Energy conservation in wireless sensor networks: A survey. *Ad hoc networks*, 7(3):537–568, 2009.

[21] Feng Zhao, Leonidas J Guibas, and Leonidas Guibas. *Wireless sensor networks: an information processing approach.* Morgan Kaufmann, 2004.

[22] Zeyu Zhang, Amjad Mehmood, Lei Shu, Zhiqiang Huo, Yu Zhang, and Mithun Mukherjee. A survey on fault diagnosis in wireless sensor networks. *IEEE Access*, 6:11349–11364, 2018.

[23] Roozbeh Jafari, Andre Encarnacao, Azad Zahoory, Foad Dabiri, Hyduke Noshadi, and Majid Sarrafzadeh. Wireless sensor networks for health monitoring. In *The second annual international conference on mobile and ubiquitous systems: networking and services*, pages 479–481. IEEE, 2005.

[24] Dirk Trossen, Dana Pavel, Glenn Platt, Joshua Wall, Philip Valencia, Corey A Graves, Myrna S Zamarripa, Victor M Gonzalez, Jesus Favela, Erik Lovquist, et al. Sensor networks, wearable computing, and healthcare applications. *IEEE Pervasive Computing*, 6(2):58–61, 2007.

[25] Charles Herring and Simon Kaplan. Component-based software systems for smart environments. *IEEE Personal Communications*, 7(5):60–61, 2000.

[26] Andrea J Goldsmith and Stephen B Wicker. Design challenges for energy-constrained ad hoc wireless networks. *IEEE wireless communications*, 9(4):8–27, 2002.

[27] Ramesh Rajagopalan and Pramod K Varshney. Data aggregation techniques in sensor networks: A survey. 2006.

[28] Ameer Ahmed Abbasi and Mohamed Younis. A survey on clustering algorithms for wireless sensor networks. *Computer communications*, 30(14-15):2826–2841, 2007.

[29] Mohammad Ilyas and Imad Mahgoub. *Smart Dust: Sensor network applications, architecture and design*. CRC press, 2018.

[30] Ravi Yadav and AK Daniel. Performance and analysis of mac protocols based on application. In *AIP Conference Proceedings*, volume 1952, page 020076. AIP Publishing LLC, 2018.

[31] Eugene Shih, Seong-Hwan Cho, Nathan Ickes, Rex Min, Amit Sinha, Alice Wang, and Anantha Chandrakasan. Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks. In *Proceedings of the 7th annual international conference on Mobile computing and networking*, pages 272–287, 2001.

[32] Ravindra K Ahuja, Thomas L Magnanti, and JB Orlin Network Flows. Theory, algorithms, and applications. *Network flows*, 1993.

[33] Ilker Demirkol, Cem Ersoy, and Fatih Alagoz. Mac protocols for wireless sensor networks: a survey. *IEEE Communications magazine*, 44(4):115–121, 2006.

[34] Muneeb Ali and Zartash Afzal Uzmi. Medium access control with mobility-adaptive mechanisms for wireless sensor networks. *International Journal of Sensor Networks*, 1(3-4):134–142, 2006.

[35] Jin Ding, Krishna Sivalingam, Raghava Kashyapa, and Lu Jian Chuan. A multi-layered architecture and protocols for large-scale wireless sensor networks. In *2003 IEEE 58th Vehicular Technology Conference. VTC 2003-Fall (IEEE Cat. No. 03CH37484)*, volume 3, pages 1443–1447. IEEE, 2003.

[36] Raphael Rom and Moshe Sidi. *Multiple access protocols: performance and analysis*. Springer Science & Business Media, 2012.

[37] Sergio Barbarossa, Massimiliano Pompili, and Georgios B Giannakis. Channel-independent synchronization of orthogonal frequency division multiple access systems. *IEEE Journal on Selected Areas in Communications*, 20(2):474–486, 2002.

[38] William CY Lee. Spectrum efficiency in cellular (radio). *IEEE Transactions on Vehicular Technology*, 38(2):69–75, 1989.

[39] Petros Nicopolitidis, Georgios I Papadimitriou, and Andreas S Pomportsis. Learning automata-based polling protocols for wireless lans. *IEEE Transactions on Communications*, 51(3):453–463, 2003.

[40] Hsiao-Hwa Chen. *The next generation CDMA technologies*. John Wiley & Sons, 2007.

[41] Dong Geun Jeong and Wha Sook Jeon. Performance of an exponential backoff scheme for slotted-aloha protocol in local wireless environment. *IEEE transactions on vehicular technology*, 44(3):470–479, 1995.

[42] S Andrew. Tanenbaum computer networks. *Computer Networks, Englewood Cliffs*, pages 141–148, 1996.

[43] IEEE Computer Society LAN MAN Standards Committee et al. Wireless lan medium access control (mac) and physical layer (phy) specifications. *ANSI/IEEE Std. 802.11-1999*, 1999.

[44] Phil Karn et al. Maca-a new channel access method for packet radio. In *ARRL/CRRL Amateur radio 9th computer networking conference*, volume 140, pages 134–140. London, Canada, 1990.

[45] Vaduvur Bharghavan, Alan Demers, Scott Shenker, and Lixia Zhang. Macaw: A media access protocol for wireless lan's. *ACM SIGCOMM Computer Communication Review*, 24(4):212–225, 1994.

[46] Sumit Kumar and Siddhartha Chauhan. A survey on scheduling algorithms for wireless sensor networks. *International Journal of Computer Applications*, 20(5):7–13, 2011.

[47] Wei Ye, John Heidemann, and Deborah Estrin. An energy-efficient mac protocol for wireless sensor networks. In *Proceedings. Twenty-first annual joint conference of the IEEE computer and communications societies*, volume 3, pages 1567–1576. IEEE, 2002.

[48] Amre El-Hoiydi. Spatial tdma and csma with preamble sampling for low power ad hoc wireless sensor networks. In *Proceedings ISCC 2002 seventh international symposium on computers and communications*, pages 685–692. IEEE, 2002.

[49] Ibrahim Ammar, Irfan Awan, and Andrea Cullen. Clustering synchronisation of wireless sensor network based on intersection schedules. *Simulation Modelling Practice and Theory*, 60:69–89, 2016.

[50] Wei Ye, John Heidemann, and Deborah Estrin. An energy-efficient mac protocol for wireless sensor networks. In *Proceedings. Twenty-first annual joint conference of the IEEE computer and communications societies*, volume 3, pages 1567–1576. IEEE, 2002.

[51] Wei Ye, John Heidemann, and Deborah Estrin. Medium access control with coordinated adaptive sleeping for wireless sensor networks. *IEEE/ACM Transactions on networking*, 12(3):493–506, 2004.

[52] Tijs Van Dam and Koen Langendoen. An adaptive energy-efficient mac protocol for wireless sensor networks. In *Proceedings of the 1st international conference on Embedded networked sensor systems*, pages 171–180, 2003.

[53] Koen Langendoen and Gertjan Halkes. Energy-efficient medium access control. *Embedded systems handbook*, 6000:34–1, 2005.

[54] Sha Liu. *Energy efficient mac layer design for wireless sensor networks*. PhD thesis, The Ohio State University, 2008.

[55] Joseph Polastre, Jason Hill, and David Culler. Versatile low power media access for wireless sensor networks. In *Proceedings of the 2nd international conference on Embedded networked sensor systems*, pages 95–107, 2004.

[56] Michael Buettner, Gary V Yee, Eric Anderson, and Richard Han. X-mac: a short preamble mac protocol for duty-cycled wireless sensor networks. In *Proceedings of the 4th international conference on Embedded networked sensor systems*, pages 307–320, 2006.

[57] Alberto Cerpa and Deborah Estrin. Ascent: Adaptive self-configuring sensor networks topologies. *IEEE transactions on mobile computing*, 3(3):272–285, 2004.

[58] Juha Petäjäjärvi, Heikki Karvonen, Konstantin Mikhaylov, Aarno Pärssinen, Matti Hämäläinen, and Jari Iinatti. Wban energy efficiency and dependability improvement utilizing wake-up receiver. *IEICE Transactions on Communications*, 98(4):535–542, 2015.

[59] Gang Lu, Bhaskar Krishnamachari, and Cauligi S Raghavendra. An adaptive energy-efficient and low-latency mac for data gathering in wireless sensor networks. In *18th International Parallel and Distributed Processing Symposium, 2004. Proceedings.*, page 224. IEEE, 2004.

[60] Venkatesh Rajendran, Katia Obraczka, and Jose Joaquin Garcia-Luna-Aceves. Energy-efficient collision-free medium access control for wireless sensor networks. In *Proceedings of the 1st international conference on Embedded networked sensor systems*, pages 181–192, 2003.

[61] I Rhee, A Warrier, M Aia, and J Min. et sichitiu, ml (2008). *Z-mac: a hybrid mac for wireless sensor networks. IEEE/ACM Transactions on Networking (TON)*, 16(3):511–524.

[62] Nikolaos A Pantazis, Stefanos A Nikolidakis, and Dimitrios D Vergados. Energy-efficient routing protocols in wireless sensor networks: A survey. *IEEE Communications surveys & tutorials*, 15(2):551–591, 2012.

[63] Samina Ehsan and Bechir Hamdaoui. A survey on energy-efficient routing techniques with qos assurances for wireless multimedia sensor networks. *IEEE communications surveys & tutorials*, 14(2):265–278, 2011.

[64] Ian D Chakeres and Elizabeth M Belding-Royer. Aodv routing protocol implementation design. In *24th International Conference on Distributed Computing Systems Workshops, 2004. Proceedings.*, pages 698–703. IEEE, 2004.

[65] David Johnson, Yin-chun Hu, and David Maltz. The dynamic source routing protocol (dsr) for mobile ad hoc networks for ipv4. Technical report, 2007.

[66] J-E Garcia, A Kallel, K Kyamakya, K Jobmann, J-C Cano, and P Manzoni. A novel dsr-based energy-efficient routing algorithm for mobile ad-hoc networks. In *2003 IEEE 58th Vehicular Technology Conference. VTC 2003-Fall (IEEE Cat. No. 03CH37484)*, volume 5, pages 2849–2854. IEEE, 2003.

[67] Jukka Suhonen, Mauri Kuorilehto, Marko Hannikainen, and Timo D Hamalainen. Cost-aware dynamic routing protocol for wireless sensor networks-design and prototype experiments. In *2006 IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications*, pages 1–5. IEEE, 2006.

[68] Bengt Ahlgren, Christian Dannewitz, Claudio Imbrenda, Dirk Kutscher, and Borje Ohlman. A survey of information-centric networking. *IEEE Communications Magazine*, 50(7):26–36, 2012.

[69] Xuelian Cai, Yulong Duan, Ying He, Jin Yang, and Changle Li. Bee-sensor-c: an energy-efficient and scalable multipath routing protocol for wireless sensor networks. *International Journal of Distributed Sensor Networks*, 11(3):976127, 2015.

[70] Gerhard P Hancke and C Jaco Leuschner. Seer: a simple energy efficient routing protocol for wireless sensor networks. *South African Computer Journal*, 2007(39):17–24, 2007.

[71] Wendi Rabiner Heinzelman, Joanna Kulik, and Hari Balakrishnan. Adaptive protocols for information dissemination in wireless sensor networks. In *Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking*, pages 174–185, 1999.

[72] Wendi Rabiner Heinzelman, Joanna Kulik, and Hari Balakrishnan. Adaptive protocols for information dissemination in wireless sensor networks. In *Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking*, pages 174–185, 1999.

[73] Ya Xu, John Heidemann, and Deborah Estrin. Geography-informed energy conservation for ad hoc routing. In *Proceedings of the 7th annual international conference on Mobile computing and networking*, pages 70–84, 2001.

[74] Wendi Rabiner Heinzelman, Anantha Chandrakasan, and Hari Balakrishnan. Energy-efficient communication protocol for wireless microsensor networks. In *Proceedings of the 33rd annual Hawaii international conference on system sciences*, pages 10–pp. IEEE, 2000.

[75] Sunil Kumar Singh, Prabhat Kumar, and Jyoti Prakash Singh. A survey on successors of leach protocol. *Ieee Access*, 5:4298–4328, 2017.

[76] Chunhung Richard Lin and Mario Gerla. Adaptive clustering for mobile wireless networks. *IEEE Journal on Selected areas in Communications*, 15(7):1265–1275, 1997.

[77] Mario Gerla and Jack Tzu-Chieh Tsai. Multicluster, mobile, multimedia radio network. *Wireless networks*, 1(3):255–265, 1995.

[78] Geng Chen, Fabian Garcia Nocetti, Julio Solano Gonzalez, and Ivan Stojmenovic. Connectivity based k-hop clustering in wireless networks. In *Proceedings of the 35th Annual Hawaii International Conference on System Sciences*, pages 2450–2459. IEEE, 2002.

[79] Ching-Chuan Chiang, Hsiao-Kuang Wu, Winston Liu, and Mario Gerla. Routing in clustered multihop, mobile wireless networks with fading channel. In *proceedings of IEEE SICON*, volume 97, pages 197–211. Citeseer, 1997.

[80] Mainak Chatterjee, Sajal K Das, and Damla Turgut. Wca: A weighted clustering algorithm for mobile ad hoc networks. *Cluster computing*, 5(2):193–204, 2002.

[81] Wendi Rabiner Heinzelman, Anantha Chandrakasan, and Hari Balakrishnan. Energy-efficient communication protocol for wireless microsensor networks. In *Proceedings of the 33rd annual Hawaii international conference on system sciences*, pages 10–pp. IEEE, 2000.

[82] Ossama Younis and Sonia Fahmy. Heed: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks. *IEEE Transactions on mobile computing*, 3(4):366–379, 2004.

[83] Stephanie Lindsey and Cauligi S Raghavendra. Pegasis: Power-efficient gathering in sensor information systems. In *Proceedings, IEEE aerospace conference*, volume 3, pages 3–3. IEEE, 2002.

[84] Mao Ye, Chengfa Li, Guihai Chen, and Jie Wu. Eecs: an energy efficient clustering scheme in wireless sensor networks. In *PCCC 2005. 24th IEEE International Performance, Computing, and Communications Conference, 2005.*, pages 535–540. IEEE, 2005.

[85] Yan Jin, Ling Wang, Yoohwan Kim, and Xiaozong Yang. Eemc: An energy-efficient multi-level clustering algorithm for large-scale wireless sensor networks. *Computer networks*, 52(3):542–562, 2008.

[86] Arati Manjeshwar and Dharma P Agrawal. Teen: Arouting protocol for enhanced efficiency in wireless sensor networks. In *ipdps*, volume 1, page 189, 2001.

[87] Levente Buttyán and Péter Schaffer. Position-based aggregator node election in wireless sensor networks. *International Journal of Distributed Sensor Networks*, 6(1):679205, 2010.

[88] Jiman Hong, Joongjin Kook, Sangjun Lee, Dongseop Kwon, and Sangho Yi. T-leach: The method of threshold-based cluster head replacement for wireless sensor networks. *Information Systems Frontiers*, 11(5):513–521, 2009.

[89] Fotis Foukalas, Vangelis Gazis, and Nancy Alonistioti. Cross-layer design proposals for wireless mobile networks: a survey and taxonomy. *IEEE Communications Surveys & Tutorials*, 10(1):70–85, 2008.

[90] Sanjay Shakkottai, Theodore S Rappaport, and Peter C Karlsson. Cross-layer design for wireless networks. *IEEE Communications magazine*, 41(10):74–80, 2003.

[91] Vineet Srivastava and Mehul Motani. Cross-layer design: a survey and the road ahead. *IEEE communications magazine*, 43(12):112–119, 2005.

[92] Qi Wang and Mosa Ali Abu-Rgheff. Cross-layer signalling for next-generation wireless systems. In *2003 IEEE Wireless Communications and Networking, 2003. WCNC 2003.*, volume 2, pages 1084–1089. IEEE, 2003.

[93] Vijay T Raisinghani and Sridhar Iyer. Cross-layer design optimizations in wireless protocol stacks. *Computer communications*, 27(8):720–724, 2004.

[94] Vineet Srivastava and Mehul Motani. Cross-layer design: a survey and the road ahead. *IEEE communications magazine*, 43(12):112–119, 2005.

[95] Wenbo Zhang, Xuanren Wei, Guangjie Han, and Xiaobo Tan. An energy-efficient ring cross-layer optimization algorithm for wireless sensor networks. *IEEE Access*, 6:16588–16598, 2018.

[96] Jiuqiang Xu, Wei Liu, Fenggao Lang, Yuanyuan Zhang, and Chenglong Wang. Distance measurement model based on rssi in wsn. *Wirel. Sens. Netw*, 28, 2010.

[97] Liqi Shi and Abraham O Fapojuwo. Tdma scheduling with optimized energy efficiency and minimum delay in clustered wireless sensor networks. *IEEE Transactions on Mobile Computing*, 9(7):927–940, 2010.

[98] Tao Shu and Marwan Krunz. Energy-efficient power/rate control and scheduling in hybrid tdma/cdma wireless sensor networks. *Computer Networks*, 53(9):1395–1408, 2009.

[99] Geoffrey G Messier, Jennifer A Hartwell, and Robert J Davies. A sensor network cross-layer power control algorithm that incorporates multiple-access interference. *IEEE Transactions on Wireless Communications*, 7(8):2877–2883, 2008.

[100] Jelena Misic, Shairmina Shafi, and Vojislav B Misic. Cross-layer activity management in an 802-15.4 sensor network. *IEEE Communications Magazine*, 44(1):131–136, 2006.

[101] Sung-Hwa Hong and Hoon-ki Kim. A multi-hop reservation method for end-to-end latency performance improvement in asynchronous mac-based wireless sensor networks. *IEEE Transactions on Consumer Electronics*, 55(3):1214–1220, 2009.

[102] Changsu Suh, Young-Bae Ko, and Dong-Min Son. An energy efficient cross-layer mac protocol for wireless sensor networks. In *Asia-Pacific Web Conference*, pages 410–419. Springer, 2006.

[103] Wesam Lootah, William Enck, and Patrick McDaniel. Tarp: Ticket-based address resolution protocol. *Computer networks*, 51(15):4322–4337, 2007.

[104] Mohamed S Hefeida, Turkmen Canli, and Ashfaq Khokhar. Cl-mac: A cross-layer mac protocol for heterogeneous wireless sensor networks. *Ad Hoc Networks*, 11(1):213–225, 2013.

[105] Jaehyun Kim, Jaiyong Lee, and Seoggyu Kim. An enhanced cross-layer protocol for energy efficiency in wireless sensor networks. In *2009 Third International Conference on Sensor Technologies and Applications*, pages 657–664. IEEE, 2009.

[106] Fuad Alnajjar and Yahao Chen. Snr/rp aware routing algorithm: cross-layer design for manets. *International Journal of Wireless & Mobile Networks (IJWMN)*, 1(2):127–136, 2009.

[107] Xiaodong Wang, Jun Yin, Qi Zhang, and Dharma P Agrawal. A cross-layer approach for efficient flooding in wireless sensor networks. In *IEEE Wireless Communications and Networking Conference, 2005*, volume 3, pages 1812–1817. IEEE, 2005.

[108] Gordon L Stüber and Gordon L Steuber. *Principles of mobile communication*, volume 2. Springer, 1996.

[109] Hideaki Takagi and Leonard Kleinrock. Optimal transmission ranges for randomly distributed packet radio terminals. *IEEE Transactions on communications*, 32(3):246–257, 1984.

[110] Quang Ngoc Nguyen, Rehmat Ullah, Byung-Seo Kim, Rosilah Hassan, Takuro Sato, and Tarik Taleb. A cross-layer green information-centric networking design toward the energy internet. *IEEE Transactions on Network Science and Engineering*, 9(3):1577–1593, 2022.

[111] Irfan Al-Anbagi, Melike Erol-Kantarci, and Hussein T Mouftah. A survey on cross-layer quality-of-service approaches in wsns for delay and reliability-aware applications. *IEEE Communications Surveys & Tutorials*, 18(1):525–552, 2014.

[112] Jian Chen, Zhen Li, Juanwei Liu, and Yonghong Kuo. Qos multipath routing protocol based on cross layer design for ad hoc networks. In *2011 international conference on internet computing and information services*, pages 261–264. IEEE, 2011.

[113] Tarunpreet Kaur and Dilip Kumar. Maco-qcr: multi-objective aco-based qos-aware cross-layer routing protocols in wsn. *IEEE Sensors Journal*, 21(5):6775–6783, 2020.

[114] Aboobeker Sidhik Koyamparambil Mammu, Unai Hernandez-Jayo, Nekane Sainz, and Idoia De la Iglesia. Cross-layer cluster-based energy-efficient protocol for wireless sensor networks. *Sensors*, 15(4):8314–8336, 2015.

[115] Sachin Gajjar, Mohanchur Sarkar, and Kankar Dasgupta. Famacrow: Fuzzy and ant colony optimization based combined mac, routing, and unequal clustering cross-layer protocol for wireless sensor networks. *Applied Soft Computing*, 43:235–247, 2016.

[116] Wenbo Zhang, Xuanren Wei, Guangjie Han, and Xiaobo Tan. An energy-efficient ring cross-layer optimization algorithm for wireless sensor networks. *IEEE Access*, 6:16588–16598, 2018.

[117] Johannes Blanckenstein, Jirka Klaue, and Holger Karl. A survey of low-power transceivers and their applications. *IEEE Circuits and Systems Magazine*, 15(3):6–17, 2015.

[118] Anders Froytlog, Thomas Foss, Ole Bakker, Geir Jevne, M Arild Haglund, Frank Y Li, Joaquim Oller, and Geoffrey Ye Li. Ultra-low power wake-up radio for 5g iot. *IEEE Communications Magazine*, 57(3):111–117, 2019.

[119] Debasish Ghose, Anders Froytlog, and Frank Y Li. Reducing overhearing energy in wake-up radio-enabled wpans: Scheme and performance. In *2018 IEEE International Conference on Communications (ICC)*, pages 1–6. IEEE, 2018.

[120] Johannes Blanckenstein, Jirka Klaue, and Holger Karl. A survey of low-power transceivers and their applications. *IEEE Circuits and Systems Magazine*, 15(3):6–17, 2015.

[121] Dora Spenza, Michele Magno, Stefano Basagni, Luca Benini, Mario Paoli, and Chiara Petrioli. Beyond duty cycling: Wake-up radio with selective awakenings for long-lived wireless sensing systems. In *2015 IEEE conference on computer communications (INFOCOM)*, pages 522–530. IEEE, 2015.

[122] Bas Van der Doorn, Winelis Kavelaars, and Koen Langendoen. A prototype low-cost wakeup radio for the 868 mhz band. *International Journal of Sensor Networks*, 5(1):22–32, 2009.

[123] T Kumberg, R Tannhaeuser, and L Reindl. Using antenna diversity to improve wake-up range and probability. In *Proceedings of the PIERS*, 2015.

[124] Wen-Chan Shih, Raja Jurdak, David Abbott, Pai H Chou, and Wen-Tsuen Chen. A long-range directional wake-up radio for wireless mobile networks. *Journal of Sensor and Actuator Networks*, 4(3):189–207, 2015.

[125] Ilker Demirkol, Cem Ersoy, and Ertan Onur. Wake-up receivers for wireless sensor networks: benefits and challenges. *IEEE wireless Communications*, 16(4):88–96, 2009.

[126] Mayssa Ghribi and Aref Meddeb. Survey and taxonomy of mac, routing and cross layer protocols using wake-up radio. *Journal of Network and Computer Applications*, 149:102465, 2020.

[127] Lucas DP Mendes and Joel JPC Rodrigues. A survey on cross-layer solutions for wireless sensor networks. *Journal of Network and Computer Applications*, 34(2):523–534, 2011.

[128] Honggang Wang, Wei Wang, Shaoen Wu, and Kun Hua. A survey on the cross-layer design for wireless multimedia sensor networks. In *International Conference on Mobile Wireless Middleware, Operating Systems, and Applications*, pages 474–486. Springer, 2010.

[129] Bo Fu, Yang Xiao, Hongmei Deng, and Hui Zeng. A survey of cross-layer designs in wireless networks. *IEEE Communications Surveys & Tutorials*, 16(1):110–126, 2013.

[130] Lucas DP Mendes and Joel JPC Rodrigues. A survey on cross-layer solutions for wireless sensor networks. *Journal of Network and Computer Applications*, 34(2):523–534, 2011.

[131] Fouzi Semchedine, Wahiba Oukachbi, Naima Zaichi, and Louiza Bouallouche-Medjkoune. Eecp: a new cross-layer protocol for routing in wireless sensor networks. *Procedia Computer Science*, 73:336–341, 2015.

[132] Curt Schurgers, Vlasios Tsiatsis, Saurabh Ganeriwal, and Mani Srivastava. Topology management for sensor networks: Exploiting latency and density. In *Proceedings of the 3rd ACM international symposium on Mobile ad hoc networking & computing*, pages 135–145, 2002.

[133] Stefano Basagni, Valerio Di Valerio, Georgia Koutsandria, and Chiara Petrioli. Wake-up radio-enabled routing for green wireless sensor networks. In *2017 IEEE 86th Vehicular Technology Conference (VTC-Fall)*, pages 1–6. IEEE, 2017.

[134] Felix Sutton, Bernhard Buchli, Jan Beutel, and Lothar Thiele. Zippy: On-demand network flooding. In *Proceedings of the 13th ACM Conference on Embedded Networked Sensor Systems*, pages 45–58, 2015.

[135] Thanos Stathopoulos, Martin Lukac, Dustin McIntire, John Heidemann, Deborah Estrin, and William J Kaiser. End-to-end routing for dual-radio sensor networks. In *IEEE INFOCOM 2007-26th IEEE International Conference on Computer Communications*, pages 2252–2260. IEEE, 2007.

[136] Kaveh Pahlavan and Allen H Levesque. *Wireless information networks*. John Wiley & Sons, 2005.

[137] Sachin Gajjar, Mohanchur Sarkar, and Kankar Dasgupta. Famacrow: Fuzzy and ant colony optimization based combined mac, routing, and unequal clustering cross-layer protocol for wireless sensor networks. *Applied Soft Computing*, 43:235–247, 2016.

[138] Michele Rondinone, Junaid Ansari, Janne Riihijärvi, and Petri Mähönen. Designing a reliable and stable link quality metric for wireless sensor networks. In *Proceedings of the workshop on Real-world wireless sensor networks*, pages 6–10, 2008.

[139] Giuseppe Bianchi, Luigi Fratta, and Matteo Oliveri. Performance evaluation and enhancement of the csma/ca mac protocol for 802.11 wireless lans. In *Proceedings of PIMRC'96-7th International Symposium on Personal, Indoor, and Mobile Communications*, volume 2, pages 392–396. IEEE, 1996.

[140] Peyman Neamatollahi, Mahmoud Naghibzadeh, Saeid Abrishami, and Mohammad-Hossein Yaghmaee. Distributed clustering-task scheduling for wireless sensor networks using dynamic hyper round policy. *IEEE Transactions on Mobile Computing*, 17(2):334–347, 2017.