A Survey on Sensor Networks

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ABSTRACT

Recent advancement in wireless communications and electronics has enabled the development of low-cost sensor networks. The sensor networks can be used for various application areas (e.g., health, military, home). For different application areas, there are different technical issues that researchers are currently resolving. The current state of the art of sensor networks is captured in this article, where solutions are discussed under their related protocol stack layer sections. This article also points out the open research issues and intends to spark new interests and developments in this field.

INTRODUCTION

Recent advances in wireless communications and 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. Sensor networks represent a significant improvement over traditional sensors.

A sensor network is composed of a large number of sensor nodes that are densely deployed either inside the phenomenon or very close to it. The position of sensor nodes need not be engineered or predetermined. 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 onboard processor. Instead of sending the raw data to the nodes responsible for the fusion, they 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 home. In military, for example, the rapid deployment, self-organization, and fault tolerance characteristics of sensor networks make them a very promising sensing technique for military *command*, *control*, *communications*, *computing*, *intelligence*, *surveillance*, *reconnaissance*, and *targeting systems*. In health, sensor nodes can also be deployed to monitor patients and assist disabled patients. Some other commercial applications include *managing inventory*, *monitoring product quality*, and *monitoring disaster areas*.

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 to the unique features and application requirements of sensor networks. To illustrate this point, the differences between sensor networks and ad hoc networks are:
- 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 a 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.

Many researchers are currently engaged in developing schemes that fulfill these requirements.

In this article 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 emerging 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 article is organized as follows. We discuss the communication architecture of the sensor networks as well as the factors that influence sensor network design. We provide a detailed investigation of current proposals in the physical, data link, network, transport, and application layers, respectively. We then conclude our article.

Sensor Networks Communication Architecture

The sensor nodes are usually scattered in a *sensor field* as shown in Fig. 1. Each of these scattered sensor nodes has the capabilities to collect data and route data back to the *sink*. Data are routed back to the sink by a multihop infrastructureless architecture through the sink as shown in Fig. 1. The sink may communicate with the *task manager node* via Internet or satellite. The design of the sensor network as described by Fig. 1 is influenced by many factors, including *fault tolerance*, *scalability*, *production costs*, *operating environment*, *sensor network topology*, *hardware constraints*, *transmission media*, and *power consumption*.

Design Factors

The design factors are addressed by many researchers as surveyed in this article. However, none of these studies has a fully integrated view of all the factors 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.

Fault Tolerance — Some sensor nodes may fail or be blocked due to lack of power, or 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 [1, 2]. The reliability $R_k(t)$ or fault tolerance of a sensor node is modeled in [2] using the Poisson distribution to capture the probability of not having a failure within the time interval $(0,t)$:

$$R_k(t) = e^{-\lambda_k t}, \tag{1}$$

where λ_k is the failure rate of sensor node k and t is the time period.

Scalability — The number of sensor nodes deployed in studying a phenomenon may be on the order of hundreds or thousands. Depending on the application, the number may reach an extreme value of millions. New schemes must be able to work with this number of nodes. They must also utilize the high density 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. The density μ can be calculated according to [3] as

$$\mu(R) = (N \cdot \pi R^2)/A, \tag{2}$$

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

Production Costs — Since 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 network. If the cost of the
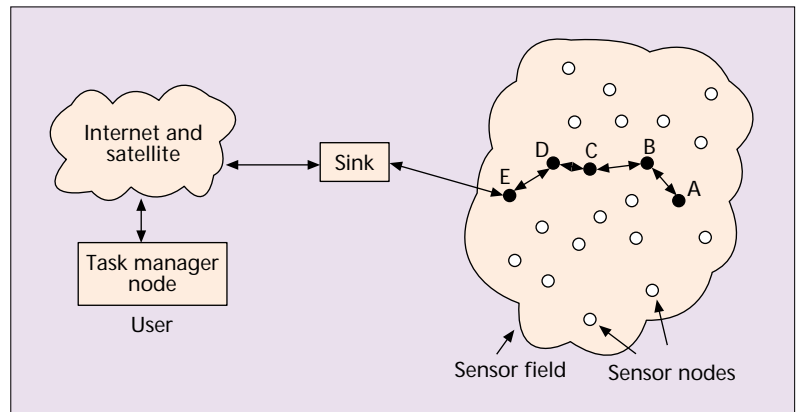

■ **Figure 1.** *Sensor nodes scattered in a sensor field.*
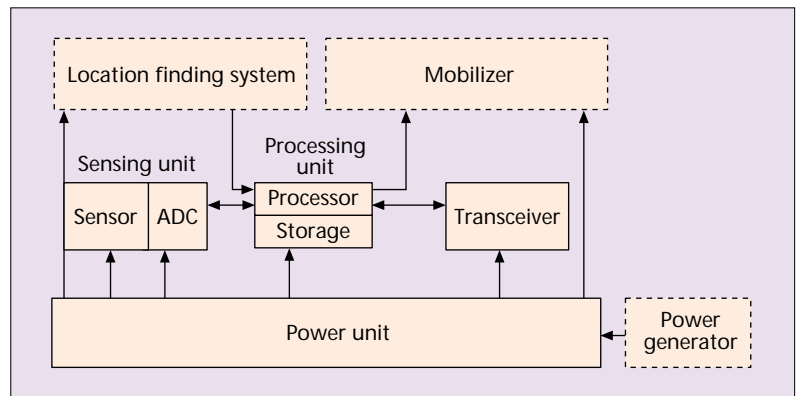

■ **Figure 2.** *The components of a sensor node.*

network is more expensive than deploying traditional sensors, 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 US$10 [4]. Also, the price of a piconode is targeted to be less than US$1. The cost of a sensor node should be much less than US$1 in order for the sensor network to be feasible. 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.

Hardware Constraints — A sensor node is made up of four basic components, as shown in Fig. 2: a *sensing unit*, a *processing unit*, a *transceiver unit*, and a *power unit*. They may also have additional application-dependent components such as a *location finding system*, *power generator*, and *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 power scavenging units such as solar cells. There are also other subunits that are

application-dependent. Most of the sensor network routing techniques and sensing tasks require 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 [5]. The required size may be smaller than even a cubic centimeter [6], which is light enough to remain suspended in the air. Apart from size, there are some other stringent constraints for sensor nodes. These nodes must [7] consume extremely low power, operate in high volumetric densities, have low production cost, be dispensable and autonomous, operate unattended, and be adaptive to the environment.

Sensor Network Topology — Hundreds to several thousands of nodes are deployed throughout the sensor field. They are deployed within tens of feet of each other [5]. The node densities may be as high as 20 nodes/m^3 [8]. Deploying a high number of nodes densely requires careful handling of topology maintenance. We examine issues related to topology maintenance and change in three phases:

• *Predeployment and deployment phase*: Sensor nodes can be either thrown in as a mass or placed one by one in the sensor field. They can be deployed by dropping from a plane, deliveried in an artillery shell, rocket, or missile, and placed one by one by either a human or a robot.
• *Post-deployment phase*: After deployment, topology changes are due to change in sensor nodes' [5] position, reachability (due to jamming, noise, moving obstacles, etc.), available energy, malfunctioning, and task details.
• *Redeployment of additional nodes phase*: Additional sensor nodes can be redeployed at any time to replace malfunctioning nodes or due to changes in task dynamics.

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 the interior of large machinery, at the bottom of an ocean, in a biologically or chemically contaminated field, in a battlefield beyond the enemy lines, and in a home or large building.

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.

Much of the current hardware for sensor nodes is based on RF circuit design. The μAMPS wireless sensor node described in [8] uses a Bluetooth-compatible 2.4 GHz transceiver with an integrated frequency synthesizer. The low-power sensor device described in [9] uses a single-channel RF transceiver operating at 916 MHz. The *Wireless Integrated Network Sensors* (WINS) architecture [6] 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. Another interesting development is that of the *Smart Dust* mote [7], which is an autonomous sensing, computing, and communication system that uses the optical medium for transmission. Both infrared and optical require a line of sight between the sender and receiver.

Power Consumption — The wireless sensor node, being a microelectronic 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 malfunctioning of a few nodes can cause significant topological changes and might require rerouting of packets and reorganization 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.

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*.

PROTOCOL STACK

The protocol stack used by the sink and sensor nodes shown in Fig. 1 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 *physical layer, data link layer, network layer, transport layer, application layer, power management plane, mobility management plane*, and *task management plane*. The physical layer addresses the needs of simple but robust modulation, transmission, and receiving techniques. Since the environment is noisy and sensor nodes can be mobile, the medium access control (MAC) protocol must be power-aware and able to minimize collision with neighbors' broadcasts. The network layer takes care of routing the data supplied by the transport layer. The transport layer helps to maintain the flow of data if the sensor networks application requires it. Depending on the sensing tasks, different types of application software can be built and used on the application layer. 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 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
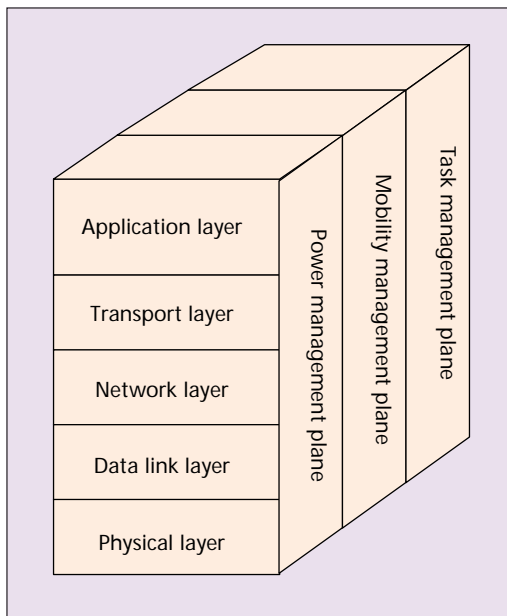
■ Figure 3. *The sensor networks protocol stack.*

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 their neighbor sensor nodes are. By knowing who the neighbor sensor nodes are, 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 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.

THE PHYSICAL LAYER

The physical layer is responsible for frequency selection, carrier frequency generation, signal detection, modulation, and data encryption. Thus far, the 915 MHz industrial, scientific, and medical (ISM) band has been widely suggested for sensor networks. Frequency generation and signal detection have more to do with the underlying hardware and transceiver design and hence are beyond the scope of our article. In the following discussion, 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, in terms of both energy and implementation complexity. While designing the physical layer for sensor networks, energy minimization assumes significant importance, over and above the propagation and fading effects. In general, the minimum output power required to transmit a signal over a distance d is proportional to d^n, where $2 <= n < 4$. The exponent n is closer to four for low-lying

antennae and near-ground channels [6], as is typical in sensor network communication. This can be attributed to the partial signal cancellation by a ground-reflected ray. Measurements carried out in [10] indicate that the power starts to drop off with higher exponents at smaller distances for low antenna heights. 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 reuse. 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 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 [8]. 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 [8], and it is concluded that under startup power dominant conditions, the binary modulation scheme is more energy-efficient. A low-power direct-sequence spread-spectrum modem architecture for sensor networks is presented in [11]. This low-power architecture can be mapped to an application-specific integrated circuit (ASIC) technology to further improve efficiency.

Ultra wideband (UWB) or impulse radio (IR) has been used for baseband pulse radar and ranging systems, and has recently drawn considerable interest for communication applications, especially in indoor wireless networks. UWB employs baseband transmission and thus requires no intermediate or radio carrier frequencies. Generally, pulse position modulation (PPM) is used. The main advantage of UWB is its resilience to multipath [12]. Low transmission power and simple transceiver circuitry make UWB an attractive candidate for sensor networks.

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:

• *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*
• *Hardware design*: Tiny, low-power, low-cost transceiver, sensing, and processing units need to be designed. Power-efficient hardware management strategies are also essential. Some strategies are managing frequencies of operation, reducing switching power, and predicting work load in processors.

> *The physical layer is responsible for frequency selection, carrier frequency generation, signal detection, modulation and data encryption. Thus far, the 915 MHz ISM band has been widely suggested for sensor networks.*

THE 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.

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.

Reasons Existing MAC Protocols Cannot Be Used — It has been emphasized in earlier sections 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 quality of service (QoS) and bandwidth efficiency. Power conservation assumes only secondary importance since 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 since there is no central controlling agent like the base station. This makes networkwide synchronization a difficult task. 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 sensor networks. Bluetooth is an infrastructureless 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 time-division multiple access (TDMA) schedule and frequency hopping pattern. Transmission power is typically around 20 dBm and the transmission range is on 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 Bluetooth or MANET. Topology changes are more frequent in a sensor network and can be attributed to both 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 — Thus far, both *fixed allocation* and *random access* versions of medium access have been proposed [9, 13]. *Demand-based* MAC schemes may be unsuitable for sensor networks due to their large messaging overhead and link setup delay. Power conservation is achieved by the use of power saving operation modes and by preferring timeouts to acknowledgments, wherever possible. Some of the proposed MAC protocols are discussed next.

Self-Organizing Medium Access Control for Sensor Networks (SMACS) and the Eavesdrop-And-Register (EAR) Algorithm — The SMACS protocol [13] achieves network startup 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 that 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 the available bandwidth is much higher than the maximum data rate for sensor nodes. Such a scheme avoids the necessity for networkwide 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 [13] 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. EAR is transparent to SMACS, so SMACS is functional until the introduction of mobile nodes into the network. In this model, the network is assumed to be mainly static, that is, any mobile node has a number of stationary

MAC protocol	Channel access mode	Sensor network specifics	Power conservation
SMACS and EAR [13]	Fixed allocation of duplex time slots at fixed frequency	Exploitation of large available bandwidth compared to sensor data rate	Random wake up during setup and turning radio off while idle
Hybrid TDMA/FDMA [8]	Centralized frequency and time division	Optimum number of channels calculated for minimum system energy	Hardware-based approach for system energy minimization
CSMA-based [9]	Contention-based random access	Application phase shift and pretransmit delay	Constant listening time for energy efficiency

■ **Table 1**. *A qualitative overview of MAC protocols for sensor networks*

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 carrier sense multiple access (CSMA)-based MAC scheme for sensor networks is presented in [9]. Traditional CSMA-based schemes are deemed inappropriate since 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 [9], 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 in [9]. 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-through traffic to propagate. A progressive signaling mechanism is used to inform the nodes to lower their data originating rate. The ARC uses a linear increase and multiplicative decrease approach. While the linear increase leads to more aggressive channel competition, the multiplicative decrease controls transmission failure penalty. Since dropping route-through traffic is costlier, the associated penalty is less than that for originating data transmission failure. This ensures that route-through traffic is preferred over 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 [8]. In this work, the effect of nonideal 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-frequency-division multiple access (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 [8] 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 deeper insight into the salient features and effectiveness of MAC protocols for sensor networks, we present a qualitative overview in Table 1. It also serves as an indicator for comparative evaluation of some of the MAC schemes 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.

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. Although 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 an earlier section, the shorter the

packets, the more the dominance of startup 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 microprocessor, memory, A/D converter, and transceiver. Each of these modes can be characterized by its power consumption and latency overhead, which is the transition power to and from that mode. A dynamic power management scheme for wireless sensor networks is discussed in [14] 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.

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 forward error correction (FEC) and automatic repeat request (ARQ). The usefulness of ARQ in multihop sensor network environments is limited by the additional retransmission energy cost and overhead. On the other hand, the decoding complexity is greater in FEC since 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 following subsection, we briefly review the basic design considerations for FEC in sensor networks.

Forward Error Correction — 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 signal-to-noise ratio (SNR) (E_s/N_0) and the transmitter power level P_{out}.

Reliable data communication can 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. A given BER can be achieved at lower transmit powers with the use of FEC. 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, although it can be negligibly small in other wireless networks. If the associated processing power is greater than the coding gain, the whole process is energy-inefficient.

In [8], a frequency nonselective, slow Rayleigh fading channel is assumed, and convolutional codes are used for FEC. It is shown 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, it is also found that FEC is generally inefficient if the decoding is performed using a microprocessor, and an onboard dedicated Viterbi decoder is recommended. 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.

OPEN RESEARCH ISSUES

Although some medium access schemes have been proposed for sensor networks, link layer protocol design is still largely open to research. Key open research issues include:

• *MAC for mobile sensor network*s: The proposed SMACS and EAR [13] perform well only in 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 [8]. 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 [14].

NETWORK LAYER

Sensor nodes are scattered densely in a field either close to or inside the phenomenon, as shown in Fig. 1. As discussed in the first section, special multihop wireless routing protocols between the sensor nodes and the sink node are needed. Traditional ad hoc routing techniques do not usually fit the requirements of the sensor networks due to the reasons explained earlier. 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.

Energy-efficient routes can be found based on the available power (PA) in the nodes or the energy required (α) for transmission in the links along the routes. In Fig. 4a, node T is the source node
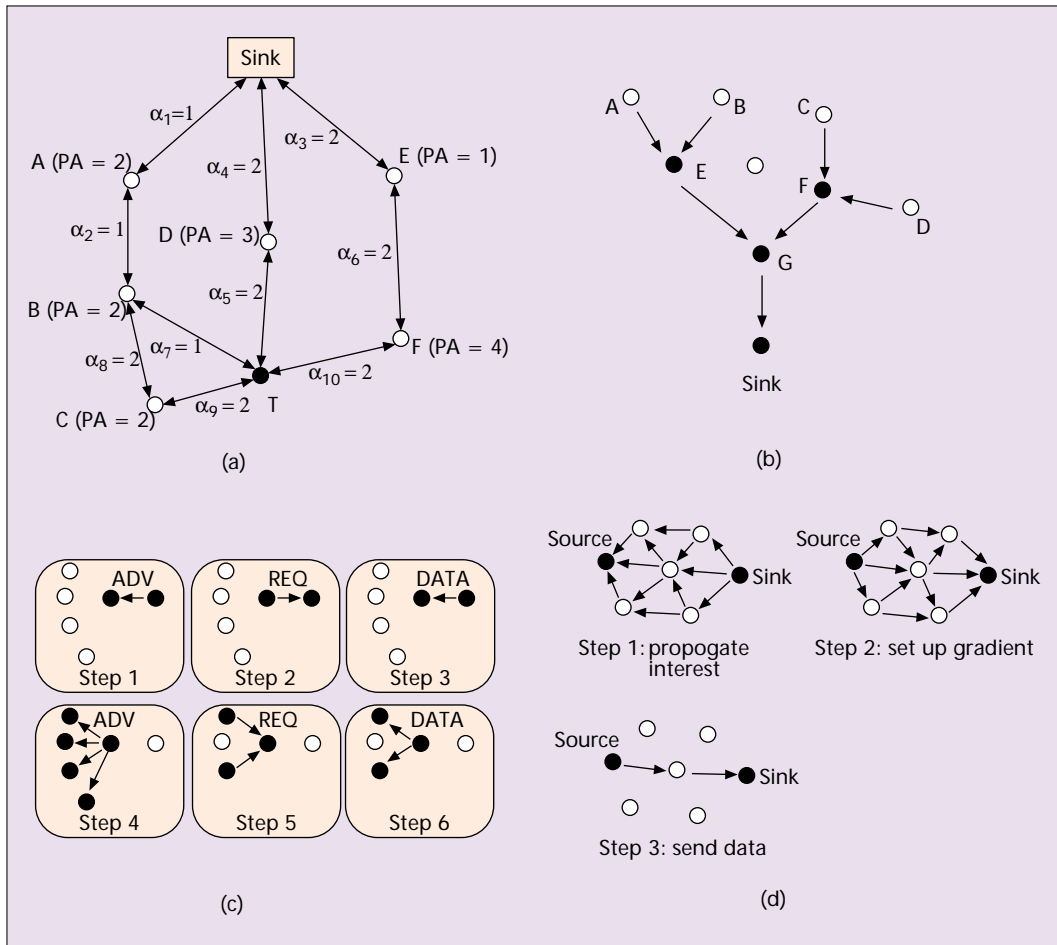
■ **Figure 4.** *a) The power efficiency of the routes; b) an example of data aggregation; c) the SPIN protocol [15]; d) an example of directed diffusion [5].*

that senses the phenomena. It has the following possible routes to communicate with the sink:

- *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 $\alpha = 6$

An energy-efficient route is selected by one of the following approaches.

Maximum PA route: The route that has maximum total PA 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. 4a. However, route 2 includes the nodes in route 1 and an extra node. Therefore, although it has a higher total PA, it is not power-efficient. As a result, it is important not to consider routes derived by extending routes that can connect the sensor node to the sink as an alternative route. Eliminating route 2, we select route 4 as our power-efficient route when we use the maximum PA scheme.

Minimum energy (ME) route: The route that consumes minimum energy to transmit the data packets between the sink and the sensor node is the ME route. As shown in Fig. 4a, route 1 is the ME route.

Minimum hop (MH) route: The route that makes the minimum hop to reach the sink is preferred. Route 3 in Fig. 4a 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. 4a, route 3 is the most efficient and route 1 is the second most efficient. 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 that have very high PAs.

Another important issue is that routing may be based on the data-centric approach. In data-centric routing, 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 [5], and sensor nodes broadcast an advertisement for the available data [15] and wait for a request from the interested nodes.

Data-centric routing requires attribute-based naming [1]. 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.*" Attribute-based naming is used to carry out queries by using the attributes of the phenomenon. Attribute-based naming also makes broadcasting, attribute-based multicasting, geocasting, and anycasting important for sensor networks.

Data aggregation is a technique used to solve the implosion and overlap problems in data-centric routing [15]. In this technique, a sensor network is usually perceived as a reverse multicast tree, as shown in Fig. 4b, 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. 4b. 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 [16]. With this respect, data aggregation is known as *data fusion* [15]. 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.

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. 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 sensor networks for the rest of this section.

SMALL MINIMUM ENERGY COMMUNICATION NETWORK

A protocol is developed in [17] that computes an energy-efficient subnetwork, namely the minimum energy communication network (MECN), when a communication network is given. A new algorithm called Small MECN (SMECN) is proposed by [18] to also provide such a subnetwork. The subnetwork (i.e., subgraph) constructed by SMECN is smaller than the one constructed by MECN if the broadcast region is circular around a broadcaster for a given power setting. Subgraph G of 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 υ, 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 *minimum-energy property*, which MECN uses to construct the subnetwork. The minimum-energy property is such that there exists a minimum-energy path in subgraph G between nodes u and υ for every pair (u, υ) of nodes that are connected in G'.

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 [15]:

* *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, 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 the available energy resources. An energy resource aware protocol must take into account the amount of energy available to them at all times.

GOSSIPING

A derivation of flooding is gossiping [19] 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 randomly selects another sensor node. Although this approach avoids the implosion problem by just having one copy of a message at any node, it takes a long time to propagate the message to all sensor nodes.

SENSOR PROTOCOLS FOR INFORMATION VIA NEGOTIATION

A family of adaptive protocols called Sensor Protocols for Information via Negotiation (SPIN) [15] 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 all the data; for example, image and sensor nodes must monitor the changes in their energy resources.

SPIN has three types of messages, that is, ADV, REQ, and DATA. Before sending a DATA message, the sensor node broadcasts an ADV message containing a descriptor (i.e., meta-data) of the DATA, as shown in step 1 of Fig. 4c. 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. 4c, respectively. The neighbor sensor node then repeats this process, as illustrated in steps 4, 5, and 6 of Fig. 4c. As a result, the sensor nodes in the entire sensor network that are interested in the data will get a copy. Note that SPIN is based on data-centric routing [15] where the sensor nodes broadcast an advertisement for the available data and wait for a request from interested sinks.

SEQUENTIAL ASSIGNMENT ROUTING

In [13], a set of algorithms that perform organization, management and mobility management operations in sensor networks are proposed. 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 EAR algorithm is designed to support seamless interconnection of the mobile nodes. The EAR algorithm is based on invitation messages and the registration of stationary nodes by mobile nodes. The SAR algorithm creates multiple trees where the root of each tree is a 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 are estimated by the number of packets 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 Sequential Assignment Routing (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 (SWR) and Multi Winner Election (MWE) handle the necessary signaling and data transfer tasks in local cooperative information processing.

LOW-ENERGY ADAPTIVE CLUSTERING HIERARCHY

Low-Energy Adaptive Clustering Hierarchy (LEACH) is a clustering-based protocol that minimizes energy dissipation in sensor networks [16]. The purpose of LEACH is to randomly select sensor nodes as clusterheads, 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 setup phase and the steady phase. The duration of the steady phase is longer than the duration of the setup phase in order to minimize overhead.

During the setup 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 clusterhead. $T(n)$ 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 clusterhead, r is the current round, and G is the set of nodes that have not being selected as a clusterhead in the last $1/P$ rounds. After the clusterheads are selected, the clusterheads advertise to all sensor nodes in the network that they are the new clusterheads. Once the sensor nodes receive the advertisement, they determine the cluster to which they want to belong based on the signal strength of the advertisement from the clusterheads to the sensor nodes. The sensor nodes inform the appropriate clusterheads that they will be a member of the cluster. Afterward, the clusterheads assign the time on which the sensor nodes can send data to the clusterheads based on a TDMA approach.

During the steady phase, the sensor nodes can begin sensing and transmitting data to the clusterheads. The clusterheads 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 setup phase again and enters another round of selecting clusterheads.

DIRECTED DIFFUSION

The *directed diffusion* data dissemination paradigm is proposed in [5], where the sink sends out *interest*, which is a task description, to all sensors, as shown in Fig. 4d. 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. 4d. When the source has data for the interest, the source sends the data along the interest's gradient path, as shown in Fig. 4d. 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.

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 developed to address higher topology changes and higher scalability.

TRANSPORT LAYER

The need for a transport layer is pointed out in the literature [4]. This layer is especially needed when the system is planned to be accessed through the Internet or other external networks. However, to the best of our knowledge there has been no attempt thus far to propose a scheme or discuss the issues related to the transport layer

> *Transport layer protocols are still unexplored; they may be purely UDP-type protocols, because each sensor node has limited memory and power.*

Network layer scheme	Description
SMECN [18]	Creates a subgraph of the sensor network that contains the minimum energy path
Flooding	Broadcasts data to all neighbor nodes regardless if they receive it before or not
Gossiping [19]	Sends data to one randomly selected neighbor
SPIN [15]	Sends data to sensor nodes only if they are interested; has three types of messages (i.e., ADV, REQ, and DATA)
SAR [13]	Creates multiple trees where the root of each tree is one hop neighbor from the sink; selects a tree for data to be routed back to the sink according to the energy resources and additive QoS metric
LEACH [16]	Forms clusters to minimize energy dissipation
Directed diffusion [5]	Sets up gradients for data to flow from source to sink during interest dissemination

■ **Table 2**. *An overview of network layer schemes.*

of a sensor network in literature. TCP with its current transmission window mechanisms does match the extreme characteristics of the sensor network environment. An approach such as TCP splitting may be needed to make sensor networks interact with other networks such as the 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 shown in Fig. 1. As a result, communication between the user and the sink node is by UDP or TCP via the Internet or satellite; on the other hand, 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. Attributed-based naming is described in an earlier section. Factors such as power consumption and scalability, and characteristics like data-centric routing mean sensor networks need different handling in the transport layer. Thus, these requirements stress the need for new types of transport layer protocols.

OPEN RESEARCH ISSUES

The development of transport layer protocols is a challenging effort because the sensor nodes are influenced by the factors explained in an earlier section, especially the hardware constraints such as limited power and memory. As a result, each sensor node cannot store large amounts of data like a server in the Internet, and acknowledgments 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.

THE 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 remain a largely unexplored region. In this survey, we examine three possible application layer protocols: *Sensor Man-*

agement 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.

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 the Internet is aimed at in some current projects [6]. An application layer management protocol makes the hardware and software of the lower layers transparent to the sensor network management applications.

System administrators interact with sensor networks using SMP. Unlike many other networks, sensor networks consist of nodes that do not have global identifications and are usually infrastructureless. Therefore, SMP needs to access the nodes by using attribute-based naming and location-based addressing, which are explained in detail earlier, 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 reconfiguring the sensor network
- Authentication, key distribution, and security in data communications

The descriptions of some of these tasks are given in [1].

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 the whole network. This interest may be about

Project name	Research area	HTTP location
SensoNet [20]	Transport, network, data link, and physical layers. Power control, mobility, and task management planes.	http://www.ece.gatech.edu/research/labs/bwn/
WINS [6]	Distributed network and Internet access to sensors, controls, and processors.	http://www.janet.ucla.edu/WINS/
SPINS [7]	Data dissemination protocols.	http://nms.lcs.mit.edu/projects/leach
SPINS [15]	Security protocol.	http://paris.cs.berkeley.edu/~perrig/projects.html
SINA [20]	Information networking architecture.	http://www.eecis.udel.edu/~cshen/
mAMPS [8]	Framework for implementing adaptive energy-aware distributed microsensors.	http://www-mtl.mit.edu/research/icsystems/uamps/
LEACH [16]	Cluster formation protocol.	http://nms.lcs.mit.edu/projects/leach
Smart Dust [7]	Laser communication from a cubic millimeter. Mote delivery. Submicrowatt electronics. Power sources. Macro Motes (COTS Dust).	http://robotics.eecs.berkeley.edu/~pister/SmartDust/
SCADDS [3, 5]	Scalable coordination architectures for deeply distributed and dynamic systems.	http://www.isi.edu/scadds/
PicoRadio [4]	Develop a "system-on-chip" implementation of a PicoNode.	http://bwrc.eecs.berkeley.edu/Research/Pico_Radio/PicoNode.htm
PACMAN	Mathematical framework that incorporates key features of computing nodes and networking elements.	http://pacman.usc.edu
Dynamic Sensor Networks	Routing and power aware sensor management. Network services API.	http://www.east.isi.edu/DIV10/dsn/
Aware Home	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	Distributed query processing.	http://www.cs.cornell.edu/database/cougar/index.htm
DataSpace	Distributed query processing.	http://www.cs.rutgers.edu/dataman/

■ Table 3. *Current research projects.*

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 in which they are interested. An application layer protocol that provides the user software with efficient interfaces for interest dissemination is useful for lower-layer operations, such as routing, explained in an earlier section.

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- 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 of location-based naming.

Sensor query and tasking language (SQTL) [1] is proposed as an application that provides an even larger set of services. SQTL supports three types of events, defined by keywords *receive, every,*

and *expire. Receive* defines events generated by a sensor node when the sensor node receives a message; *every* defines events occurring periodically due to timer timeout; and *expire* defines events occurring 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.

OPEN RESEARCH ISSUES

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

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 shown in Fig. 3. A list of current sensor network research projects is given in Table 3. Along with the current research projects, we encourage more insight into the problems and intend to motivate a search for solutions to the open research issues described in this article.

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