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Wireless sensor networks: a survey

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Abstract

This paper describes the concept of sensor networks which has been made viable by the convergence of micro-electro-mechanical systems technology, wireless communications and digital electronics. First, the sensing tasks and the potential sensor networks applications are explored, and a review of factors influencing the design of sensor networks is provided. Then, the communication architecture for sensor networks is outlined, and the algorithms and protocols developed for each layer in the literature are explored. Open research issues for the realization of sensor networks are also discussed. © 2002 Published by Elsevier Science B.V.

Keywords: Wireless sensor networks; Ad hoc networks; Application layer; Transport layer; Networking layer; Routing; Data link layer; Medium access control; Error control; Physical layer; Power aware protocols

1. Introduction

Recent advances in micro-electro-mechanical systems (MEMS) technology, wireless communications, and digital electronics have enabled the development of low-cost, low-power, multifunctional sensor nodes that are small in size and communicate untethered in short distances. These tiny sensor nodes, which consist of sensing, data processing, and communicating components, leverage the idea of sensor networks based on collaborative effort of a large number of nodes. Sensor networks represent a significant improvement over traditional sensors, which are deployed in the following two ways [39]:

- Sensors can be positioned far from the actual *phenomenon*, i.e., something known by sense perception. In this approach, large sensors that use some complex techniques to distinguish the targets from environmental noise are required.
- Several sensors that perform only sensing can be deployed. The positions of the sensors and communications topology are carefully engineered. They transmit time series of the sensed phenomenon to the central nodes where computations are performed and data are fused.

A sensor network is composed of a large number of sensor nodes, which are densely deployed either inside the phenomenon or very close to it.

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The position of sensor nodes need not be engineered or pre-determined. This allows random deployment in inaccessible terrains or disaster relief operations. On the other hand, this also means that sensor network protocols and algorithms must possess self-organizing capabilities. Another unique feature of sensor networks is the cooperative effort of sensor nodes. Sensor nodes are fitted with an on-board processor. Instead of sending the raw data to the nodes responsible for the fusion, sensor nodes use their processing abilities to locally carry out simple computations and transmit only the required and partially processed data.

The above described features ensure a wide range of applications for sensor networks. Some of the application areas are health, military, and security. For example, the physiological data about a patient can be monitored remotely by a doctor. While this is more convenient for the patient, it also allows the doctor to better understand the patient's current condition. Sensor networks can also be used to detect foreign chemical agents in the air and the water. They can help to identify the type, concentration, and location of pollutants. In essence, sensor networks will provide the end user with intelligence and a better understanding of the environment. We envision that, in future, wireless sensor networks will be an integral part of our lives, more so than the present-day personal computers.

Realization of these and other sensor network applications require wireless ad hoc networking techniques. Although many protocols and algorithms have been proposed for traditional wireless ad hoc networks, they are not well suited for the unique features and application requirements of sensor networks. To illustrate this point, the differences between sensor networks and ad hoc networks [65] are outlined below:

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

Since large number of sensor nodes are densely deployed, neighbor nodes may be very close to each other. Hence, multihop communication in sensor networks is expected to consume less power than the traditional single hop communication. Furthermore, the transmission power levels can be kept low, which is highly desired in covert operations. Multihop communication can also effectively overcome some of the signal propagation effects experienced in long-distance wireless communication.

One of the most important constraints on sensor nodes is the low power consumption requirement. Sensor nodes carry limited, generally irreplaceable, power sources. Therefore, while traditional networks aim to achieve high quality of service (QoS) provisions, sensor network protocols must focus primarily on power conservation. They must have inbuilt trade-off mechanisms that give the end user the option of prolonging network lifetime at the cost of lower throughput or higher transmission delay.

Many researchers are currently engaged in developing schemes that fulfill these requirements. In this paper, we present a survey of protocols and algorithms proposed thus far for sensor networks. Our aim is to provide a better understanding of the current research issues in this field. We also attempt an investigation into pertaining design constraints and outline the use of certain tools to meet the design objectives.

The remainder of the paper is organized as follows: In Section 2, we present some potential sensor network applications which show the usefulness of sensor networks. In Section 3, we discuss the factors that influence the sensor network design. We provide a detailed investigation of current proposals in this area in Section 4. We conclude our paper in Section 5.

2. Sensor networks applications

Sensor networks may consist of many different types of sensors such as seismic, low sampling rate magnetic, thermal, visual, infrared, acoustic and radar, which are able to monitor a wide variety of ambient conditions that include the following [23]:

- temperature,
- humidity,
- vehicular movement,
- lightning condition,
- pressure,
- soil makeup,
- noise levels,
- the presence or absence of certain kinds of objects,
- mechanical stress levels on attached objects, and
- the current characteristics such as speed, direction, and size of an object.

Sensor nodes can be used for continuous sensing, event detection, event ID, location sensing, and local control of actuators. The concept of micro-sensing and wireless connection of these nodes promise many new application areas. We categorize the applications into military, environment, health, home and other commercial areas. It is possible to expand this classification with more categories such as space exploration, chemical processing and disaster relief.

2.1. Military applications

Wireless sensor networks can be an integral part of military *command*, *control*, *communications*, *computing*, *intelligence*, *surveillance*, *reconnaissance and targeting* (C4ISRT) systems. The rapid deployment, self-organization and fault tolerance characteristics of sensor networks make them a very promising sensing technique for military C4ISRT. Since sensor networks are based on the dense deployment of disposable and low-cost sensor nodes, destruction of some nodes by hostile actions does not affect a military operation as much as the destruction of a traditional sensor, which makes sensor networks concept a better approach for battlefields. Some of the military applications of sensor networks are monitoring friendly forces, equipment and ammunition; battlefield surveillance; reconnaissance of opposing forces and terrain; targeting; battle damage assessment; and nuclear, biological and chemical (NBC) attack detection and reconnaissance.

Monitoring friendly forces, equipment and ammunition: Leaders and commanders can constantly monitor the status of friendly troops, the condition and the availability of the equipment and the ammunition in a battlefield by the use of sensor networks. Every troop, vehicle, equipment and critical ammunition can be attached with small sensors that report the status. These reports are gathered in sink nodes and sent to the troop leaders. The data can also be forwarded to the upper levels of the command hierarchy while being aggregated with the data from other units at each level.

Battlefield surveillance: Critical terrains, approach routes, paths and straits can be rapidly covered with sensor networks and closely watched for the activities of the opposing forces. As the operations evolve and new operational plans are prepared, new sensor networks can be deployed anytime for battlefield surveillance.

Reconnaissance of opposing forces and terrain: Sensor networks can be deployed in critical terrains, and some valuable, detailed, and timely intelligence about the opposing forces and terrain can be gathered within minutes before the opposing forces can intercept them.

Targeting: Sensor networks can be incorporated into guidance systems of the intelligent ammunition.

Battle damage assessment: Just before or after attacks, sensor networks can be deployed in the target area to gather the battle damage assessment data.

Nuclear, biological and chemical attack detection and reconnaissance: In chemical and biological warfare, being close to ground zero is important for timely and accurate detection of the agents. Sensor networks deployed in the friendly region and used as a chemical or biological warning system can provide the friendly forces with critical reaction time, which drops casualties drastically. We can also use sensor networks for detailed reconnaissance after an NBC attack is detected. For instance, we can make a nuclear reconnaissance without exposing a recce team to nuclear radiation.

2.2. Environmental applications

Some environmental applications of sensor networks include tracking the movements of birds, small animals, and insects; monitoring environmental conditions that affect crops and livestock; irrigation; macroinstruments for large-scale Earth monitoring and planetary exploration; chemical/biological detection; precision agriculture; biological, Earth, and environmental monitoring in marine, soil, and atmospheric contexts; forest fire detection; meteorological or geophysical research; flood detection; bio-complexity mapping of the environment; and pollution study [2,6–8,10,11,14,31,35,39,40,42,61,81,88,89].

Forest fire detection: Since sensor nodes may be strategically, randomly, and densely deployed in a forest, sensor nodes can relay the exact origin of the fire to the end users before the fire is spread uncontrollable. Millions of sensor nodes can be deployed and integrated using radio frequencies/optical systems. Also, they may be equipped with effective power scavenging methods [12], such as solar cells, because the sensors may be left unattended for months and even years. The sensor nodes will collaborate with each other to perform distributed sensing and overcome obstacles, such as trees and rocks, that block wired sensors' line of sight.

Biocomplexity mapping of the environment [11]: A biocomplexity mapping of the environment requires sophisticated approaches to integrate information across temporal and spatial scales [26,87]. The advances of technology in the remote sensing and automated data collection have enabled higher spatial, spectral, and temporal resolution at a geometrically declining cost per unit area [15]. Along with these advances, the sensor nodes also have the ability to connect with the Internet, which allows remote users to control, monitor and observe the biocomplexity of the environment.

Although satellite and airborne sensors are useful in observing large biodiversity, e.g., spatial complexity of dominant plant species, they are not fine grain enough to observe small size biodiversity, which makes up most of the biodiversity in an ecosystem [43]. As a result, there is a need for ground level deployment of wireless sensor nodes to observe the biocomplexity [29,30]. One example of biocomplexity mapping of the environment is done at the James Reserve in Southern California [11]. Three monitoring grids with each having 25–100 sensor nodes will be implemented for fixed view multimedia and environmental sensor data loggers.

Flood detection [7]: An example of a flood detection is the ALERT system [90] deployed in the US. Several types of sensors deployed in the ALERT system are rainfall, water level and weather sensors. These sensors supply information to the centralized database system in a pre-defined way. Research projects, such as the COUGAR Device Database Project at Cornell University [7] and the DataSpace project at Rutgers [38], are investigating distributed approaches in interacting with sensor nodes in the sensor field to provide snapshot and long-running queries.

Precision Agriculture: Some of the benefits is the ability to monitor the pesticides level in the drinking water, the level of soil erosion, and the level of air pollution in realtime.

2.3. Health applications

Some of the health applications for sensor networks are providing interfaces for the disabled; integrated patient monitoring; diagnostics; drug administration in hospitals; monitoring the movements and internal processes of insects or other small animals; telemonitoring of human physiological data; and tracking and monitoring doctors and patients inside a hospital [8,42,60,71,88].

Telemonitoring of human physiological data: The physiological data collected by the sensor networks can be stored for a long period of time [41], and can be used for medical exploration [62]. The installed sensor networks can also monitor and detect elderly people's behavior, e.g., a fall [9,16]. These small sensor nodes allow the subject a greater freedom of movement and allow doctors to identify pre-defined symptoms earlier [56]. Also, they facilitate a higher quality of life for the subjects compared to the treatment centers [5]. A "Health Smart Home" is designed in the Faculty of Medicine in Grenoble—France to validate the feasibility of such system [60].

Tracking and monitoring doctors and patients inside a hospital: Each patient has small and light weight sensor nodes attached to them. Each sensor node has its specific task. For example, one sensor node may be detecting the heart rate while another is detecting the blood pressure. Doctors may also carry a sensor node, which allows other doctors to locate them within the hospital.

Drug administration in hospitals: If sensor nodes can be attached to medications, the chance of getting and prescribing the wrong medication to patients can be minimized. Because, patients will have sensor nodes that identify their allergies and required medications. Computerized systems as described in [78] have shown that they can help minimize adverse drug events.

2.4. Home applications

Home automation: As technology advances, smart sensor nodes and actuators can be buried in appliances, such as vacuum cleaners, micro-wave ovens, refrigerators, and VCRs [67]. These sensor nodes inside the domestic devices can interact with each other and with the external network via the Internet or Satellite. They allow end users to manage home devices locally and remotely more easily.

Smart environment: The design of smart environment can have two different perspectives, i.e., human-centered and technology-centered [1]. For human-centered, a smart environment has to adapt to the needs of the end users in terms of input/output capabilities. For technology-centered, new hardware technologies, networking solutions, and middleware services have to be developed. A scenario of how sensor nodes can be used to create a smart environment is described in [36]. The sensor nodes can be embedded into furniture and appliances, and they can communicate with each other and the room server. The room server can also communicate with other room servers to learn about the services they offered, e.g., printing, scanning, and faxing. These room servers and sensor nodes can be integrated with existing embedded devices to become self-organizing, self-regulated, and adaptive systems based on control theory models as described in [36]. Another example of smart environment is the "Residential Laboratory" at Georgia Institute of Technology [21]. The computing and sensing in this environment has to be reliable, persistent, and transparent.

2.5. Other commercial applications

Some of the commercial applications are monitoring material fatigue; building virtual keyboards; managing inventory; monitoring product quality; constructing smart office spaces; environmental control in office buildings; robot control and guidance in automatic manufacturing environments; interactive toys; interactive museums; factory process control and automation; monitoring disaster area; smart structures with sensor nodes embedded inside; machine diagnosis; transportation; factory instrumentation; local control of actuators; detecting and monitoring car thefts; vehicle tracking and detection; and instrumentation of semiconductor processing chambers, rotating machinery, wind tunnels, and anechoic chambers [2,8,14,23,24,42,63,69–71,77,88].

Environmental control in office buildings: The air conditioning and heat of most buildings are centrally controlled. Therefore, the temperature inside a room can vary by few degrees; one side might be warmer than the other because there is only one control in the room and the air flow from the central system is not evenly distributed. A distributed wireless sensor network system can be installed to control the air flow and temperature in different parts of the room. It is estimated that such distributed technology can reduce energy consumption by two quadrillion British Thermal Units (BTUs) in the US, which amounts to saving of \$55 billion per year and reducing 35 million metric tons of carbon emissions [71].

Interactive museums: In the future, children will be able to interact with objects in museums to learn more about them. These objects will be able to respond to their touch and speech. Also, children can participate in real time cause-and-effect experiments, which can teach them about science and environment. In addition, the wireless sensor networks can provide paging and localization inside the museum. An example of such museums is the San Francisco Exploratorium that features a combination of data measurements and cause-and-effect experiments [71].

Detecting and monitoring car thefts: Sensor nodes are being deployed to detect and identify threats within a geographic region and report these threats to remote end users by the Internet for analysis [69].

Managing inventory control: Each item in a warehouse may have a sensor node attached. The end users can find out the exact location of the item and tally the number of items in the same category. If the end users want to insert new inventories, all the users need to do is to attach the appropriate sensor nodes to the inventories. The end users can track and locate where the inventories are at all times.

Vehicle tracking and detection: There are two approaches as described in [77] to track and detect the vehicle: first, the line of bearing of the vehicle is determined locally within the clusters and then it is forwarded to the base station, and second, the raw data collected by the sensor nodes are forwarded to the base station to determine the location of the vehicle.

3. Factors influencing sensor network design

A sensor network design is influenced by many factors, which include *fault tolerance*; *scalability*; *production costs*; *operating environment*; *sensor network topology*; *hardware constraints*; *transmission media*; and *power consumption*. These factors are addressed by many researchers as surveyed in this paper. However, none of these studies has a full integrated view of all factors that are driving the design of sensor networks and sensor nodes. These factors are important because they serve as a guideline to design a protocol or an algorithm for sensor networks. In addition, these influencing factors can be used to compare different schemes.

3.1. Fault tolerance

Some sensor nodes may fail or be blocked due to lack of power, have physical damage or environmental interference. The failure of sensor nodes should not affect the overall task of the sensor network. This is the reliability or fault tolerance issue. Fault tolerance is the ability to sustain sensor network functionalities without any interruption due to sensor node failures [37,55,75]. The reliability $R_k(t)$ or fault tolerance of a sensor node is modelled in [37] using the Poisson distribution to capture the probability of not having a failure within the time interval $(0, t)$:

$$R_k(t) = \exp(-\lambda_k t) \tag{1}$$

where λ_k and t are the failure rate of sensor node k and the time period, respectively.

Note that protocols and algorithms may be designed to address the level of fault tolerance required by the sensor networks. If the environment where the sensor nodes are deployed has little interference, then the protocols can be more relaxed. For example, if sensor nodes are being deployed in a house to keep track of humidity and temperature levels, the fault tolerance requirement may be low since this kind of sensor networks is not easily damaged or interfered by environmental noise. On the other hand, if sensor nodes are being deployed in a battlefield for surveillance and detection, then the fault tolerance has to be high because the sensed data are critical and sensor nodes can be destroyed by hostile actions. As a result, the fault tolerance level depends on the application of the sensor networks, and the schemes must be developed with this in mind.

3.2. Scalability

The number of sensor nodes deployed in studying a phenomenon may be in the order of hundreds or thousands. Depending on the application, the number may reach an extreme value of millions. The new schemes must be able to work with this number of nodes. They must also utilize the high density nature of the sensor networks. The density can range from few sensor nodes to few hundred sensor nodes in a region, which can be less than 10 m in diameter [14]. The density can be calculated according to [8] as

$$\mu(R) = (N\pi R^2)/A \qquad (2)$$

where N is the number of scattered sensor nodes in region A; and R, the radio transmission range. Basically, $\mu(R)$ gives the number of nodes within the transmission radius of each node in region A.

In addition, the number of nodes in a region can be used to indicate the node density. The node density depends on the application in which the sensor nodes are deployed. For machine diagnosis application, the node density is around 300 sensor nodes in a 5×5 m^2 region, and the density for the vehicle tracking application is around 10 sensor nodes per region [77]. In general, the density can be as high as 20 sensor nodes/m^3 [77]. A home may contain around two dozens of home appliances containing sensor nodes [67], but this number will grow if sensor nodes are embedded into furniture and other miscellaneous items. For habitat monitoring application, the number of sensor nodes ranges from 25 to 100 per region [11]. The density will be extremely high when a person normally containing hundreds of sensor nodes, which are embedded in eye glasses, clothing, shoes, watch, jewelry, and human body, is sitting inside a stadium watching a basketball, football, or baseball game.

3.3. Production costs

Since the sensor networks consist of a large number of sensor nodes, the cost of a single node is very important to justify the overall cost of the networks. If the cost of the network is more expensive than deploying traditional sensors, then the sensor network is not cost-justified. As a result, the cost of each sensor node has to be kept low. The state-of-the-art technology allows a Bluetooth radio system to be less than 10$ [71]. Also, the price of a PicoNode is targeted to be less than 1$ [70]. The cost of a sensor node should be much less than 1$ in order for the sensor network to be feasible [70]. The cost of a Bluetooth radio, which is known to be a low-cost device, is even 10 times more expensive than the targeted price for a sensor node. Note that a sensor node also has some additional units such as sensing and processing units as described in Section 3.4. In addition, it may be equipped with a location finding system, mobilizer, or power generator depending on the applications of the sensor networks. As a result, the cost of a sensor node is a very challenging issue given the amount of functionalities with a price of much less than a dollar.

3.4. Hardware constraints

A sensor node is made up of four basic components as shown in Fig. 1: a *sensing unit*, a *processing unit*, a *transceiver unit* and a *power unit*. They may also have application dependent additional components such as a *location finding system*, a *power generator* and a *mobilizer*. Sensing units are usually composed of two subunits: sensors and analog to digital converters (ADCs). The analog signals produced by the sensors based on the observed phenomenon are converted to digital signals by the ADC, and then fed into the processing unit. The processing unit, which is generally associated with a small storage unit, manages the procedures that make the sensor node collaborate with the other nodes to carry out the assigned sensing tasks. A transceiver unit connects the node to the network. One of the most important components of a sensor node is the power unit. Power units may be supported by a power scavenging unit such as solar cells. There are also other subunits, which are application dependent.

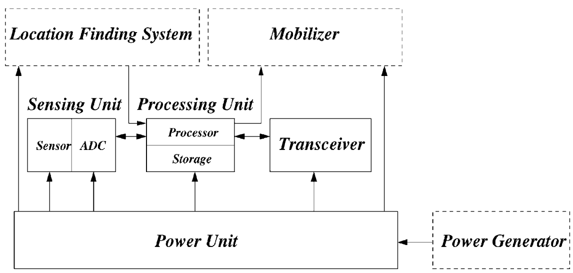

Fig. 1. The components of a sensor node.

Most of the sensor network routing techniques and sensing tasks require the knowledge of location with high accuracy. Thus, it is common that a sensor node has a location finding system. A mobilizer may sometimes be needed to move sensor nodes when it is required to carry out the assigned tasks.

All of these subunits may need to fit into a matchbox-sized module [39]. The required size may be smaller than even a cubic centimeter [69] which is light enough to remain suspended in the air. Apart from the size, there are also some other stringent constraints for sensor nodes. These nodes must [42]

- consume extremely low power,
- operate in high volumetric densities,
- have low production cost and be dispensable,
- be autonomous and operate unattended,
- be adaptive to the environment.

Since the sensor nodes are often inaccessible, the lifetime of a sensor network depends on the lifetime of the power resources of the nodes. Power is also a scarce resource due to the size limitations. For instance, the total stored energy in a *smart dust mote* is on the order of 1 J [69]. For wireless integrated network sensors (WINS) [86], the total average system supply currents must be less than 30 μA to provide long operating life. WINS nodes are powered from typical lithium (Li) coin cells (2.5 cm in diameter and 1 cm in thickness) [86]. It is possible to extend the lifetime of the sensor networks by energy scavenging [71], which means extracting energy from the environment. Solar cells is an example for the techniques used for energy scavenging.

The transceiver unit of sensor nodes may be a passive or active optical device as in smart dust motes [69] or a radio frequency (RF) device. RF communications require modulation, band pass, filtering, demodulation and multiplexing circuitry, which make them more complex and expensive. Also, the path loss of the transmitted signal between two sensor nodes may be as high as the fourth order exponent of the distance between them, because the antennas of the sensor nodes are close to the ground [69]. Nevertheless, RF communication is preferred in most of the ongoing sensor network research projects, because the packets conveyed in sensor networks are small, data rates are low (i.e., generally less than 1 Hz) [71], and the frequency re-use is high due to short communication distances. These characteristics also make it possible to use low duty cycle radio electronics for sensor networks. However, designing energy efficient and low duty cycle radio circuits is still technically challenging, and current commercial radio technologies such as those used in Bluetooth is not efficient enough for sensor networks because turning them on and off consumes much energy [77].

Though the higher computational powers are being made available in smaller and smaller processors, processing and memory units of sensor nodes are still scarce resources. For instance, the processing unit of a smart dust mote prototype is a 4 MHz Atmel AVR 8535 micro-controller with 8 KB instruction flash memory, 512 bytes RAM and 512 bytes EEPROM [66]. TinyOS operating system is used on this processor, which has 3500 bytes OS code space and 4500 bytes available code space. The processing unit of another sensor node prototype, namely μAMPS wireless sensor node, has a 59–206 MHz SA-1110 micro-processor [77]. A multithreaded μ-OS operating system is run on μAMPS wireless sensor nodes.

Most of the sensing tasks require the knowledge of position. Since sensor nodes are generally deployed randomly and run unattended, they need to corporate with a location finding system. Location finding systems are also required by many of the proposed sensor network routing protocols as explained in Section 4. It is often assumed that each sensor node will have a global positioning system (GPS) unit that has at least 5 m accuracy [48]. In [74] it is argued that equipping all sensor nodes with a GPS is not viable for sensor networks. An alternative approach where a limited number of nodes use GPS and help the other nodes to find out their locations terrestrially as proposed in [74].

3.5. Sensor network topology

Sheer numbers of inaccessible and unattended sensor nodes, which are prone to frequent failures, make topology maintenance a challenging task. Hundreds to several thousands of nodes are deployed throughout the sensor field. They are deployed within tens of feet of each other [39]. The node densities may be as high as 20 nodes/m^3 [77]. Deploying high number of nodes densely requires careful handling of topology maintenance. We examine issues related to topology maintenance and change in three phases:

3.5.1. Pre-deployment and deployment phase

Sensor nodes can be either thrown in mass or placed one by one in the sensor field. They can be deployed by

- dropping from a plane,
- delivering in an artillery shell, rocket or missile,
- throwing by a catapult (from a ship board, etc.),
- placing in factory, and
- placing one by one either by a human or a robot.

Although the sheer number of sensors and their unattended deployment usually preclude placing them according to a carefully engineered deployment plan, the schemes for initial deployment must

- reduce the installation cost,
- eliminate the need for any pre-organization and pre-planning,
- increase the flexibility of arrangement, and
- promote self-organization and fault tolerance.

3.5.2. Post-deployment phase

After deployment, topology changes are due to change in sensor nodes' [39,50]

- position,
- reachability (due to jamming, noise, moving obstacles, etc.),
- available energy,
- malfunctioning, and
- task details.

Sensor nodes may be statically deployed. However, device failure is a regular or common event due to energy depletion or destruction. It is also possible to have sensor networks with highly mobile nodes. Besides, sensor nodes and the network experience varying task dynamics, and they may be a target for deliberate jamming. Therefore, sensor network topologies are prone to frequent changes after deployment.

3.5.3. Re-deployment of additional nodes phase

Additional sensor nodes can be re-deployed at any time to replace the malfunctioning nodes or due to changes in task dynamics. Addition of new nodes poses a need to re-organize the network. Coping with frequent topology changes in an ad hoc network that has myriads of nodes and very stringent power consumption constraints requires special routing protocols. This issue is examined in detail in Section 4.

3.6. Environment

Sensor nodes are densely deployed either very close or directly inside the phenomenon to be observed. Therefore, they usually work unattended in remote geographic areas. They may be working

- in busy intersections,
- in the interior of a large machinery,
- at the bottom of an ocean,
- inside a twister,
- on the surface of an ocean during a tornado,
- in a biologically or chemically contaminated field,
- in a battlefield beyond the enemy lines,
- in a home or a large building,
- in a large warehouse,
- attached to animals,
- attached to fast moving vehicles, and
- in a drain or river moving with current.

This list gives us an idea about under which conditions sensor nodes are expected to work. They work under high pressure in the bottom of an ocean, in harsh environments such as a debris or a battlefield, under extreme heat and cold such as in the nozzle of an aircraft engine or in arctic regions, and in an extremely noisy environment such as under intentional jamming.

3.7. Transmission media

In a multihop sensor network, communicating nodes are linked by a wireless medium. These links can be formed by radio, infrared or optical media. To enable global operation of these networks, the chosen transmission medium must be available worldwide.

One option for radio links is the use of industrial, scientific and medical (ISM) bands, which offer license-free communication in most countries. The International Table of Frequency Allocations, contained in Article S5 of the Radio Regulations (Volume 1), species some frequency bands that may be made available for ISM applications. They are listed in Table 1.

Some of these frequency bands are already being used for communication in cordless phone systems and wireless local area networks (WLANs). For sensor networks, a small-sized, low-cost, ultralow power transceiver is required. According to [68], certain hardware constraints and the trade-off between antenna efficiency and power consumption limit the choice of a carrier frequency for such transceivers to the ultrahigh frequency range. They also propose the use of the 433 MHz ISM band in Europe and the 915 MHz ISM band in North America. The transceiver design issues in these two bands are addressed in [25,51]. The main advantages of using the ISM bands are the free radio, huge spectrum allocation and global availability. They are not bound to a particular standard, thereby giving more freedom for the implementation of power saving strategies in sensor networks. On the other hand, there are various rules and constraints, like power limitations and harmful interference from existing applications. These frequency bands are also referred to as unregulated frequencies.

Table 1
Frequency bands available for ISM applications

Frequency band	Center frequency
6765–6795 kHz	6780 kHz
13,553–13,567 kHz	13,560 kHz
26,957–27,283 kHz	27,120 kHz
40.66–40.70 MHz	40.68 MHz
433.05–434.79 MHz	433.92 MHz
902–928 MHz	915 MHz
2400–2500 MHz	2450 MHz
5725–5875 MHz	5800 MHz
24–24.25 GHz	24.125 GHz
61–61.5 GHz	61.25 GHz
122–123 GHz	122.5 GHz
244–246 GHz	245 GHz

Much of the current hardware for sensor nodes is based upon RF circuit design. The μAMPS wireless sensor node, described in [77], uses a Bluetooth-compatible 2.4 GHz transceiver with an integrated frequency synthesizer. The low-power sensor device described in [93], uses a single channel RF transceiver operating at 916 MHz. The WINS architecture [69] also uses radio links for communication.

Another possible mode of internode communication in sensor networks is by infrared. Infrared communication is license-free and robust to interference from electrical devices. Infrared based transceivers are cheaper and easier to build. Many of today's laptops, PDAs and mobile phones offer an infrared data association interface. The main drawback though, is the requirement of a line of sight between sender and receiver. This makes infrared a reluctant choice for transmission medium in the sensor network scenario.

An interesting development is that of the smart dust mote [42], which is an autonomous sensing, computing and communication system that uses optical medium for transmission. Two transmission schemes, passive transmission using a corner-cube retroreflector (CCR), and active communication using a laser diode and steerable mirrors, are examined in [88]. In the former, the mote does not require an onboard light source. A configuration of three mirrors (CCR) is used to communicate a digital high or low. The latter uses an onboard laser diode and an active-steered laser communication system to send a tightly collimated light beam toward the intended receiver.

The unusual application requirements of sensor networks make the choice of transmission media more challenging. For instance, marine applications may require the use of the aqueous transmission medium. Here, one would like to use long-wavelength radiation that can penetrate the water surface. Inhospitable terrain or battlefield applications might encounter error prone channels and greater interference. Moreover, a sensor antenna might not have the height and radiation power of those in other wireless devices. Hence, the choice of transmission medium must be supported by robust coding and modulation schemes that efficiently model these vastly different channel characteristics.

3.8. Power consumption

The wireless sensor node, being a micro-electronic device, can only be equipped with a limited power source (<0.5 Ah, 1.2 V). In some application scenarios, replenishment of power resources might be impossible. Sensor node lifetime, therefore, shows a strong dependence on battery lifetime. In a multihop ad hoc sensor network, each node plays the dual role of data originator and data router. The disfunctioning of few nodes can cause significant topological changes and might require re-routing of packets and re-organization of the network. Hence, power conservation and power management take on additional importance. It is for these reasons that researchers are currently focusing on the design of power-aware protocols and algorithms for sensor networks.

In other mobile and ad hoc networks, power consumption has been an important design factor, but not the primary consideration, simply because power resources can be replaced by the user. The emphasis is more on QoS provisioning than the power efficiency. In sensor networks though, power efficiency is an important performance metric, directly influencing the network lifetime. Application specific protocols can be designed by appropriately trading off other performance metrics such as delay and throughput with power efficiency.

The main task of a sensor node in a sensor field is to detect events, perform quick local data processing, and then transmit the data. Power consumption can hence be divided into three domains: *sensing*, *communication*, and *data processing*.

The sensing unit and its components were introduced in Section 3.4. Sensing power varies with the nature of applications. Sporadic sensing might consume lesser power than constant event monitoring. The complexity of event detection also plays a crucial role in determining energy expenditure. Higher ambient noise levels might cause significant corruption and increase detection complexity. Power consumption in data communication and processing are discussed in detail in the following subsections.

3.8.1. Communication

Of the three domains, a sensor node expends maximum energy in data communication. This involves both data transmission and reception. It can be shown that for short-range communication with low radiation power (~0 dbm), transmission and reception energy costs are nearly the same. Mixers, frequency synthesizers, voltage control oscillators, phase locked loops (PLL) and power amplifiers, all consume valuable power in the transceiver circuitry. It is important that in this computation we not only consider the active power but also the start-up power consumption in the transceiver circuitry. The start-up time, being of the order of hundreds of micro-seconds, makes the start-up power non-negligible. This high value for the start-up time can be attributed to the lock time of the PLL. As the transmission packet size is reduced, the start-up power consumption starts to dominate the active power consumption. As a result, it is inefficient in turning the transceiver ON and OFF, because a large amount of power is spent in turning the transceiver back ON each time.

In [77], the authors present a formulation for the radio power consumption (P_c) as

$$P_c = N_T[P_T(T_{on} + T_{st}) + P_{out}(T_{on})] + N_R[P_R(R_{on} + R_{st})] \quad (3)$$

where $P_{T/R}$ is the power consumed by the transmitter/receiver; P_{out}, the output power of the transmitter; T/R_{on}, the transmitter/receiver on time; T/R_{st}, the transmitter/receiver start-up time and $N_{T/R}$, the number of times transmitter/receiver is switched on per unit time, which depends on the task and medium access control (MAC) scheme used. T_{on} can further be rewritten as L/R, where L is the packet size and R, the data rate. Today's state-of-the-art low power radio transceiver has typical P_T and P_R values around 20 dbm and P_{out} close to 0 dbm [59]. Note that PicoRadio aims at a P_c value of −20 dbm.

The design of a small-sized, low-cost, ultralow power transceiver is discussed in [68]. A direct-conversion architecture is proposed for the transceiver circuitry. Based on their results, the authors present a power budget and estimate the power consumption to be at least an order of magnitude less than the values given above for P_T and P_R values.

3.8.2. Data processing

Energy expenditure in data processing is much less compared to data communication. The example described in [69], effectively illustrates this disparity. Assuming Rayleigh fading and fourth power distance loss, the energy cost of transmitting 1 KB a distance of 100 m is approximately the same as that for executing 3 million instructions by a 100 million instructions per second (MIPS)/W processor. Hence, local data processing is crucial in minimizing power consumption in a multihop sensor network.

A sensor node must therefore have built-in computational abilities and be capable of interacting with its surroundings. Further limitations of cost and size lead us to the choice of complementary metal oxide semiconductor (CMOS) technology for the micro-processor. Unfortunately, this has inbuilt limitations on energy efficiency. A CMOS transistor pair draws power everytime it is switched. This switching power is proportional to the switching frequency, device capacitance (which further depends on the area) and square of the voltage swing. Reducing the supply voltage is hence an effective means of lowering power consumption in the active state. Dynamic voltage scaling, explored in [52,64], aims to adapt processor power supply and operating frequency to match workloads. When a micro-processor handles time-varying computational load, simply reducing the operating frequency during periods of reduced activity results in a linear decrease in power consumption, but reducing the operating voltage gives us quadratic gains. On the other hand, this compromises on peak performance of the processor. Significant energy gains can be obtained by recognizing that peak performance is not always desired and therefore, the processor's operating voltage and frequency can be dynamically adapted to instantaneous processing requirements. In [80], the authors propose a workload prediction scheme based on adaptive filtering of the past workload profile and analyze several filtering schemes. Other low power CPU organization strategies are discussed in [28,49,91].

The power consumption in data processing (P_p) can be formulated as follows:

$$P_p = CV_{dd}^2 f + V_{dd} I_0 e^{V_{dd}/n'V_T} \quad (4)$$

where C is the total switching capacitance; V_{dd}, the voltage swing and f, the switching frequency. The second term indicates the power loss due to leakage currents [80]. The lowering of threshold voltage to satisfy performance requirements results in high subthreshold leakage currents. Coupled with the low duty cycle operation of the micro-processor in a sensor node, the associated power loss becomes significant [77].

It is to be noted that there may be some additional circuitry for data encoding and decoding. Application specific integrated circuits may also be used in some cases. In all these scenarios, the design of sensor network algorithms and protocols are influenced by the corresponding power expenditures, in addition to those that have been discussed.

4. Sensor networks communication architecture

The sensor nodes are usually scattered in a *sensor field* as shown in Fig. 2. Each of these scattered sensor nodes has the capabilities to collect data and route data back to the *sink* and the end users. Data are routed back to the end user by a multihop infrastructureless architecture through the sink as shown in Fig. 2. The sink may communicate with the *task manager node* via Internet or Satellite.

The protocol stack used by the sink and all sensor nodes is given in Fig. 3. This protocol stack combines power and routing awareness, integrates data with networking protocols, communicates power efficiently through the wireless medium, and promotes cooperative efforts of sensor nodes. The protocol stack consists of the *application layer*, *transport layer*, *network layer*, *data link layer*,

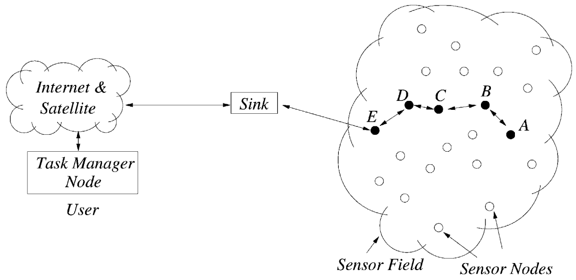

Fig. 2. Sensor nodes scattered in a sensor field.

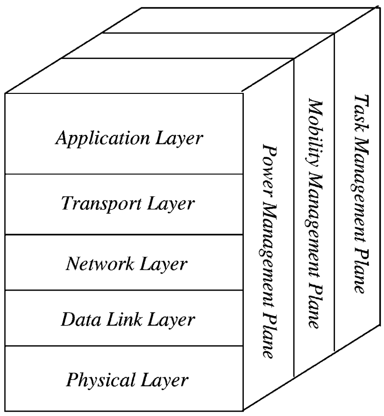

Fig. 3. The sensor networks protocol stack.

physical layer, *power management plane*, *mobility management plane*, and *task management plane*. Depending on the sensing tasks, different types of application software can be built and used on the application layer. The transport layer helps to maintain the flow of data if the sensor networks application requires it. The network layer takes care of routing the data supplied by the transport layer. Since the environment is noisy and sensor nodes can be mobile, the MAC protocol must be power aware and able to minimize collision with neighbors' broadcast. The physical layer addresses the needs of a simple but robust modulation, transmission and receiving techniques. In addition, the power, mobility, and task management planes monitor the power, movement, and task distribution among the sensor nodes. These planes help the sensor nodes coordinate the sensing task and lower the overall power consumption.

The power management plane manages how a sensor node uses its power. For example, the sensor node may turn off its receiver after receiving a message from one of its neighbors. This is to avoid getting duplicated messages. Also, when the power level of the sensor node is low, the sensor node broadcasts to its neighbors that it is low in power and cannot participate in routing messages. The remaining power is reserved for sensing. The mobility management plane detects and registers the movement of sensor nodes, so a route back to the user is always maintained, and the sensor nodes can keep track of who are their neighbor sensor nodes. By knowing who are the neighbor sensor nodes, the sensor nodes can balance their power and task usage. The task management plane balances and schedules the sensing tasks given to a specific region. Not all sensor nodes in that region are required to perform the sensing task at the same time. As a result, some sensor nodes perform the task more than the others depending on their power level. These management planes are needed, so that sensor nodes can work together in a power efficient way, route data in a mobile sensor network, and share resources between sensor nodes. Without them, each sensor node will just work individually. From the whole sensor network standpoint, it is more efficient if sensor nodes can collaborate with each other, so the lifetime of the sensor networks can be prolonged. Before we discuss the need for the protocol layers and management planes in sensor networks, we map three existing work [42,69,77] to the protocol stack as shown in Fig. 3.

The so-called WINS is developed in [69], where a distributed network and Internet access is provided to the sensor nodes, controls, and processors. Since the sensor nodes are in large number, the WINS networks take advantage of this short distance between sensor nodes to provide multi hop communication and minimize power consumption. The way in which data is routed back to the user in the WINS networks follows the architecture specified in Fig. 2. The sensor node, i.e., a WINS node, detects the environmental data, and the data is routed hop by hop through the WINS nodes until it reaches the sink, i.e., a WINS gateway. So the WINS nodes are sensor nodes A, B, C, D, and E according to the architecture in Fig. 2. The WINS gateway communicates with the user through conventional network services, such as the Internet. The protocol stack of a WINS network consists of the application layer, network layer, MAC layer, and physical layer. Also, it is explicitly pointed out in [69] that a low-power protocol suite that addresses the constraints of the sensor networks should be developed.

The smart dust motes [42], i.e., sensor nodes, may be attached to objects or even float in the air because of their small size and light weight. They use MEMS technology for optical communication and sensing. These motes may contain solar cells to collect energy during the day, and they require a line of sight to communicate optically with the base station transceiver or other motes. Comparing the smart dust communication architecture with the one in Fig. 2, the smart dust mote, i.e., the sensor node, typically communicates directly with the base station transceiver, i.e., sink. A peer-to-peer communication is also possible, but there are possible collision problems in medium access due to "hidden nodes". The protocol layers in which the smart dust motes incorporate are application layer, MAC layer, and the physical layer.

Another approach to design protocols and algorithms for sensor networks is driven by the requirements of the physical layer [77]. The protocols and algorithms should be developed according to the choice of physical layer components, such as the type of micro-processors, and the type of receivers. This bottom–up approach of the μAMPS wireless sensor node also addresses the importance of the application layer, network layer, MAC layer, and physical layer as illustrated in Fig. 3 to be tightly integrated with the sensor node's hardware. The μAMPS wireless sensor node also communicates with the user according to the architecture specified in Fig. 2. Different schemes, such as time division multiple access (TDMA) versus frequency division multiple access (FDMA) and binary modulation versus M-ary modulation are compared in [77]. This bottom–up approach points out that sensor network algorithms have to be aware of the hardware and able to use special features of the micro-processors and transceivers to minimize the sensor node's power consumption. This may push toward a custom solution for different types of sensor node design. Different types of sensor nodes deployed also lead to different types of sensor networks. This may also lead to different types of collaborative algorithms.

4.1. Application layer

To the best of our knowledge, although many application areas for sensor networks are defined and proposed, potential application layer protocols for sensor networks remains a largely unexplored region. In this survey, we examine three possible application layer protocols, i.e., sensor management protocol (SMP), task assignment and data advertisement protocol (TADAP), and sensor query and data dissemination protocol (SQDDP), needed for sensor networks based on the proposed schemes related to the other layers and sensor network application areas. All of these application layer protocols are open research issues.

4.1.1. Sensor management protocol

Designing an application layer management protocol has several advantages. Sensor networks have many different application areas, and accessing them through networks such as Internet is aimed in some current projects [69]. An application layer management protocol makes the hardware and softwares of the lower layers transparent to the sensor network management applications.

System administrators interact with sensor networks by using SMP. Unlike many other networks, sensor networks consist of nodes that do not have global IDs, and they are usually infrastructureless. Therefore, SMP needs to access the nodes by using attribute-based naming and location-based addressing, which are explained in detail in Section 4.3.

SMP is a management protocol that provides the software operations needed to perform the following administrative tasks:

- introducing the rules related to data aggregation, attribute-based naming and clustering to the sensor nodes,
- exchanging data related to the location finding algorithms,

- time synchronization of the sensor nodes,
- moving sensor nodes,
- turning sensor nodes on and off,
- querying the sensor network configuration and the status of nodes, and re-configuring the sensor network, and
- authentication, key distribution and security in data communications.

The descriptions of some of these tasks are given in [20,23,66,74,75].

4.1.2. Task assignment and data advertisement protocol

Another important operation in the sensor networks is interest dissemination. Users send their interest to a sensor node, a subset of the nodes or whole network. This interest may be about a certain attribute of the phenomenon or a triggering event. Another approach is the advertisement of available data in which the sensor nodes advertise the available data to the users, and the users query the data which they are interested in. An application layer protocol that provides the user software with efficient interfaces for interest dissemination is useful for lower layer operations, such as routing as explained in Section 4.3.

4.1.3. Sensor query and data dissemination protocol

SQDDP provides user applications with interfaces to issue queries, respond to queries and collect incoming replies. Note that these queries are generally not issued to particular nodes. Instead, attribute-based or location-based naming is preferred. For instance, "the locations of the nodes that sense temperature higher than 70 °F" is an attribute-based query. Similarly, "temperatures read by the nodes in region *A*" is an example for location-based naming.

Sensor query and tasking language (SQTL) [75] is proposed as an application that provides even a larger set of services. SQTL supports three types of events, which are defined by keywords *receive*, *every*, and *expire*. Receive keyword defines events generated by a sensor node when the sensor node receives a message; every keyword defines events occurred periodically due to a timer time-out; and expire keyword defines the events occurred when a timer is expired. If a sensor node receives a message that is intended for it and contains a script, the sensor node then executes the script. Although SQTL is proposed, different types of SQDDP can be developed for various applications. The use of SQDDPs may be unique to each application.

4.1.4. Open research issues

Although SQTL is proposed, there are still other application layer protocols need to be developed to provide a greater level of services. As mentioned before, the SMP allows software to perform administrative tasks such as moving sensor nodes and time synchronization of the nodes. Research developments should also focus on the TADAP and SQDDP as described in Sections 4.1.2 and 4.1.3.

4.2. Transport layer

The need for transport layer is pointed out in the literature [69,71]. This layer is especially needed when the system is planned to be accessed through Internet or other external networks. However, to the best of our knowledge there has not been any attempt thus far to propose a scheme or to discuss the issues related to the transport layer of a sensor network in literature. TCP with its current transmission window mechanisms does match to the extreme characteristics of the sensor network environment. An approach such as TCP splitting [4] may be needed to make sensor networks interact with other networks such as Internet. In this approach, TCP connections are ended at sink nodes, and a special transport layer protocol can handle the communications between the sink node and sensor nodes. As a result, the communication between the user and the sink node is by UDP or TCP via the Internet or Satellite; on the other hand, the communication between the sink and sensor nodes may be purely by UDP type protocols, because each sensor node has limited memory.

Unlike protocols such as TCP, the end-to-end communication schemes in sensor networks are not based on global addressing. These schemes must consider that attribute-based naming is used to indicate the destinations of the data packets.

The attributed-based naming is described in Section 4.3. The factors such as power consumption and scalability, and the characteristics like data-centric routing makes sensor networks need different handling in transport layer. Thus, these requirements stress the need for new types of transport layer protocols.

4.2.1. Open research issues

The development of transport layer protocols is a challenging effort because the sensor nodes are influenced by the factors explained in Section 3, especially the hardware constraints such as the limited power and memory. As a result, each sensor node cannot store large amount of data like a server in the Internet, and acknowledgements are too costly for sensor networks. Therefore, new schemes that split the end-to-end communication probably at the sinks may be needed where UDP type protocols are used in the sensor network and traditional TCP/UDP protocols in the Internet or Satellite network.

4.3. Network layer

Sensor nodes are scattered densely in a field either close to or inside the phenomenon as shown in Fig. 2. As discussed in Section 1, special multihop wireless routing protocols between the sensor nodes and the sink node are needed. The ad hoc routing techniques already proposed in the literature [65] do not usually fit the requirements of the sensor networks due to the reasons explained in Section 1. The networking layer of sensor networks is usually designed according to the following principles:

- Power efficiency is always an important consideration.
- Sensor networks are mostly data centric.
- Data aggregation is useful only when it does not hinder the collaborative effort of the sensor nodes.
- An ideal sensor network has attribute-based addressing and location awareness.

One of the following approaches can be used to select an energy efficient route. We use Fig. 4 to describe each of these approaches, where node T is the source node that senses the phenomena. It has the following four possible routes to communicate with the sink:

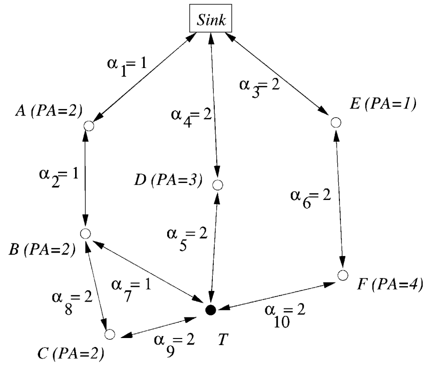

Fig. 4. The power efficiency of the routes.

- *Route 1*: Sink-A-B-T, total PA = 4, total $\alpha = 3$,
- *Route 2*: Sink-A-B-C-T, total PA = 6, total $\alpha = 6$,
- *Route 3*: Sink-D-T, total PA = 3, total $\alpha = 4$,
- *Route 4*: Sink-E-F-T, total PA = 5, total $\alpha = 6$,

where PA is the available power and α_i, the energy required to transmit a data packet through the related link.

- *Maximum available power (PA) route*: The route that has maximum total available power is preferred. The total PA is calculated by summing the PAs of each node along the route. Based on this approach, Route 2 is selected in Fig. 4. However, Route 2 includes the nodes in Route 1 and an extra node. Therefore, although it has a higher total PA, it is not a power efficient one. As a result, it is important not to consider the routes derived by extending the routes that can connect the sensor to the sink as an alternative route. Eliminating Route 2, we select Route 4 as our power efficient route when we use maximum PA scheme.
- *Minimum energy (ME) route*: The route that consumes ME to transmit the data packets between the sink and the sensor node is the ME route. As shown in Fig. 4, Route 1 is the ME route.

- *Minimum hop (MH) route*: The route that makes the MH to reach the sink is preferred. Route 3 in Fig. 4 is the most efficient route based on this scheme. Note that the ME scheme selects the same route as the MH when the same amount of energy, i.e., all α are the same, is used on every link. Therefore, when nodes broadcast with same power level without any power control, MH is then equivalent to ME.
- *Maximum minimum PA node route*: The route along which the minimum PA is larger than the minimum PAs of the other routes is preferred. In Fig. 4, Route 3 is the most efficient and Route 1 is the second efficient paths. This scheme precludes the risk of using up a sensor node with low PA much earlier than the others because they are on a route with nodes which has very high PAs.

Another important issue is that routing may be based on data centric. In data-centric routing, the interest dissemination is performed to assign the sensing tasks to the sensor nodes. There are two approaches used for interest dissemination: sinks broadcast the interest [39], and sensor nodes broadcast an advertisement for the available data [35] and wait for a request from the interested sinks.

The data-centric routing requires attribute-based naming [20,22,54,75]. For attribute-based naming, the users are more interested in querying an attribute of the phenomenon, rather than querying an individual node. For instance,"the areas where the temperature is over 70 °F" is a more common query than "the temperature read by a certain node". The attribute-based naming is used to carry out queries by using the attributes of the phenomenon. The attribute-based naming also makes broadcasting, attribute-based multicasting, geo-casting and any-casting important for sensor networks.

The data aggregation is a technique used to solve the implosion and overlap problems in data-centric routing [35]. In this technique, a sensor network is usually perceived as a reverse multicast tree as shown in Fig. 5 where the sink asks the sensor nodes to report the ambient condition of the phenomena. Data coming from multiple sensor nodes are aggregated as if they are about the same attribute of the phenomenon when they reach the same routing node on the way back to the sink. For example, sensor node E aggregates the data from sensor nodes A and B while sensor node F aggregates the data from sensor nodes C and D as shown in Fig. 5. Data aggregation can be perceived as a set of automated methods of combining the data that comes from many sensor nodes into a set of meaningful information [34]. With this respect, data aggregation is known as data fusion [35]. Also, care must be taken when aggregating data, because the specifics of the data, e.g., the locations of reporting sensor nodes, should not be left out. Such specifics may be needed by certain applications.

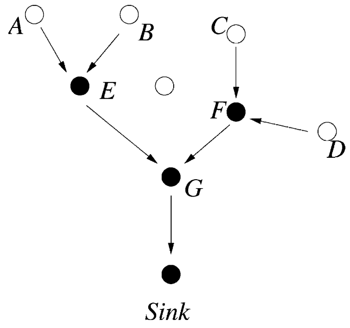

Fig. 5. Example of data aggregation.

One other important function of the network layer is to provide internetworking with external networks such as other sensor networks, command and control systems and the Internet. In one scenario, the sink nodes can be used as a gateway to other networks. While another scenario is creating a backbone by connecting sink nodes together and making this backbone access other networks via a gateway.

To provide insight into current research on the networking layer, we discuss different schemes proposed for the sensor networks for the rest of this section.

Small minimum energy communication network (SMECN): A protocol is developed in [73], which computes an energy efficient subnetwork, namely the MECN, when a communication network is given. A new algorithm called SMECN is proposed by [48] to also provide such a subnetwork.

The subnetwork, i.e., subgraph, constructed by SMECN is smaller than the one that is constructed by MECN if the broadcast region is circular around a broadcaster for a given power setting. The subgraph G of the graph G', which represents the sensor network, minimizes the energy usage satisfying the following conditions: the number of edges in G is less than in G' while containing all nodes in G'; if two nodes, u and v, are connected in graph G', they are also connected in subgraph G; the energy required to transmit data from node u to all its neighbors in subgraph G is less than the energy required to transmit to all its neighbors in graph G'. The SMECN also follows the ME property, which MECN uses to construct the subnetwork. The ME property is such that there exists a ME path in subgraph G between node u and v for every pair (u, v) of nodes that are connected in G'.

The power required to transmit data between node u and v is modelled as $p(u, v) = td(u, v)^n$, where t is a constant; $d(u, v)$, the distance between node u and v; and $n \geqslant 2$, the path-loss exponent experienced by radio transmission. Also, the power needed to receive data is c. Since $p(u, v)$ increases by nth power of the distance between node u and v, it may take less power to relay data than directly transmit data between node u and v. The path between node u (i.e., u_0) and v (i.e., u_k) is represented by r, where $r = (u_0, u_1, \ldots, u_k)$ in the subgraph $G = (V, E)$ is an ordered list of nodes such that the pair $(u_i, u_{i+1}) \in E$. Also, the length of r is k. The total power consumption between node u_0 and u_k is

$$C(r) = \sum_{i=0}^{k-1} (p(u_i, u_{i+1}) + c) \qquad (5)$$

where $p(u_i, u_{i+1})$ is the power required to transmit data between node u_i, and u_{i+1}; and c, the power required to receive data. A path r is a ME path from u_0 to u_k if $C(r) \leqslant C(r')$ for all paths r' between node u_0 and u_k in G'. As a result, a subgraph G has the ME property if for all $(u, v) \in V$, there exists a path r in G, which is a ME path in G' between node u and v.

Flooding: Flooding is an old technique that can also be used for routing in sensor networks. In flooding, each node receiving a data or management packet repeats it by broadcasting, unless a maximum number of hops for the packet is reached or the destination of the packet is the node itself. Flooding is a reactive technique, and it does not require costly topology maintenance and complex route discovery algorithms. However, it has several deficiencies such as [35]:

- *Implosion*: Implosion is a situation where duplicated messages are sent to the same node. For example, if sensor node A has N neighbor sensor nodes that are also the neighbors of sensor node B, the sensor node B receives N copies of the message sent by sensor node A.
- *Overlap*: If two nodes share the same observing region, both of them may sense the same stimuli at the same time. As a result, neighbor nodes receive duplicated messages.
- *Resource blindness*: The flooding protocol does not take into account of the available energy resources. An energy resource aware protocol must take into account the amount of energy available to them at all time.

Gossiping: A derivation of flooding is gossiping [32] in which nodes do not broadcast but send the incoming packets to a randomly selected neighbor. A sensor node randomly selects one of its neighbors to send the data. Once the neighbor node receives the data, it selects randomly another sensor node. Although this approach avoid the implosion problem by just having one copy of a message at any node, it takes long time to propagate the message to all sensor nodes.

Sensor protocols for information via negotiation (SPIN): A family of adaptive protocols called SPIN [35] is designed to address the deficiencies of classic flooding by negotiation and resource adaptation. The SPIN family of protocols are designed based on two basic ideas: sensor nodes operate more efficiently and conserve energy by sending data that describe the sensor data instead of sending the whole data, e.g., image, and sensor nodes must monitor the changes in their energy resources.

SPIN has three types of messages, i.e., ADV, REQ, and DATA. Before sending a DATA

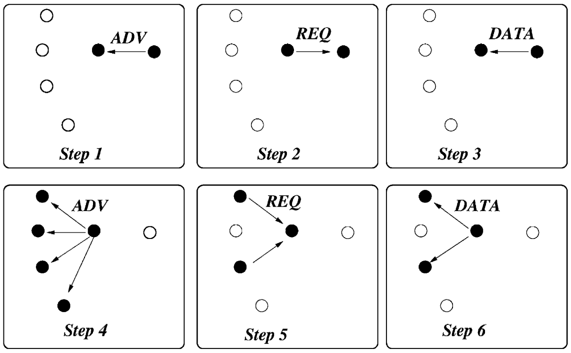

Fig. 6. The SPIN protocol [35].

message, the sensor broadcasts an ADV message containing a descriptor, i.e., meta-data, of the DATA as shown in Step 1 of Fig. 6. If a neighbor is interested in the data, it sends a REQ message for the DATA and DATA is sent to this neighbor sensor node as shown in Steps 2 and 3 of Fig. 6, respectively. The neighbor sensor node then repeats this process as illustrated in Steps 4, 5, and 6 of Fig. 6. As a result, the sensor nodes in the entire sensor network, which are interested in the data, will get a copy.

Note that SPIN is based on data-centric routing [35] where the sensor nodes broadcast an advertisement for the available data and wait for a request from interested sinks.

Sequential assignment routing (SAR): In [83], a set of algorithms, which perform organization, management and mobility management operations in sensor networks, are proposed. Self-organizing MAC for sensor networks (SMACS) is a distributed protocol that enables a collection of sensor nodes to discover their neighbors and establish transmission/reception schedules without the need for a central management system. The eavesdrop and register (EAR) algorithm is designed to support seamless interconnection of the mobile nodes. The EAR algorithm is based on the invitation messages and on the registration of stationary nodes by the mobile nodes. The SAR algorithm creates multiple trees where the root of each tree is an one hop neighbor from the sink. Each tree grows outward from the sink while avoiding nodes with very low QoS (i.e., low throughput/high delay) and energy reserves. At the end of this procedure, most nodes belong to multiple trees. This allows a sensor node to choose a tree to relay its information back to the sink. There are two parameters associated with each path, i.e., a tree, back to the sink:

- *Energy resources*: The energy resources is estimated by the number of packets, which the sensor node can send, if the sensor node has exclusive use of the path.
- *Additive QoS metric*: A high additive QoS metric means low QoS.

The SAR algorithm selects the path based on the energy resources and additive QoS metric of each path, and the packet's priority level. As a result, each sensor node selects its path to route the data back to the sink.

Also, two more algorithms called single winner election and multiwinner election handle the necessary signaling and data transfer tasks in local cooperative information processing.

Low-energy adaptive clustering hierarchy (LEACH): LEACH is a clustering-based protocol that minimizes energy dissipation in sensor networks [34]. The purpose of LEACH is to randomly select sensor nodes as cluster-heads, so the high-energy dissipation in communicating with the base station is spread to all sensor nodes in the sensor network. The operation of LEACH is separated into two phases, the set-up phase and the steady phase. The duration of the steady phase is longer than the duration of the set-up phase in order to minimize the overhead.

During the set-up phase, a sensor node chooses a random number between 0 and 1. If this random number is less than the threshold $T(n)$, the sensor node is a cluster-head. $T(n)$ is calculated as

$$T(n) = \begin{cases} \dfrac{P}{1 - P[r \bmod (1/P)]} & \text{if } n \in G, \\ 0 & \text{otherwise,} \end{cases}$$

where P is the desired percentage to become a cluster-head; r, the current round; and G, the set of nodes that have not being selected as a cluster-head in the last $1/P$ rounds. After the cluster-heads are selected, the cluster-heads advertise to all sensor nodes in the network that they are the new cluster-heads. Once the sensor nodes receive the advertisement, they determine the cluster that they want to belong based on the signal strength of the advertisement from the cluster-heads to the sensor nodes. The sensor nodes inform the appropriate cluster-heads that they will be a member of the cluster. Afterwards, the cluster-heads assign the time on which the sensor nodes can send data to the cluster-heads based on a TDMA approach.

During the steady phase, the sensor nodes can begin sensing and transmitting data to the cluster-heads. The cluster-heads also aggregate data from the nodes in their cluster before sending these data to the base station. After a certain period of time spent on the steady phase, the network goes into the set-up phase again and entering into another round of selecting the cluster-heads.

Directed diffusion: The directed diffusion data dissemination paradigm is proposed in [39] where the sink sends out interest, which is a task description, to all sensors as shown in Fig. 7(a). The task descriptors are named by assigning attribute-value pairs that describe the task. Each sensor node then stores the interest entry in its cache. The interest entry contains a timestamp field and several gradient fields. As the interest is propagated throughout the sensor network, the gradients from the source back to the sink are set up as shown in Fig. 7(b). When the source has data for the interest, the source sends the data along the interest's gradient path as shown in Fig. 7(c). The interest and data propagation and aggregation are determined locally. Also, the sink must refresh and reinforce the interest when it starts to receive data from the source. Note that the directed diffusion is based on data-centric routing where the sink broadcasts the interest.

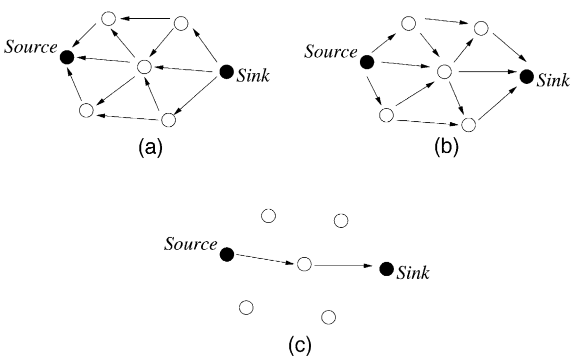

Fig. 7. An example of directed diffusion [39]: (a) propagate interest, (b) set up gradient and (c) send data.

4.3.1. Open research issues

An overview of the protocols proposed for sensor networks is given in Table 2. These protocols need to be improved or new protocols need to be developed to address higher topology changes and higher scalability. Also, new internetworking schemes should be developed to allow easy communication between the sensor networks and external networks, e.g., Internet.

4.4. Data link layer

The data link layer is responsible for the multiplexing of data streams, data frame detection, medium access and error control. It ensures reliable point-to-point and point-to-multipoint connections in a communication network. In the following two subsections, we discuss some of the medium access and error control strategies for sensor networks.

4.4.1. Medium access control

The MAC protocol in a wireless multihop self-organizing sensor network must achieve two goals. The first is the creation of the network infrastructure. Since thousands of sensor nodes are densely scattered in a sensor field, the MAC scheme must establish communication links for data transfer. This forms the basic infrastructure needed for wireless communication hop by hop and gives the sensor network self-organizing ability. The second objective is to fairly and efficiently share communication resources between sensor nodes. Traditional MAC schemes can all be categorized based on their resource sharing mechanisms. Table 3 provides an insight into the advantages and disadvantages, and application domains of these classes.

Reasons why existing MAC protocols cannot be used: It has been emphasized in earlier sections

Table 2
An overview of network layer schemes

Network layer scheme	Description
SMECN [48]	Creates a subgraph of the sensor network that contains the ME path
Flooding	Broadcasts data to all neighbor nodes regardless if they receive it before or not
Gossiping [32]	Sends data to one randomly selected neighbor
SPIN [35]	Sends data to sensor nodes only if they are interested; has three types of messages, i.e., ADV, REQ, and DATA
SAR [83]	Creates multiple trees where the root of each tree is one hop neighbor from the sink; select a tree for data to be routed back to the sink according to the energy resources and additive QoS metric
LEACH [34]	Forms clusters to minimize energy dissipation
Directed diffusion [39]	Sets up gradients for data to flow from source to sink during interest dissemination

Table 3
Categorization of MAC protocols

Category	Resource sharing mode	Application domain	Disadvantages
Dedicated assignment or fixed allocation	Pre-determined fixed allocation	Appropriate for continuous traffic and provides bounded delay	Inefficient for bursty traffic
Demand based	According to demand or user request	Useful for variable rate and multimedia traffic	Additional overhead and delay due to reservation process
Random access or contention based	Channel contention when transmission packets are available	Suitable for bursty traffic	Inefficient for delay-sensitive traffic

that novel protocols and algorithms are needed to effectively tackle the unique resource constraints and application requirements of sensor networks. To illustrate the impact of these constraints, let us take a closer look at MAC schemes in other wireless networks and analyze why they cannot be adopted into the sensor network scenario.

In a cellular system, the base stations form a wired backbone. A mobile node is only a single hop away from the nearest base station. This type of network is also referred to as infrastructure based in literature. The primary goal of the MAC protocol in such systems is the provision of high QoS and bandwidth efficiency. Power conservation assumes only secondary importance as base stations have unlimited power supply and the mobile user can replenish exhausted batteries in the handset. Hence, medium access is invariably inclined toward a dedicated resource assignment strategy. Such an access scheme is impractical for sensor networks as there is no central controlling agent like the base station. This makes network-wide synchronization a difficult proposition. Moreover, power efficiency directly influences network lifetime in a sensor network and hence is of prime importance.

Bluetooth and the mobile ad hoc network (MANET) are probably the closest peers to the sensor networks. Bluetooth is an infrastructure-less short-range wireless system intended to replace the cable between electronic user terminals with RF links. The Bluetooth topology is a star network where a master node can have up to seven slave nodes wirelessly connected to it to form a piconet. Each piconet uses a centrally assigned TDMA schedule and frequency hopping pattern. Transmission power is typically around 20 dBm and the transmission range is of the order of tens of meters. The MAC protocol in a MANET has the task of forming the network infrastructure and maintaining it in the face of mobility. Hence, the primary goal is the provision of high QoS under mobile conditions. Although the nodes are portable battery-powered devices, they can be replaced by the user and hence, power consumption is only of secondary importance.

In contrast to these two systems, the sensor network may have a much larger number of nodes. The transmission power (∼0 dBm) and radio range of a sensor node is much less than those of the Bluetooth or the MANET. Topology changes are more frequent in a sensor network and can be attributed both to node mobility and failure. The mobility rate can also be expected to be much lower than in the MANET. In essence, the primary importance of power conservation to prolong network lifetime in a sensor network means that none of the existing Bluetooth or MANET MAC protocols can be directly used.

MAC for sensor networks: It is evident from our previous discussions that the MAC protocol for sensor networks must have built-in power conservation, mobility management and failure recovery strategies. Though many schemes for medium access have been proposed for MANETs [85,94,95] the design of an efficient MAC scheme for the new regime of sensor networks is still an open research issue. Thus far, both *fixed allocation* and *random access* versions of medium access have been proposed [83,93]. *Demand-based* MAC schemes may be unsuitable for sensor networks due their large messaging overhead and link set-up delay. Power conservation is achieved by the use of power saving operation modes and by preferring time-outs to acknowledgements, wherever possible.

It has been reasoned in [69] that since radios must be turned off during idling for precious power savings, the MAC scheme should include a variant of TDMA. Such a medium access mechanism is presented in [83]. Further, contention-based channel access is deemed unsuitable due to their requirement to monitor the channel at all times. It must be noted however, that random medium access can also support power conservation, as in the IEEE 802.11 standard for WLANs, by turning off radios depending on the status of the net allocation vector. Constant listening times and adaptive rate control schemes can also help achieve energy efficiency in random access schemes for sensor networks [93]. Some of the proposed MAC protocols are discussed next.

SMACS and the EAR algorithm: The SMACS protocol [83] achieves network start-up and link-layer organization, and the EAR algorithm enables seamless connection of mobile nodes in a sensor network. SMACS is a distributed infrastructure-building protocol which enables nodes to discover their neighbors and establish transmission/reception schedules for communication without the need for any local or global master nodes. In this protocol, the neighbor discovery and channel assignment phases are combined so that by the time nodes hear all their neighbors, they would have formed a connected network. A communication link consists of a pair of time slots operating at a randomly chosen, but fixed frequency (or frequency hopping sequence). This is a feasible option in sensor networks, since, as mentioned earlier in Section 3.7, the available bandwidth can be expected to be much higher than the maximum data rate for sensor nodes. Such a scheme avoids the necessity for network-wide synchronization, although communicating neighbors in a subnet need to be time synchronized. *Power conservation* is achieved by using a random wake-up schedule during the connection phase and by turning the radio off during idle time slots.

The EAR protocol [83] attempts to offer continuous service to the mobile nodes under both mobile and stationary conditions. Here, the mobile nodes assume full control of the connection process and also decide when to drop connections, thereby minimizing messaging overhead. The EAR is transparent to the SMACS, so that the SMACS is functional until the introduction of mobile nodes into the network. In this model, the network is assumed to be mainly static, i.e., any mobile node has a number of stationary nodes in its vicinity. A drawback of such a time-slot assignment scheme is the possibility that members already belonging to different subnets might never get connected.

CSMA based medium access: A CSMA based MAC scheme for sensor networks is presented in [93]. Traditional CSMA based schemes are deemed inappropriate as they all make the fundamental assumption of stochastically distributed traffic and tend to support independent point-to-point flows. On the contrary, the MAC protocol for sensor networks must be able to support variable, but highly correlated and dominantly periodic traffic. Any CSMA based medium access scheme has two important components, the *listening mechanism* and the *backoff scheme*. As reported and based on simulations in [93], the constant listen periods are energy efficient and the introduction of random delay provides robustness against repeated collisions. Fixed window and binary exponential decrease backoff schemes are recommended to maintain proportional fairness in the network. A phase change at the application level is also advocated to get over any capturing effects. It is proposed in this work that the energy consumed per unit of successful communication can serve as a good indicator of *energy efficiency*.

An adaptive transmission rate control (ARC) scheme, that achieves medium access fairness by balancing the rates of originating and route-thru traffic is also discussed here. This ensures that nodes closer to the access point are not favored over those deep down into the network. The ARC controls the data origination rate of a node in order to allow the route-thru traffic to propagate. A progressive signalling mechanism is used to inform the nodes to lower their data originating rate. The ARC uses a linear increase and multiplicative decrease approach [57]. While the linear increase leads to more aggressive channel competition, the multiplicative decrease controls transmission failure penalty. Since dropping route-thru traffic is costlier, the associated penalty is lesser than that for originating data transmission failure. This ensures that route-thru traffic is preferred over the originating traffic.

The computational nature of this scheme makes it more energy efficient than handshaking and messaging schemes using the radio. The ARC also attempts to reduce the problem of hidden nodes in a multihop network by constantly tuning the transmission rate and performing phase changes, so that periodic streams are less likely to repeatedly collide.

Hybrid TDMA/FDMA based: This centrally controlled MAC scheme is introduced in [77]. In this work, the effect of non-ideal physical layer electronics on the design of MAC protocols for sensor networks is investigated. The system is assumed to be made up of energy constrained sensor nodes that communicate to a single, nearby, high-powered base station (<10 m). Specifically, the machine monitoring application of sensor networks, with strict data latency requirements, is considered and a hybrid TDMA–FDMA medium access scheme is proposed. While a pure TDMA scheme dedicates the full bandwidth to a single sensor node, a pure FDMA scheme allocates minimum signal bandwidth per node. Despite the fact that a pure TDMA scheme minimizes the transmit on-time, it is not always preferred due to the associated time synchronization costs. An analytical formula is derived in [77] to find the optimum number of channels which gives the lowest system *power consumption*. This determines the hybrid TDMA–FDMA scheme to be used. The optimum number of channels is found to depend on the ratio of the power consumption of the transmitter to that of the receiver. If the transmitter consumes more power, a TDMA scheme is favored, while the scheme leans toward FDMA when the receiver consumes greater power.

To get a deeper insight into the salient features and effectiveness of MAC protocols for sensor networks, we present a qualitative overview in Table 4. It also serves as an indicator for comparative evaluation of some of the MAC schemes

Table 4
Qualitative overview of MAC protocols for sensor networks

MAC protocol	Channel access mode	Sensor network specifics	Power conservation
SMACS and EAR [83]	Fixed allocation of duplex time slots at fixed frequency	Exploitation of large available bandwidth compared to sensor data rate	Random wake up during set-up and turning radio off while idle
Hybrid TDMA/FDMA [77]	Centralized frequency and time division	Optimum number of channels calculated for minimum system energy	Hardware based approach for system energy minimization
CSMA based [93]	Contention-based random access	Application phase shift and pre-transmit delay	Constant listening time for energy efficiency

proposed thus far in literature. The column titled *sensor network specifics* aims to illustrate the novel and important features in each of these schemes that enable their application in the sensor network domain. They present the deviations and differences from traditional MAC schemes, which by themselves would not be applicable. We also outline how each of these schemes achieves power efficiency.

4.4.2. Power saving modes of operation

Regardless of which type of medium access scheme is used for sensor networks, it certainly must support the operation of power saving modes for the sensor node. The most obvious means of power conservation is to turn the transceiver off when it is not required. Though this power saving method seemingly provides significant energy gains, an important point that must not be overlooked is that sensor nodes communicate using short data packets. As explained in Section 3.8.1, the shorter the packets, the more the dominance of start-up energy. In fact, if we blindly turn the radio off during each idling slot, over a period of time, we might end up expending more energy than if the radio had been left on. As a result, operation in a power saving mode is energy efficient only if the time spent in that mode is greater than a certain threshold. There can be a number of such useful modes of operation for the wireless sensor node, depending on the number of states of the micro-processor, memory, A/D convertor and the transceiver. Each of these modes can be characterized by its power consumption and the latency overhead, which is the transition power to and from that mode. A dynamic power management scheme for wireless sensor networks is discussed in [80] where five power saving modes are proposed and intermode transition policies are investigated. The threshold time is found to depend on the transition times and the individual power consumption of the modes in question.

4.4.3. Error control

Another important function of the data link layer is the error control of transmission data. Two important modes of error control in communication networks are the forward error correction (FEC) and automatic repeat request (ARQ). To the best of our knowledge, the application of ARQ schemes is thus far unexplored in the regime of sensor networks, though many adaptive and low-power versions are existent in literature for other mobile networks [44,97]. The usefulness of ARQ in sensor network applications is limited by the additional re-transmission cost and overhead. On the other hand, decoding complexity is greater in FEC, as error correction capabilities need to be built-in. Considering this, simple error control codes with low-complexity encoding and decoding might present the best solutions for sensor networks. In the design of such a scheme it is important to have good knowledge of the channel characteristics and implementation techniques. In the following subsection, we briefly review the motivation and basic design considerations for FEC, which in turn will help us understand the requirements for sensor networks.

FEC: Link reliability is an important parameter in the design of any wireless network, and more so in sensor networks, due to the unpredictable and harsh nature of channels encountered in various application scenarios. Some of the applications like mobile tracking and machine monitoring require high data precision. Channel bit error rate (BER) is a good indicator of link reliability. The BER can be shown to be directly proportional to the symbol rate R_s and inversely proportional to both the received SNR (E_s/N_0) and the transmitter power level P_{out}. Let us assume that a coding scheme with rate R is used. If the data symbol transmission rate remains the same as that before coding, the total symbol transmission rate must increase to R_s/R. Also, if the transmission power is unchanged, the received energy per symbol decreases to RE_s. The BER measured at the decoder input, the raw BER, is hence greater than the BER without coding. This loss is overcome in the decoder by exploiting the redundancy and structure of the code to correct some of the transmission errors. In fact, a good choice of the error correcting code can result in several orders of magnitude reduction in BER and an overall gain. The *coding gain* is generally expressed in terms of the additional transmit power needed to obtain the same BER without coding. A simple (15,11) Hamming code is found to reduce BER by almost 10^3 and ensures a coding gain of 1.5 dB for binary phase shift keying modulated data and additive white Gaussian noise model [92].

Reliable data communication can hence be provided either by increasing the output transmit power (P_{out}) or the use of suitable FEC. Since a sensor node has limited power resources, the former option is not feasible. We hence turn to FEC. As we have seen, FEC can achieve significant reduction in the BER for any given value of P_{out}. However, we must take into account the *additional processing power that goes into encoding and decoding*. This processing power is drawn from the limited resources possessed by the node. This might be critical for sensor networks though it can be negligibly small in other wireless networks. If the associated processing power is greater than the coding gain, then the whole process in energy inefficiency and the system is better off without coding. On the other hand, FEC is a valuable asset in sensor networks, if the sum of the encoding and decoding processing powers is less than the transmission power savings. It is to be noted that all these computations and comparisons must be carried out for a given, in most cases application specific, BER.

Though adaptive FEC has received some attention in other wireless networks, it remains largely unexplored in sensor networks. The impact of adapting packet size and error control on energy efficiency in wireless systems is investigated in [47,58]. In [76], the authors examine this issue for sensor networks. They assume a frequency non-selective, slow Rayleigh fading channel and use convolutional codes for FEC. Based on their analysis, they conclude that the average energy consumption per useful bit shows an exponential increase with the constraint length of the code and is independent of the code rate. Moreover, they find that FEC is generally inefficient if the decoding is performed using a micro-processor and recommend an on-board dedicated Viterbi decoder. To the best of our knowledge, other coding schemes remain unexplored. Simple encoding techniques that enable easy decoding might present an energy efficient solution for sensor networks.

4.4.4. Open research issues

Though some medium access schemes have been proposed for sensor networks, the area is still largely open to research. So is the mainly unexplored domain of error control in sensor networks. Key open research issues include:

- *MAC for mobile sensor networks*: The proposed SMACS and EAR [83] perform well only in a mainly static sensor networks. It is assumed in the connection schemes that a mobile node has many static nodes as neighbors. These algorithms must be improved to deal with more extensive mobility in the sensor nodes and targets. Mobility issues, carrier sensing, and backoff mechanisms for the CSMA based scheme also remain largely unexplored.
- *Determination of lower bounds on the energy required for sensor network self-organization.*
- *Error control coding schemes*: Error control is extremely important in some sensor network applications like mobile tracking and machine monitoring. Convolutional coding effects have been considered in [77]. The feasibility of other error control schemes in sensor networks needs to be explored.
- *Power saving modes of operation*: To prolong network lifetime, a sensor node must enter into periods of reduced activity when running low on battery power. The enumeration and transition management for these nodes is open to research. Some ideas are outlined in [80].

4.5. Physical layer

The physical layer is responsible for frequency selection, carrier frequency generation, signal detection, modulation and data encryption. Frequency selection aspects have been dealt with in Section 3.7. Frequency generation and signal detection have more to do with the underlying hardware and transceiver design and hence are beyond the scope of our paper. In the following, we focus on signal propagation effects, power efficiency and modulation schemes for sensor networks.

It is well known that long-distance wireless communication can be expensive, both in terms of energy and implementation complexity. While designing the physical layer for sensor networks, energy minimization assumes significant importance, over and above the decay, scattering, shadowing, reflection, diffraction, multipath and fading effects. In general, the minimum output power required to transmit a signal over a distance d is proportional to d^n, where $2 \leqslant n < 4$. The exponent n is closer to four for low-lying antennae and near-ground channels [72,82], as is typical in sensor network communication. This can be attributed to the partial signal cancellation by a ground-reflected ray. While trying to resolve these problems, it is important that the designer is aware of inbuilt diversities and exploits this to the fullest. For instance, multihop communication in a sensor network can effectively overcome shadowing and path-loss effects, if the node density is high enough. Similarly, while propagation losses and channel capacity limit data reliability, this very fact can be used for spatial frequency re-use. Energy efficient physical layer solutions are currently being pursued by researchers. Although some of these topics have been addressed in literature, it still remains a vastly unexplored domain of the wireless sensor networks. A discussion of some existing ideas follows.

The choice of a good modulation scheme is critical for reliable communication in a sensor network. Binary and M-ary modulation schemes are compared in [77]. While an M-ary scheme can reduce the transmit on-time by sending multiple bits per symbol, it results in complex circuitry and increased radio power consumption. These trade-off parameters are formulated in [76] and it is concluded that under start-up power dominant conditions, the binary modulation scheme is more energy efficient. Hence, M-ary modulation gains are significant only for low start-up power systems. A low-power direct-sequence spread-spectrum modem architecture for sensor networks is presented in [13]. This low-power architecture can be mapped to an ASIC technology to further improve efficiency.

Ultrawideband (UWB) or impulse radio (IR) has been used for baseband pulse radar and ranging systems and has recently drawn considerable interest for communication applications [18], especially in indoor wireless networks [53]. UWB employs baseband transmission and thus, it requires no intermediate or radio carrier frequencies. Generally, pulse position modulation is used. The main advantage of UWB is its resilience to multipath [17,45,46]. Low transmission power and simple transceiver circuitry, make UWB an attractive candidate for sensor networks.

4.5.1. Open research issues

The physical layer is a largely unexplored area in sensor networks. Open research issues range from power efficient transceiver design to modulation schemes. A few of these are given below

- *Modulation schemes*: Simple and low-power modulation schemes need to be developed for sensor networks. The modulation scheme can be either baseband, as in UWB, or passband.
- *Strategies to overcome signal propagation effects*: Signal propagation effects in sensor networks have been dealt with in Section 4.5.
- *Hardware design*: Tiny, low-power, low-cost transceiver, sensing and processing units need to be designed. Power efficient hardware management strategies are also essential.

5. Conclusion

The flexibility, fault tolerance, high sensing fidelity, low-cost and rapid deployment characteristics of sensor networks create many new and exciting application areas for remote sensing. In the future, this wide range of application areas will make sensor networks an integral part of our lives. However, realization of sensor networks needs to satisfy the constraints introduced by factors such as fault tolerance, scalability, cost, hardware, topology change, environment and power consumption. Since these constraints are highly stringent and specific for sensor networks, new wireless ad hoc networking techniques are required. Many researchers are currently engaged in developing the technologies needed for different layers of the sensor networks protocol stack as shown in Fig. 3. A list of current sensor networks

Table 5
Current research projects

Project name	Research area	HTTP location
SensoNet [3]	Transport, network, data link and physical layers Power control, mobility and task management planes	http://www.ece.gatech.edu/research/labs/bwn/
WINS [22,69]	Distributed network and Internet access to sensors, controls, and processors	http://www.janet.ucla.edu/WINS/
SPIN [35]	Data dissemination protocols	http://nms.lcs.mil.edu/projects/leach
SPINS [66]	Security protocol	http://paris.cs.berkeley.edu/~*perrig/projects.html*
SINA [75,84]	Information networking architecture	http://www.eecis.udel.edu/~cshen/
μAMPS [77]	Framework for implementing adaptive energy-aware distributed microsensors	http://www-mtl.mil.edu/research/icsystems/uamps/
LEACH [34]	Cluster formation protocol	http://nms.lcs.mit.edu/projects/leach
Smart dust [42]	Laser communication from a cubic millimeter Mote delivery SubmicroWatt electronics Power sources MacroMotes (COTS Dust)	http://robotics.eecs.berkeley.edu/~pister/SmartDust/
SCADDS [8,11,20,22,23,27,33,39,96]	Scalable coordination architectures for deeply distributed and dynamic systems	http://www.isi.edu/scadds/
PicoRadio [70,71]	Develop a "system-on-chip" implementation of a PicoNode	http://bwrc.eecs.berkeley.edu/Research/Pico_Radio/PicoNode.htm
PACMAN [79]	Mathematical framework that incorporates key features of computing nodes and networking elements	http://pacman.usc.edu
Dynamic sensor networks [19]	Routing and power aware sensor management Network services API	http://www.east.isi.edu/DIVl0/dsn/
Aware home [36]	Requisite technologies to create a home environment that can both perceive and assist its occupants	http://www.cc.gatech.edu/fce/ahri
COUGAR device database project [7]	Distributed query processing	http://www.cs.cornell.edu/database/cougar/index.htm
DataSpace [38]	Distributed query processing	http://www.cs.rutgers.edu/dataman

research projects is given in Table 5. Along with the current research projects, we encourage more insight into the problems and more development in solutions to the open research issues as described in this paper.

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