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A SURVEY ON POWER CONTROL ISSUES IN WIRELESS SENSOR NETWORKS

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ABSTRACT

A Wireless Sensor Network (WSN) is actually composed of a large number of very small in size, low-cost, low-power, multifunctional sensor nodes that are densely deployed either inside the phenomenon or very close to it, and they are capable of communicating freely in short distances. Power control is an important research topic in WSNs since it can guarantee basic levels of system performance, such as delay, connectivity, and throughput, in the presence or absence of mobility. A large variety of schemes for power control issues in WSNs have been proposed in the literature, whereby different approaches typically focus on different performance metrics. This article provides a classification and presents a comprehensive survey concerning passive and active power control mechanisms in wireless sensor networks, based on this classification. We also evaluate and compare the

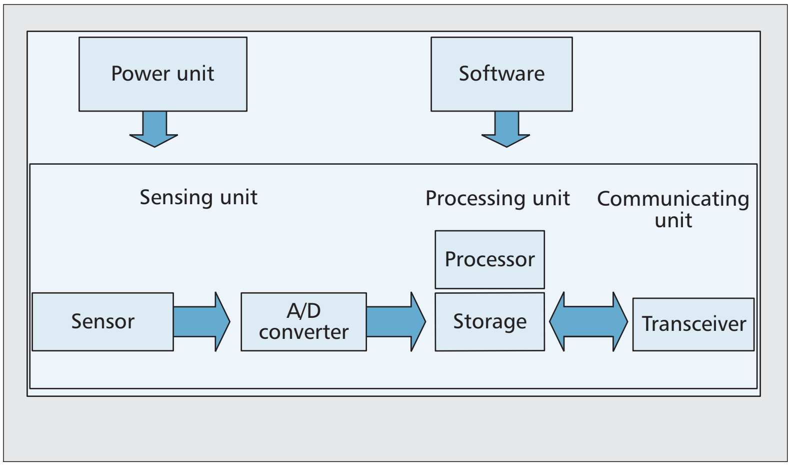
With the proliferation in sensor nodes and the development in wireless communication technologies, Wireless Sensor Networks (WSNs) have gained worldwide attention in recent years. They facilitate monitoring and controlling of physical environments from remote locations with great accuracy and represent a significant improvement over wired sensor networks. WSNs are employed in a vast variety of fields, such as: environmental monitoring (e.g., temperature, humidity), monitoring disaster areas providing relief, file exchange, conferencing, home, health (monitoring patients and assisting disabled patients), commercial applications including managing inventory and monitoring product quality and military purposes. Their function is to collect and disseminate critical data, while their position does need to be engineered or predetermined, in contrast to the wired ones. This allows random deployment in inaccessible terrains or disaster relief operations. On the other hand, this also means that WSN protocols and algorithms must possess self-organizing capabilities [1].

Realization of the wireless sensor network applications requires wireless ad-hoc networking techniques. Although a great number of protocols and algorithms have been proposed for wireless ad-hoc networks, they are not well-suited to the unique features and application requirements of WSNs for the following reasons:

- The topology of a WSN changes very frequently.
- The number of sensor nodes in a WSN can be several orders of magnitude higher than the number of sensor nodes in a wireless ad-hoc network.
- Sensor nodes are densely deployed in a sensor field
- Sensor nodes mainly use a broadcast communication paradigm, whereas most wireless ad-hoc networks are based on point-to-point communications.
- Sensor nodes may not have global identification due to their large amount of overhead and large number of sensors in the WSN.
- Sensor nodes are limited in power, computational capacity and memory.

This last requirement is the primary limitation of the WSNs. Their survivability, as it has already been mentioned, depends on power control and power management of the consumed energy, as well as on network connectivity.

Considerable research has been focused at overcoming the deficiencies of energy consumption of the sensor nodes, guaranteeing the sensor network's existence and increasing the sensor network's lifetime in such energy-constrained environments through more power control schemes regarding resource allocation, routing and low-energy consumption. This survey attempts to provide an overview of these issues as well as the solutions proposed in recent literature.



■ **Figure 1.** *A sensor node architecture.*

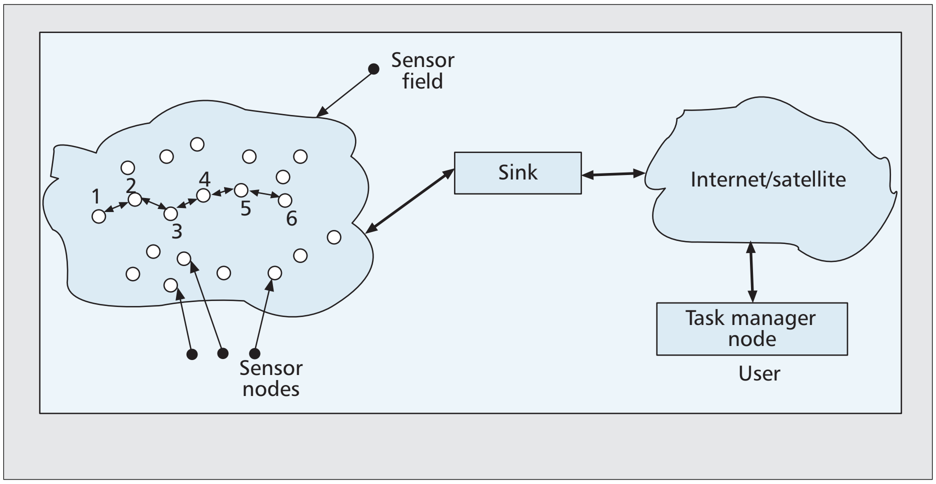
Thus, the remainder of this article is organized as follows: we present an overview on power management and classification of power control protocols in wireless sensor networks. Following later, passive power conservation mechanisms in WSNs are presented. An issue concerning active power conservation mechanisms is also presented. Detailed approaches, of how these power control protocols may be applied in a great variety of fields, are also given. Finally, we present some concluding comments.

Power Management and Classification of Power Control Protocols in Wireless Sensor Networks

A sensor node consists primarily of the sensing unit, which includes the sensor and the Analog to Digital (A/D) converter the data processing unit (processor and data storage), and the communicating unit (Transceiver = Transmitter/Receiver or radio) (Fig. 1).

The sensor node is supplied with voltage by means of the power unit that may be a battery or a power generator. Its components are activated by the appropriate software. Sensor nodes are fitted with an onboard processor. Instead of sending the raw data to the sensor nodes responsible for the processing (fusion), they use their processing abilities to locally carry out simple computations and transmit only the required and partially processed data [1–6]. Sensor nodes are often deployed in a field as shown in Fig. 2. Each sensor node is in the position of sensing its environment, collecting and transmitting data to the destination (sink or base station). Moreover, data can be routed back to the sink through a more-than-one-hop infrastructureless architecture [1].

Wireless sensor networks are typically deployed in remote or polluted environments where battery's replacement is not easy. Thus, the design of fault-tolerant wireless sensor networks with long lifetimes is challenging [7–9]. The extension of the system's lifetime can be accomplished through the application of energy-efficient techniques at all levels of the system hierarchy.



■ **Figure 2.** *Sensor nodes deployed in a sensor field (redrawn from [1]).*

Therefore, power management is a very important issue in sensor networks in order to guarantee basic levels of system performance, such as connectivity, throughput and delay. The power management models and the classification of power management protocols in WSNs will be analyzed in the following chapters.

Power Management Overview

The main question that should be answered is: "Why do WSNs require power management?" Wireless sensor nodes, as it was mentioned before, constitute more often static devices, rather than moving devices with various energy and computational constraints due to their inexpensive nature, limited size, weight, and ad-hoc method of deployment. In some application scenarios, replenishment of power resources might be impossible, due to the non-accessible or polluted areas they are deployed in. Therefore, a sensor node's lifetime, presents a unique dependence on battery lifetime [1]. The energy problem is a valuable commodity in WSNs. The communication energy is defined as the sum of the energy required to transmit data, using a transceiver (radio), and the energy required for the data processing (to perform encoding and decoding). WSNs should operate with the least possible energy required in order to increase the lifetime of the sensor nodes, ensuring at the same time network connectivity and availability. To make it possible, the following requirements should be fulfilled:
- Power-aware computation and communication component technology
- Power-aware software infrastructure
- Low-energy signaling

Sensor nodes partitioning or clustering should necessarily be taken into consideration to ensure low-energy data processing and intra-node communication [10].

In a multihop wireless sensor network, each node plays the dual role of data originator (source or generator) and data router. The failure of even few sensor nodes can cause significant topological changes and might require rerouting of the packets and reorganization of the network. Hence, energy conservation and power management mechanisms obtain additional significance. An energy-efficient power control protocol may also limit the interference between the sensor nodes and at the same time to achieve the optimum utilization of

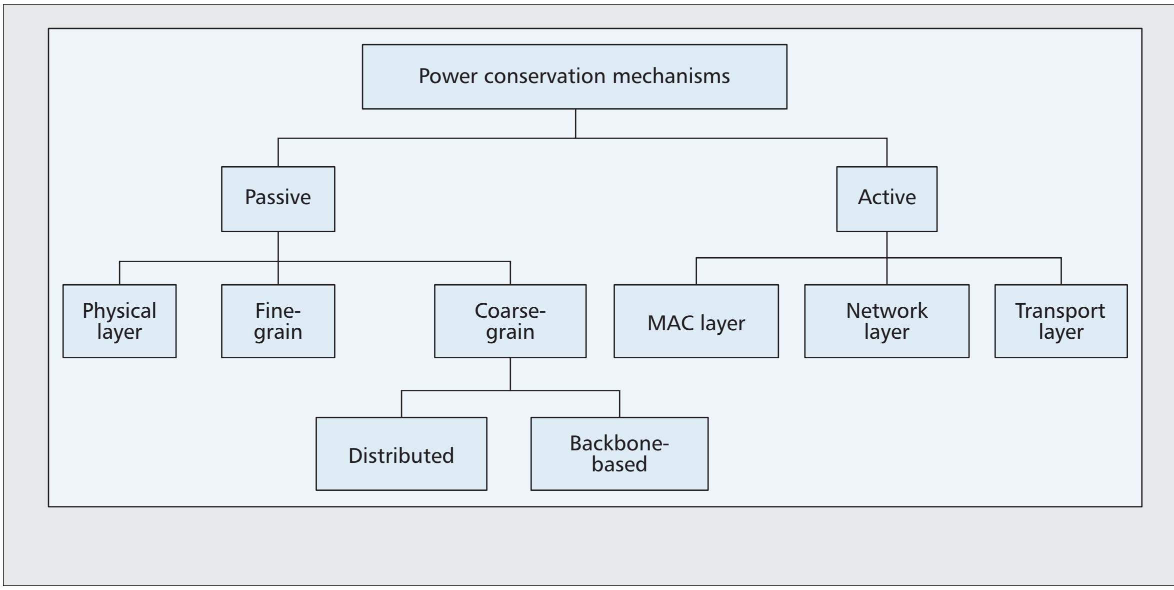


Figure 3. *The block diagram of power conservation mechanisms.*

the system resources.

The second question that arises is: "What is the cost of power management?" A power-management-based WSN has its side effects and drawbacks because the construction and maintenance of a power control protocol usually requires additional cost compared with a wired sensor network. The cost of power management is a key issue to validate the effectiveness of a power control scheme. By analyzing the cost of a power control protocol in different aspects, qualitatively or quantitatively, its usefulness and drawbacks can be clearly specified. The operational part of the sensor is determined by the application it supports, e.g. the frequency of data collection, the packet size of the collected data, the duration of measurements, the kind of the sensor node employed and its characteristics.

Classification of Power Control Protocols in Wireless Sensor Networks

Existing power conservation mechanisms for WSNs may be classified into two main categories [11]: Active and Passive (Fig. 3). *Active* refers to mechanisms that achieve energy conservation by smartly utilizing energy-efficient network protocols (by not turning-off the radio interface), while *Passive* refers to mechanisms that save a node's power by turning-off the radio (transceiver) interface module [11].

Passive Power Conservation Mechanisms — Passive power conservation mechanisms reduce the energy consumption of the sensor node by turning-off its transceiver interface module when there is no communication activity [11]. *Periodic hibernation* is another synonymous term which can be found in the literature. According to this protocol, the wireless transceiver is turned-off during the periods, where the sensor node can neither transmit nor receive [12].

The idea of turning-off the transceiver was firstly introduced in IEEE 802.11 [13]. According to this standard, a sensor node may switch to sleep mode, by turning-off its transceiver in accordance with the Network Allocation Vector (NAV). Also, every mobile sensor node in the network must wake-up during an Announcement Traffic Indication Message (ATIM) period, during which transmitters inform their destination not to turn to power-save mode. If no notification is received, the mobile sensor node can turn to power-save mode and wake-up right in the next ATIM period [13–15]. A sending mobile sensor node can also defer its transmission (or at least decrease the transmission rate) in noisy channels. It is possible to try to compensate any loss, when the channel gets better.

In this classification, the physical layer in the passive branch of the power conservation mechanisms tree was added, (while taking into account the scheme in [11]). Thus, according to this new consideration, passive power conservation mechanisms are classified into three basic categories according to the possible levels of control for turning-off the radio interface module (Fig. 3):

- Physical Layer Power Conservation (FLPC)
- Fine-Grain Power Conservation (FGPC)
- Coarse-Grain Power Conservation (CGPC)

Physical Layer Power Conservation (FLPC) — The application of turn-off techniques at the physical layer can produce substantial energy savings by reducing to the minimum the energy of the Central Processing Unit (CPU) in idle system states. Dynamic Voltage Scaling (DVS) [16–18], and Dynamic Power Management (DPM) [19] are typical examples of the passive power conservation mechanisms.

Fine-Grain Power Conservation (FGPC) — According to Fine-Grain Power Conservation (FGPC) mechanism, Medium Access Control (MAC) layer is led to decide whether there is a frame transmission that is destined to it, and then turn-off the radio interface module for just one transmission frame [11]. A sensor node can save power from every frame transmission if MAC layer is let to decide. Moreover, there will be no delay to all incoming traffic to a sensor node, since a sensor node has never been turned off for more than one transmission frame [11]. PAMAS [20] is a typical example of the FGPC algorithm.

Coarse-Grain Power Conservation (CGPC) — In contrast, Coarse-Grain Power Conservation (CGPC) mechanism utilizes higher layer application information to decide when to turn-off the radio interface module. A dedicated application, usually operating in a higher than the MAC layer, controls the radio interface module operation. Therefore, the radio interface module may be turned-off longer than the transmission time of a single MAC frame [11]. To implement the CGPC mechanisms, there are two different approaches: the Distributed Approach (DA), and the Backbone-based Approach

PCM	Decision is taken by	Radio turned off for a transmission time of	Energy can be saved from every frame transmission	Amount of saved energy	Delay
FGPC	MAC layer	a single MAC frame	Yes	small	big
CGPC	Higher layers than the MAC layer	longer than a single MAC frame	No	big	small

■ Table 1. *Features of fine-grain and coarse-grain power conservation mechanisms.*

CGPC	Required infrastructure	Independent schedule of the sensor nodes' sleeping intervals
DA	No	Yes
BA	Yes	No

■ Table 2. *Main differences between distributed and backbone-based approaches.*

(BA).

The comparison between Fine-Grain and Coarse-Grain approaches, as the amount of power savings concerns, shows that Coarse-Grain approach is more energy efficient than Fine-Grain approach [11], but it may induce longer delay for incoming traffic destined to sleeping sensor nodes, as shown in Table 1.

- The Distributed Approach (DA): According to the DA approach sensor nodes independently schedule their sleeping intervals based on both internal information and/or neighbor information. The coordination of sleeping schedules between sensor nodes is done implicitly through exchanged beacon or hello messages. All sensor nodes in the network are equal in terms of their functionality [11]. Several schemes may be found in the literature [21–28].
- The Backbone-based Approach (BA): In the BA approach, a backbone infrastructure is required to be set up and the power conservation application resides on the backbone sensor nodes. The power conservation applications can have better view of their local network environment.

With the BA approach, protocols may perform a coordination task for surrounding sensor nodes, such as synchronization of their sleeping schedules to ensure enough bandwidth and to function as a proxy for sleeping sensor nodes [11]. The main differences between the Distributed and the Backbone-based Approaches are summarized in Table 2.

SPAN [29] is a very common coarse-grain conservation scheme utilizing a backbone to facilitate routing. SPAN also modifies 802.11 ad-hoc power saving mode standard and uses it to lengthen the sleeping interval longer than one MAC transmission frame and to reduce the chance of packet loss and delay [11].

Active Power Conservation Mechanisms (APCMs) — APCMs decrease the energy consumption of a sensor node counting on the concept of improving the node's operation (instead of turning-off the radio interface module into the power-save mode) [11].

According to the classification scheme, APCMs can be performed at different protocol layers: Physical, MAC, Network and Transport layer.

MAC Layer — One indicated approach to adaptively adjust the transmission power to an appropriate level for generating signal strength, just enough to reach the next hop destination, is to control the power consumption rate of a sensor node and thus to reduce the collision probability. A MAC layer approach, for decreasing the chance of collision and thus resulting in the reduction of energy consumption, used in retransmission, is proposed in [11].

Network Layer — Two basic power-saving schemes are employed at the network layer: Power-Aware Routing and Maximum Lifetime Routing.

- Power-Aware Routing (PAR): A representable selected scheme for power-aware routing in wireless packet networks is proposed by J. Gomez *et al.* [11, 30]. According to this scheme, routing protocols are designed in such a way as to find a route that consumes the least possible power.
- Maximum Lifetime Routing (MLR): In contrast to the PAR scheme, Maximum Lifetime Routing balances energy dissipation among sensor nodes to prolong the operational lifetime of the network. In addition, several ad-hoc routing protocols are based on the mechanism of creating a virtual infrastructure over a flat network to reduce the number of nodes involved in routing which results in better power utilization [11]. A typical lifetime ad-hoc routing protocol is presented in [31]. The utilized techniques and drawbacks of power-aware routing and maximum lifetime routing are shown in Table 3.

Transport Layer — Transmission Control Protocol (TCP), in its original form, was not designed to be a power-aware protocol, but to reduce the retransmissions in a network [32]. ATCP and TCP-Probing [33] can alter TCP's retransmission behavior by reducing unnecessary retransmissions to the mini-

Network layer: Power-saving schemes	Utilized technique for consuming less power	Drawbacks
Power-Aware Routing	Routing protocols find the appropriate route	Decreased sensor node lifetime if in minimum power path of several flows
Maximum Lifetime Routing	Balanced energy dissipation among sensor nodes	Poor power utilization if the number of sensor nodes is not decreased to a minimum

■ Table 3. *Utilized techniques and drawbacks of power-aware routing and maximum lifetime routing.*

Power Conservation Mechanisms (PCM)	Utilized technique	Layers applied to
Passive	Turning-off radio	all
Active	Smart utilization of energy-efficient network protocols	all

■ Table 4. *Main features of power conservation mechanisms.*

mum possible achieving lower power consumption and higher throughput [11]. An experimental study, that efficiently utilizes wireless station's energy to improve TCP performance, is proposed by S. Agrawal *et al.* [34]. The main features of power conservation mechanisms are summarized in Table 4.

Passive Power Conservation Mechanisms

A thorough study and analysis of the most outstanding passive power control protocols in WSNs is presented in this chapter. The study is based on the previous mentioned classification of the power management mechanisms and it is concentrated only on sleep/awake mode.

Physical Layer Protocols

The application of turn-off techniques can produce substantial energy savings in idle system states; however, additional energy savings are possible through the optimization of the sensor node's performance in the active state. If it is considered that peak performance is not always required, then, significant energy savings can be accomplished without affecting the peak performance in processors. The processor must be tuned in such a way, as to deliver the required throughput to avoid idle cycles. This implies the dynamic adaptation of the processor's operating voltage and frequency based on instantaneous processing requirements. The use of a Variable Speed Processor (VSP) is one of the most promising methods to reduce power consumption [10].

Dynamic Voltage Scheduling (DVS) — Dynamic Voltage Scheduling is the first power control protocol examined, which refers mainly to the variable-speed processor of the physical layer. It is an effective mechanism for reducing the CPU energy to the minimum and thus achieving the requirements as described in [3, 16–19]. It is a method which assigns a supply voltage for each task of the processor to utilize the slack time [10].

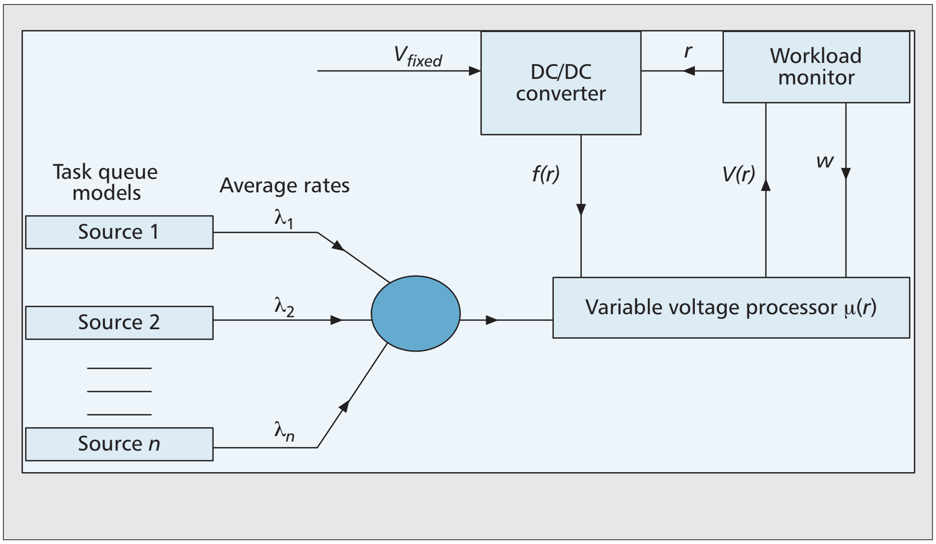
According to this protocol, the reduction of the operating frequency, during periods of reduced activity, results in linear decreases of the power consumption without affecting the total energy consumed per processing task. The reduction of the operational voltage implies greater critical path delays, resulting in a continuous effort to compromise the peak performance [10]. Thus, the main idea behind DVS is to allow devices, like Voltage Speed Processors (VSPs), to dynamically change their speed by varying the operating frequency along with the power supply to match the workload without degrading the required performance [10]. The reduction of the power consumption of a VSP can be achieved by exploiting the idle intervals of the processor. This allows the processor to provide the minimum required clock frequency with the maximum possible energy efficiency. To achieve this, DVS requires algorithms, termed Voltage Schedulers (VSs), to determine the operating speed of the processor at run-time. The implementation of DVS, for a general-purpose microprocessor, requires substantial software support and new metrics to fully realize and understand the advantages of this capability.

More specifically; a time-varying computational load characterizes most microprocessor systems. However, the hard part of the problem lies in the fact that future workloads are often non-deterministic. Therefore, the efficiency of the microprocessor depends on the prediction of the future workloads. The rate at which DVS is done must be taken seriously into account, because it has an important bearing on energy and performance. A low update rate implies greater workload averaging, which results in lower energy. The update performance and energy cost is also amortized over a longer time frame. A low update rate also implies a greater performance success since the system will not respond to a sudden increase in workload. The block diagram of a DVS processor system is shown in Fig. 4.

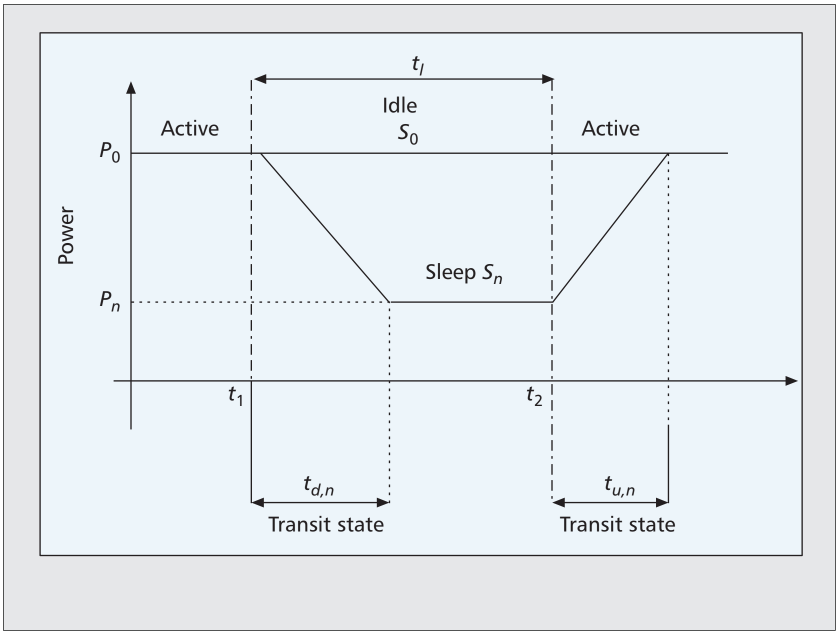
The task queue models are the different events of a processor, like, inputs/outputs, disk drives, network links, etc. Each of the n sources produces events at an average rate λ_k (where $k = 1, 2, 3, \ldots n$). An Operating System (OS) scheduler not only manages tasks but also decides which event should run on the processor with average rate l. This rate is equal to the sum of n average arrival rates. The processor offers a time-varying processing rate $\mu(r)$.

The kernel of the operating system measures the idle cycles and computes the normalized workload during the observed period. Workload monitor sets processing rate r based on workload w and previous workloads during an observation period. The processing rate r decides about the operating voltage $V(r)$ and the operating frequency $f(r)$. Therefore it acts as a closed-loop control system [16–19]. Experimental results, concerning the following techniques:

• No VS technique with power-down [16]



■ **Figure 4.** *Block diagram of a DVS processor system.*



■ **Figure 5.** *State transition latency and power.*

- The intra-task timeslot VS technique [17, 18]
- The proposed buffering VS technique [16, 17]
- The proposed technique with multiple subtasks (for both of best and average execution time assumptions) [16–18] show that the proposed technique achieves the most energy saving up to 80 percent

Dynamic Power Management (DPM) in Wireless Sensor Networks — Dynamic Power Management (DPM) in WSNs, proposed by A. Sinha and A. Chandrakasan [19], is another physical layer operating-system-directed power management technique, contributing to a dynamic increase of the lifetime of the sensor node. Once the system has been designed, additional power savings can be obtained by using dynamic power management.

DPM is an effective mechanism for reducing system power consumption without significantly degrading performance. This model, which was actually based on the previously mentioned DVS [16–18, 35], deals with the switching of node state in a power efficient manner. The basic idea behind this protocol is to turn sensor node components (sensor with A/D converter, processor, memory and transceiver) off when it is not required (if no events occur) and get them back (wake them up) when it is necessary. Such event-driven power consumption is critical to achieving maximum battery life.

This power-saving method, at a first look, provides considerable energy gains, however, one should not overlook the fact that sensor nodes communicate with each other using short data packets. The shorter the data packets are, the more the consumption of start-up energy is. This is because the switching of a node, from one state to another, takes some finite time and resource. The sleep-state transitioning (Fig. 5) has the overhead of storing processor state and turning-off power. The awakening also takes a finite amount of time. Therefore, if one keeps turning the transceiver off during each idling slot, over a certain period of time, then one might end up consuming more energy than if the transceiver had been left on. So, the operation in a power-saving mode is energy-efficient only if the time spent in that mode is greater than a certain threshold. It is obvious that the implementation of the correct policy for sleep-state transitioning is critical for the success of DPM [1]. There can be a number of such useful modes of operation for the wireless sensor node and they actually depend on the number of states of the sensor node components. Each mode of operation can be characterized by its power consumption and latency overhead, which is the transition power to and from that mode.

The DPM scheme proposes five power-saving modes of operation (Table 5). The threshold time depends on the transition times. Thus, one has to be very careful when using DPM to accomplish maximum life of a sensor node. One may achieve good savings in power with this turning off of the sensor node; however, in many cases it may not be known a priori, when a particular device is required for the performance evaluation.

Consider the network studied by A. Sinha and A. Chandrakasan [19]. This network consists of n homogeneous sensor nodes distributed over a rectangular region. Each sensor node consists of N embedded components (the sensor and the A/D converter, the processor with memory and the transceiver) which can be in different sleep-states [19]. This model describes the power consumption in different levels of node's sleep-states. Each sensor node's sleep-state corresponds to a particular combination of component power modes. Therefore, a sensor node will have the sleep states shown in Table 5. Each sleep state is characterized by latency and power consumption. The deeper the sleep state, the lesser the power consumption, and more the latency. It can be seen in Table 5 that not all the combinations of the sensor node's states are useful. For example, if the processor is in idle state then the memory should be in the sleep state. This removes some combinations from the node states.

Assume $P_n(T_{th},0)$ as the probability that no events occur in the area covered by node n. The different states should be switched in order to achieve savings in power usage. State transition latency and power are depicted in Fig. 5.

Consider also that an event occurred at time T_1 and next event occurred at time $T_2 = T_1 + T_i$, where T_i is the idle time (Fig. 5). At T_1, node n wants to go into the sleep state n from active state S_0. Each state has a power consumption P_n, transition times $T_{d,n}$ and $T_{u,n}$.

The energy savings of the sensor node n is given then by:

Sleep States	Sensor with A/D converter	Processor	Memory	Transceiver (Radio)
S_0	On	Active	Active	T_x/R_x
S_1	On	Idle	Sleep	T_x
S_2	On	Sleep	Sleep	R_x
S_3	On	Sleep	Sleep	Off
S_4	Off	Sleep	Sleep	Off

■ Table 5. *Sensor node's sleep state.*

Proposed Scheme	Refers to the VSP of the physical layer	Reduces CPU energy	Algorithms and Protocols used
DVS	Yes	Yes	Algorithms, termed voltage schedulers, to determine the operating speed of the processor at run-time.
DPM	Yes	Yes	Energy-scalable algorithms and protocols for energy-constrained situations.

■ Table 6. *Main features of DVS and DPM — part I.*

$$E_{save,n} = P_{0,T_i} - \left(\frac{P_0 + P_n}{2}\right) \cdot (T_{d,n} + T_{u,n}) - P_n(T_i - T_{d,n}) \qquad (1)$$

where, P_0 is the probability that at least one event occurs at node 0, and P_0,T_i is the probability that at least one event occurs in interval T at node 0.

A transition is only useful when $E_{save,n} > 0$. This leads to the threshold value of the sensor node which is given by:

$$T_{T_{h,n}} = \frac{1}{2}\left[T_{d,n} + \left(\frac{P_0 + P_n}{P_0 - P_n}\right)T_{u,n}\right] \qquad (2)$$

The last Eq. 2 implies that the longer the delay overhead of the transition from S_0 to S_n, the higher the energy-gain threshold. Therefore, the more the difference between P_0 and P_n is, the smaller the threshold. Thus, the system puts the node into the sleep state S_n by testing the probability of an event occurring in the corresponding sleep time threshold $T_{th,n}$ against system defined $P_{th},_0$. Node n also updates $P_{th},_0$ after every event. All the states, as mentioned before, must be controlled by the operating system present in the node. From the results in [19] it is shown that in the case where there is no power management, there is uniform energy consumption at all the nodes. The use of a higher $P_{th},_0$ would result in frequent transitions to the sleep states. If events occur fast enough, this would produce a higher energy dissipation which is unavoidably associated with wake-up energy cost. On the other hand, a lower value of $P_{th},_0$ would result in an unacceptable scheme for sleep-state transition and therefore, in lesser energy savings.

The deficiency of this protocol is that it presents a finite and small window of inter-arrival rates λ_{tot} over which the fine-grained sleep-states can be used. Generally speaking, the greater the difference in their energy and latency overheads the wider the inter-arrival time range in which all sleep-states can be used. Thus, increased energy dissipation will be associated with wake-up energy cost [19].

Conclusively, both power-saving physical-layer protocols DVS and DPM refer to the variable-speed processor of the physical layer, achieving reduction in CPU energy as shown in Table 6. Moreover, DVS adapts the power supply voltage and operating frequency to the changes of the workload, while DPM uses an embedded micro-operating system to reduce sensor node energy consumption by exploiting both sleep state and active power management (Table 7).

Embedded Power Supply for Low-Power DSP — Most techniques to lower power consumption of Integrated Circuits (ICs) assume static behavior; in other words, circuit and system parameters are chosen at the designed time to minimize power dissipation. The number of operations performed per sample in many Digital Signal Processor (DSP) systems can be minimized dynamically by exploiting time-varying signal statistics.

"Embedded Power Supply for Low-Power DSP" (EPS) [35] analyzes the use of dynamically adjustable power supplies as a method to minimize power dissipation in DSP. Power-down techniques can be used to make power dissipation directly proportional to the computational workload per sample.

Thus, the basic idea is to lower power supply voltage and slow down the clock during reduced workload periods, instead of working at a fixed speed and idling. V. Gutnik and A. P. Chandrakasan [35] have shown that this scheme can yield a typical power savings of up to 30–50 percent. If latency can be tolerated, buffering data and averaging processing rate can yield power savings of an order of magnitude in some applications. The continuous variation of the supply voltage can be approximated by very crude quantization and dithering: A four-level controller is sufficient to get within a few percent of the optimal power savings. Significant savings are possible only if the voltage can be changed on the same time scale as the variations in workload.

Proposed Scheme	Based on	Basic Idea	Proposed Strategy/ Proposed Technique
DVS	Dynamic Voltage Scaling (DVS)	1. To *turn* sensor node components *OFF* when not needed (if no events occur) and get them back (wake them up) when necessary. 2. To *adapt* the power supply and operating frequency to the *changes* of the workload.	Future workload prediction on which the efficiency depends on.
DPM	Dynamic Voltage Scaling (DVS).	1. To *turn* sensor node components *OFF* when not needed (if no events occur) and get them back (wake them up) when necessary. 2. Using an embedded micro-operating system to reduce sensor node energy consumption by exploiting both sleep state and active power management.	A workload prediction based on adaptive filtering of the past workload profile and analysis of several filtering schemes.

■ Table 7. *Main features of DVS and DPM — part II.*

Symbol	Description
P_{tx}, P_{rx}	the power consumption of the transmitter/receiver (T_x, R_x.)
$T_{on\text{-}tx}$, $T_{on\text{-}rx}$	the transmit/receive on-tim (actual data transmission/reception time on T_x and R_x.
$T_{startup-tx}$, $T_{startup-rx}$	the startup time of the transceiver (T_x and R_x)
P_{out}	the output transmit power which drives the antenna
$E_{dsp}^{(e)}$	the encoding power
$E_{dsp}^{(d)}$	the decoding power

Table 8. *Symbols and description of the used quantities.*

Energy-Efficient System Partitioning for Distributed Wireless Sensor Networks (EESP) — Research [36] has shown recently that local computation of the sensor data at the sensor node level can be highly energy-efficient because redundant data transmission can be reduced. One of the best techniques proposed, at the chip level, is to exploit parallelism and voltage scaling [36]. The partitioning of the computation among multiple sensor nodes, as well as, the performing of the computation in parallel permits a greater control on latency. This results in energy consumption through voltage scaling and frequency scaling. The parallelization of the computation leads to the lowering of the voltage supply level and the clock frequency of the sensor nodes, which, in turn, reduces energy consumption. Therefore, the development of energy-efficient signal processing algorithms running at the level of the sensor nodes is of great importance. More specifically, one way to improve energy-efficiency is the collaboration between the sensor nodes throughout the wireless network [36]. Sensors located very closely to one another have highly correlated data. For the reduction of the redundant information in the wireless network, sensors are grouped in clusters and signal processing is done locally within the cluster. The sensor nodes are in the position of extracting the important and relevant information through signal processing, and thus reducing communication costs. Thus, it is important to design low-power signal processors for each node, while at the same time to consider energy-efficient system partitioning of the computation among the sensor nodes. Research results, as described in [36], show that energy reductions of up to 60 percent can be achieved in a source localization application, by parallelizing computation.

Energy-Efficient Link Layer for Wireless Micro-Sensor Networks (EELL) — In this section, energy-efficient techniques that adapt link and physical layer parameters, such as output transmit power and error control coding on system energy dissipation are examined [37]. Since the wireless communication cost, over long distances, can be high enough, the reduction of the energy required for communication to the minimum possible is of a great importance. In general, the minimum output transmit power required to transmit a signal over a distance d is proportional to d^n, where n is a variable derived from the experimentation and $2 \leq n \leq 4$. Reliable data transfer can be provided either by increasing the output transmit power (P_{out}) of the transceiver (radio), or by adding Forward Error Correction (FEC) to the data. The probability of bit error (P_b), for any fixed value of the output transmit power, can be decreased with the use of FEC. However, FEC will, at any rate, require additional processing and thus, additional energy at the receiver and transmitter, which is not desirable. The protocol in [36] attempts to reduce to the minimum the system energy, which is required to send data between a transmitter and receiver, by partitioning the energy between the output transmit power and the processing required by error-correction coding. The used wireless sensor node has the ability of scaling the energy consumption, of many different subcomponents, in response to changes in the environment, the state of the wireless network, and the application requirements. This way, maximization of the system lifetime and reduction of the energy consumption of the sensor node is ensured.

Thus, all layers of the system can adapt layer-specific parameters (e.g. error correction scheme) to minimize energy usage. The selected processor of the sensor node [37] was adapted to provide dynamic voltage scaling. The micro-Operating System (μ-OS) had been customized to allow software to scale the energy consumption of the processor. The on-board Phase-Locked Loop (PLL), transmitter and receiver were capable of being turned-off via energy software (or hardware) control for energy dissipation reduction. The encoding and decoding of error-correcting codes can be performed on different platforms. The energy consumed is directly measured instead of modeling the energy required for encoding and decoding the data. Reduction of the energy consumption can be achieved through the compromise on quality of the established link layer. This can be accomplishable by maintaining Bit Error Rate (BER) just below the user requirements.

The average energy consumption of radio communication can be modeled by:

$$E_{radio} = E_{tx} + E_{rx} \tag{3}$$

Where E_{tx}, and E_{rx} is the energy consumption of the transmitter/receiver, respectively.

The total energy cost of the communication can be derived by:

$$\begin{aligned} E &= P_{tx}(T_{on-tx} + T_{startup-tx}) + P_{out}T_{on-tx} \\ &\quad + E_{dsp}^{(e)}\, dP_{rx}(T_{on-rx} + T_{startup-rx}) + E_{dsp}^{(d)} \end{aligned} \tag{4}$$

The meaning of used expressions is indicated in Table 8.

From the Eq. 4, the average communication energy to transmit, receive, encode and decode each information bit may be calculated. As a conclusion, the use of this decoder can lower the decoding energy per information bit by up to five orders of magnitude. Thus, sensor data can be encoded using a convolutional code to allow for lower output transmitted power.

Fine Grain (FG) Protocols

The basic scheme, for low-energy consumption and at the same time for prolonging the battery lifetime of sensor nodes, is proposed in the IEEE MAC WLAN Specifications [13]. In the CSMA/CA protocol, Request-To-Send/Clear-To-Send (RTS/CTS) handshake packets are needed to reserve a transmission floor (a threshold) for the subsequent data packets. The handshake signaling should be used only for comparatively long data [13]. Sensor nodes transmit their control and data packets at a common maximum power level, preventing all potentially interfering sensor nodes from starting their own transmission. Only one transmission proceeds at a time, since all sensor nodes are within the carrier-sense range of each other. So, interfering nodes are not allowed to transmit concurrently. The protocol addresses the issue from a single-layer

Technique	Synchronized periodical sleep	Formation of virtual clusters	Message passing
purpose	No waste of energy when a neighboring node is transmitting to another node or by listening to an empty channel	Synchronization of the sensor node's wake-up and sleep period	Reduction of the contention latency
avoidance of	overhearing problem	–control packet overhead –inter-cluster communication problem	control overhead

■ Table 9. *Techniques used for energy reduction.*

perspective (which is inefficient). The IEEE 802.11 scheme uses the RTS/CTS packets to silence the neighboring nodes. The maximum power (P_{max}) is used to determine node connectivity. P_{max} is a fixed power level at which sensor nodes send their control (RTS/CTS) packets. This scheme allows the communication with any sensor node within the maximum range and, hence, produces higher progress toward the destination per hop. The transmitter-receiver distance may be smaller than the range determined by the maximum power. Therefore, sensor nodes using the IEEE 802.11 scheme waste more energy than necessary, by transmitting at a higher power level than required for communicating with their peer.

A large variety of low-energy consumption schemes for conventional WSNs have been proposed in the literature in order to improve the deficiencies of the IEEE 802.11 scheme [13].

Power-Aware Multi-Access Protocol with Signaling (PAMAS) for Ad-hoc Networks — PAMAS is a multi-access protocol for ad-hoc wireless networks [20]. It brought an improvement on energy savings (compared with the standardized IEEE 802.11 Distributed Coordination Function — DCF) [13] by trying to avoid overhearing among neighboring sensor nodes. It was built on the research protocol Multiple Access with Collision Avoidance Wireless (MACAW) [38]. Actually, it is a combination of the original Multiple Access with Collision Avoidance (MACA) [39] protocol and the idea of using a separate signaling channel [14, 40].

PAMAS main characteristic is that it requires two independent radio channels. In most cases, this indicates two independent radio systems on each sensor node. PAMAS does not attempt to reduce idle listening, which is a disadvantage comparing to sensor-MAC (S-MAC) [24], another very well-known protocol presented right in the next section. It saves sensor nodes' battery power by intelligently turning-off the sensor nodes which are not in active transmission or sending packets. In PAMAS protocol the receiving mobile sensor nodes transmit a busy tone (in a separate control channel), when they start receiving frames so that other mobile sensor nodes know when to turn off. When a mobile sensor node does not have data to transmit, it should power itself off if a neighbor begins transmitting to some other node. A sensor node should turn-off, even if it has data to transmit, if it perceives that at least one of its neighbor-pairs is communicating. A mobile sensor node, which has been turned-off when one or more of its neighbor-pairs started communicating, can determine the length of time that it should be turned-off by using a probe protocol. In this protocol, the sensor node performs a binary search to determine the time when the current transmission will end. However, the loss of probe frames may cause significant power wastage [20].

S. Singh, and C. Raghavendra [20] showed that power saving in the range from 10 percent (for sparsely connected sensor networks) to almost 70 percent (for fully connected sensor networks) could be achieved without affecting the delay or throughput characteristics of PAMAS.

Coarse-Grain Distributed Approach (CG-DA) Protocols

Sensor-MAC (S-MAC) — S-MAC protocol [24] gives the possibility to nodes to discover their neighbors and build sensor networks for communication without requiring the existence of master nodes in the network. Thus, there are no clusters or cluster heads in this protocol and the topology is flat. S-MAC focuses mainly on the major energy wastage sources, while achieving good scalability and collision avoidance capability. The major energy wastage sources may be classified into overhearing, idle listening, collisions and control packet overhead. All sensor nodes try to achieve a single common task (and do not require equal opportunity to transmit).

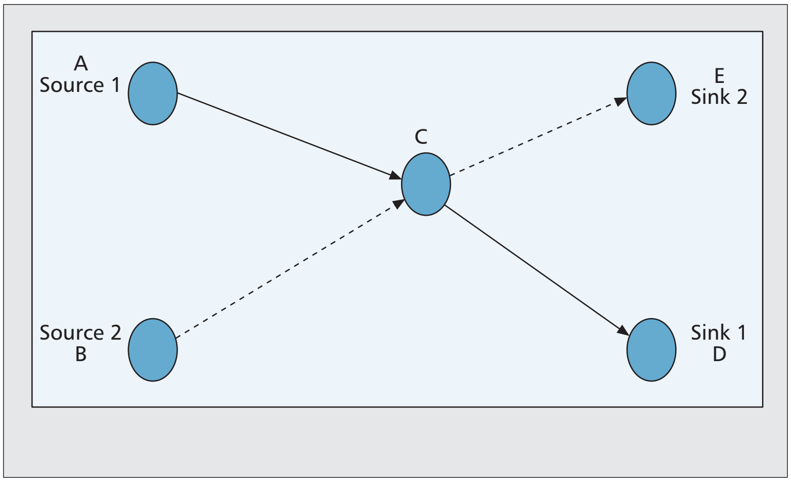
S-MAC consists of three basic components:

- *Periodic Listen and Sleep*: Neighboring nodes are synchronized in such a way as to *listen together and sleep together*. This way a heavy control overhead is avoided.
- *Collision and Overhearing Avoidance*: Collision is avoided through the adoption of a contention-based scheme. Overhearing can be avoided by letting the nodes, which get RTS and CTS packets (not meant for them), go to sleep.
- *Message Passing*: The indicated method here is the fragmentation of long messages into smaller messages and their transmission in a burst.

S-MAC introduces the following three techniques (Table 9), to achieve the reduction of energy consumption: Neighboring nodes are synchronized to go to sleep periodically, so that they do not waste energy when a neighboring node is transmitting to another node or by listening to an empty channel. The overhearing problem is avoided also this way. The control packet overhead of the network is kept low, because synchronized neighboring nodes form virtual clusters to synchronize their wake-up and sleep periods. Actually, there is no real clustering and no inter-cluster communication problem. Message passing is used to reduce the contention latency and control overhead.

The S-MAC protocol reveals very good energy conserving properties comparing with IEEE 802.11 protocol. The MAC layer can affect considerably the power management, thus, the S-MAC has an effect on the consumed energy, through the periodical switching of the two operational states of the sensor node (SLEEP/WAKE-UP mode). This way, the sensor node can save energy, since it does not have to work continually, but periodically, and only when it has to send some control or data packets. On the contrary, a sensor node, using the IEEE 802.11 protocol, is always active because it continually exchanges synchronization packets with its neighboring nodes and this implies the faster consumption of its energy [24]. Another interesting property of the protocol is that it has the ability to make trade-offs between energy and latency according to traffic conditions.

W. Ye, *et al.* [24] considered in their studies a two-hop network simulated topology with two sources and two sinks, as shown in Fig. 6. The topology is simple, but is sufficient enough to show the basic characteristics of the MAC proto-



■ **Figure 6.** *Two-hop network topology with two sources and two sinks (redrawn from [24]).*

cols.

According to results gained in [24], 802.11 MAC spends more than twice the energy used by S-MAC when the traffic is heavy. Moreover, energy savings from periodic sleeping is very limited since idle listening rarely happens. S-MAC achieves energy savings mainly by avoiding overhearing and efficiently transmitting a long message. The complete (with periodic sleep) S-MAC protocol has the best energy savings, and far outperforms 802.11 MAC, when the message inter-arrival period is larger than 4s (the traffic load becomes light).

Comparison between S-MAC and PAMAS — The comparison between S-MAC and PAMAS protocols leads to the following conclusions: S-MAC does not use any out-of-channel signaling, while PAMAS requires two independent radio channels and therefore, two independent radio (transmitter/receiver) systems on each sensor node. PAMAS does not make any attempt to reduce idle listening.

TDMA Scheduling for Energy Efficiency in Wireless Sensor Networks — TDMA scheduling is a very challenging approach for increasing energy efficiency in wireless sensor networks. TDMA scheduling scheme proposed by D. D. Vergados *et al.* [28] has been altered for energy efficiency in WSNs, taking advantage of the power conservation mechanism of the S-MAC protocol [24], and extends it in order to minimize the end-to-end delay [41, 42]. The main disadvantage of the S-MAC scheme is that each wireless sensor node must wait until the next WakeUP (WU) time of the next hop before forwarding a message. This makes the end-to-end delay proportional to the number of intermediate forwarders times the sleep time of each node [28]. On the contrary, in the scheme proposed by D. D. Vergados *et al.* [28], all nodes in the network are synchronized to sleep at the same time, and wake up at the WakeUP period. Instead of transmitting the entire message during the WakeUP period, the nodes transmit a short WakeUP packet, which is forwarded until it reaches the gateway. Nodes that receive the WakeUP packet remain in idle mode, anticipating the following packet reception, whereas nodes that do not receive a WakeUP packet go to sleep mode. Also, multiple WakeUP packets can be aggregated when two paths merge, in order to minimize the WakeUP duration and to avoid unnecessary transmissions. A further improvement to the scheme is not to let the transmitter of each node on for the entire WakeUP period, but only for the specific timeslots the node anticipates a reception.

The question that arises is which slot should each node use to transmit its WU messages (originated or forwarded) and at which slots should each node listen to. Path WakeUP requires that the first nodes in the path should be assigned in timeslots earlier than the nodes that follow. On the other hand, collisions can be avoided if nodes that receive simultaneously are not one-hop neighbors (TDMA — Time Division Multiple Access — does not suffer from the exposed terminal situation). Also, possible transmissions to the same destination should be assigned in different time slots. However, the scheduling algorithm should maximize the concurrent receptions made by nodes that are not one-hop neighbors, in order to minimize the total frame length. Therefore timeslots scheduling should take into account the routing paths and the neighboring information. These limitations make distributed TDMA scheduling schemes inefficient, since they do not take into account the desired order of transmissions. The following algorithm can create a TDMA schedule appropriate for WU transmissions in sensor networks.

The TDMA scheduling algorithm assigns a transmission slot for every node in the sensor network, and a number of reception slots for every forwarding node, one for each corresponding transmitting node. In order to calculate the TDMA schedule, the algorithm needs the following information for every node in the network:
- The number of hops from the node to the gateway
- The one-hop neighbors of the node
- The next hop of every node

Based on the above information, the number of time slots that each node has to receive prior to transmitting is calculated.
- *Performance Evaluation*: The performance of power-aware MAC protocols depends on many different parameters, such as the traffic arrival rates, the channel congestion, the topology of the sensor network, and the routing algorithms. Here we will quantify the power savings achieved by the proposed protocols, in various network and traffic conditions and compare it to other power saving approaches.

In general, the power consumption of a node in a sensor network can be approximated by:

$$P = P_{rob}\{SEND\}P_{send} + P_{rob}\{RECV\}P_{recv} + P_{rob}\{IDLE\}\,P_{idle} + P_{rob}\{SLEEP\}\,P_{sleep} \quad (5)$$

where $P_{rob}\{SEND\}$, $P_{rob}\ \{RECV\}$, $P_{rob}\{IDLE\}$, $P_{rob}\{SLEEP\}$ are the probabilities of the transmitter of the node being in SEND, RECV, IDLE and SLEEP state, and P_{send}, P_{recv}, P_{idle}, P_{sleep} are the amounts of power consumed when the node is in each state. In our analysis we consider that P_{sleep} is very small.

If a specific node in the network produces originating packets of average size L (in transmission time units) at a rate λ_O, and forwards packets through at a rate λ_T, then it must be in the SEND and RECV states with the following probabilities:

$$P_{rob}\{SEND\} = (\lambda_O + \lambda_T)L,\ P_{rob}\ \{RECV\} = \lambda_T L \quad (6)$$

If the node is never in the sleep mode when idle, then the $P_{rob}\{IDLE\}$ is given by:

$$P_{rob}\{IDLE\} = 1 - \lambda_O L - 2\lambda_T L. \quad (7)$$

The above probabilities are calculated without taking into account possible re-transmissions and without considering control packets, like ACK's, RTS's, CTS's etc. Moreover, they are accurate only when there is no congestion i.e., $\lambda_O L + 2\lambda_T L \ll 1$. Power efficiency in sensor networks that produce very little traffic under normal conditions is studied, so the above assumptions are close to reality. The power consumed by the node, if it never enters SLEEP mode, is given by:

$$P_{ALWAIS\_ON} = (\lambda_O + \lambda_T)L\, P_{send} + \lambda_T L\, P_{recv} + (1 - \lambda_O L - 2\lambda_T L)\, P_{idle} \tag{8}$$

The power consumption of the S-MAC protocol is given by:

$$P_{S\text{-}MAC} = (\lambda_O + \lambda_T)L\, P_{send} + \lambda_T L\, P_{recv} + (T_i/T_f)(1 - \lambda_O L - 2\lambda_T L)\, P_{idle} \tag{9}$$

where T_f is the period, and T_i is the wake up time.

The time a node spends in periodical wakeups is equal to $n(T_{slot}/T_f)$, where n is the number of timeslots the node can receive in, T_f is the period as above, and T_{slot} is the length of each TDMA time slot. The transmission and reception of the WU messages that happens prior to transmitting a data packet, is assumed to require much less energy than the data transmission and reception, and is ignored. But after the reception of a WU message, the node has to remain awake until the reception of the data packet. This waiting time, denoted L_{Wait}, can be approximated by the product of the number of nodes from the source of the packet until the examined node, times the data packet transmission time. In case the packet arrival rate is low, compared to the sleep-wakeup interval, the WU packets arrival is equal to the data packet arrival rate λ_O.

Taking the above into account, the power consumption of the TDMA algorithm is given by:

$$P_{TDMA} = (\lambda_O + \lambda_T)L\, P_{send} + 1_T L P_{recv} + n(T_{slot}/T_f)P_{idle} + L_{Wt} L_{Wait} P_{idle} \tag{10}$$

Power-efficient MAC protocols in wireless sensor networks have a negative effect on the system delay. The reason for this is that transmissions have to wait until the receiving node switches on its radio unit. The end-to-end delay, in a sensor network, is the sum of the transmission delay, the access delay, the queuing delay, and the propagation delay. When the packet arrival rate is relatively low, the queuing delay can be neglected, and the small distance between the wireless sensors makes the propagation delay small. In a multi-hop transmission with $(N - 1)$ intermediate forwarders, the average delay can be expressed by:

$$\mathrm{E}\{\mathrm{D(N)}\} = N(t_{cs} + \mathrm{L}) \tag{11}$$

where t_{cs} is the access time. The delay is proportional to the number of hops.

The delay in the S-MAC protocol is calculated in [24]. More specifically, the end-to-end delay is found to be equal to:

$$E\{D(N)\} = N\, T_f - T_f/2 + t_{cs} + L \tag{12}$$

while the end-to-end delay is equal to (13) when the "adaptive listening" technique is used.

$$E\{D(N)\} = N\, T_f/2 + 2t_{cs} + 2L - T_f/2 \tag{13}$$

In both cases, the end-to-end delay is proportional to the number of hops times the period T_f. This happens because the transmission at each hop is delayed until the next receiving node wakes up. "Adaptive listening" reduces the end-to-end delay, but only by a factor of 2.

The end-to-end delay in the algorithm presented in this article, is equal to the end-to-end delay of the Always-on case plus the delay introduced by power-saving. When a new packet is generated, the node must wait until the next TDMA frame. Then it transmits the Path-WU to wake-up all the nodes. Since the packet is generated randomly, the average time until the next frame is $T_f/2$. Thus, the delay is given by:

$$E\{D(N)\} = N(t_{cs} + L) + T_f/2 \tag{14}$$

The end-to-end delay increases with the achieved power conservation in all cases, and increases rapidly, in the S-MAC based schemes, as the number of intermediate nodes increase. The scheme [28] proposed by D. D. Vergados, provides much lower end-to-end delay times for messages sent from the sensor nodes to the gateway, in scenarios where numerous sensor nodes are used for sensing rare events for a long period of time.

Yu *et al.* [43] studied the problem of scheduling packet transmissions for data gathering in wireless sensor networks. They present algorithms in order to reduce the overall energy dissipation of the sensor nodes, in the aggregation tree subject, to the latency limitation. For the off-line problem, they propose, firstly, a numerical algorithm in order to find the optimal solution, and secondly, a pseudo-polynomial time approximation algorithm based on dynamic programming. They also discuss techniques for handling interference among the sensor nodes. The simulation results [43] show that considerable energy savings can be achieved compared with the classic shutdown techniques, under different settings of several key parameters. It is also demonstrated there, through several run time scenarios, the adaptability of the protocol with respect to variations in the packet size and latency constraint.

S. Cui *et al.* [44] propose a simple link scheduling algorithm to find the minimum-delay schedule that gives the slot lengths for all the links. Their next step is to combine the obtained results with their previous work concerning an energy-optimal cross-layer design in order to reduce to the minimum the delay in transferring a fixed number of bits from the source nodes to the sink, in an energy-limited manner. Moreover, they study the tradeoff between the total energy consumption and the delay.

Intra-Super-Frame Power Management for IEEE 802.15.3 WPAN (ISFPM) — IEEE 802.15.3 [26] has gained much research attention recently, since it is to enable a high-speed and low-power wireless connectivity among portable devices within a Wireless Personal Area Networks (WPAN). In particular, it may act as a MAC support for Ultra-WideBand (UWB). IEEE 802.15.3 MAC is mainly based on TDMA (Time Division Multiple Access). IEEE 802.15.3 MAC defines a wireless ad-hoc network (piconet) allowing a number of devices to communicate with each other in a peer-to-peer mode, as shown in Table 10. One of the devices is selected as piconet coordinator to perform the central controlling functions, (e.g., QoS, system timing, power management, etc.). Thus, power management is critical for the portable devices in IEEE 802.15.3 WPAN.

Due to the property of TDMA-based MAC of 802.15.3, one of the key issues for power management is to schedule the order of the multiple streams among multiple users to minimize the total wakeup times.

In this scheme, it is revealed that the power management problem is in general a Hamilton path problem. Using the graph theory, Z. Guo, *et al.* [26] define the lower bounds and upper bounds for minimum wakeup times. An efficient Minimum-Degree Searching (MDS) algorithm is proposed to find the suboptimal order. They showed that the proposed MDS algorithm is usually near-optimal (more than 95 percent) and

Type of communication	Type of MAC	Key issues to minimize the total wakeup times	Type of algorithm used to find the suboptimal order
peer-to-peer mode	TDMA-based MAC	Scheduling of the order of the multiple streams among multiple users.	Minimum-Degree Searching (MDS)

■ Table 10. *IEEE 802.15.3 MAC.*

can actually achieve the lower bound for the minimum wake-up times in most cases and outperforms the existing approach.

Joint Scheduling and Power Control for Wireless Ad-hoc Networks (JSPC) — A scheme for the energy reduction, and at the same time for prolonging the battery lifetime, is presented in [27]. More specifically, a cross-layer design framework is introduced to the multiple access problems in contention-based wireless ad-hoc sensor networks. The motivation for this study is twofold: limiting multi-user interference to increase single-hop throughput and reducing power consumption to prolong battery life. The multiple-access problem is solved via two alternating phases, namely scheduling and power control. The scheduling algorithm is essential to coordinate the transmission of independent users in order to eliminate strong levels of interference. On the other hand, power control is executed in a distributed fashion to determine the admissible power vector that can be used by the scheduled users to satisfy their single-hop transmission requirements. This is done for two types of networks, namely Time-Division Multiple Access (TDMA) and TDMA/CDMA (Code-Division Multiple Access) wireless ad-hoc networks.

The proposed "Joint Scheduling and Power Control Algorithm" [27] is executed at the beginning of each time slot in order to cope with excessive interference levels that might be developed in some slots. This algorithm determines the admissible set of users that can safely transmit in the current slot without disrupting each other's transmission. Thus, the objective is twofold: first, to determine the set of users who can attempt transmission simultaneously in a given slot and second to specify the set of powers needed in order to satisfy Signal to Interference Noise Ratio (SINR) constraints at their respective receivers. This is done via two alternating phases, namely scheduling and power control. Also, the key observation that led to the development of the proposed two-phase solution is double: firstly, examining the "validity" constraints of a given transmission scenario is much easier and computationally more efficient than examining the "admissibility" conditions. Secondly, eliminating strong levels of interference in the scheduling phase is essential since they cannot be overcome by power control alone. In addition, the employment of a scheduling algorithm makes the structure of the power control problem in wireless ad-hoc sensor networks exactly similar to the structure of the power control problem in cellular networks. This interesting observation has led to the applicability of existing power control algorithms to emerging wireless ad-hoc networks.

T. El Batt *et al.* [27] showed that distributed power control algorithms, introduced earlier for cellular networks, are directly applicable to emerging wireless sensor networks. It was shown that CDMA, on top of TDMA, improves the single-hop throughput and reduces transmission power consumption at the expense of excessive processing power. Thus, there is a trade-off between transmission power and processing power consumption that needs further investigation. Furthermore, it was shown that the performance of the optimum scheduling policies is compared to simple heuristic policies under light and heavy load conditions. The conclusion is that there is room for performance improvement via introducing distributed, heuristic, and fair scheduling policies within the proposed framework.

Geographical Adaptive Fidelity (GAF) — Geographical Adaptive Fidelity (GAF) or "Geography-Informed Energy Conservation for Ad-hoc Routing" [22] was first designed as a power-aware location-based routing algorithm for mobile ad-hoc networks. However, it was also proved to be applicable to wireless sensor networks.

GAF conserves energy by powering-off sensor nodes, not needed in the network, without affecting much the level of routing fidelity. Each sensor node uses its location information, which is gathered by means of the Global Positioning System (GPS), in order to connect itself with a point in the virtual grid. Sensor nodes connected to the same point on the grid are considered equivalent in terms of packet routing cost. One effective way to save energy is to keep some sensor nodes, located in a particular grid area, in sleeping state. Hence, GAF can effectively increase the sensor network's lifetime as the number of nodes augments. The sensor nodes' change of states, from sleeping to active, is accomplished in turn and in such a way that the load is balanced.

Three basic states are defined in GAF:
- *Discovery state*, for allocating the neighbors in the grid
- *Active state*, for hitting participation in routing
- *Sleep state*, when the radio transceiver is powered off

Each sensor node in the grid makes an estimation of its time that leaves the grid and informs its neighbors about its action. The sleeping neighbor sensor nodes adjust their sleeping time according to the information they received, as to keep the routing fidelity. The implementation of GAF is realized both for non-mobility and mobility sensor nodes.

Y. Xu, J. Heidemann, and D. Estrin [22], through analysis and simulation studies of GAF over unmodified AODV and DSR routing protocols, showed that it can consume 40 percent to 60 percent less energy than an unmodified ad-hoc routing protocol. Moreover, they suggest that sensor network lifetime increases proportionally to node density; for example, a four-time increase in node density leads to network lifetime increase for 3 to 6 times depending on the mobility pattern. Conclusively, this protocol performs at least as well as a normal ad-hoc routing protocol in terms of latency and packet loss and increases the lifetime of the network by saving energy. GAF may be considered as a hierarchical protocol, where the clusters are based on geographical position, although it is a power-aware location-based routing algorithm.

Energy-Efficient Communication Protocol for Wireless Micro-Sensor Networks (LEACH) — Wireless distributed micro-sensor networks have gained importance in a wide spectrum of civil and military applications. The analysis of the advantages and drawbacks of the Conventional Routing Protocols (CRP) proved that the protocols of direct transmission, minimum transmission-energy, multi-hop routing, and static clustering might not be optimal for wireless micro-sensor networks. For this reason, the Low Energy Adaptive Clustering Hierarchy (LEACH) protocol [25] was developed. LEACH is focused on communication protocols, which may have significant effect on the overall energy dissipation of these networks.

LEACH is a self-organizing, clustering-based protocol, which minimizes energy dissipation in wireless micro-sensor networks by using randomized rotation of the high-energy cluster-head position and in such a way as to rotate among the various sensors, in order to distribute the energy load evenly among the sensors in the network. This rotation allows the energy requirements of the system to be evenly distributed among all the sensor nodes in the network without draining the battery of a single sensor node. LEACH randomly selects some micro-sensor nodes as cluster-heads, so the high-energy dissipation in communicating with the base station is spread to all the sensor nodes in the micro-sensor network.

More specifically, in LEACH, the nodes organize themselves into local clusters, with one node acting as the local base-station or cluster-head. If the cluster-heads were chosen a priori and fixed throughout the system lifetime, as in conventional clustering algorithms, it is easy to see that the unlucky sensors, chosen to be cluster-heads, would die quickly, ending the useful lifetime of all the sensor nodes belonging to those clusters.

In addition, LEACH performs local data fusion to "compress" the amount of data being sent from the clusters to the base station, further reducing energy dissipation and enhancing system lifetime. Sensor nodes elect themselves to be local cluster-heads at any given time with a certain probability. Each sensor node determines to which cluster it wants to belong by choosing the cluster head that requires the minimum communication energy. Once all the nodes are organized into clusters, each cluster head creates a schedule for the nodes in its cluster. This allows the radio components of each non-cluster-head node to be turned-off at all times except during their transmit time, thus minimizing the energy dissipated in the individual sensors. Once the cluster-head has all the data from the nodes in its cluster, it aggregates the data and then transmits the compressed data to the base station. Since there are only a few cluster heads, this only affects a small number of nodes. Also, the decision to become a cluster head depends on the amount of energy left at the node.

The system can determine, a priori, the optimal number of clusters to have in the system, used on several parameters, such as the network topology and the relative costs of computation versus communication. It was found that there exists an optimal percent of nodes $\hat{N}$ that should be cluster heads. In a simple model, where the radio dissipates energy $E = 50$ nJ/bit to run the transmitter in a 100-node random network, there must be $\hat{N} = 5$ percent.

LEACH can achieve as much as a factor of 8 reductions in energy dissipation compared with direct communication and a factor of 4 to 8 reduction in energy compared with Minimum-Transmission-Energy (MTE) routing [25]. In addition to reducing energy dissipation, LEACH successfully distributes energy-usage among the nodes in the network such that the nodes die randomly and at essentially the same rate. With random death, there is no one section of the environment that is not being "sensed" as nodes die, as occurs in the other protocols.

Adaptive Energy-Conserving Routing (AdECoR) for Multi-hop Ad-Hoc Networks — Adaptive Energy-Conserving Routing (AdECoR) for multi-hop ad-hoc networks [23] proposes two algorithms for routing in energy-constrained ad-hoc wireless networks. Nodes running these algorithms can trade-off energy dissipation and data delivery quality according to application requirements. The proposed algorithms work above existing on-demand ad-hoc routing protocols, such as AODV and DSR, without modification to the underlying routing protocols. Here are the two primary contributions of this scheme:

- *First Contribution*: "Algorithms that turn off the radio to improve power consumption with the involvement of application-level information" [23]. Here, the cost of turning-off the radio is added latency and possibly more packet loss, compared to unmodified protocols. Therefore, the energy-saving algorithm was designed to find a trade-off between energy conservation and data delivery quality.
- *Second Contribution*: "The use of node deployment density to adaptively adjust routing fidelity" [23]. This is based on the following observation: In ad-hoc networks, where the nodes are densely deployed with overlapping coverage areas, (which means that many can hear each other), some nodes are interchangeable for routing purposes. It is shown [23], how to use the application-level information to further increase node duty cycles and to extend the lifetime of the network as a whole.

Y. Xu *et al.* [23] have shown the following results: The two proposed energy-saving algorithms consume as little as 50 percent of the energy of an unmodified ad-hoc routing protocol over the same duration. In networks with a fixed energy budget, typical networks all run out of power at the same time, while these adaptive fidelity approaches keep half of the network alive 50 percent longer, and some nodes alive twice as long.

Comparison between AdECoR and PAMAS — As it was presented earlier PAMAS proposes a MAC protocol that conserves energy by turning-off radios to avoid overhearing cross-traffic.

AdECoR employs information from layers that lie above the MAC layer in order to control radio power (The Application-or-Routing Layers provide better information concerning the time where the radio is not needed). AdECoR is able to turn-off the radio for much longer periods (not only by using information at the routing and application layers) by lengthening sleep intervals, since nodes are interchangeable for routing purposes. This technique accomplishes the reduction of the substantial energy dissipated during the idle state.

Application-Driven Power Management for Mobile Communication (ADPM) — Application-Driven Power Management (ADPM) for mobile communication [21] is an innovative transport level protocol capable of significantly reducing the power usage of the communication device. It provides mechanisms for managing and reducing the power consumption of the communication device. This protocol achieves power savings by selectively choosing short periods of time to suspend communication and turn-off the communication devices. It manages the important task of queuing data for future delivery during periods of communication suspension, and decides when to restart communication. The trade-off between reducing power consumption and reducing delay for incoming data is also presented in the protocol. R. Kravets and P. Krishnam [21] showed up to 83 percent savings in the energy consumed by the communication. The resulting delay is small (0.4s to 3.1s) depending on the power management level.

Coarse-Grain — Backbone-based Approach (CG-BBA) Protocols

An Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad-Hoc Wireless Sensor Networks (SPAN) — SPAN [29] is a power-saving technique for multi-hop ad-hoc wireless networks. It reduces energy consumption without significantly diminishing the capacity or connectivity of the network. It is a very common coarse-grain conservation scheme utilizing a backbone to facilitate routing. It also modifies the 802.11 ad-hoc power-saving mode and uses it to lengthen the sleeping interval (longer than one MAC transmission frame), and to reduce the chance of packet loss and delay. It is mainly based on the following observation: "When a region of a shared-channel wireless network has a sufficient density of nodes, only a small number of them need to be ON at any time to forward traffic for active connections."

SPAN is a distributed, randomized algorithm where all nodes make local decisions on whether to sleep, or to join a forwarding backbone as a coordinator. Each node bases its decision on an estimation of how many of its neighbors will benefit from it if it is awake and the amount of energy available to it. Due to SPAN, the system's lifetime increases as the ratio of idle-to-sleep energy consumption increases, and as the density of the network increases.

B. Chen *et al.* showed that SPAN improves communication, latency, capacity, and system's lifetime, when run in conjunction with the 802.11 power-saving mode.

Comparison between SPAN and GAF — GAF [22] has similar goals to those of SPAN. In GAF, nodes use geographical location information to divide the world into fixed square grids. The size of each grid stays constant regardless of node density. Nodes within a grid switch between sleeping and listening, with the guarantee that one node in each grid stays up to route packets.

However, SPAN differs from GAF in two points:

- Unlike GAF, SPAN does not require that nodes know their geographical positions. Instead, SPAN uses broadcast messages to discover and react to changes in the network topology.
- SPAN integrates nicely with 802.11 power-saving mode: "Non-coordinator nodes can still receive packets when operating in power-saving mode."

Comparison between SPAN and PAMAS — The PAMAS [20] protocol turns off a node's transceiver when the node is overhearing a packet which is not addressed to it. This approach is suitable for transceivers where the processing of a received packet is expensive compared to listening to an idle radio medium.

SPAN assumes the presence of an ad-hoc polling mechanism such as that provided by 802.11, and could potentially work in concert with application hints. Such hints would apply only to sleeping nodes, not to coordinators.

Comparison between SPAN and Adaptive Energy-Conserving Routing for Multi-hop Ad-Hoc Networks (AdECoR) — In AdECoR [23], each node has a counter that counts the number of nodes within radio range, obtained by listening to transmissions on the channel. A node switches between sleeping and listening, with randomized sleep times proportional to the number of nearby nodes. The net effect is that the number of listening nodes is roughly constant, regardless of node density; more energy can be saved as the density increases.

AdECoR's constants are chosen so that there is a high probability that the listening nodes will form a connected graph, so that ad-hoc forwarding works. An AdECoR node does not know whether it is required to listen in order to maintain connectivity, so to be conservative. AdECoR tends to make nodes listen even when they could be asleep.

SPAN differs from AdECoR, in the following points:

- SPAN never keeps a node awake unless it is absolutely essential for connecting two of its neighbors.
- SPAN explicitly attempts to preserve the same overall system capacity as the underlying network where all nodes are awake, which ensures that no increase in congestion occurs.

Comparison between "SPAN" and "Application-Driven Power Management for Mobile Communication" — "Application-Driven Power Management for Mobile Communication" [21] is a system in which mobile units wake up periodically and poll a base station for newly arrived packets.

SPAN assumes the presence of an ad-hoc polling mechanism such as that provided by 802.11, and could potentially work in concert with application hints. Such hints would apply only to sleeping nodes, not coordinators.

Active Power Conservation Mechanisms

A study and analysis of the most outstanding active power control protocols in WSNs is made in this section. The study is based on the previous mentioned classification of the Power Conservation Mechanisms (PCM) (Section II B) and is concentrated only on power-aware routing protocols.

MAC Layer Protocols

Multiple-Access with Collision Avoidance (MACA) — The Multiple Access with Collision Avoidance (MACA) protocol [39] was one of the first channel-access protocols developed for wireless networks. It was proposed to give a solution to the hidden node and the exposed node problems and moreover to provide the ability to perform transmission power control per frame. MACA does not use carrier sensing. In MACA, a three-layer handshake RTS/CTS/DATA is adopted. It is based on the RTS/CTS exchange. A source station transmits an RTS frame to the destination station for request of transmission. If the destination receives the RTS frame in a correct manner, then it will receive the transmission by sending back a CTS frame. When a mobile node overhears some RTS/CTS frames corresponding to transmissions in other nodes, it is not necessary to remain completely silent. It can communicate with other neighboring nodes with lower transmission power [12]. Moreover, stations that hear the RTS or CTS frames are required to make a new scheduling of their transmissions at a later time in order to prevent frame collisions. The recovery of collisions is then left up to the transport layer thus, greatly decreasing throughput [45] and therefore power consumption.

Multiple-Access with Collision Avoidance Wireless — The Multiple-Access with Collision Avoidance Wireless (MACAW) protocol [38] is another derivative of the CSMA/CA protocol which makes use of the RTS/CTS/DS/DATA/ACK handshake signaling. It is a modified version of MACA protocol where link layer acknowledgements (ACKs) have been added. According to this protocol, a sender has the possibility of retransmitting a packet which was not successfully received by the receiver. This acknowledgement scheme improves the reliability of a wireless link, and avoids the long recovery cost at the upper transport layer, and thus consuming less energy in transmitting a packet.

Floor Acquisition Multiple Access — The Floor Acquisition Multiple Access (FAMA) protocol [41], like MACA, employs RTS/CTS/DATA handshake signaling. It proposes that a station must acquire a channel before the transmission of data. One of the ways to acquire the channel is by means of

Approaches	Throughput/delay	Fairness	Energy efficiency
MACA	+ + +	0	+
MACAW	+ + +	0	+
FAMA	+	+	0
PAMAS	–	0	+ +

"+" or "–" denote "improvement/falloff (degradation)" in the corresponding performance metric, while 0 denotes "no effect" [12].

Table 11. *Performance comparison among different protocols.*

RTS/CTS exchange. The IEEE 802.11 standard for wireless LANs includes the collision avoidance of MACA and MACAW. Moreover, all directed traffic uses positive ACKs (as in MACAW). PAMAS was actually based on MACA, MACAW and FAMA protocols in order to improve power consumption.

The performance comparison, among the PAMAS, MACA, MACAW and Floor Acquisition Multiple Access (FAMA) [41] protocols, reveals that PAMAS is more energy-efficient than the rest of the protocols but it falls short as far as the throughput and delay concerns, as shown in Table 11.

Intelligent Medium Access for Mobile Ad-hoc Networks with Busy Tones and Power Control — Intelligent Medium Access (IMA) for mobile ad-hoc networks with busy tones and power control is another scheme for saving power proposed by S. L. Wu *et al.* [46]. It is a combination of the concept of power control with the RTS/CTS-based and busy-tone-based protocols to further increase channel utilization. An effort was made to bring the concept of power control into the medium access problem in a MANET [14, 40].

The main idea is to use the exchange RTS and CTS packets between two intending communicators to determine their relative distance. This information is then utilized to limit the power level on which a mobile host transmits its data packets. The use of lower power can increase channel reuse, and thus channel utilization. It also saves the valuable battery energy of wireless mobile/or immobile sensor nodes and reduces co-channel interference with the other neighbors. With Dual Busy Tone Multiple Access (DBTMA) [14, 40] it is possible to use busy tones to save power. According to the DBTMA protocol, the single common channel is split into two sub-channels: a data channel and a control channel. The control channel is to transmit RTS/CTS dialogues. All the effort was made to show the way to optimize the DBTMA protocol with power control. The use of smaller transmission power may increase channel reuse on a physical area. The main idea here is to tune properly each transmitter's power level, so all communication pairs can co-exist without any interference. Power control is incorporated into the original protocol. This protocol follows the following rules:

- Data packets and Transmission Busy Tone (Btt) are transmitted with power control that is based on the power level of the received CTS.
- CTS and receiver Busy Tone (Btr) are transmitted at the largest power level, and RTS is transmitted of a power level to be determined based on how strong the Btr tones are around the requesting host.

For the performance evaluation a comparison was made with the DBTMA protocol. The analysis was made only for two communication pairs. Extending to more communication pairs would be difficult, if not possible. In practice, the levels of power, provided by the physical layer, may not be infinitely tunable. A more realistic assumption is that only a certain number of discrete power levels are offered. The target is to try to answer the question: Given a fixed integer k, how do k power levels are determined to maximize channel utilization? J. Deng and Z. J. Hass [40] have shown that the best choice is to evenly spread the k power levels.

A Power Controlled Multiple-Access Protocol for Wireless Packet Networks (PCMA) — The Power Controlled Multiple-Access (PCMA) protocol for wireless packet networks [47] achieves power controlled transmission, while still presenting the collision avoidance property of multiple-access protocols. It is focused on wireless ad-hoc multiple-access networks, where all sensor nodes share a single channel and there is no centralized control or access and power control, for increasing channel efficiency rather than increasing the battery life. The goal of the PCMA protocol is to evaluate the performance of MAC protocols by achieving power controlled multiple access within the framework of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) base multiple access protocols. The PCMA algorithm has one-to-one analogs of the key components of standard CSMA/CA protocols [39]. At the sender side, monitoring the busy tone is equivalent to sensing the carrier. At the receiver side, pulsing periodically the busy tone is equivalent to sending CTS for collision avoidance.

Assuming the same gain in both directions, the transmission power for the Acceptable-Power-To-Send (APTS) packet is computed to be:

$$Pt_j = \max\left\langle \frac{RX\_Des}{G_{ij}}, \frac{SIR\_Des \cdot Pn\_S_i}{G_{ij}} \right\rangle \quad (15)$$

where, G^{ij} is the actual gain based on the sender power (advertised in the packet) and the receiver power, while *Pn Si* is the source noise power, (obtained from the air interface), placed in the packet.

The destination of the noise power is replaced here with that of the source, which was extracted from the Request-Power-To-Send (RPTS) packet. The throughput is normalized by the carrier sense range (i.e. 550 meters) and the slot time, such that the total number of arrivals and departures is divided by a scaling factor, *sf*, as follows:

$$sf = \frac{network\_area}{carrier\_range\_area} \frac{1}{data\_slot\_size} \quad (16)$$

J. Monks, *et al.* [47] have shown that the performance of the PCMA increases as the number of busy tone pulses increases [13] (approaching the performance of an Ideal Power Controlled — IPC protocol). The performance of the PCMA is also substantially better than that of the 802.11. Moreover, the throughput increases as the network becomes more clustered since a greater number of concurrent transmissions are possible and less sensor nodes compete within each cluster. PCMA shows improvements in aggregate channel utilization by more than a factor of 2 compared to the IEEE 802.11 protocol. The control and data packets must be transmitted with a fixed power [13]. However, from the view of channel reuse, the adjusting transmission for data has no consequence in terms of increasing channel reuse, and is equivalent to a "fixed power" MAC protocol.

The comparison between the 802.11 and PCMA protocols, made in [47], shows the following results: The 802.11 protocol has an equal probability of sending packets to destinations at any distance since the transmission power is not taken into account while contending. However, because of all the transmissions sent at a fixed power level, there is less noise protection for destinations further from their sources resulting in a great number of lost packets at greater network loads. PCMA, on the other hand, has the same amount of protection for destination at all ranges. The main idea here is to increase the range distributions, while still limiting simultaneously the transmission ranges to the same distance. This is the way to improve the fairness for power controlled multiple access protocols. For dense networks, with a spatial reuse to be exploited, PCMA performs significantly better than the 802.11 protocol.

Power Adaptation for Starvation Avoidance to Deliver Wireless Multimedia (PASA) — A scheme for the energy reduction and at the same time for prolonging the battery lifetime of a sensor node is proposed by an effective distributed power adaptation algorithm termed "Power Adaptation for Starvation Avoidance" (PASA) [48]. It is a simple, effective and autonomous algorithm without control message overhead. Despite the collision avoidance mechanisms developed in recent years in wireless ad-hoc networks, the IEEE 802.11 cannot eliminate collisions completely, which may lead to channel capture phenomenon, where the common channel is monopolized by a single or a few nodes [49, 50]. Capture leads to starvation in some nodes, and thus degrading the network fairness and throughput.

PASA dynamically adjusts the transmission power in each sensor node to break capture and achieve higher spatial reuse, hence, providing to all the sensor nodes fair access to the transmission channel, while most of the various previously proposed protocols focus on modifying the MAC protocol. [51]. The main idea of this scheme is to adjust the transmission power in each sensor node according to its current condition so that all the mobile nodes in the network can share the medium channel more efficiently.

PASA has the following properties:
- It is a control mechanism without control message overhead. It does not require any change in MAC or protocol in other layers.
- Every node in the network adapts its power level independently.
- It is able to resolve starvation in many channel capture scenarios and to be implementable independent of the underlying MAC protocols. It is also applicable in Non-Line-of-Sight (NLOS) wireless systems with fixed antennas or base stations.
- It is fair because it can achieve better short-term fairness in channel sharing among the nodes.

J. Chen *et al.* [48] show that PASA can efficiently break starvation and, hence, achieve substantially better fairness without compromising throughput. It is self-adjustable in nature and the sensor node would adjust its power continuously and dynamically so as to find the minimum power. The simulation traces confirm that the power of a sensor node would not reach a level far below the minimum. After adopting the dynamic power control scheme, the two sources share the channel much more fairly. Such fairness is achieved by the power adjustment according to the status of each node. It is, also, shown that the start-up delay with PASA is much lower than that without using it.

Network Layer Power-Aware Routing Protocols

The five power-aware metrics for determining routes in ad-hoc wireless networks, are based on battery consumption at sensor nodes, and are listed below [52]:
- *Minimization of the consumed energy per packet*. The goal of this metric is to minimize the energy which is consumed per packet. Its serious drawback is that some sensor nodes will present enormously different energy consumption profiles resulting in early death of some sensor nodes.
- *Maximization of time to network partition*. It is very useful in critical applications such as battlefield sensor networks. Its main drawback is that it can not provide simultaneously low delay and high throughput.
- *Minimization of variance in sensor node power levels*. The idea of this metric is that all sensor nodes in the network are of the same importance. This metric ensures that all the sensor nodes in the network remain alive and run together for as long as possible.
- *Minimization of the cost per packet*. The goal is to minimize the cost per packet. The selected paths should be such that sensor nodes with depleted energy reserves do not lie on many different paths.
- *Minimization of the maximum sensor node cost*. The minimization of the cost per node definitely reduces the minimum sensor node cost.

These new metrics can be used in most traditional routing protocols for ad-hoc wireless sensor networks.

Power-Aware Routing in Mobile Ad-Hoc Networks — Power-Aware Routing (PAR) protocol in mobile ad-hoc networks [52] uses the above mentioned five new power-aware metrics for determining routes in ad-hoc wireless networks. The ultimate goal is to develop strategies for reducing the energy consumption of the communication subsystem and thus to increase the lifetime of the sensor nodes.

The present scheme has focused on designing protocols that increase the life of nodes and the network. Each layer (MAC, Network, and Transport) has been attacked individually. S. Singh *et al.* [52] have shown that the presented MAC layer protocol, used in ad-hoc wireless networks, reduces energy consumption by 40 percent up to 70 percent for different load and network conditions. As far as the network layer protocol concerns, it is best to route packets through nodes that have sufficient remaining power (rather than through a node whose battery is low). Similarly, routing packets through lightly-loaded nodes is also energy-conserving because the energy consumed in contention is minimized. Conclusively, power-aware routing (built on top of MAC protocol) can save overall energy consumption in the network and, simultaneously, increase battery life at all sensor nodes.

Energy Aware Routing for Low Energy Ad-hoc Sensor Networks — Energy Aware Routing (EAR) for low energy ad-hoc sensor networks [53] is another routing protocol that achieves an increase of the lifetime of the wireless sensor network. R. Shah *et al.* [53] proposed to use a set of sub-optimal paths occasionally to increase the lifetime of the network. These paths are chosen by means of a probability function, which depends on the energy consumption of each path. Network survivability is the main metric that the approach is concerned with. The approach argues that using the minimum energy path all the time will deplete the energy of nodes on that path. Instead, one of the multiple paths is used with a certain probability so that the whole network lifetime increases. The protocol assumes that each sensor node is addressable through a class-based addressing, which includes the location and types of the nodes. In this protocol, there are three phases:

1 *Setup phase*: Localized flooding occurs to find the routes and create the routing tables. While doing this, the total energy cost is calculated in each sensor node. For, instance, if the request is sent from node N_i to node N_j, then the N_j calculates the cost of the path as follows:

$$C_{N_j,N_i} = Cost(N_i) + Metric(N_j,N_i) \tag{17}$$

Here, the energy metric used captures transmission and reception costs along with the remaining energy of the sensor nodes. Paths that have a very high cost are discarded. The sensor node selection is done according to closeness of the destination. The sensor node assigns a probability to each of its neighbors in routing or Forwarding Table (FT) corresponding to the formed paths. The probability is inversely proportional to the cost, that is:

$$P_{N_j,N_i} = \frac{1/C_{N_j,N_i}}{\sum_{k \in FT_j} 1/C_{N_j,N_k}} \tag{18}$$

Then, N_j calculates the average cost for reaching the destination using the neighbors in the forwarding table (FT_j) using the formula:

$$Cost(N_j) = \sum_{i \in FT_j} P_{N_j,N_i} C_{N_j,N_i} \tag{19}$$

This average cost for N_j is set in the cost field of the request and forwarded.

2 *Data communication phase*: Each sensor node forwards the packet by randomly choosing a node from its forwarding table using the probabilities.

3 *Root maintenance phase*: Localized flooding is performed infrequently to keep all the paths alive.

The described approach is similar to Directed Diffusion (DD) in the way potential paths from data sources to the sink are discovered. In Directed Diffusion, data is sent through multiple paths, one of them being reinforced to send at higher rates. On the other hand, R. Shah *et al.* [53] select a single path randomly from the multiple alternatives in order to save energy. Therefore, when compared to Directed Diffusion, it provides an overall improvement of 21.5 percent energy saving and a 44 percent increase in sensor network lifetime. However, such single path usage hinders the ability of recovering from a sensor node or path failure as opposed to directed diffusion. In addition, the approach requires gathering the location information and setting up the addressing mechanism for the sensor nodes, which complicate route setup compared to directed diffusion.

Power Management for Throughput Enhancement in Wireless Ad-Hoc Networks — Power Management for Throughput Enhancement (PMTE) in wireless ad-hoc networks [54] attempts to improve the end-to-end network throughput and the average power consumption. More specifically: As the power gets higher, and the connectivity range increases, each node would reach almost all other nodes in a single hop. However, since higher powers cause a higher interference level, more collisions occur, and hence there will be more transmission attempts. By reducing the transmission power levels at each sensor node, such that the node can directly be connected to only a small subset of nodes in the network, the interference zones are considerably reduced. However, under this proposition, a packet has to be relayed by many intermediate nodes in order to reach the destination. Since there are a lot of transmissions, throughput may again degrade due to the increase in interference.

The scheme [54] presented by T. A. ElBatt *et al.* introduces the notion of power management within the context of wireless ad-hoc networks. The effects of using different transmit powers on the average power consumption and end-to-end network throughput in a wireless ad-hoc environment is investigated. This power management approach would help in reducing the system power consumption and hence prolonging the battery life of mobile nodes. Furthermore, it improves the end-to-end network throughput as compared to other ad-hoc networks in which all mobile nodes use the same transmit power. The improvement is due to:

- The achievement of a trade-off between minimizing interference ranges
- The reduction in the average number of hops to reach a destination
- The probability of having isolated clusters
- The average number of transmissions (including retransmissions due to collisions)

The main purpose of this scheme [54] is to investigate the impact of manipulating the Connectivity Range N for different network loads on the end-to-end network throughput and on the average power consumption. "No power adjustment within a cluster" and "Power adjustment within a cluster" approaches are considered. It is shown that the average node throughput decreases as the connectivity range N increases. When N increases, more sensor nodes compete for transmitting in the same time slot, and hence collisions are more probable. Therefore the average sensor node throughput decreases. Thus, according to results in [54], if $N > 10$, then the average sensor node throughput is approximately 0.3 (if there is no power adjustment within the cluster) or 0.48 (if there is power adjustment within the cluster). The average power consumption increases as the connectivity range N increases. Thus if $N = 15$, then the average power consumption is 100 percent (if there is no power adjustment within the cluster) or 35 (if there is power adjustment within the cluster). Conclusively, minimal power routing is used to further enhance performance.

A Distributed Transmission Power Control Protocol for Mobile Ad-hoc Networks (DTPC) — The Distributed Transmission Power Control (DTPC) protocol for mobile ad-hoc networks is proposed by A. Muqattash *et al.* in [55]. It is based on physical layer techniques to moderate the multi-path effect and this assumption will hold in modest fading channels. The main goal of this scheme is to reduce energy consumption, by producing power-efficient routes and build a power-efficient network topology. The algorithm of this protocol aims at producing power-efficient end-to-end routes while at the same time maintaining network connectivity and introducing as little overhead as possible. In the protocol designation, the following assumptions were taken into account: The channel gain is stationary for the duration of the control and the resultant data packet transmission periods. The gain between two sensor nodes is the same in both directions, and the data and control packets between a pair of sensor nodes present similar channel gains. In addition to the above assumptions, they assume that the radio interface can provide the MAC layer with the average power of a received control signal as well as the average interference power. In this scheme, collisions can be avoided if sensor nodes send their control (RTS/CTS) packets at a fixed power level (P_{max}), but send their data packets at an adjustable (lower) power level. This is the key issue to this protocol. Separate channels are needed for data and control packets to enable dynamic adjustment of the data packets transmission power. The control packets are transmitted at a power level P_{max} and are received by all potentially interfering nodes, as in the IEEE 802.11 standard. In contrast to the IEEE 802.11, interfering nodes may be allowed to transmit concurrently, depending on some criteria.

Unlike the IEEE 802.11 approach and the previously presented schemes, DTPC [55] does not use the RTS/CTS packets to silence the neighboring sensor nodes. Instead, collision avoidance information is inserted in the CTS packets and sent over an out-of-band control channel. This information is used to dynamically set a bound for the transmission power of potentially interfering sensor nodes in the vicinity of a receiver. A proper estimation of the required transmission power allows interference-limited simultaneous transmission to take place in the neighborhood of a receiver sensor node.

Upon receiving the RTS packet, the intended receiver, i.e. node I, uses the known P_{max} value and the power of the received signal $P^{(ji)}_{received}$ to estimate the channel gain between nodes i and j at that time. The channel gain is given by:

$$G_{ji} = \frac{P^{(ji)}_{received}}{P_{\max}} \tag{20}$$

Accordingly, node i will be able to correctly decode the data packet if this packet was transmitted at power $P^{(ji)}_{min}$ given by:

$$P^{(ji)}_{\min} = \frac{SNR_{th}(P_{thermal} + P^{i}_{MAI-current})}{G_{ji}} = \frac{SNR_{th}n^{i}}{G_{ji}} \tag{21}$$

where, SNR_{th} is the minimum Signal to Noise Ratio (SNR) that is needed to achieve the target bit error rate at that receiver, $P_{thermal}$ is the thermal noise power, $P^{(i)}_{MAI-current}$, is the current Multiple Access Interference (MAI). The $SNR(j)$ at node j is given by:

$$SNR^{(i)} = \frac{P^{(i)}_{j}}{P_{thermal} + P^{i}_{MAI-current} + P^{i}_{MAI-future}} \tag{22}$$

where, $P^{(i)}_{MAI-future}$ is the additional interference that node i can tolerate from future unintended transmission.

As the determination of the floor reserved for the sensor node's transmission is a MAC layer issue, the power control is introduced from the perspective of both layers. It is shown that a higher network throughput can be achieved by transmitting packets to the nearest neighbor in the forward progress directions. The halving of the transmission range [55, 56], increases the number of hops by two, but decreases the area of the reserved floor to one-fourth of its original value, allowing for more transmission in the neighborhood. In addition to improving network throughput, reducing of the transmission range implies the reduction of energy consumption.

Comparing the performance of this scheme and that of the IEEE 802.11 protocol, it is shown [55] that the present scheme can improve the channel utilization by up to 50 percent and the end-to-end throughput by over 45 percent (for random grid topologies). At the same DTPC provides more than 76 percent reduction in the energy consumed to successfully deliver a packet from the source destination. It also reduces the end-to-end packet delay. Thus it seems to be the first protocol that provides a comprehensive and efficient solution to the power control problem in Mobile Ad-hoc NETworks (MANETs).

Network Layer — Maximum Lifetime Routing (MLR) Protocols

Routing in Ad-hoc Networks using Minimum Connected Dominating Sets (RAN-MCDS) — RAN-MCDS [31] uses a virtual backbone structure in order to support unicast, multicast, and fault-tolerant routing within the wireless ad-hoc sensor network. This virtual backbone differs from the wired backbone of cellular networks in two ways: It may change as nodes move, and it is not used primarily for routing packets or flows, but only for computing and updating routes. The primary routes for packets and flows are still computed by a shortest-path computation. The virtual backbone can, if necessary, provide backup routes to handle temporary failures. Because of the dynamic nature of the virtual backbone, the present approach splits the routing problem into two levels: First, it finds and updates the virtual backbone, and then, it finds and updates the routes. The key contribution of this scheme is that it describes several alternatives for the first part of finding and updating the virtual backbone. To keep the virtual backbone as small as possible, an approximation to the Minimum Connected Dominating Set (MCDS) of the ad-hoc network topology as the virtual backbone is used. Therefore this MCDS routing algorithm provides shortest paths for routes and updates routes quickly after node movement. The presented variations of this MCDS approximation algorithm exploit special cases of bounded degree graphs.

Energy Efficient Broadcast Routing (EEBR) in Static Ad-hoc Wireless Networks — Another scheme that prolongs the battery lifetime is the one that faces the problem of broadcast routing in ad-hoc wireless sensor networks termed "Energy efficient broadcast routing in static ad-hoc wireless networks" [58]. In this scheme, the energy cost of a broadcast is defined as the sum of energy cost of all the sensor nodes that transmit the broadcast message in the broadcast tree. The problem here, which is similar to the ones presented in [59, 60], is called MEB (Minimum Energy Broadcast) for short. According to MEB, given an ad-hoc wireless network, find a broadcast tree such that the energy cost of the broadcast tree is minimized. The MEB tree problem is proven to be NP-hard [58, 59].

The authors in [58], in order to find the optimal solution, propose three heuristic algorithms. More specifically, they model the network using a directed graph $G = (V, A)$, where V represents the set of wireless nodes and A represents the set of arcs in the network. The nodes are assumed to be static and for each node in the network ($u \in V$) a given level of transmission power p(u) is assigned. For any two nodes u_1 and u_2, there is a directed link between them ($(u_1, u_2) \in A$) if u_2 is in the transmission power range of u_1.

For every broadcast request, e.g. from node s, a broadcast directed tree T is constructed. Assuming that a node costs energy only when it transmits data, then, the total energy cost $C(T)$ of T can be represented as:

$$C(T) = \sum_{u \in NL(T)} p(u) \tag{23}$$

where $NL(T)$ denotes the set of nodes of T which transmit/relay broadcast messages for s. In order to find the broadcast tree, in which the total energy cost of these transmitting nodes is minimized, the following, three heuristic algorithms are proposed [58].

First Heuristic Algorithm (Transforming the MEB to Directed Steiner Tree Problem) — In ad-hoc networks, the MEB problem is to find a broadcast tree such that the total energy cost of these transmitting nodes is minimized. In this network model, the transmission power of a node, as the weight of it, is assigned. Any heuristic of the directed Steiner tree problem [61] can be used to find the solution to this problem. In the simulation, the shortest path tree-based heuristic is used to compute the directed Steiner tree problem on G' (a new graph that was weight on arcs) to get a broadcast tree on G (network graph).

Second Heuristic Algorithm (Sound or Greedy Heuristic Algorithm) — The problem is transformed to a special kind of set cover problem that requires the set cover to form a connected and directed tree rooted at source. Two sets are introduced: One is the cover-set, containing the nodes which transmit/relay messages; the other one is the covered set, containing the nodes that are outgoing neighbors of the nodes in the cover set. In order to choose the nodes into cover-set such that the total energy cost of the broadcast tree is minimized, the following function is introduced:

$$|V_i \cap U| \ / \ p(u_i) \tag{24}$$

Where, V_i is a set of outgoing neighbors of node u_i and U a set of nodes which are not covered at each iteration. This function represents the number of nodes that a node can cover per energy unit. Each time, a node, with the maximum value of this function, will be selected into the cover set. By doing so, the total energy cost of the broadcast tree can thus be kept small.

Third Heuristic Algorithm (A Node-Weighted Steiner Tree-based Algorithm) — This heuristic takes a global approach, starting from any node in the network, to construct a broadcast tree that has efficient energy cost. The basic idea mimics the strategy used in the node weighted Steiner tree problem [62, 63].

The simulation of the three algorithms, namely, the Shortest-Path Tree-based heuristic (*SPT-h*), Greedy heuristic (*Greedy-h*), and Node-Weighted Steiner Tree-based heuristic (*NST-h*) shows how the *total energy cost* is affected by varying the number of nodes in the network (N) and the mean value of radius (R) over a wide range. According to the "total energy cost" versus "the number of nodes" graphs, the following observations were made:

- *Greedy-h* performs all the time.
- The *Greedy-h* and the *NST-h* both have better performance than the SPT-h.
- The results of *Greedy-h* and *NST-h* are very close when R (the mean value of radius) is very small (less than 0.4) or large (more than 0.7).

According to the "total energy cost" versus "the mean value of radius (R)" graphs, it was observed [58] that *the total energy cost increases as R increases*. When R is very large, all algorithms are very close because the source node can almost directly reach all the other nodes without using relaying nodes. In all the simulations, nodes have different transmission power (i.e. with different transmission radius). If the transmission radius is the same for all nodes, then, the simulation results are quite consistent with the case where nodes have different transmission powers. Moreover, the proposed heuristics also perform well in the case of uniform transmission power.

Conclusively, the reception cost is constant irrelevant to the distance from the signal source and the total reception cost of any broadcast tree is a constant regardless of what the tree is.

Future work will be concentrated firstly, on whether the reception cost is also distance-sensitive, resulting in much more complicated construction of the broadcast tree, and secondly on the development of distributed algorithms for energy efficient broadcasting which will take node mobility into consideration.

Transport Layer Protocols

To our knowledge, there has been little work to address the energy consumption issues at the transport layer for wireless sensor networks; even though some techniques found in IP networks have some relevance to the solution space, such as, the body of work on reliable multicast. Following, some of the most known schemes are presented.

An Experimental Study of TCP's Energy Consumption over a Wireless Link — In [34] it is examined, how TCP's energy consumption can be reduced while remaining within the standards-imposed constraints. It is an experimental study to efficiently utilize wireless sensor nodes energy to improve TCP performance. The various modifications and fine tunings to TCP code proposed in this scheme help in conserving battery power at sensor nodes by saving on software overhead and reducing protocol processing. Wireless ad-hoc sensor networks have a relatively small bandwidth (11 Mbits/s for the new WaveLAN cards) and the propagation delay of the medium is low (since the distance between the source and the destination is generally not very long). The consequence of this is that the delay bandwidth product for wireless ad-hoc networks is much smaller than for Long Fat Networks (LFNs) and thus many of the options implemented to support LFNs will not be suited to wireless ad-hoc sensor networks. The various options, included in current TCP implementations [34], are suitable only for LFNs and they need to be modified for slow sensor wireless networks. This study describes how each of these options works and gives reasons why they may need to be turned off in wireless sensor networks. S. Agrawal and S. Singh have shown that as much as a 25 percent improvement in TCP's efficiency for the same amount of energy consumed can be achieved.

PSFQ: A Reliable Transport Protocol for Wireless Sensor Networks — C. Wan *et al.* [64] propose PSFQ (Pump Slowly, Fetch Quickly), a new reliable transport protocol suitable for wireless sensor networks, that is simple, scalable, robust, and customizable to different applications' needs. PSFQ expresses a simple approach with minimum requirements on the routing infrastructure (as opposed to IP multicast/unicast routing requirements), minimum signaling thereby reducing the communication cost for data reliability, and finally, responsive to high error rates allowing successful operation even under highly error-prone conditions. It has been shown [64], through simulation studies (NS-2 simulator) and experimentation on a wireless sensor test bed, based on Berkeley motes, that PSFQ can outperform existing related techniques (e.g., an idealized SRM scheme) and is highly responsive to the various error conditions experienced in wireless sensor networks.

ESRT (Event-to-Sink Reliable Transport in Wireless Sensor Networks — Y. Sankarasubramaniam *et al.* [65] propose ESRT (Event-to-Sink Reliable Transport), a novel transport scheme developed to achieve reliable event detection in Wireless Sensor Networks with the least possible energy consumption. It includes a component that is able to control congestion in the network and thus serving the dual purpose of achieving reliability and conserving energy. The algorithms of ESRT run mainly on the sink, with the minimum required functionality at energy constrained sensor nodes. If the event-to-sink reliability is lower than the one required, then, ESRT adjusts the reporting frequency of source nodes in an aggressive way in order to reach the target reliability level the soonest possible. This self-configuring nature of ESRT makes it robust to random, dynamic topology in WSN. Simulation results show that ESRT converges to the desired reliability with minimum energy expenditure, starting from any initial network state.

Conclusions

As power management schemes for wireless sensor networks have attracted more attention in recent years, much research has been addressing all kinds of issues related to them. Power management plays an important role in the good performance of a wireless sensor network, and research associated with power management is always a focus. Different types of power management schemes may have different focus and objectives. However, power management cost always needs to be considered when discussing a power control scheme, because power management cost is important to evaluate the performance of a power control scheme no matter which specific objectives it bears.

In this article, fundamental concepts about power management, including the necessity of power management for a wireless sensor network, and the side effects as well as the cost of power management, were provided. More specifically: Power Conservation Mechanisms (PCMs) were divided into two main categories based on their main objectives. Passive and Active. Following, *Passive PCMs* were divided into three sub-categories: *Physical Layer*, *Fine-Grain,* and *Coarse-Grain PCMs*. For the implementation of the Coarse-Grain PCMs, two basic approaches were distinguished: *Distributed and Backbone-based*. The classification of the *Active PCMs* was based on the layer (MAC, Network, Transport) they can be performed at.

Various algorithms have been studied for each class of the classification. Each power management scheme was discussed in terms of objective, mechanism, performance, and application scenario, and the similarities and differences between schemes of the same clustering category were also presented. Thus, their performance evaluation and comparison showed the great importance of the energy application on energy efficiency schemes in Wireless Sensor networks.

With this survey, readers can have a more comprehensive understanding of power management schemes for wireless sensor networks, especially those schemes discussed in this article. Although each scheme is well suited for certain scenarios, it is not guaranteed that any of them is the best for all situations. We hope that this survey article can facilitate researchers to offer more efficient and effective power control schemes for wireless sensor networks.

Although the performance of the presented power management schemes is promising, further research would be necessary to address issues, such as quality of service (QoS) proposed by imaging sensors and real-time applications. Energy-aware QoS in wireless sensor networks will certainly ensure guaranteed bandwidth, or delay, through the duration of connection as well as providing the use of most energy-efficient path. Currently, there is minimal research that looks at handling QoS requirements in a highly energy-constrained environment like sensor networks.

Other possible future research for energy-efficient protocols includes the integration of wireless sensor networks with wired networks. More specifically, most of the applications in environmental monitoring require the data, gathered from the sensor nodes, to be transmitted to a server, so that further analysis can be done. On the other hand, the requests from the user's side should be made to the base station through Internet. Since the energy-efficiency routing requirements of each environment are quite different, further research is needed to face this kind of situations.

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