Power saving and energy optimization techniques for Wireless Sensor Networks

(Invited Paper)

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Abstract— **Wireless sensor networks have become increasingly popular due to their wide range of applications. Energy consumption is one of the biggest constraints of the wireless sensor node and this limitation combined with a typical deployment of large number of nodes have added many challenges to the design and management of wireless sensor networks. They are typically used for remote environment monitoring in areas where providing electrical power is difficult. Therefore, the devices need to be powered by batteries and alternative energy sources. Because battery energy is limited, the use of different techniques for energy saving is one of the hottest topics in WSNs. In this work, we present a survey of power saving and energy optimization techniques for wireless sensor networks, which enhances the ones in existence and introduces the reader to the most well known available methods that can be used to save energy. They are analyzed from several points of view: Device hardware, transmission, MAC and routing protocols.**

Index Terms— Power-saving strategies, energy consumption, energy management, network communication protocols, wireless sensor networks.

I. INTRODUCTION

A Wireless Sensor Network (WSN) can be defined as a network of small embedded devices, called sensors, which communicate wirelessly following an ad hoc configuration. They are located strategically inside a physical medium and are able to interact with it in order to measure physical parameters from the environment and provide the sensed information [1]. The nodes mainly use a broadcast communication and the network topology can change constantly due, for example, to the fact that nodes are prone to fail. Because of this, we should keep in mind that nodes should be autonomous and, frequently, they will be disregarded. This kind of device has limited power, low computational capabilities and limited memory. One of the main issues that should be studied in WSNs is their scalability feature [2], their connection strategy for communication [3] and the limited energy to supply the device.

The desire to advance in research and development of WSN was initially motivated by military applications such as surveillance of threats on the battlefield, mainly because WSN can replace single high-cost sensor assets with large arrays of distributed sensors. There are other interesting fields like home control, building automation and medical applications. A number of hospitals and medical centers are exploring the use of WSN technology in a wide range of applications, including pre-hospital and in-hospital patient monitoring and rehabilitation and disaster response. WSNs can also be found in environmental monitoring applications such as marine fish farms [4] and fire detection in forest and rural areas [5].

As we already mentioned, sensor nodes in WSNs are usually battery powered but nodes are typically unattended because of their deployment in hazardous, hostile or remote environments. A number of power-saving techniques must be used both in the design of electronic transceiver circuits and in network protocols. The first step towards reduced power consumption is a sound electronic design [6], selecting the right components and applying appropriate design techniques to each case.

One of the major causes of energy loss in the WSN node is the idle mode consumption, when the node is not transmitting/receiving any information but listening and waiting for information from other nodes. There is also an energy loss due to packet collision, as all packets involved in the collision are discarded and must be retransmitted. A third cause of energy loss is the reception of packets not addressed to the node. The fourth major source of wasted energy is the transmission –and possible retransmission- of control packets, as these can be seen as protocol overhead.

There are several studies that present different aspects related to power saving techniques, but all of them are focused in a single way to improve the energy consumption and save power in WSNs. The main objective of this paper is to present a survey of the different power saving and energy optimization techniques for WSNs and ad-hoc connections, so we will tackle this issue from several perspectives in order to provide a whole view in this matter.

The paper is organized as follows. Section 2 shows some previously published surveys related to power saving techniques in WSN. The description of the typical hardware architecture that can be seen in any sensor node and the considerations that should be taken in into account for energy-aware sensor deployment are show in section 3. Section 4 describes the main energy parameters that should be considered in the transmission system.

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Some important energy-aware MAC protocols are explained in Section 5. In Section 6, we discuss different routing protocols that are focused on saving energy methods. Finally, the conclusion is drawn in Section 7.

II. EXISTING SURVEYS

The power management schemes of wireless sensor networks have attracted high attention in recent years. Much published research has addressed all kinds of issues related to them.

We can find several works related to energy conservation techniques. They tend to focus on comparative routing protocols or MAC-protocols. Some of them show techniques related to the operation mode of the nodes and its radio system. In this section we will see some of these works, and we will provide some of the key conclusions presented in these papers.

In [7], G.P. Halkes et al. compared S-MAC and T-MAC, which try to save energy by introducing a duty-cycle to mitigate idle listening time, with CSMA/CA. This choice was taken because it is the most important cause of energy consumption in typical sensor network scenarios where the communications between nodes is not continuous. They show the effects of low-power listening, a physical layer optimization, in combination with these MAC protocols. The results show that using a low-power listening is very effective at mitigating idle listening. The absolute lowest energy consumption is reached in combination with T-MAC, while the results about S-MAC show that this protocol suffers from over-provisioning. Since its duty cycle is fixed for all nodes, often a rather large value must be selected to avoid dropping messages under peak loads, which causes S-MAC's idle-listening to deteriorate for increasing traffic loads. Although S-MAC achieves acceptable results, they are not as good as those of T-MAC with low-power listening. T-MAC presents an aggressive time-out policy that allows it to adapt seamlessly to variations in traffic induced by typical sensor network applications at the expense of a reduction in peak throughput. T-MAC performs slightly better for variations over time (events) than for variations in location.

V. Raghunathan et al. [8] review several techniques to address the energy consumption challenge. This work also describes recent advances in energy-aware platforms for information processing and communication protocols for sensor collaboration. The article looks at emerging and hitherto largely unexplored techniques such as the use of environmental energy harvesting and the optimization of the energy consumed during sensing. The paper presents some promising research directions for alleviating the energy problem in WSNs, including hierarchical architectures, ultra-low-power MAC protocols, environmental energy harvesting, and energy aware sensing. The authors explain and present an architecture of sensor node in order to be considered energy efficient. At the same time, they present a wireless sensor module, a heliomote, which is used in different tests in order to show that it is possible to provide energy to the nodes from alternative sources instead of from a battery, which has a limited life time. They also compare three MAC protocols. These are B-MAC, STEM-T, and WiseMAC, which are characterized by low power consumption in the media access process.

Another significant work is presented by N. A. Pantazis et al. in [9]. The authors focus their explanations on the fundamental concepts of energy management, including the need of power management in the wireless sensor network, and discuss the side effects of power management in terms of cost. They say that the cost of power management must always be borne in mind when speaking about a power control system. The cost of power management is important for evaluating the performance of a power control system, no matter what the specific objectives may be. Throughout the document, they describe different types of power management systems and different approaches and goals they may have. The authors divide the power conservation mechanisms into two main categories based on their primary objectives. On the one hand, Passive PCMs are divided into three sub-categories: Physical Layer, Fine-Grain, and Coarse-Grain PCMs. In the implementation of the Coarse-Grain PCMs, two basic approaches were distinguished: Distributed and Backbone-based. On the other hand, the classification of the Active PCMs is based on the layer (MAC, Network, and Transport). Various algorithms were studied for each classification. Each power management scheme is discussed in terms of objective, mechanism, performance, and application scenario. The similarities and differences between schemes of the same clustering category are also presented. The authors conclude the paper by stating that although the performance of the presented power management schemes is promising, further research would be necessary to address other issues, such as quality of service (QoS). Energy-aware QoS in wireless sensor networks will certainly ensure guaranteed bandwidth, or delay, through the duration of a connection as well as provide the most energy-efficient path.

S. Saxena et al. review the main approaches for energy conservation in wireless sensor networks in [10]. They presented a systematic and comprehensive classification of the solutions related to save energy. This involves characterizing the interactions between different protocols and exploiting cross-layer interactions. They also made a protocol classification and explain each part. The authors comment that most of the solutions presented by other authors are based on the assumption that the radio energy consumption is much higher than data sampling or processing consumption, while many real applications have greater power consumption in data sampling/processing than in radio transmission. Furthermore, they observed that the data acquisition research field of has not been fully explored in terms of energy conservation. Finally, the authors come to the conclusion that there is an increasing interest towards MAC protocols used for time synchronization and energy conservation in the recent years. They also made a reference to the node's mobility, which is yet another challenging task in energy optimization.

Another survey related to protocols and energy-saving techniques is [11]. It was presented by K. Akkaya et al. This paper surveys several routing protocols for sensor networks and presents a classification of various pursued approaches. The classification is focused on three main categories: data-centric, hierarchical and location-based. This work analyzes several protocols that use contemporary methodologies such as network flow and quality of service modeling. From this work, several conclusions can be extracted. On the one hand, many protocols base their functions in some attributes such as data and query in order to avoid overhead-forming clusters, the use of specialized nodes, etc. However, in some cases, where queries can be more complex schemes, such attribute-value pairs may not be enough. On the other hand, routing protocols based on cluster are carried out by group sensor nodes to efficiently relay the sensed data to the sink. The cluster heads are specialized nodes that are sometimes chosen in function of their available energy. A cluster-head performs the data aggregation and sends it to the sink. The authors show a table which summarizes the classification of the protocols covered in this survey. They also included in the table whether the protocol is utilizing data aggregation or not, since it is an important consideration for routing protocols in terms of energy saving and traffic optimization. In their future works they will study the factors that affect cluster formation, cluster-head communication and how to form clusters in order to improve energy consumption and contemporary communication metrics, such as latency.

Finally, C. E. Jones et al. present in [12] a study on power saving techniques in WSN. This paper addresses the incorporation of energy conservation considerations on all layers of the wireless network protocol stack for mobile devices. Therefore, throughout the document, the authors cover the protocol stack and gradually introduce various energy saving modes (starting from low-power design within the physical layer). They show different sources of power consumption within mobile terminals and general guidelines for reducing the power consumed. They also show energy efficient protocols within the wireless networks’ MAC layer, power saving protocols within the LLC layer and power aware protocols within the network layer. Finally, they provide some battery power considerations that should be taken into account.

As far as we know, there is not any survey such as the one presented in this paper. We will tackle power saving techniques and energy saving issues in WSNs from all perspectives, starting from the hardware side until arriving at the routing protocol side.

III. ENERGY ISSUES IN HARDWARE

This section describes the main functional blocks of a sensor node. Each of these blocks has intrinsic energy losses, mainly due to its function. The main considerations to be taken into account in a sensor node for deploying a WSN are presented. Finally, some of the main sources of energy loss in the WSN are discussed.

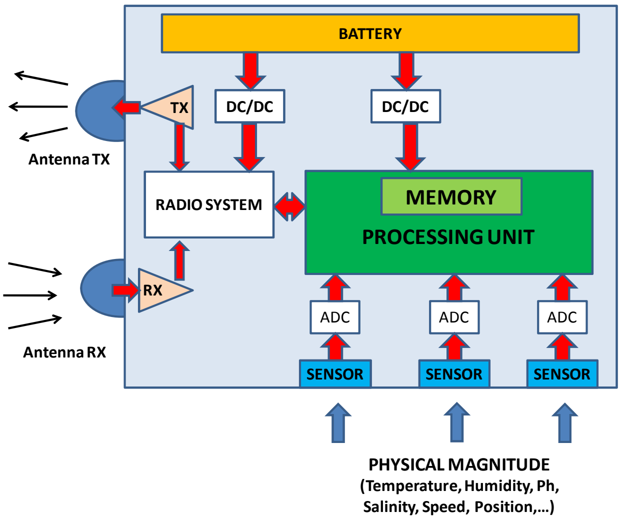

Figure 1. Block diagram of a typical wireless sensor node.

A. *Wireless senor node hardware structure*

A sensor node is an electronic device that is used as an interface between the physical magnitudes that can be sensed from the medium and a data wireless network [13, 14].

A node is made up of four main parts: (1) a power unit, consisting of a battery and a number of DC/DC converters, (2) a processing unit -which usually consists of a small processor and memory, (3) the physical sensors and (4) the transceiver circuit (radio system that should be formed by a transmitter and a receiver). Figure 1 shows the block diagram of a typical wireless sensor node.

- The Processing Unit (PU) is responsible for reading out the physical sensors, extracting relevant information from the digitized data and implementing the network protocols. The PU of a wireless sensor node determines both the energy and the computing capabilities of a sensor node.
- The radio system allows wireless communication between the nodes in the network and to the outside world. Factors such as modulation scheme, data throughput in the network, transmission power and duty cycle can directly affect the energy consumption characteristics of the global system. In general, a node can work basically in three different operating modes: active (either transmit or receive), idle and sleep. Some studies on WSN and routing protocols show that contrary to popular belief, power consumption in idle mode is considerably high, comparable to the energy consumed in active mode [15]. For this reason, it is recommended to completely shut down the radio transceiver when it is not going to be used. Moreover, some important issues must be considered, e.g., a change in the system state and the related transient effects in the transceiver generate a significant increase in the amount of energy dissipated.

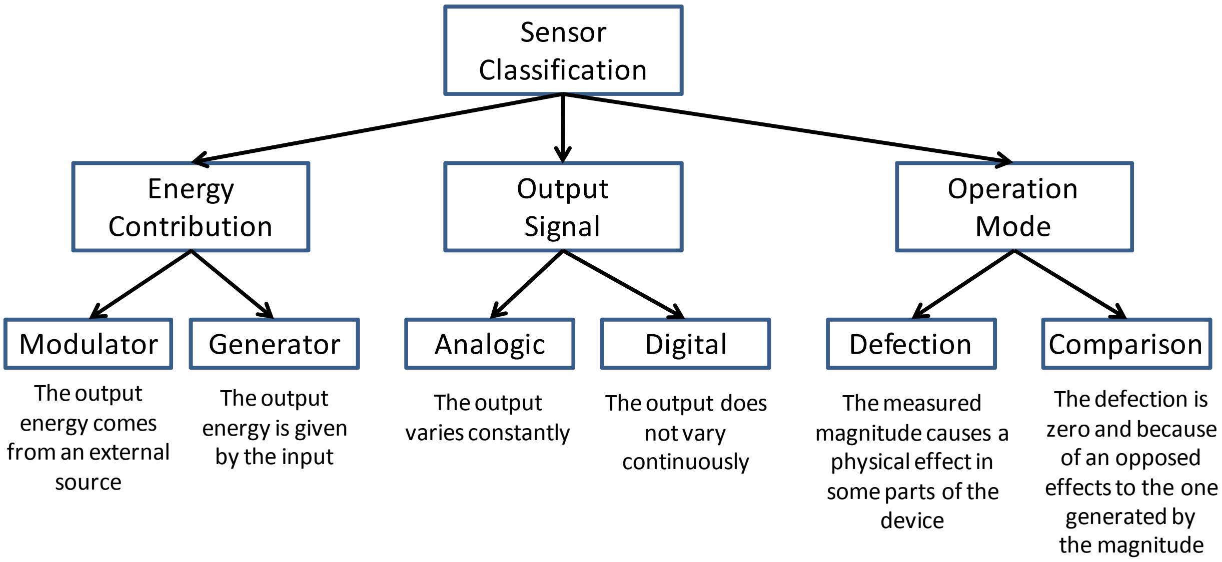

Figure 2. Sensor classification.

- Sensors transform a physical or chemical magnitude (instrumentation variable) into a useful electrical signal. Several examples of instrumentation variables are temperature, distance, acceleration, inclination, displacement, pressure, humidity and pH. The electrical signal can be derived from a change (like resistance or capacity) in the sensor. All sensors can be classified and included within one of the groups shown in figure 2 [16].
- Batteries are complex elements whose operation depends on many factors including the size of the battery, the electrode material and the rate of diffusion of the active materials in the electrolyte. There are many types of rechargeable and non-rechargeable batteries that can be used in WSN applications. According to their electrochemical composition, which determines the energy efficiency, we can distinguish between Ni-Cd, Ni-Zn, Ag-Zn, Ni-MH and lithium ion batteries, among others. There are some important effects to consider, like the relaxation effect and the rated capacity effect [13], which largely determine the battery life.
- DC/DC converters (also called voltage regulators) are responsible for providing appropriate voltages to the different circuits in the sensor node. Linear regulators have larger energy losses (approximately the output current multiplied by the voltage drop across the device) than switched regulators (typical energy loss in the range 5-15%). Thus, the design of the voltage regulator section has a large impact on the node power consumption.

It is possible to recharge the sensor node battery with energy extracted from the environment, like light, wind, vibration [17] and electromagnetic fields.

B. *Characteristics and requirements of a wireless sensor node.*

When a WSN is being implemented, particular sensor nodes features must be taken into account. In this sub-section we discuss some of the characteristics and requirements that are sought in the design and development of a wireless sensor node [13, 14]. These are the following:

- High energy efficiency, in order to increase the node autonomy.
- Low cost, as a network that covers a large area can consist of hundreds or thousands of nodes. An estimation of the number of the nodes that are required to cover a given area is presented in [18].
- Distributed Sensing, in order to cover a large area despite the obstacles in the environment.
- Wireless communication, as it is the only choice for nodes deployed in remote areas or where no cabling infrastructure is available.
- Multi-hop networking. Depending on the radio parameters [19], it can be more efficient to reach a distant node or a base station using two or more wireless hops than a single large distance hop.
- Local data processing in the node, like zero suppression, data compression and parameter extraction can reduce the transmitted payload, and, thus, the power consumption.

C. *Factors to be considered in the network and in its protocol design.*

Despite the limited bandwidth of the wireless links, limited processing power and limited energy supply in the wireless nodes, many network designs are focused on taking advantage of the network in order to mitigate these limitations. One of the main pursued objectives of the WSN design is to prolong the network lifetime and prevent information degradation and loss.

In order to provide the right communication between the wireless sensor nodes some design factors and considerations that depend on the type of required application should be taken into account [20, 21, 22]. Table 1 shows some of the major considered items and their descriptions.

TABLE I.

Item	Description
Connectivity	The connectivity in a WSN depends on the random distribution of nodes, mainly due to node failures that may cause the network topology and network size to change. However, the complete interconnection of nodes is desired.
Coverage	Radio coverage is an important design parameter in WSNs. A sensor can only monitor a limited area, but it should be connected with other nodes in order to transmit the sensed information. The limit is set by the wireless technology, the accuracy of the transmission and the data rate (lower data rate in larger distances).
Data aggregation	Data aggregation is the combination of data from different sources according to a specific aggregation function, e.g., duplicate suppression, minimum, maximum and average. In a network, nodes may generate duplicate packets. Therefore, it is important to reduce the number of duplicate packets in the network in order to reduce the energy consumption and latency in communications.
QoS	The latency in a circuit sets the delivery time data from the transmitter to the receiver. However, sometimes power consumption is more important than complete data accuracy. Therefore, routing protocols should be aware of the quality of service and adapt to each situation.
Node deployment	The node Implementation in the WSN depends on the type of application and directly affects the performance of the routing protocol. On the one hand, it can be a deterministic distribution, where sensors are placed manually and the data is routed through default routes. On the other hand, it can be a random distribution, where the resulting distribution of the nodes is not uniform. It always has to find the optimal clustering that allows the best connectivity. Sometimes it has to assume that the network has an energy-efficient behavior. Because the communication between nodes is usually limited in bandwidth and the packet's delivery time, the most probable routes can be formed by multi-hop wireless paths.
Energy consumption	Sensor nodes often use limited energy sources such as batteries. Therefore, the implementation of energy saving techniques is needed.
Fault tolerance	Some sensor nodes may fail and stop the data transmission due to power shortage, physical damage or environmental interference. Node failures should not interfere with the purpose of the network. Therefore, MAC layer protocols and routing protocols must adapt to the formation of new links and routes. The network should remain functional and should continue data transmission. Sometimes, if there are many node failures to implement redundancy techniques at various levels may be necessary to ensure a good level of fault tolerance
Network Dynamics	Many network architectures have stationary sensor nodes. However, the mobility of the nodes is necessary in many applications. The routing of messages between mobile devices is more difficult as the path stability, the bandwidth, energy, etc, becomes a more important consideration. Moreover, the position of sensor can be detected by the network either dynamically or statically using a periodic monitoring.
Transmission Media	In a multi-hop sensor network, the nodes involved in the communication process are connected by a wireless medium. The traditional problems associated with a wireless channel (for example, the losses by vegetation or rain attenuation, the error in height, etc. [5]) may also affect the operation of the sensor network. Good Medium Access Control (MAC) should be used in order to save energy.
Scalability	The number of sensor nodes that can form a network could be of the order of hundreds, thousands or more. Therefore, the network and routing systems must be able to handle large number of sensor nodes. Moreover, the administrator should assume that the network could grow.
Data sensing and reporting model	Data sensing and reporting as well as the data speed in wireless sensor networks depends on the type of application. Data reporting can be categorized as either time-driven (continuous), event-driven, query-driven, and hybrid [23]. The use of a reporting model depends on the type of required monitoring in the system. However, it is possible to use mixed models, which bring together the advantages of various types of reporting models. The routing protocol, also plays an important role in this item, because its performance is greatly influenced by the model of data presentation, and this fact is related to energy consumption and reliability of the chosen route.

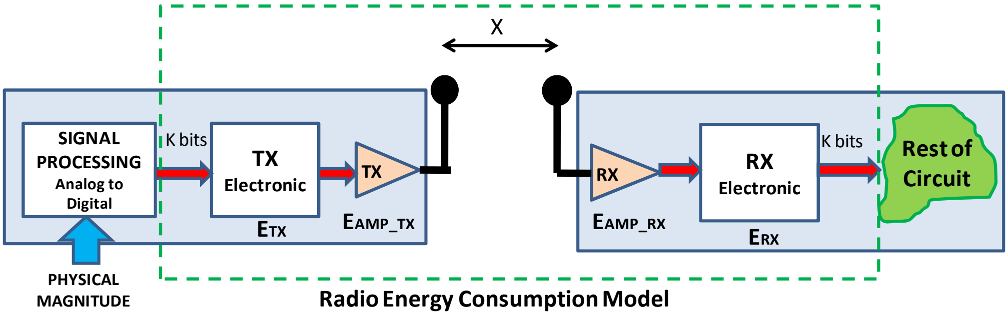

Figure 3. Radio energy consumption model.

$$E_{bit} = \frac{\left((P_{tx\_e}+P_{tx\_out})\cdot\left(\frac{header+payload+trailer}{Rate}\right)+P_{tx\_ini}\cdot T_{tx\_ini}\right)}{payload} + \frac{\left(P_{rx\_e}\cdot\left(\frac{header+payload+trailer}{Rate}\right)+P_{rx\_ini}\cdot T_{rx\_ini}\right)}{payload} + \frac{E_{decoding}}{payload} \quad (1)$$

Where each parameter represents:

E_{bit} : energy consumed per bit
P_{tx_e}: Power consumption in electronic transmission.
P_{tx_out}: Output transmit power.
P_{rx_e}: Power consumption in electronic reception
P_{tx_ini}: Start-up power consumed in Transmission.
T_{tx_ini}: Transmitter start-up time.
P_{rx_ini}: Start-up power consumed in reception.
T_{rx_ini}: Receiver start-up time.
Header: Length of packet header
Payload: Length of packet payload
Trailer: Length of packet trailer
$E_{decoding}$: Decoding energy per packet.

IV. ENERGY CONSUMPTION IN TRANSMISSION

The sensor output is usually an analog signal. After signal conditioning (amplification, filtering) and digitization, data are processed locally in the node. As a result, a packet is eventually sent to the network using a transmitter circuit. The signal level needs to be amplified before reaching the antenna and propagated through a dispersive medium, such as water [23] or air (which does not generate as many losses as water) [5]. This guarantees an acceptable signal level at the receiver input. In addition, adequate modulation techniques should be implemented in order to minimize the loss of information.

The inverse system is implemented at the receiver node. The first stage is an amplifier or attenuator that sets the input level at the receiver circuit. The receiver applies the appropriate demodulation to obtain the original bit sequences, which are interpreted by the node.

Each of these stages involves electronic circuits that generate a considerable level of energy consumption. The distance between transmitter and receiver must also be taken into account in order to calculate the overall power dissipation [24]. Figure 3 shows the described block diagram. Equation 1 can be used to estimate the energy consumed per bit in the transmitter-receiver model depicted in figure 3 [25]. Several energy saving methods are discussed in [26].

A first, obvious measure consists of adjusting the transmission power to the characteristics of the propagation path, like attenuation and range. Other more sophisticated techniques can be used, like preventing the duplication of packets in the network by using specialized routing protocols.

A frequently used approach is to control the node activity, switching the operation mode between active, idle and sleep modes. The processor consumes the most amount of energy in the active mode. In this mode the device can receive and send data and control packets and can perform data processing. Equation 1 represents this energy value as Ptx_e and Prx_e. In sleep mode, a device consumes the least amount of energy as the transmitter is turned off, the frequency of the main processor may be reduced and it is not possible to realize any processing operation. A considerable amount of time is required to enter and exit this mode. An intermediate state for a node, between active and sleep, is the idle state. In this mode, a device consumes less energy than in the active mode, as no data processing can take place. The device can quickly enter and exit this mode.

A scheme for dynamic power management in WSNs is described in [27]. This work proposes five different operation modes and the rules to switch between them.

A technique called Sparse Topology and Energy Management (STEM) is described in [28]. It reduces the energy consumption in the monitoring state to a bare minimum while ensuring satisfactory latency for transitioning to the transfer state by efficiently waking up nodes from a deep sleep state. The designers have full flexibility in trading latency, density, and energy versus each other.

The work presented in [29] describes several techniques to reduce dynamic power consumption in mobile battery-powered 802.11 WLAN systems. The authors propose to reduce the device energy consumption from its initial design, bearing in mind that, usually, small devices consume less power. But, the price of the final product is considerably increased when reduced manufacturing technology is used.

V. MAC PROTOCOLS

The MAC (acronym for medium access control) sub-layer is responsible for regulating the access to a physical medium shared by several devices. MAC protocols must avoid collisions due to simultaneous transmissions and must perform other important functions like addressing, error checking and delivery notification. An efficient MAC protocol should possess many characteristics. The most important are:

- Predictability of delay
- Adaptability
- Energy efficiency
- Reliability
- Scalability

In this section, a number of works that propose MAC protocols concerned with energy efficiency are briefly described.

A. *Energy and Rate based MAC Protocol - ER-MAC*

The first work that can be cited is the one presented by R. Kannan et al. [30]. This work presents the Energy and Rate based MAC Protocol (ER-MAC). It is based on TDMA and aims at avoiding energy waste. Packet loss due to collisions is absent because two nodes do not transmit in the same time slot. Although packet loss may occur due to other reasons like interference and loss of signal strength, there is no need to use a contention mechanism because the slots are pre-assigned to each node. ER-MAC uses the concept of periodic listen and sleep. Each node is assigned two TDMA slots for transmission and nodes know the transmission slots of its neighbors. Nodes periodically share information about their power levels and determine whether to use one or two slots for transmission. The proposed protocol is simulated in a scenario of 100 nodes. The results show that ER-MAC achieves a significant increase in energy savings compared to other existing MAC layer protocols.

B. *Dominating-awake-interval protocol, Periodically-fully-awake-interval protocol and Quorum-based protocol.*

In [31], the authors propose three asynchronous protocols that are directly applicable to MANET technology based on IEEE 802.11. These protocols are named as dominating-awake-interval protocol, periodically-fully-awake-interval protocol and quorum-based protocol. The authors state that devices really send more beacon packets than original IEEE 802.11 standard and they study the best manners to wake-up the devices. Designed protocols use the following rules: (1) send the highest number of beacons in order to prevent the problem of false neighbors and (2) mobile hosts in power saving mode must put more emphasis on sending beacons. Their protocol does not use a clock synchronization system. Moreover, the patterns to wake-up two devices overlap as a function of the difference of time between them. Finally, in order to predict the exact timing to wake-up, when a host hears a beacon from another host, it must wake-up based on another time pattern. The simulations of their protocol show that it is efficient, saves energy and establishes the most likely route.

C. *Distributed Wireless Ordering Protocol - DWOP*

V. Kanodia et al. present the design and the analysis of the Distributed Wireless Ordering Protocol (DWOP) [32]. It is a distributed scheduling algorithm and media access protocol for wireless ad-hoc networks. It exploits overheard information from other nodes to estimate channel contention. The design of DWOP is based on a graph-theoretic problem formulation. It allows well-characterized deviations from the reference order in more complex topologies and achieves the exact reference ordering in fully connected graphs. DWOP enables QoS differentiation as well as fairness when combined with TCP. A theoretical model indicates that the scheme provides rapid convergence for newly arriving nodes, and extensive simulations indicate that nearly exact reference ordering can be achieved, even in complex asymmetric and perceived-collision topologies. The authors use the piggybacking head-of-line packet priorities in IEEE 802.11 control messages. This allows the nodes to assess the relative priority of their own queued packets. Moreover, the authors propose a distributed stale entry detection method that enables a quick recovery to the steady state.

D. *Battery Aware Medium Access Control - BAMAC*

Usually, MAC protocols for ad-hoc wireless networks are designed without taking into account the state of the node battery. In [33], S. Jayashree presents a MAC protocol in which each node contains a table that contains information about the battery charge level for each of its neighbors (close nodes that can be accessed). RTS, CTS, Data and ACK packets carry information regarding the battery level of the node that originated the packet. Any listening node fills its table with the information of the load levels of each neighboring nodes. This protocol uses a back-off mechanism, in order to determine which node should receive the packet. The goal of the back-off mechanism is to provide a near round-robin scheduling of the nodes which is based on some temporal parameters like the longest possible time required to transmit a packet successfully, including the RTS-CTS-Data-ACK handshake and the Short and DCF inter-frame spacing durations used in IEEE 802.11. Factors such as the minimum size of the contention window and rank are also considered. The nodes are scheduled based on their remaining battery capacities, that is, the higher the remaining battery capacity, the lower the back-off period. The algorithm allows a node to send the packet to a neighboring node with a higher level of battery. In this way, a uniform rate of battery discharge is guaranteed across all the nodes and consequently, the network lifetime will be longer, because the fall of nodes will be later. The proposed protocol is implemented using GloMoSim simulator and it is compared with the DWOP protocol. The simulations show that the battery life lasts around 70% and reduces battery consumption to nominal packet transmission by 21% compared with IEEE 802.11 and MAC DWOP protocol.

E. Wireless Indoor Flexible High Bit rate Modem Architecture - WIND-FLEX

G. Razzano [34] describes a control architecture that is widely used in local area networks on the structure of WIND-FLEX (Wireless Indoor Flexible High Bit rate Modem Architecture). The author studies the energy consumption in a wireless modem and presents a control method based on fuzzy logic, which has already been applied for determining the transmission power in CDMA (Code-Division Multiple-Access). Power consumption depends on the data rate and thus a reduction in the energy consumption is possible selecting the bit data rate as a function of the traffic situation.

F. Distributed Coordination Function - DCF

In [35], E.-S. Jung and N. H. Vaidya present a mechanism for optimizing the energy saving mechanism in the Distributed Coordination Function (DCF) of IEEE 802.11 networks. In DCF, the time is divided into beacon intervals. At the beginning of each beacon interval, each node in power saving mode periodically wakes up in a period of time called ATIM window. During this period, nodes exchange packets to determine whether the node needs to stay in active mode during the remaining time of the beacon. The energy saving and performance achieved by the nodes is directly proportional to the size of the ATIM window. The authors propose a dynamic adaptation mechanism where a suitable size of ATIM window can be chosen according to network conditions. The protocol has been called Dynamic Power Saving Mechanism (DPSM). A node is able to turn off the wireless network interface every time it finishes the packet transmission process. Initially, each node starts with a minimum ATIM window size, which is increased if they meet some rules. The authors show that the proposed system improves energy consumption without degrading the network performance.

G. Multiple Access with Collision Avoidance

Multiple Access Collision Avoidance MACA [36] protocol makes use of RTS, CTS, DATA and ACK sequences to operate. MACA proceeds as follows:

1) Before sending a message, the transmitter sends a RTS control message ("ready to send"), containing the length of the upcoming data message. The time taken to transmit a control message (~30 bytes) is called a slot.

2) If the receiver hears the RTS and is not currently "deferring," it replies with a CTS control message ("clear to send"), which includes a copy of the length field from the RTS.

3) Any station that hears a CTS defers any transmissions for long enough to allow someone to send a data message of the specified length. This avoids colliding with the CTS sender (the receiver of the upcoming data message).

4) Any station that hears an RTS defers any transmissions for a single slot (long enough for the reply CTS to be received, but not long enough for the actual data message to be sent, because contention is receiver-local).

5) Backoff: if no CTS response is received for an RTS, the sender must retransmit the RTS. It waits for an integer number of slots before retransmitting. The integer is chosen randomly between 1 and BO (backoff counter). BO is doubled for every retransmit, and reduced to 1 for every successful RTS-CTS pair.

H. Multiple Access with Collision Avoidance for Wireless - MACAW

MACAW (MACA for Wireless) [37] presents a series of improvements to the basic MACA algorithm. First, the authors suggest a less aggressive backoff algorithm because the exponential increase/reset to 1 policy of MACA leads to large oscillations in the retransmission interval. They propose to increase the backoff by 1.5 after a timeout, and decrease it by 1 after a successful RTS-CTS pair. Moreover, they arrange values for the backoff counter between clients in order to let the clients with lower backoff counter access the media. They also changed the backoff counter to be per-destination, rather than a single counter. The second proposal is that receivers should send an ACK to the sender after successfully receiving a data message. This is suggested because the minimum TCP retransmission timeout is relatively long (0.5 seconds), so it takes a long time to recover from lost or corrupted messages. A link layer timeout can be more aggressive, because it can take advantage of the knowledge of the individual link latency (rather than the end-to-end timeout in TCP). Thirdly, they propose two related techniques for allowing transmitters to more effectively avoid contention:

- A DS (Data Sending) packet should be sent after a successful RTS-CTS exchange, just before the data message itself. The idea here is to explicitly announce that the RTS-CTS succeeded, so that if a pad can hear an RTS but not the CTS response, it does not attempt to transmit a message during the subsequent data transfer period. The reasoning here is subtle: as noted before, contention is only at the receiver, so one wouldn't think that a node that can hear the RTS but not the CTS should avoid transmitting. However, sending a message requires that the sender hear the CTS response (as well as the eventual ACK); therefore, if another node within range is sending, it would be pointless to also try to transmit.
- Suppose that two devices, A and B, in different cells/cluster are competing for the channel, if one of them "wins", it will effectively monopolize the channel. The authors propose to fix it by the following manner: when a receiver hears an RTS while it is deferring a transmission, at the end of the deferral period it replies with an RRTS ("ready for RTS") packet, prompting the sender to resend the RTS.

Note that the best-case performance of MACAW is actually lower than that of MACA, because the additional ACK and DS messages sent by MACAW incur overhead. However, MACAW is much more resistant to interference, and ensures much fairer allocation of the medium among different transmitters.

I. Power Aware Multi-Access protocol with Signalling-PAMAS

In [38], the authors develop a multi-access protocol for ad hoc radio networks. The protocol is based on the original MACA protocol [36], with the addition of a separate signaling channel. The protocol conserves the battery power of the nodes by intelligently powering off the nodes that are not actively transmitting or receiving packets. This protocol uses 6 operational modes for the node. It is based on RTS-CTS Schemes and achieves these power savings without affecting the delay or throughput behavior of the basic protocol. The RTS-CTS message exchange takes place over a signaling channel that is separate from the channel used for packet transmissions. This separate signaling channel enables the nodes to determine when and how long they can be powered off. In order to characterize the energy conserving behavior of PAMAS protocol, the authors provide several simulations where they compared the energy used by PAMAS without power conservation and PAMAS with power conservation. The results show that this improvement over the MACA protocol, produce energy savings of approximately 10%.

J. Sensor MAC – S-MAC

S-MAC [39] is an improvement of PAMAS. It reduces further wastage from idle listening by making idle nodes shut off their radios. S-MAC reduces the waste of energy and self-configures. It adopts a contention-based scheme in order to have collision avoidance and good scalability. Overhearing makes contention-based protocols less efficient, so each node chooses a schedule, stores the schedule table, and exchanges it with its neighbors before starting its periodic listen and sleep modes. Their schedules are broadcasted to all their immediate neighbors, thus the time interval for listening and sleeping can be selected according to different application scenarios. In order to demonstrate the effectiveness and measure the performance of S-MAC, the authors implemented it on a wireless sensor network test bed. Motes were developed by some researchers of the University of California, Berkeley. These devices were based on an 8-bit Atmel AT90LS8535 microcontroller running at 4 MHz. However, S-MAC does not avoid collisions between two RTS or CTS messages (like PAMAS), which is a significant wastage of energy. Moreover, the sleep time interval is the same for each node, which is unfair for the nodes with less energy. To make weaker nodes sleep more can increase efficiency. Furthermore, S-MAC assigns sleep schedules without taking into account the criticality of a node.

K. Floor Acquisition Multiple Access - FAMA

FAMA is another MACA-based scheme that requires every transmitting station to acquire the control of the floor (i.e., the wireless channel) before it actually sends any data packet [40]. Unlike MACA or MACAW, FAMA requires that collision avoidance should be performed both at the transmitter as well as at the receiver.

In order to “acquire the floor”, the transmitter node sends a RTS using either non-persistent packet sensing (NPS) or non-persistent carrier sensing (NCS), and the receiver replies with a CTS packet, which contains the address of the source node. Any station that hears the CTS packet will know which station has acquired the floor. CTS packets are repeated long enough for the benefit of any hidden sender. Authors recommend NCS variant for ad hoc networks since it addresses the hidden terminal problem effectively.

L. Interleaved Carrier Sense Multiple Access - ICSMA

The presence of exposed terminals is a significant problem in ad hoc wireless networks. S. Jagadeesan et al. propose a new MAC protocol called Interleaved Carrier Sense Multiple Access (ICSMA) Protocol for Ad hoc wireless networks to solve this problem in [41]. ICSMA reduces the number of exposed terminals and tries to maximize the number of simultaneous sessions in ad hoc networks. ICSMA access mechanism is based on the RTS-CTS-DATA-ACK access mechanism of the IEEE 802.11 DCF. It bases its operation in the use of two identical channels, where its handshaking process is interleaved between them. A node can originate the transmission in either channel 1 or channel 2 depending on the channel availability. In the ICSMA access mechanism, node A sends a RTS packet over channel 1 to Node B after waiting for a time period of DCF Inter Frame Spacing (IFS). Node B verifies the E-NAV in order to find out the availability of free time slots. If there are free available slots, then it responds a CTS packet over the channel 2 within Short Inter Frame Space (SIFS) time. If the CTS packet is not received by Node A successfully, it assumes a collision of the RTS packet or unavailability of Node B and it tries to send the RTS again after a back-off time (it uses a back-off mechanism similar to that used in IEEE 802.11 DCF). When Node A receives the CTS packet over channel 2, it transmits a DATA packet over channel 1, within SIFS time and expects the ACK through channel 2. If the ACK does not arrive within SIFS time, then Node A assumes a collision and attempts a re-transmission after back-off time. The simulations show that this protocol performed better than IEEE 802.11 when they are compared in terms of throughput, channel access delay, throughput fairness, and delay fairness.

M. Multiple Access with Collision Avoidance by Invitation - MACA-BI

Another MAC protocol based on MACA is MACA-BI. It was presented by F. Talucci et al. in [42]. MACA-BI eliminates the need of RTS packets, thus reducing the overhead given by each packet transmission and simplifying the implementation, while preserving the data collision free property of MACA. MACA-BI is less vulnerable to control packet corruption than MACA. In addition, the “receiver driven” mechanism of MACA-BI automatically provides traffic regulation, flow control and congestion control. This protocol is more robust to failures such as hidden terminal collision, direct collision or noise corruption and it also is less sensitive to the TX-

RX turn-around time. In order to test the performance of this protocol the authors developed an analytical model in a single-hop configuration and a simulation model to evaluate it in multihop environments (all of them operating at 1 Mbps). The results show the efficiency of MACA-BI in wireless networks where improving the steady (predictable) traffic at higher channel speeds plays a key role. Collisions between control packets, and between control and data packets, may exist because of carrier sense failure due to non-zero propagation delays or due to the hidden terminal transmission. The authors conclude by letting us know that the probability of collisions among data packets is not possible in MACA-BI. The best manner to recover from this kind of data loss is only by using explicit ACKs.

N. Multiple Access with Reduced Handshake - MARCH

Multiple Access with Reduced Handshake (MARCH) protocol, presented by C.-K.Toh et al. in [43], improves communication throughput in wireless multihop ad hoc networks by reducing the amount of control overhead. It combines the advantages of both sender and receiver-initiated protocols. Unlike other receiver-initiated protocols, MARCH operates without resorting to any traffic prediction. This protocol reduces the number of handshakes required to transmit a data packet, so it outperforms other sender-initiated protocols. The novelty of this approach is that a mobile host (MH) has knowledge of the data packet arrival of its neighboring MH from the overheard CTS packets. The simulation results show that MARCH outperforms MACA in several issues. MARCH protocol has a lower probability of control packet collision. Therefore its control overhead is much lower than MACA at all traffic loads. Furthermore, because it exploits the fact that control messages are overheard by the neighbors, this protocol is more deterministic and does not resort to network prediction, unlike most receiver-initiated protocols.

O. Hop-Reservation Multiple Access - HRMA

In [44], Z. Yang et al. describe a multichannel MAC protocol for ad-hoc networks operating with simple FHSS radios on ISM bands. HRMA is based on a common hopping sequence for the entire network and requires half-duplex slow frequency-hopping radios with no carrier sensing to operate. In HRMA the time is slotted. The protocol can be viewed as a time-slot reservation protocol in which a time slot is also assigned a separate frequency channel. Each slot consists of one synchronizing period, one HR period, one RTS period and one CTS period, each of which is used to exclusively send or receive the synchronizing packet, the HR packet, the RTS packet, and the CTS packet, respectively. For synchronization purposes, a special slot, called synchronizing slot, is defined. It has the same size as the regular slot. Each slot is assigned to a frequency hop. All the nodes that are not transmitting or receiving data packets are called idle nodes. They must hop to the synchronizing frequency and exchange synchronizing messages during the synchronizing period of each slot. During the HR, RTS and CTS periods of each slot, all idle nodes must dwell on the common frequency hop assigned to each slot. HRMA dynamically allocates frequency bands to nodes using a common frequency-hopping pattern. In this way, the data and acknowledgements are transmitted without hidden-terminal interference, which allows merging systems and permits nodes to join existing systems. The simulation results show that HRMA's throughput performance is significantly better than the slotted ALOHA. HRMA can achieve a maximum throughput that is comparable to the theoretical maximum value, especially when data packets are large compared to the slot size used for frequency hopping. This high throughput is obtained through a very simple reservation mechanism without the need of complex code assignment.

P. Receiver-Based AutoRate (RBAR) protocol - RBAR

Receiver-Based AutoRate (RBAR) protocol is a rate adaptive MAC protocol [45]. G. Holland et al. base their design on different assumptions. The first one is that the rate selection can be improved by providing timelier and more complete channel quality information. The second one is that the channel quality information is best acquired at the receiver and, finally, the third one is that the transmitting channel quality information to the sender can be costly, both in terms of the resources consumed in transmitting the quantity of information needed as well as the potential loss in timeliness of the information due to transmission delays. The novelty of RBAR is that it allows the channel quality estimation mechanism to directly access all of the information made available to it by the receiving hardware, for more accurate rate selection. The rate selection is performed on a per-packet basis during the RTS/CTS exchange, just prior to data packet transmission. Simulations show that this protocol results in a more efficient channel quality estimation which is then respected in a higher overall throughput. RBAR can be implemented inside IEEE 802.11 without significant changes.

There are some other works proposing other MAC protocols. Some of them are new proposals and others are schemes based on existing protocols. However, we have presented in this paper the most important ones. Table 2 shows the classification of the explained protocols. It summarizes the main characteristics of each one. A dash (-) means that the information is not provided by the authors or it cannot be correctly ascertained from their paper.

VI. ROUTING PROTOCOLS

Routing protocols provide different mechanisms to develop and maintain the routing tables of the nodes of the network and find a path between all nodes of the network. Routing protocols must be adaptable to any type of topology to allow reaching any remote host in any network. Initially, a metric used for measurement must be defined in the routing protocol in order to find the best route. A routing protocol must be designed looking for very specific main objectives. Among the functions that it should have, here we highlight the following:

TABLE II.

Classification			**MAC Protocol**	**Collision Avoidance**	**Reliability**	**The Energy is taken into account**	**Adaptability**	**Delay Predictability**
Contention-Based Protocols	Sender-initiated Protocols	Single-Channel Protocols	MACAW	Yes	Reliability in the channel which is shared between participating nodes.	More efficient than MACA	-	-
			FAMA	Yes	-	-	-	-
			MACA	Yes	When the delivery is unidirectional	Few efficient	-	-
		Multi-Channel Protocols	S-MAC	No	-	Yes	Yes	-
			ICSMA	Yes	-	-	-	-
			PAMAS	-	-	Yes	-	-
	Receiver-initiated Protocols		MACA-BI	Yes	-	-	-	Yes
			MARCH	Yes	-	-	-	No
Protocols with Reservations mechanisms	Synchronous Protocols		DPSM	-	-	Yes	-	-
			HRMA	Yes	-	-	-	-
			DCF	-	-	Yes	-	-
	Asynchronous Protocols		Periodically-Fully-Awake	Yes	-	Yes	-	-
			Quorum-Based	Yes	-	Yes	-	-
			Dominated-Awake	Yes	-	Yes	-	-
Protocols with scheduling mechanisms			DWOP	-	-	Yes	-	-
			ER-MAC	-	-	Yes	-	-
Other MAC protocols			BAMAC	-	-	Yes	-	-
			RBAR	No	-	-	Yes	-

- Maintain a reasonably small routing table.
- Choose the best route to a given destination. This would imply be the fastest, most reliable, highest capacity or the least cost route.
- Maintain a regular basis to update the routing table when nodes change their position appear in the network.
- Have a small number of messages in order to waste low bandwidth and save energy.
- Require little time to converge in order to provide the most updated network.

In this section, we will review the most well known routing protocols for WSNs that are related to energy saving techniques.

A. Energy Aware Routing protocol - EAR

Energy aware routing protocol [46] is a reactive protocol that aims to increase the lifetime of the network. This protocol seeks to maintain a set of paths instead of maintaining or enforcing one optimal path at higher rates, although the behavior of this protocol is similar to directed diffusion protocols. These routes are selected and maintained by a probability factor. The value of this probability depends on the lowest level of energy achieved in each path. Because the system has several ways to establish a route, the energy of a path cannot be determined easily. Network survivability is the main metric of this protocol. The protocol assumes that each node is addressable through a class-based addressing scheme which includes the location and the type of nodes. When the protocol starts, there is a process of flooding, which is used to discover all the routes between various source/destination pairs and their costs. This will allow creating routing tables, where high-cost paths are discarded. By using these tables, data is sent to its destination with a probability that is inversely proportional to the cost of the node. The destination node performs a localized flooding in order to maintain the paths that are still operative. Compared to other protocols, the energy aware routing protocol provides an overall improvement of 21.5% in energy savings and increases the network life by about 44%. However, having to collect location information, and the establishment of the steering mechanism for nodes, complicates the path settings.

B. Low Energy Adaptive Clustering Hierarchy - LEACH

Heinzelman et al. presented in [47] a hierarchical clustering algorithm for sensor networks called Low Energy Adaptive Clustering Hierarchy (LEACH). It is a clustering based protocol that includes the formation of distributed groups. It randomly selects a few nodes as cluster heads (CHs) and rotates this role to evenly distribute the energy load among the nodes of the network. In LEACH, CH nodes compress the data arriving from the nodes in their respective groups, and send summary packets to the base station. This reduces the amount of information transmitted to the base station. Data collection is centralized and is carried out periodically. Therefore, this protocol is appropriate when constant monitoring of the WSN is needed. The operation of LEACH is separated into two phases, the setup phase and the steady-state phase. In the setup phase the groups are organized and certain fraction of nodes are elected as CHs. In the steady-state phase, data transfer to the base station occurs. All elected CHs announce to the other nodes of the network, through a broadcast message, that they are the new CHs. All non-CH nodes, after receiving this notice, choose the group they want to belong to. This decision is based on the intensity of the warning signal. Non-CH nodes inform the appropriate CHs that it is a member of their group. After receiving all messages from the nodes that wish to be included in the cluster, the CH node creates a TDMA program and assigns to each node a time slot to transmit data. This program is broadcasted to all nodes in the cluster. During the steady state, the sensor nodes can sense and transmit data to the CHs. The CH node, after receiving all data, adds its information and sends it to the base station. After some time, which is determined a priori, the network returns to the setup phase again and starts another round of new CHs election. Each group communicates using different CDMA codes in order to reduce interference with nodes that belong to other groups. Although LEACH is able to increase the network lifetime, there are still a number of questions about the assumptions used in this protocol. LEACH assumes that all nodes have enough transmission power to reach the base station and each node has the computational power to support different MAC protocols. Therefore, it is not applicable to networks deployed in large regions. It also assumes that nodes always have data to send, and nodes that are located close to each other have correlated data. It is unclear how the CHs are uniformly distributed over the network. Therefore, it may happen that the elected CHs are concentrated in one part of the network, so some nodes may not have a CH in their surroundings. Moreover, the idea of dynamic clustering can result in an extra overhead that can increase the energy consumption. Finally, the protocol assumes that all nodes start with the same amount of energy in each round of election, and assumes that a CH consumes approximately the same amount of energy.

C. Hybrid Energy-Efficient Distributed clustering-HEED

The paper in [48] proposes a method of saving energy for clusters of nodes in WSNs. HEED (*Hybrid Energy-Efficient Distributed clustering)* periodically selects the main nodes in the cluster according to a set of parameters such as residual energy and a secondary endpoint. It also seeks to extend the network lifetime by distributing energy consumption. It also tries to reduce high control on the network. The authors explain the grouping process and the determination of the responsible node. The system does not take care of the type of technology used. This work compares HEED protocol with others. HEED optimizes the use of resources according to the network density and the application requirements.

D. Hierarchical Power-Aware Routing (HPAR)

Another example of hierarchical protocol is presented by Q. Li et al. in [49]. The Hierarchical Power-Aware Routing (HPAR) protocol bases its operation on the division of the network into groups of sensors. Each group is formed by geographically close sensors covering a zone. Each zone is treated as an entity. In order to perform the routing between nodes, each zone is allowed to decide how a message is routed through the other areas, so maximizing the battery life of the nodes. Messages are routed along the path that has the maximum value on all the remaining minimum power values. This route is called max-min path. In order to send a message through an area, the route through the area and the sensors involved in estimating the power level of the area should be found. Each message is routed through the areas with the information about the estimation. The role of area management for message routing is assigned to a node. This protocol is based on the idea that the use of high residual energy nodes can be more expensive than the path with minimum energy consumption. The protocol seeks a balance between minimizing the total power consumption (using Dijkstra algorithm to find the path with least power consumption) and maximizing the minimal residual power of the network.

E. Power-Efficient Gathering in Sensor Information Systems - PEGASIS

In [50], an enhancement over LEACH protocol was proposed. The protocol, called Power-Efficient Gathering in Sensor Information Systems (PEGASIS), is a near optimal chain-based protocol. The basic foundation of this protocol is that nodes need only to communicate with their nearest neighbors, taking turns to communicate with the base station. When all nodes have established a connection with the base station, a new round will start and so on. This type of communication between nodes reduces the power required to transmit data through a path and ensures power distribution in all nodes. Therefore, PEGASIS has two main objectives. On the one hand, PEGASIS increases the lifetime of each node using collaboration techniques and, as a result, the network lifetime is extended. Moreover, the protocol allows only local coordination among close nodes, so the bandwidth consumed in communication is reduced. In addition, PEGASIS assumes that all nodes maintain a comprehensive database of the location of other nodes. To set the distance that each node has to its neighbor, the protocol uses the received signal strength to subsequently adjust the intensity of the signal in order to hear just one node. By contrast, PEGASIS requires adjustments to dynamic topologies in order to know where to find the destination node and in order to know where to route their data. Simulation results show that PEGASIS is able to double the network lifetime in comparison to using LEACH protocol.

F. Hierarchical-PEGASIS

An extension and improvement of PEGASIS (called hierarchical-PEGASIS) was introduced in [51]. Its aim is to reduce the delay of the packets transmitted to the base station. This protocol bases its operation in the assumption that only those spatially separated nodes may transmit simultaneously. It is a chain-based protocol with CDMA capable nodes, which constructs a chain of nodes forming a hierarchical structure and each selected node in a particular level transmits data to the node in the upper level of the hierarchy. In the performance test, the authors simulate simultaneous data transmissions to show how it avoids collisions through approaches that incorporate signal coding and spatial transmissions. The simulation shows that the new method ensures data transmitting in parallel and reduces the delay significantly. It has also shown that the proposal improves the previous version (PEGASIS) by a factor of about 60.

G. Minimum Energy Communication Network - MECN

In [52], the authors propose a protocol, called Minimum Energy Communication Network (MECN), which calculates the energy efficiency of the subnets. It uses low-power GPS system. MECN identifies a region for every node. The region consists of nodes in a surrounding area where the transmission through those nodes is more energy efficient than direct transmission. The enclosure of a node is created by joining all regions that the region of the node can achieve. The main idea of MECN is to find a subnet that has fewer nodes and requires less transmission power between two particular nodes. In this way, global minimum power paths are not taken into account for all the network nodes. This is done using a localized search for each node considering its region. MECN is self-reconfigurable and thus can dynamically adapt to node failures or to the deployment of new sensors.

H. Small Minimum Energy Communication Network - SMECN

Small Minimum Energy Communication Network (SMECN) [53] is an improvement of MECN. In their algorithm, the authors considered for MECN the possible obstacles between any pair of nodes. Simulations show that SMECN is more energy-efficient than MECN and the links cost maintenance is lower. In addition, the number of hops for transmissions is decreased. On the other hand, finding a sub-network with a smaller number of edges introduces more overhead in the algorithm.

I. Threshold sensitive Energy Efficient sensor Network - TEEN

Threshold sensitive Energy Efficient sensor Network protocol (TEEN) [54] was developed for reactive networks. Sensor nodes continuously detect the environment but data transmission is only carried out when a parameter reaches a threshold value. The sensed value is stored in an internal variable in the node, called the sensed value (SV). There are two thresholds, hard threshold and soft threshold. When a parameter reaches its hard threshold value, the node switches on its transmitter and sends the sensed data to the cluster head. The soft threshold is a small change in the value of the attribute that causes the node to change to transmit mode and to start the transmission process. It gives a more accurate picture of the network, even if it means higher energy consumption. Thus, the user can decide on the tradeoff between energy efficiency and data accuracy. When CHs are changed, the new values of the above parameters are broadcasted. The main drawback of this system is that if the thresholds are not received, the sensed reported is not transmitted, and the user does not get any data from the network. In the TEEN protocol, the process of data detection consumes less power than the transmission of messages, so that energy consumption in this system is less than proactive networks. In addition, if necessary, the user can modify the soft threshold and broadcast the new parameters to the other sensors.

J. Adaptive Threshold sensitive Energy Efficient sensor Network - APTEEN

On the other hand, Adaptive Threshold sensitive Energy Efficient sensor Network protocol (APTEEN) [55] is a hybrid protocol that changes the frequency and threshold values used in the TEEN protocol according to the user needs and the type of application. The main feature of the APTEEN scheme is that it includes a combination of proactive and reactive policies. It has the possibility of adjusting the interval timer and the threshold values so as to redress power consumption according to the type of implemented application. In APTEEN, the node continuously monitors the environment, and only the nodes that detect an attribute value above the hard threshold will transmit data. The nodes will also transmit when the attribute value changes are equal to or greater than the soft threshold. If a node does not send data over a period of time equal to the timer, it will have to retransmit lost data. APTEEN uses a modified TDMA scheme to implement the hybrid network. The operation is based on the performance of TDMA, where a transmission time slot is assigned to each node in the cluster. The biggest weakness is the additional complexity to implement the features of the threshold and timer. APTEEN performance is between LEACH and TEEN in terms of energy dissipation and lifetime of the network. TEEN offers better performance by decreasing the number of transmissions.

K. ACtive QUery forwarding In sensoR nEtworks-ACQUIRE

In [56], Sadagopan et al. proposed a technique for querying sensor networks, which was called ACtive QUery forwarding In sensoR nEtworks (ACQUIRE).This protocol is a novel mechanism for data extraction in energy-constrained sensor networks. The key features of ACQUIRE are the injection of active queries into the network with triggered local updates. ACQUIRE performs its function in an energy efficient manner compared to other approaches. The network is a distributed database where complex queries can be further divided into several sub queries. The sink node sends a query, which is then forwarded by each node.

Nodes with relevant data will respond. It is not a continuously persistent query, so the flooding does not dominate the costs associated with querying. Moreover, when data aggregation is employed, duplicate responses can generate in suboptimal data collection in terms of energy costs, so, once the query is being resolved completely, it is sent back through either the reverse or shortest-path to the base station. Moreover, ACQUIRE can provide efficient query by adjusting the value of the look-ahead number of hops. When the number of hops is equal to the network diameter, ACQUIRE mechanism behaves similar to flooding mechanism. ACQUIRE protocol shows good results with optimal parameter settings that outperform all the other schemes on complex, one-shot, non-aggregate queries for replicated data. It can reduce the energy consumption of other approached by more than 60% in some cases.

L. Information-Driven Sensor Querying and Constrained Anisotropic Diffusion Routing – IDSQ and CADR

Two routing techniques called information-driven sensor querying (IDSQ) and constrained anisotropic diffusion routing (CADR) are presented by M. Chu et al. in [57]. The main idea of both protocols is to maximize the information gain, by choosing the best query sensors and route data, while latency and bandwidth are minimized. This is achieved by activating only the sensors that are close to a particular event, thus data routes are dynamically adjusted. There are some differences between these protocols. While CADR aims to be a general form of directed diffusion, IDSQ is based on a protocol in which the querying node could determine which node can provide the most useful information while balancing the energy cost. Moreover, in CADR, the local information/cost gradient and end-user requirements are used in order specify an information/cost objective, and routes data, for each node. In addition, CADR can diffuse its queries only to the sensor nodes that can get the data (by only activating the right ones). IDSQ can be seen as a complementary optimization procedure because it does not specifically define how the query and the information are routed between sensors and the base station. However, simulation results shows that directed diffusion techniques, where queries are diffused in an isotropic fashion and reaching nearest neighbors first, are less energy-efficient than these approaches. A disadvantage of both protocols is that both need too much processing in their nodes.

M. COUGAR

Another data-centric protocol, presented by Y. Yao et al., is COUGAR [24]. This protocol views the network as a huge distributed database system. The main idea is to use declarative queries to summarize query processing such as the election of relevant sensors, etc. COUGAR utilizes in-network data aggregation to obtain more energy savings. In order to reduce resource usage and thus extend the lifetime of a sensor network, COUGAR uses a user query technique, where a query optimizer generates an efficient query plan for in-network query processing. Through an additional query layer that lies between the network and application layers, this protocol supports the summary. COUGAR adds an architecture for the sensor database system, where sensor nodes elect a leader node in order to perform data aggregation and transmit the data to the sink. This fact provides in-network computation ability that can provide energy efficiency in situations where the number of sensors generating and sending data to the leader is very large. In contrast, COUGAR has some drawbacks. On the one hand, the addition of a query layer on each sensor node may add an extra overhead in terms of energy consumption and memory storage. On the other hand, in order to obtain successful in-network data computation, synchronization among nodes is required before sending the data to the leader node. Finally, the leader nodes should be dynamically maintained to prevent them from being hot-spots.

N. Geographic Adaptive Fidelity - GAF

Geographic Adaptive Fidelity (GAF) was presented by Y. Xu et al. in [15]. It is an energy-aware location-based routing algorithm designed primarily for mobile ad hoc networks, although it may also be applicable to sensor networks. This protocol divides the network area into fixed zones where nodes collaborate with each other to play different roles and form a virtual grid. The main goal of GAF is the energy conservation by turning off unnecessary nodes in the network without affecting the level of routing fidelity. There is a virtual grid formed to cover an area. Each node uses a GPS-indicated location to associate itself with a point in the virtual grid. Inside these virtual grids, the nodes associated with the same point on the grid, receive the same value in terms of the cost of packet routing. GAF defines three states. These states are: discovery, for determining the neighbors in the grid, active reflecting participation in routing, and sleep, when the radio is turned off. GAF can increase the network lifetime even increasing the number of nodes, because, some nodes located in a particular grid area can remain in sleep mode in order to reduce the global energy consumption of the network. When a node is in sleep mode, it can change its state from sleep mode to active mode in order to balance the network load. Furthermore, the parameters related to the time for the sleep mode are specified during the routing process. In addition, to handle mobility, each node in the grid estimates its transmission time in the grid and sends its data to its neighbors. The sleeping neighbors adjust their sleeping time accordingly in order to keep the routing fidelity. Simulation results show that GAF performs as well as a regular ad hoc routing protocol in terms of latency and packet loss and increases the lifetime of the network by saving energy. However, GAF can be considered as a hierarchical protocol without aggregation, and consequently it can have the same weaknesses as a hierarchical protocol.

O. Geographic and Energy Aware Routing - GEAR

Geographic and Energy Aware Routing (GEAR) is a location based routing protocol too. It was presented by

Y. Yu et al. in [58]. The main idea of this protocol is to restrict the number of queries in directed diffusion considering a certain region rather than sending the queries to the whole network. In GEAR, each node keeps an estimated cost and a learning cost to reach the destination through its neighbors. In order to estimate the cost as a combination of the residual energy and the distance to a destination, it uses energy aware and geographically-informed neighbor selection heuristics to route a packet towards the destination region. The learned cost is obtained as a refinement of the estimated routing cost around the holes of the network. A hole is generated when a node does not have any closer neighbor to the target region than itself. If there are no holes, the estimated cost is equal to the learned cost and it is spread one hop back every time a packet reaches the destination. We can distinguish two phases in the algorithm flow. In the first one, when a node receives a packet, it checks its neighbors to see if there is a neighbor closer to the target region. The nearest neighbor node is selected as the next hop. When the network registers a hole, one of the neighbors is picked to forward the packet based on the learning cost function. In the second phase, when a packet has reached the region, it can be diffused in that region by either recursive geographic forwarding or by restricted flooding. Restricted flooding is usually used when the sensors are not densely deployed while recursive geographic flooding is more energy efficient in high-density networks. GEAR reduces energy consumption in the route setup and it performs better than GPSR in terms of packet delivery. The simulations show that for an uneven traffic distribution, this protocol delivers from 70% to 80% more packets than GPSR. For uniform traffic pairs GEAR, it delivers from 25% to 35% more packets than GPSR.

P. Sequential Assignment Routing - SAR

Sequential assignment routing (SAR) [59] was the first protocol for sensor networks that includes the notion of QoS in its routing decisions. The SAR algorithm generates multiple trees where the root of each tree is a one hop neighbor from the sink. Each tree grows outward from the sink by taking into consideration the QoS metric, the energy of each path and the priority level of each packet. This algorithm selects the path based on them. When the sensor node has exclusive use of a path, the energy resources are estimated by the number of packets. As a result, each sensor node selects its path to route the data back to the sink. Simulation results show that it offers less power consumption than other network algorithms, which only focus the energy consumption of each packet without considering its priority. In contrast, SAR maintains multiple paths from nodes to the sink which generates an overhead because of the tables and states maintenance of each sensor node, especially when the number of nodes is too big.

Q. SPEED

A real-time communication protocol for sensor networks, called SPEED, is proposed by T. Hea et al. in [60]. SPEED is specifically tailored to be a stateless-localized algorithm with minimal control overhead. This protocol provides three types of real-time communication services, called, real-time unicast, real-time area-multicast and real-time area-anycast, for ad hoc sensor networks. SPEED is an efficient and scalable protocol for sensor networks where the resources of each node are scarce. It can also provide congestion avoidance when the network is congested. In this protocol, each node maintains information about its neighbors and uses geographic forwarding to find the paths. Furthermore, SPEED tries to ensure a certain speed for each packet so each application can estimate the end-to-end delay for the packets by dividing the distance to the sink by the speed of the packet before making the admission decision. The beacon exchange mechanism collects information about the nodes and their location. Then, the delay estimation at each node is calculated by the elapsed time when an ACK is received from a neighbor as a response to a transmitted data packet. After that, the node, which meets the speed requirement, is selected. If it is not possible, the relay ratio of the node will be checked. The Neighborhood Feedback Loop module calculates the relay ratio by looking at the packet failure ratios of the neighbors of a node. The algorithm eliminates congestion by sending messages back to the source nodes, thus they will pursue new routes. SPEED maintains a desired delivery speed across the network through a novel combination of feedback control and non-deterministic QoS-aware geographic forwarding. The design takes into account that the end-to-end delay depends on not only single hop delay, but also on the distance a packet travels. SPEED algorithm tries to support a real-time communication service with a desired delivery speed across the wireless sensor network, so the end-to-end delay is proportional to the distance between the source and the destination. Delivery speed is always smaller than the actual speed of the packet in the network, unless the packet is routed exactly along a straight line.

R. Directed Diffusion

Directed diffusion is data-centric protocol where all nodes in the directed diffusion-based network are application aware. This protocol was presented by C. Intanagonwiwat et al. in [61]. Directed diffusion protocol is suitable for query applications, which does not need global network topology maintenance. In addition, it enables diffusion to achieve energy savings by selecting good paths empirically and by caching and processing the data. This protocol has several features that can be highlighted. On the one hand, directed diffusion has the potential for significant energy efficiency. It outperforms an idealized traditional data dissemination scheme like omniscient multicast, even with an un-optimized path selection. On the other hand, diffusion mechanisms are stable under certain ranges of network dynamics. By contrast, this protocol is not the most suitable for continuous monitoring of a medium, because the computational requirements needed are high, which will imply more energy consumption.

S. Rumor Routing

Rumor Routing [62], presented by D. Braginsky et al. is a variation of the Directed Diffusion protocol. It represents a compromise between flooding queries and flooding event notifications. This protocol was designed for contexts in which geographic routing criteria are not applicable because a coordinate system is not available or the phenomenon of interest is not geographically correlated. The protocol is based on the following assumption: when the number of events is low, compared to the number of queries, event flooding can be efficient. Rumor routing algorithm uses long-lived packets called agents, to flood events through the network. When a node detects an event, it adds such event to its local table and generates an agent. Agents travel through the network in order to propagate information about local events to distant nodes. When a node generates a query for an event, the nodes that know the route, can respond to the query by referring its event table, thus the cost of flooding the whole network is avoided. Simulations show that Rumor Routing algorithm is a good method for delivering queries to events in large networks under a wide range of conditions, while maintaining energy requirements lower than other alternatives. Its design is able to be adjusted to different application requirements, to support different queries to event ratios, successful delivery rates, and route repair. In addition, it is capable to handling node failures and degrade its delivery rate linearly with the number of failed nodes.

T. Self Organizing Protocol - SOP

In [63], Subramanian et al. proposed a genetic architecture and a self-organizing protocol that allows large number of sensors to coordinate among themselves. The main goals of the algorithm are to minimize power utilization, localize operations and tolerate node and link failures. This routing protocol is based on a hierarchical architecture where groups of nodes are formed and merge when needed. It uses the Local Markov Loops algorithm in order to support fault tolerance. SOP can consider mobile or stationary sensors. Collected data are forwarded through the nodes to the most powerful base station.

U. Two-Phase geographic Greedy Forwarding - TPGF

We can also find papers which present protocols for very specific applications. In [64], presented by L. Shu et al., authors propose an efficient Two-Phase geographic Greedy Forwarding (TPGF) routing algorithm for Wireless multimedia Sensor Networks (WMSNs). TPGF is different from other geographic routing algorithms, because TPGF is a pure geographic routing algorithm that does not include the face routing concept and also does not require the computation and preservation of the planar graph in WSNs. This fact allows more links to be available for TPGF to explore more node disjoint routing paths. However, TPGF does not have the well-known Local Minimum Problem. The operation of this algorithm is divided mainly in two phases. In the first of them, the algorithm should explore the possible routing path, guarantying the correct delivery through routing path while bypassing holes in WMSNs. The second phase is responsible for optimizing the found routing path with the least number of hops. TPGF can be considered an iterative algorithm due to it can be executed repeatedly to find multiple node-disjoint routing paths. The algorithm structure contemplates as inputs, the location of the current forwarding node, the location of the base station and the locations of 1-hop neighbor nodes; meanwhile, its outputs are the location of the next-hop node or successful acknowledgement or unsuccessful acknowledgement. The goals of the simulation try to demonstrate that TPGF can find more routing paths and prove that it can have shorter average path length than other algorithms like GPSR. To evaluate the TPGF routing algorithm, the authors use a sensor network simulator NetTopo. The network size in simulation is fixed as 600 × 400. For each fixed number of sensor nodes and transmission radius, the average number of paths and the average path length are computed from 100 simulation results using 100 random seeds for network deployment. The simulations results show that, on the one hand, TPGF can find much more number of paths than that of GPSR on both GG and RNG planar graphs. In addition, the after optimization the average path length of TPGF is much shorter than GPSR and finally, it is proved that TPGF can have shorter average path length than that of GPSR.

V. Energy Consumed uniformly-Connected K-Neighborhood - EC-CKN

Related with Network lifetime, Z. Yuan et al. present a paper [65] where propose a new sleep scheduling algorithm, named EC-CKN (Energy Consumed uniformly-Connected K-Neighborhood) algorithm, to prolong the network lifetime. In this work, the authors propose a new sleep scheduling algorithm, named EC-CKN, which is proposed to balance the energy consumption and prolongs the network lifetime. This algorithm takes the nodes' residual energy information as the parameter to decide whether a node to be active or sleep and not only can achieve the k_connected neighborhoods problem, it also can assure the k awake neighbor nodes have more residual energy than other neighbor nodes at the current epoch. To do the simulations, the authors suppose a model of transmitter and receiver, considering the power consumption of each part of the circuit, depending on the number of bits transmitted. To these nodes, the sleep scheduling algorithm is applied. The algorithm takes an input parameter K, the required minimum number of awake neighbors per node. In EC-CKN, a node broadcasts its current residual energy information and computes a subset of neighbors. Before the node can go to sleep it makes sure that all nodes in subset are connected by nodes with major amount of energy and each of its neighbors has at least k neighbors from subset. With this process, the system guarantees, that if a node has less than k neighbors, none of its neighbors goes to sleep and if it has more than k neighbors, at least k neighbors of them decide to remain awake.

TABLE III.

	Network Structure				**Main Functions**						**Energy**
Routing Protocol	**Flat**	**Hierarchical**	**Location Based**	**QoS based**	**Scalability**	**Data Aggregation**	**Mobility**	**Query Based**	**Multipath**	**Negotiation Based**	**Power Consumption**
ACQUIRE	Yes	-	-	-	Limited	Yes	Limited	Yes	No	No	-
APTEEN	-	Yes	-	-	Good	Yes	Fixed BS	No	No	No	Maximum
CADR	Yes	-	-	-	Limited	Yes	No	No	No	No	-
COUGAR	Yes	-	-	-	Limited	Yes	No	Yes	No	No	Limited
Directed Diffusion	Yes	-	-	-	Limited	Yes	Limited	Yes	Yes	Yes	Limited
EC-CKN	-	-	-	YES	Good	No	No	Yes	-	-	-
Energy Aware Routing	Yes	-	-	-	Limited	No	Limited	Yes	No	No	-
GAF	-	-	Yes	-	Good	No	Limited	No	No	No	Limited
GEAR	-	-	Yes	-	Limited	No	Limited	No	No	No	Limited
HEED	-	Yes	-	-	Good	Yes	Yes	No	No	No	-
Hierarchical-PEGASIS	-	Yes	-	-	Low	No	Fixed BS	No	No	No	Maximum
HPAR	-	Yes	-	-	Good	No	No	No	No	No	-
IDSQ	Yes	-	-	-	Limited	Yes	No	No	No	No	-
LEACH	-	Yes	-	-	Good	Yes	Fixed BS	No	No	No	Maximum
MECN	-	Yes	-	-	Low	No	No	No	No	No	Maximum
PEGASIS	-	Yes	-	-	Low	No	Fixed BS	No	No	No	Maximum
Rumor Routing	Yes	-	-	-	Good	Yes	Limited	Yes	No	No	-
SAR	-	-	-	Yes	Limited	Yes	No	Yes	No	Yes	-
SMECN	-	Yes	-	-	Low	No	No	No	No	No	Maximum
SOP	-	Yes	-	-	Low	No	No	No	No	No	-
SPEED	-	-	-	Yes	Limited	No	No	Yes	No	No	-
TEEN	-	Yes	-	-	Good	Yes	Fixed BS	No	No	No	Maximum
TPGF	-	-	Yes	-	Good	Yes	No	No	-	-	-

The information needed to maintain this situation is extracted by computing locally with 2-hop neighborhood information and from the information about the residual energy exchanged. To prove its energy consumption, authors show a comparison between the energy consumption and network lifetime comparison among CKN and EC-CKN algorithm. Finally they conclude that the energy consumption in EC-CKN based WSN is well balanced.

There are more works published proposing other routing protocols for WSNs. Some of them are new, while others are based on existing protocols. Table 3 classifies the energy-aware routing protocols described in this section. It shows their main characteristics. A dash (-) means that the information is not provided by the authors or it cannot be correctly ascertained from their paper. Fixed BS means fixed base station.

VII. CONCLUSION

In this paper, we have presented the main causes of energy loss in wireless sensor nodes.

The main characteristics required to make a wireless sensor node and the factors to be considered when implementing a WSN or ad-hoc network have been discussed.

We discussed the energy wastage given by the electronic circuit. Therefore, counting on a sound electronic design that includes the right components for the sensor device is absolutely essential.

Finally, we show and compare several MAC and routing protocols that have been designed to optimize the power consumption without compromising the data delivery in WSNs.

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