–Draft–
(DO NOT DISTRIBUTE)

Wireless Sensor Networks: A Survey Revisited

Ian F. Akyildiz† **Mehmet C. Vuran**† **Özgür B. Akan**‡ **Weilian Su**§

†Broadband & Wireless Networking Laboratory
School of Electrical & Computer Engineering
Georgia Institute of Technology, Atlanta, GA 30332
Tel: (404) 894-5141 Fax: (404) 894-7883
Email:{ian,mcvuran}@ece.gatech.edu

‡Department of Electrical and Electronics Engineering
Middle East Technical University
06531, Ankara, Turkey
Email: akan@eee.metu.edu.tr

§Electrical and Computer Engineering
Naval Postgraduate School, Monterey, CA 93943
Email: weilian@nps.edu

***Abstract*— With the recent advances in Micro Electro-Mechanical Systems (MEMS) technology and wireless communications; the implementation of lowcost, low-power, multifunctional sensor nodes that are small in size and communicate untethered in short distances has become feasible. The ever-increasing capabilities of these tiny sensor nodes enable the realization of wireless sensor networks (WSN) based on the collaborative effort of a large number of nodes. However, in order to realize the existing and envisioned applications and hence take the advantages of the potential gains of WSN necessitate effective communication protocols which can address the unique challenges posed by the WSN paradigm. Since the time these challenges had been been first pointed out in the literature, there has been a great deal of research effort focused on addressing them. Furthermore, the promising results of the research efforts since then have enabled the development and realization of practical sensor network deployment scenarios. In this paper, a survey of the applications, developed communication protocols, and real deployment scenarios proposed thus far for WSN is revisited. The objective of this survey revisit is to provide a contemporary look at the current state-of-the-art in WSN and discuss the still-open research issues in this field.**

I. INTRODUCTION

With the recent advances in *Micro Electro-Mechanical Systems* (MEMS) technology, wireless communications, and digital electronics; the construction of low-cost, low-power, multifunctional sensor nodes that are small in size and communicate untethered in short distances has become feasible. The ever-increasing capabilities of these tiny sensor nodes, which consist of sensing, data processing, and communicating components, enable the realization of wireless sensor networks (WSN) based on the collaborative effort of a large number of nodes.

Wireless Sensor Networks have a wide range of applications such as environmental monitoring [187], biomedical research [166], human imaging and tracking [53], [54], and military applications [117]. In accordance with our vision [3], WSN are slowly becoming an integral part of our lives. Recently, considerable amount of research efforts have enabled the actual implementation of sensor networks tailored to the unique requirements of certain sensing and monitoring applications.

In order to realize the existing and potential applications for WSNs, sophisticated and extremely efficient communication protocols are required. WSNs are composed of a large number of sensor nodes, which are densely deployed either inside a physical phenomenon or very close to it. In order to enable reliable and efficient observation and initiate right actions, physical phenomenon features should be reliably detected/estimated from the collective information provided by sensor nodes [3]. Moreover, 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. Hence, these properties of WSN impose unique challenges for development of communication protocols in such an architecture.

The intrinsic properties of individual sensor nodes, pose additional challenges to the communication protocols in terms of energy consumption. As will be explained in the following sections, WSN applications and communication protocols are mainly tailored to provide high energy efficiency. Sensor nodes carry limited, generally irreplaceable power sources. Therefore, while traditional networks aim to achieve high *Quality of Service* (QoS) levels, sensor network protocols focus primarily on power conservation. Moreover, the deployment of the WSN is another constraint that is considered in developing WSN protocols. 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, the random deployment constraints of WSN result in self-organizing protocols to emerge in the WSN protocol stack. In addition to the placement of nodes, the density in the network is also exploited in WSN protocols. Since generally, large number of sensor nodes are densely deployed in WSN, neighbor nodes may be very close to each other. Hence, multihop communication in sensor networks is exploited in communication between nodes since it leads to less power consumption than the traditional single hop communication. Furthermore, the dense deployment coupled with the physical properties of the sensed phenomenon introduce correlation in spatial and temporal domain. As a result, the spatio-temporal correlation-based protocols emerged for improved efficiency in networking wireless sensors.

After the first and the most comprehensive survey on WSN [3] which was published three years ago, the research on the unique challenges of WSN has accelerated significantly. The promising results of the existing research that has been developed in the last three years have enabled the development and production of mature products, which have eventually created a brand new market empowered by the WSN phenomenon. Throughout these three years, the deployment of WSN has become a reality. Consequently, research community has gained significant experiences out of these WSN deployment cases. Furthermore, many researchers are currently engaged in developing schemes that address the unique challenges of WSN. In this paper, we present a survey of existing products, developed protocols, and research on algorithms proposed thus far for WSN. Our aim is to provide a contemporary look at the current state of the art in WSN since its initial steps [3] and discuss the still-open research issues in this field.

The remainder of the paper is organized as follows. In Section II, we present existing applications and ongoing research efforts on some sensor network applications which show the usefulness of sensor networks. The existing work on the WSN protocol stack is surveyed in Sections VI, VII, VIII, and IX for transport, routing, data link and physical layers, respectively. Moreover, the open research issues are discussed for each of the protocol layer. Furthermore, the synchronization and localization problems in WSN are investigated in Section XI and Section X, respectively, along with the existing solutions and open research issues. The existing evaluation approaches for WSN including physical testbeds and software simulation environments are overviewed in Section XIII. We conclude our paper in Section XIV.

II. Wireless Sensor Network Applications

The emergence of WSN paradigm has triggered extensive research on many aspects of the sensor networking. However, the applicability of sensor networks has long been discussed with the emphasis on potential applications that can be realized using wireless sensor networks. In this section, we present the existing commercial and academic products using the sensor networking concept and provide an extensive survey on the existing applications of WSN.

It has been stated that WSNs 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 [3]. As a result, wide range of applications are possible using the WSN paradigm. This spectrum of applications includes homeland security, monitoring of space assets for potential and man-made threats in space, ground-based monitoring on both land and water, defense intelligence gathering, environmental monitoring, urban warfare, weather and climate analysis and prediction, battlesphere monitoring and surveillance, exploration of the solar system and beyond, monitoring of seismic acceleration, strain, temperature, wind speed and GPS data.

The heterogeneity in the available sensor technologies and applications, hence, requires a common standardization to achieve the practicality of sensor networks applications for industrial purposes. For this purpose, IEEE 802.15.4 [81] standards body is formed for a specification for low data rate wireless transceiver technology with long battery life and very low complexity. Three different bands are chosen for communication, i.e., 2.4GHz (global), 915Mhz (Americas) and 868Mhz (Europe). While the PHY layer uses BPSK in the 868/915 MHZ bands and O-QBPSK at 2.4 GHz band, the MAC layer provides communication for star, mesh and cluster-tree based topologies with controllers. The transmission range of the nodes is assumed to be 10-100m with data rates 20Kbps to 250Kbps [80]. Applications for the IEEE 802.15.4 standard include sensor networks, industrial sensing and control devices, building and home automation products, and even networked toys.

Along with IEEE 802.15.4, ZigBee [223], an international, non-profit industry consortium of leading semiconductor manufacturers, and technology providers has been formed. ZigBee was created to address the market need for cost-effective, standards-based wireless networking solutions that support low data rates, low power consumption, security and reliability [223]. Moreover, Wireless Industrial Networking Alliance (WINA) was formed in 2003 to stimulate the development and promote the adoption of wireless networking technologies and practices to help increase industrial efficiency. As a first step, this ad hoc group of suppliers and end-users is working to define end-user needs and priorities for industrial wireless systems [206]. It is widely recognized that standards such as Bluetooth and WLAN are not suited for low power sensor applications. On the other hand, standardization attempts such as ZigBee and WINA, which specifically address the typical needs of wireless control and monitoring applications, will enable rapid improvement of WSN in the industry.

In this section, we categorize the applications in terms of military, environment, health, home, industry and other commercial areas.

A. Military Applications

WSNs are characterized by their autonomous usage, rapid deployment, self-organization and fault tolerant protocols. Hence, WSN are used as an integral part of military *command, control, communications, computing, intelligence, surveillance, reconnaissance and targeting* (C4ISRT) systems [3].

Dust Networks [43] provide sensor networks for military operations in hostile environments where it is too dangerous for humans to operate. WSNs obtain information needed to assess critical situations by dropping a robust, self-configuring, self-organizing wireless sensor network into a battlefield. The military applications include collecting information from enemy movements, hazardous chemicals and infrastructure stability [43].

B. Environmental Applications

The autonomous coordination capabilities of WSNs help wide variety of environmental applications be realized. As reported in [3], environmental applications may range from tracking the movements of birds, to forest fire detection and bio-complexity mapping of the environment.

CORIE [34] is built by the Center for Coastal and Land Margin Research at the Oregon Graduate Institute. It consists of sensor stations in the Columbia River Estuary that carry various environment sensors. The readings include temperature, salinity, water levels, and flow velocities. The information gathered from these sensors are used for online control of vessels, marine research and rescue, and ecosystem research and management. 13 stations are located throughout the Columbia River estuary with one off-shore station on a buoy. The stations communicate via a Freewave DGR-115 spread-spectrum wireless network. In addition, the transmission of signals is carried through an ORBCOMM LEO satellite in case of disruptions in line-of-sight.

A new observing system, Global Environmental MEMS Sensors (GEMS), which features a wireless network of airborne probes, is currently being designed by ENSCO [48]. The GEMS system features ”micron-scale” airborne probes that can take measurements over all regions of the Earth with high spatial and temporal resolution. The minimal sizes will allow the probes to be suspended in the atmosphere and carried by wind currents for long periods of time to make environmental measurements that could improve weather forecast accuracy. With a modular sensor suite, probes could also be used to measure acoustic, chemical, biological, nuclear or other parameters of interest to defense agencies for intelligence gathering, battlefield situational awareness and urban warfare monitoring [48].

C. Health Applications

The developments in implanted biomedical devices and smart integrated sensors make the usage of sensor networks for biomedical applications possible. Many applications in this field with sensor networks are proposed [166]

The Smart Sensors and Integrated Microsystems (SSIM) project at Wayne State University and the Kresge Eye Institute aims to build a chronically implanted artificial retina for visually impaired people. Sensor chips consisting 100 microsensors in a 10x10 array are placed along the retina. The sensors produce electrical signals which are converted by the underlying tissue into a chemical response. The chemical signals are then carried out to the brain via optic nerves. The chemical signals coming from the brain are picked up by the microsensors and the smart sensors at the retina are stimulated accordingly [166].

The receptors along the retina have different functionalities. The peripheral is specialized on temporal events, whereas the center of the macula is specialized on spatially-oriented information. In order to mimic the functionality of the retina, the distribution and the transmission principles of smart sensors on each segment of the retina should be tailored. However, since the deployment of the sensors are performed by precise medical surgeries, the mobility and location problems encountered in typical sensor networks need not be taken into account.

Monitoring glucose levels and treating diabetes can be improved by the use of wireless sensors [166]. Wireless biomedical sensors can be implanted in the patient and the glucose level can be monitored continuously. In addition, insulin could be automatically injected [166].

D. Home Applications

WSN enable interconnection of various devices at residential places with convenient control of various applications at home.

Cricket project at MIT utilizes ultrasound ranging to determine the location of users as they move through and interact with indoor environments. Using both fixed and mobile wireless nodes, *Cricket* provides fine-grained location information to applications running on handhelds, laptops, and sensor nodes. *Cricket* uses a combination of RF and ultrasound technologies to provide location information to attached host devices. Using the *Cricket*, many applications involving precise location information of various devices can be realized. As an example tracking of a moving train toy has been demonstrated using laptops and handheld devices [37].

E. Industrial Applications

The emergence of WSN has made a big impact on industrial fields such as industrial sensing and control applications, building automation, and access control.

Sensicast is producing *H900 Sensor Network Platform*, a wireless mesh networking system, which can be used in many of the industrial applications [168]. Moreover, *Xsiology* produces systems for real-time monitoring of a wide variety of remote industrial applications including wastewater, oil and gas, utilities and railroads [209].

Soflinx provides a perimeter security system that provides real-time detection of hazardous explosive, nuclear, biological and chemical warfare agents. *Soflinx* uses its *Datalinx* technology which pushes the intelligence of the network closer to the source of the data by using gateways in the network edges and enabling the individual components to automate responses to these data. Moreover, a transportable security system for the detection of explosive, nuclear, biological and chemical warfare agents is also produced [184].

The deep networking group at *INTEL* is working on networking large numbers of wireless sensor nodes while maintaining a high level of network performance [85]. The solution is to use an 802.11 mesh network of high-end nodes overlaid on the sensor network. The high-end nodes serve as highway roads where the underlying sensor network can be used as side roads.

Moreover, the sensor network concept will be used in the *INTEL's semiconductor fabs* [84]. As of now, thousands of sensors track the vibrations coming from various pieces of equipment. Based on the established science that determines a particular signature to a well-functioning device, the machines are monitored continuously. However, the data from the sensors are collected by the employees manually. Since creating a wired network of sensors is expensive, the 802.11 mesh topology with wireless sensor networks will be used in *INTEL's fabs*.

F. Other Commercial Applications

Wireless Automatic Meter Reading (AMR) is one of the fastest growing markets for short-range radio devices. Wireless collection of utility meter data (electricity, water, gas) is a very cost-efficient way of gathering consumption data to the billing system. *Chipcon* produces low-cost, low-power radio chips, and transceivers for wireless AMR applications [27].

Heating, ventilating, and air conditioning (HVAC) applications is another field where WSNs have important impact. In commercial buildings, it is common to control multiple spaces or rooms with a single HVAC unit and controller. Hence, systems configured this way are most commonly controlled with a single sensor in one of the rooms. However, low-cost wireless sensor technology offers the opportunity to replace the single sensor in one room with a network of sensors where there is at least one sensor per room. *ZenSys* produces wireless RF-based communications technology designed for residential and light commercial control and status reading applications such as meter reading, lighting and appliance control [218].

In a collaborative project between four research centers at the University of California: The Center for the Built Environment (CBE), the Berkeley Sensor and Actuator Center (BSAC), the Berkeley Wireless Research Center (BWRC), and the Integrated Manufacturing Lab (IML), in the Department of Mechanical Engineering, WSN is used for control of the indoor environment in buildings. In the project, the air velocity is measured over arbitrarily long path lengths. Ultimately, the goal is to use networks of these sensors for flow visualization indoors which will help evaluate thermal comfort, indoor air quality, and energy consumption in buildings [102].

Wireless Sensor Network applications has gained significant momentum during the past three years with the acceleration in WSN research. Although existing applications provide wide variety of possibilities where the WSN phenomenon can be exploited, there exists many areas waiting for WSN empowerment. Moreover, the further enhancements in WSN protocols as will be explained in the following sections, will open up new areas of applications for WSN.

III. 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.

A. 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 [71], [130], [175]. The reliability $R_k(t)$ or fault tolerance of a sensor node is modeled in [71] 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 maybe 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.

B. 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 [30]. The density can be calculated according to [20] as

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

where N is the number of scattered sensor nodes in region A, and R is the radio transmission range. Basically, μ *(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 m x 5 m region, and the density for the vehicle tracking application is around 10 sensor nodes per region [177]. In general, the density can be as high as 20 sensor nodes/m^3 [177]. A home may contain around 2 dozens of home appliances containing sensor nodes [145], 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 [21].

C. 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-art technology allows a Bluetooth radio system to be less than ten dollars [150]. Also, the price of a PicoNode is targeted to be less than one dollar [151]. The cost of a sensor node should be much less than one dollar in order for the sensor network to be feasible [151]. The cost of a Bluetooth radio, which is known to be a low cost device, is even ten 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 III-D. 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.

D. Hardware Constraints

A sensor node is made up of four basic components as shown in Figure 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 enable 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. 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.

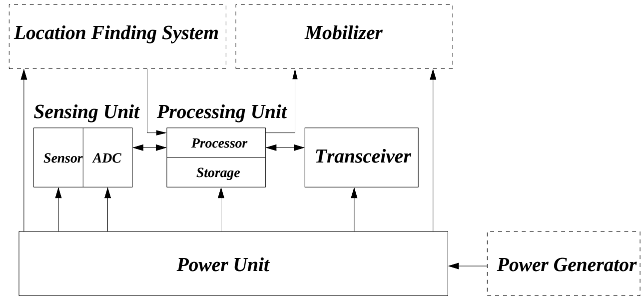

Fig. 1. The components of a sensor node.

All of these subunits may need to fit into a matchbox-sized module [83]. The required size may be smaller than even a cubic centimeter [148] 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 [89]

- 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 Joule [148]. For WINS [197], 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) [197]. It is possible to extend the lifetime of the sensor networks by energy scavenging [150], 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* [148] 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 4^{th} order exponent of the distance between them, because the antennas of the sensor nodes are close to the ground [148]. 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) [150], and the frequency reuse 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 [177].

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 microcontroller with 8 KB instruction flash memory, 512 bytes RAM and 512 bytes EEPROM [144]. 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 $\mu AMPS$ wireless sensor node, has a 59 MHz to 206 MHz SA-1110 microprocessor [177]. A multithreaded μ-*OS* operating system is run on $\mu AMPS$ 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 IV. It is often assumed that each sensor node will have a Global Positioning System (GPS) unit that has at least 5 m accuracy [97]. In [161] 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 [161].

E. 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 [83]. The node densities may be as high as 20 nodes/m^3 [177]. Deploying high number of nodes densely requires careful handling of topology maintenance. We examine issues related to topology maintenance and change in three phases:

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 preplanning,
- increase the flexibility of arrangement, and
- promote self-organization and fault tolerance.

2) Post-Deployment Phase: After deployment, topology changes are due to change in sensor nodes' [83], [114]

- 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) 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 IV.

F. 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.

G. *Transmission Media*

In a multi-hop 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), specifies some frequency bands that may be made available for ISM applications. They are listed in Table I.

Frequency Band	Center Frequency
6765-6795 kHz	6780 kHz
13553-13567 kHz	13560 kHz
26957-27283 kHz	27120 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

TABLE I
FREQUENCY BANDS AVAILABLE FOR ISM APPLICATIONS.

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 [147], certain hardware constraints and the tradeoff between antenna efficiency and power consumption limit the choice of a carrier frequency for such transceivers to the *Ultra High Frequency* (UHF) 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 [116] and [52]. 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.

Much of the current hardware for sensor nodes is based upon RF circuit design. The μAMPS wireless sensor node, described in [177], uses a Bluetooth-compatible 2.4 GHz transceiver with an integrated frequency synthesizer. The low-power sensor device described in [208], uses a single channel RF transceiver operating at 916 MHz. The *Wireless Integrated Network Sensors* (WINS) architecture [148] also uses radio links for communication.

Another possible mode of inter-node 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* (IrDA) 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 [89], 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 [203]. 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.

H. 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 multi-hop 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 rerouting 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 III-D. 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.

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 ($\sim$ 0 dbm), transmission and reception energy costs are nearly the same. Mixers, frequency synthesizers, voltage control oscillators (VCO), 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 100s of microseconds, 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 to turn the transceiver ON and OFF, due to the large amount of power spent while turning the transceiver back ON each time.

In [177], 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} is the output power of the transmitter, T/R_{on} is the transmitter/receiver on time, T/R_{st} is the transmitter/receiver startup time and $N_{T/R}$ is 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 is 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 [131]. 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 [147]. 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.

2) Data Processing: Energy expenditure in data processing is much less compared to data communication. The example described in [148], effectively illustrates this disparity. Assuming Rayleigh fading and fourth power distance loss, the energy cost of transmitting 1Kb 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 microprocessor. Unfortunately, this has inbuilt limitations on energy efficiency. A CMOS transistor pair draws power every time 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* (DVS), explored in [119], [143], aims to adapt processor power supply and operating frequency to match workloads. When a microprocessor 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 [181], 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 [62], [204], and [106].

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

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

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 [181]. The lowering of threshold voltage to satisfy performance requirements results in high subthreshold leakage currents. Coupled with the low duty cycle operation of the microprocessor in a sensor node, the associated power loss becomes significant [177].

It is to be noted that there may be some additional circuitry for data encoding and decoding. *Application Specific Integrated Circuits* (ASICs) 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.

IV. WSN Architecture and Protocol Stack

The sensor nodes are usually scattered in a *sensor field* as shown in Figure 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 Figure 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 Figure 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*, *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 can not 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 their neighbors. With the knowledge of neighbor 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 a specific region are required to perform the sensing task at the same time. As a result, some sensor nodes perform the task more than the

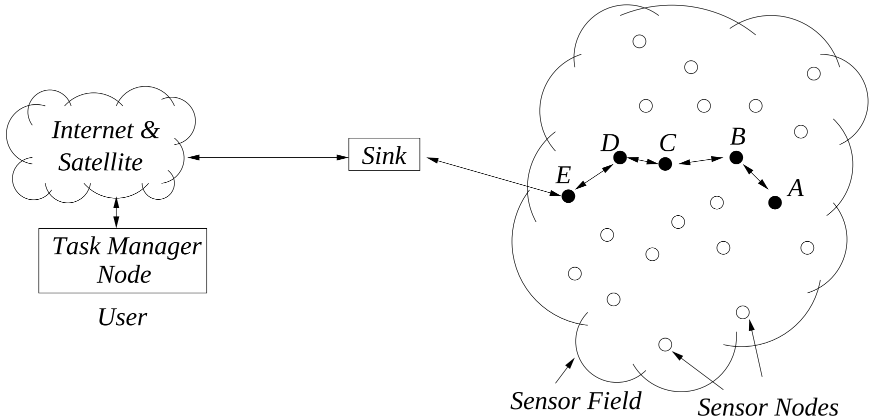

Fig. 2. Sensor nodes scattered in a sensor field.

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 life-time 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 [148], [89], [177] to the protocol stack as shown in Figure 3.

The so-called *wireless integrated network sensors* (WINS) is developed in [148], 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 Figure 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 Figure 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 [148] that a low-power protocol suite that addresses the constraints of the sensor networks should be developed.

The Smart Dust motes [89], 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 Figure 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 [177]. The protocols and algorithms should be developed according to the choice of physical layer components, such as the type of microprocessors, 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 Figure 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 Figure 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 [177]. 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 microprocessors 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.

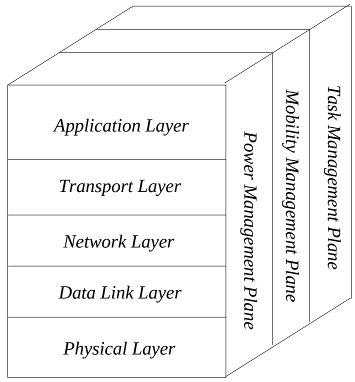

Fig. 3. The sensor networks protocol stack.

V. Application Layer

The role of the application layer is to abstract the physical topology of the WSN for the applications and provide necessary interfaces to interact with the physical world through the WSN.

A. Query Processing

WSNs consist of many sensor nodes that monitor the physical phenomenon according to the requirements of the applications. The sink ensures the delivery of the interested data through queries sent to the nodes containing information about the requested information. The query replies can be made simply by sending the requested raw data immediately to the sink. However, the processing capabilities of sensor nodes provide alternative ways to process these queries inside the network leading to significant energy conservation [4]. This phenomenon is referred to as *query processing*.

The WSN can be viewed as a distributed database where nodes continuously deliver streams of data to the sink [108]. Although there exists many database management systems (DBMS) developed for traditional distributed databases, the unique characteristics of WSNs make these solutions not applicable. The unique characteristics of the WSN can be listed as follows:

- *Streaming data:* Sensor nodes produces data continuously, usually at well defined time intervals, without having been explicitly asked for that data [108].
- *Real-time processing:* Sensor data usually represent real-time events. Moreover, it is often expensive to save raw sensor streams to disk at the sink. Hence, queries over streams need to be processed in real time [108].
- *Communication errors:* Since sensors deliver data through multi-hop wireless communication, wireless errors effect the reliability and the delay of the distributed information reaching the sink.
- *Uncertainty:* The information gathered by the sensors contain noise from environment. Moreover, factors such as sensor malfunction, and sensor placement might bias individual readings [212].
- *Limited disk space:* Sensor nodes have strictly limited disk space. Hence, the information sent by the sensors cannot be queried later.
- *Processing vs. communication:* As explained in Section III-H, energy expenditure in data processing in WSN is much less compared to data communication. Hence, the data processing capabilities of sensor nodes should be exploited in query processing.

The processing power available in sensor nodes provide potential solutions for the challenges encountered in WSN query processing. It is clear that the queries sent by the sink can be easily replied by sending the raw sensor observation to the sink. This approach is referred to as *warehousing approach* in [14], where processing of sensor queries and access to the sensor network are separated. However, this approach leads to both over-utilization of communication resources in the WSN and accumulation of highly redundant data at the sink. As an example, if an application is only interested in an average value of a specific information at a specific location, it would be more efficient for nodes at this location to calculate the average locally and send this information as a single packet to the sink instead of sending all individual information. It is shown in [212], [109] and [110] that distributed implementation of aggregation and query processing schemes provide significant improvements in the WSN performance. We overview the existing query processing techniques in the following.

In [14], the *COUGAR* sensor database system has been presented. The data in the database is classified in two classes, i.e., stored data and sensor data. In *COUGAR*, the stored data is modeled as relations while the sensor data are represented as time series. More specifically, the sensors are assumed to be synchronized and sensor data is regarded as outputs of a signal processing function at a specific location, at the time of the record. Based on the stored and sensor data modeling, the sensor query is defined as relational and sequence operators. Moreover, the signal processing functions, i.e., the outputs of individual sensors on a node, are represented as Abstract Data Type (ADT) functions. As a result, an ADT object in the database corresponds to a physical sensor in the real world. Using this abstraction, the *COUGAR* database system uses SQL-like query language to issue queries to the sensors.

An architecture for queries over streaming sensor data is proposed in [108]. The architecture consists of proxies that control the sampling rate and aggregation parameters of sensors which are connected to them. Using multiple queries, the user can control the proxies and hence the sensor field. The proxies serve as sensor interface into the rest of the query processor and are responsible for adjusting sensor sampling rate, directing sensors to aggregate samples, packaging samples as tuples, routing these tuples to user queries as needed, and downloading new programs to sensors. Using this architecture, the user issues queries using Fjords. Fjords integrate the sensor data pushed to the system with saved data pulled by traditional operators. Moreover, various proxy principles are also proposed to decrease energy consumption in the sensor field. Evaluations show that both performance and energy consumption improvement is possible using Fjords.

Query processing is investigated in terms of a distributed aggregation scheme in [109], where *TAG*, a Tiny AGgregation Service is introduced. The *TAG* service provides a simple, declarative interface for data collection and aggregation, while distributively executing aggregation queries in the WSN. The *TAG* approach relies on the routing tree built by broadcast messages sent by the sink. Based on the routing tree, parents wait for their children to send data and discard irrelevant data combining relevant readings into more compacts records based on the aggregation principles specified by queries. The authors provide an SQL-like query syntax for aggregation queries, where the main difference is that the output of a *TAG* query is a stream of values rather than a single aggregate value. Similar to aggregation computation in traditional large scale networks, the aggregation is performed via three functions, i.e, a merging function, an initializer and an evaluator. The aggregates are classified according to four properties, i.e., tolerance of loss, duplicate sensitivity, monotonicity, and the amount of state required for each partial state record. Based on the specific class of the aggregate, the query is first distributed into the network and the aggregate values are then collected. Simulations show that depending on the aggregate type, using the *TAG* approach, the communication costs can be decreased an order of magnitude compared to centralized approaches.

In [212], the design of a *query layer* is presented. The query layer is regarded as a layer between application and network layers and provides cross-layer interaction between routing protocol and distributed query protocol. The main goal of the design of the query layer is to abstract the functionality of a large class of applications into a common interface of declarative queries. However, since query layer has different requirements in terms of routing, some modifications to existing routing protocols have been proposed. More specifically, route initialization procedure is modified such that the routing tree is built according to a query tree originated at the leader of aggregation. Moreover, it is argued that for in-network aggregation, nodes should be able to intercept packages that are not destined to themselves. Furthermore, since packets containing aggregated results are more important than individual readings of sensors, a route maintenance technique that considers the depth of the node in a query tree is proposed. Overall, the query layer provides an efficient aggregation technique for WSN with periodic traffic characteristics. The simulation results reveal the possible gains that is possible with in-network aggregation.

In [110], Acquisitional Query Processing (ACQP) is presented along with TinyDB that runs on top of TinyOS. In addition to periodic monitoring data, TinyDB also supports event-based data using an *event* mechanism for initiating data collection. As a result, significant energy savings is possible for event-based applications. As in *COUGAR* and *TAG*, TinyDB also views sensor data as a single table with one column per sensor type. Simple extensions to SQL are proposed for controlling data acquisition using this table. In TinyDB, users send their queries to the sink, and the sink performs a simple query optimization for correct ordering of sampling, selections, and joins. A query tree is also used to disseminate the queries and collect the results. Consequently, the parent nodes propagate their transmission rates to their children in order to match the transmission rate of the root nodes. TinyDB performs lifetime estimation in order to further save energy by controlling the reporting rate of the sensor nodes such that a lifetime constraint for the overall network is met. Simulation results show that significant gains in terms of energy consumption.

VI. Transport Layer

The Wireless Sensor Network is an event driven paradigm that relies on the collective effort of numerous microsensor nodes. This collaborative nature brings several advantages over traditional sensing including greater accuracy, larger coverage area and extraction of localized features. The realization of these potential gains, however, directly depends on the efficient reliable communication between the wireless sensor network entities, i.e., the sensor nodes and the sink.

To accomplish this, in addition to robust modulation and media access, link error control and fault tolerant routing, a reliable transport mechanism is imperative. The functionalities and design of a suitable transport solution for the wireless sensor networks are the main issues addressed in this section.

The need for transport layer in the wireless sensor networks is pointed out in the literature [148], [150]. In general, the main objectives of the transport layer are (i) to bridge application and network layers by application multiplexing and demultiplexing; (ii) to provide data delivery service between the source and the sink with an error control mechanism tailored according to the specific reliability requirement of the application layer; (iii) to regulate the amount of traffic injected to the network via flow and congestion control mechanisms. Although these objectives are still valid, the required transport layer functionalities to achieve these objectives in the wireless sensor networks are subject to significant modifications in order to accommodate unique characteristics of the wireless sensor network paradigm. The energy, processing, and hardware limitations of the wireless sensor nodes bring further constraints on the transport layer protocol design. For example, the conventional end-to-end retransmission-based error control and the window-based additive-increase multiplicative-decrease (AIMD) congestion control mechanisms adopted by the vastly used TCP protocols may not be feasible for the wireless sensor domain and hence may lead to waste of scarce wireless sensor resources.

On the other hand, unlike the other conventional networking paradigms, the wireless sensor networks are deployed with a specific sensing application objective. For example, sensor nodes can be used within a certain deployment scenario to perform continuous sensing, event detection, event identification, location sensing, and local control of actuators for a wide range of applications such as military, environment, health, space exploration, and disaster relief. The specific objective of a sensor network also influences the design requirements of the transport layer protocols. For example, wireless sensor networks deployed for different applications may require different reliability level as well as different congestion control approaches.

Consequently, the development of transport layer protocols is a challenging effort because the limitations of the sensor nodes and the specific application requirements primarily determine the design principles for the transport layer protocols. With this respect, the main objectives of the transport layer and its desired essential features to address the unique challenges posed by the characteristics of the wireless sensor networks paradigm can be stated as follows:

- *Reliable Transport:* Based on the application requirements, the extracted event features should be reliably transferred to the sink. Similarly, the programming/retasking data for sensor operation, command and queries should be reliably delivered to the target sensor nodes to assure the proper functioning of the wireless sensor network.
- *Congestion Control:* Packet loss due to congestion can impair event detection at the sink even when enough information is sent out by the sources. Hence, congestion control is an important component of the transport layer to achieve reliable event detection. Furthermore, congestion control not only increases the network efficiency but also helps conserve scarce wireless sensor resources.
- *Self-configuration:* The transport layer protocols must be adaptive to dynamic topologies caused by node mobility/failure/temporary power-down, spatial variation of events and random node deployment.
- *Energy Awareness:* The transport layer functionalities should be energy-aware, i.e., the error and congestion control objectives must be achieved with minimum possible energy expenditure. For instance, if reliability levels at the sink are found to be in excess of that required for the event detection, the source nodes can conserve energy by reducing the amount of information sent out or temporarily powering down.
- *Biased Implementation:* The algorithms must be designed such that they mainly run on the sink with minimum functionalities required at sensor nodes. This helps conserve limited sensor resources and shifts the burden to the high-powered sink.
- *Constrained Routing/Addressing:* Unlike protocols such as TCP, the transport layer protocols for wireless sensor networks should not assume the existence of an end-to-end global addressing. It is more likely to have attribute-based naming and data-centric routing which call for different transport layer approaches.

Due to the application-oriented and collaborative nature of the wireless sensor networks, the main data flow takes place in the *forward path* where the wireless sensors are the source nodes transmitting their data to the sink. The *reverse path*, on the other hand, carries the data originated from the sink such as programming/retasking binaries, queries and commands to the sensor nodes. Although the above objectives and the desired features are common for the transport layer protocols, different functionalities are required to handle the transport needs of the forward and reverse paths.

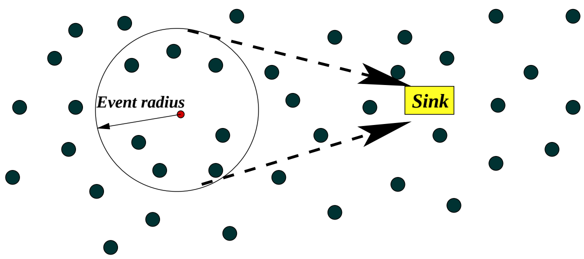

Fig. 4. Typical sensor network topology with event and sink. The sink is only interested in collective information of sensor nodes within the event radius and not in their individual data.

For example, the correlated data flows in the forward path are loss-tolerant to the extent that event features are reliably communicated to the sink. However, data flows in the reverse channel are mainly related to the operational communication such as dissemination of the new operating system binaries which usually requires 100 % reliable delivery. Therefore, a reliability mechanism would not suffice to address the requirements of both forward and reverse paths. Hence, we will study the transport layer issues pertaining to these distinct cases separately in the following sections.

A. Event-to-Sink Transport

In order to take the advantage of collective effort of numerous microsensor nodes, it is imperative that desired event features are reliably communicated to the sink. This necessitates a reliable transport layer mechanism that can assure the *event-to-sink reliability*.

The need for a transport layer for data delivery in the wireless sensor networks was questioned in [149] under the premise that data flows from source to sink are generally loss tolerant. While the need for end-to-end reliability may not exist due to the sheer amount of correlated data flows, an event in the sensor field needs to be tracked with a certain accuracy at the sink. Hence, unlike traditional communication networks, the sensor network paradigm necessitates an *event-to-sink* reliability notion at the transport layer. This involves in reliable communication of the event features to the sink rather than conventional packet-based reliable delivery of the individual sensing reports/packets generated by each sensor in the field. Such *event-to-sink reliable transport* notion based on collective identification of data flows from the event to the sink is illustrated in Fig. 4.

In order to provide reliable event detection at the sink, possible congestion in the forward path should be also addressed by the transport layer. Once the event is sensed by a number of sensor nodes within the coverage of the phenomenon, i.e., event radius, significant amount of traffic is triggered by these sensor nodes which may easily lead to congestion in the forward path. The need for transport layer congestion control to assure reliable event detection at the sink is revealed by the results in [86]. It has been shown in [86] that exceeding network capacity can be detrimental to the observed goodput at the sink. Moreover, although the event-to-sink reliability may be attained even in the presence of packet loss due to network congestion thanks to the correlated data flows, a suitable congestion control mechanism can also help conserve energy while maintaining desired accuracy levels at the sink.

On the other hand, although the transport layer solutions in conventional wireless networks are relevant, they are simply inapplicable for the event-to-sink reliable transport in the wireless sensor networks. These solutions mainly focus on reliable data transport following end-to-end TCP semantics and are proposed to address the challenges posed by wireless link errors and mobility [8]. The primary reason for their inapplicability is their notion of end-to-end reliability which is based on acknowledgments and end-to-end retransmissions. Due to inherent correlation in the data flows generated by the sensor nodes, however, these mechanisms for strict end-to-end reliability are significantly energy-draining and superfluous. Furthermore, all these protocols bring considerable memory requirements to buffer transmitted packets until they are ACKed by the receiver. In contrast, sensor nodes have limited buffering space (<4KB in MICA motes [117]) and processing capabilities.

In [186], the Reliable Multi-Segment Transport (RMST) protocol is proposed to address the requirements of reliable data transport in wireless sensor networks. RMST is mainly based on the functionalities provided by *directed diffusion* [83]. Furthermore, RMST utilizes in-network caching and provides guaranteed delivery of the data packets generated by the event flows. However, as discussed above, event detection/tracking does not require guaranteed end-to-end data delivery since the individual data flows are correlated loss tolerant. Moreover, such guaranteed reliability via in-network caching may bring significant overhead for the sensor networks with power and processing limitations.

The congestion detection and avoidance (CODA) protocol for sensor networks is presented in [200]. CODA mainly aims to detect and avoid on the forward path in WSN via *receiver-based congestion detection*, *open-loop hop-by-hop backpressure* signaling to inform the source about the congestion, and *closed-loop multi-source regulation* for persistent and larger-scale congestion conditions. The simulation results presented in [200] show that CODA can increase the network performance by congestion avoidance. However, the CODA protocol does not address the reliable event transport in the sensor networks. On the contrary, it has been observed in the experiment results [200] that the congestion control performed at the sensor nodes without considering the reliability impairs the event-to-sink transport reliability.

In contrast to the transport layer protocols for conventional end-to-end reliability, Event-to-Sink Reliable Transport (ESRT) protocol [159] is based on the event-to-sink reliability notion and provides reliable event detection without any intermediate caching requirements. ESRT is a novel transport solution developed to achieve reliable event detection in the wireless sensor networks with minimum energy expenditure. It includes a congestion control component that serves the dual purpose of achieving reliability and conserving energy. ESRT also does not require individual sensor identification, i.e., an event ID suffices. Importantly, the algorithms of ESRT mainly run on the sink, with minimal functionality required at resource constrained sensor nodes. It mainly exploits the fact that the sheer amount of data flows generated by the sensor nodes toward the sink are correlated due to spatial and temporal correlation among the individual sensor readings [199]. Consequently, ESRT protocol achieves application-specific desired transport reliability levels via collective effort of resource constrained wireless sensor nodes.

B. *Sink-to-Sensors Transport*

While the data flows in the forward path carry correlated sensed/detected event features, the flows in the reverse path mainly contain data transmitted by the sink for an operational or application-specific purposes. This may include the operating system binaries, programming/retasking configuration files, application-specific queries and commands. Dissemination of this type of data mostly requires 100 % reliable delivery. Therefore, the event-to-sink reliability approach introduced before would not suffice to address such tighter reliability requirement of the flows in the reverse paths.

Such strict reliability requirement for the sink-to-sensors transport of operational binaries and application-specific query and commands involves in certain level of retransmission as well as acknowledgment mechanisms. However, these mechanisms should be incorporated into the transport layer protocols cautiously in order not to totally compromise scarce wireless sensor resources. With this respect, local retransmissions and negative acknowledgment approaches would be preferable over the end-to-end retransmissions and acknowledgments to maintain minimum energy expenditure.

On the other hand, sink is involved more in the sink-to-sensor data transport on the reverse path. Hence, the sink with plentiful energy and communication resources can broadcast the data with its powerful antenna. This helps reduce the amount of traffic forwarded in the multi-hop wireless sensor network infrastructure and hence help sensor nodes conserve energy. Therefore, data flows in the reverse path may experience less congestion in contrast to the forward path which is totally multi-hop communication. This calls for less aggressive congestion control mechanisms for the reverse path compared to that for forward path in the wireless sensor networks.

The multi-hop and one-to-many nature of data flows in the reverse path of the wireless sensor networks prompts a review of reliable multicast solutions proposed in other wired/wireless networks. There exist many such schemes that address the reliable transport and congestion control for the case of single sender and multiple receivers [55]. Although the communication structure of the reverse path, i.e., from sink to sources, is an example of multicast, these schemes do not stand as directly applicable solutions; rather they need significant modifications/improvements to address the unique requirements of the wireless sensor network paradigm.

In [149], the PSFQ (Pump Slowly, Fetch Quickly) mechanism is proposed for reliable retasking/ reprogramming in the wireless sensor networks. PSFQ is based on slowly injecting packets into the network, but performing aggressive hop-by-hop recovery in case of packet loss. The pump operation in PSFQ simply performs controlled flooding and requires each intermediate node to create and maintain a data cache to be used for local loss recovery and in-sequence data delivery. Although this is an important transport layer solution for the wireless sensor networks, PSFQ does not address packet loss due to congestion.

A new framework called GARUDA for providing sink-to-sensors reliability in WSN is introduced in [138]. The GARUDA sink-to-sensors reliability framework incorporates an efficient pulsing based solution, which informs the sensor nodes about an impending reliable short-message delivery by transmitting a specific series of pulses at a certain amplitude and period. A virtual infrastructure called the *core* that approximates a near optimal assignment of local designated servers is instantaneously constructed during the course of a single packet flood. In case of a packet loss detected by a core node via an out-of-sequence packet reception, a core node initiates a two-stage negative-acknowledgment (NACK) based packet recovery process that performs out-of-sequence forwarding to assure the reliable delivery of the original message. GARUDA also supports other reliability semantics that might be required for sink-to-sensors communication such as (i) reliable delivery to all nodes within a sub-region of the sensor network; (ii) reliable delivery to minimal number of sensors required to cover entire sensing area; and (iii) reliable delivery to a probabilistic subset of the sensor nodes in the network.

C. Open Research Issues

In summary, the transport layer mechanisms that can address the unique challenges posed by the wireless sensor network paradigm are essential to realize the potential gains of the collective effort of wireless sensor nodes. As we have discussed above, there exist promising solutions for both event-to-sink reliable transport and sink-to-sensors reliable transport. However, there are still several important open issues to be researched as outlined below:

- **Real-time communication support:** Despite the existence of reliable transport solutions for WSN as discussed above, none of these protocols provide real-time communication support for the applications with strict delay bounds. Therefore, new transport solutions which can also meet certain application deadlines must be researched.
- **Multimedia delivery over WSN:** In some sensor applications, the data that needs to be gathered from the field may contain multimedia information such as target images, acoustic signal, and even video captures of a moving target. However, the multimedia traffic has significantly different characteristics and hence different reliable transport requirements compared to conventional data traffic. Therefore, new transport layer solutions which address the requirements of multimedia delivery over WSN must be developed.
- **Integration of WSN with the next-generation wireless Internet:** In most of the sensor deployment scenarios, the sink is usually assumed to reside within or very near to the sensor field, which makes it part of the multi-hop communication in receiving the sensor readings. However, it would be desirable to be able to reach sensor network from a distant monitoring or management node residing in the wireless Internet. Therefore, new adaptive transport protocols must be developed to provide seamless reliable transport of event features throughout the WSN and next-generation wireless Internet.
- **Cross-layer optimization:** Due to the severe processing, memory and energy limitations of sensor nodes, it is imperative that communication must be achieved with maximum efficiency. With this respect, cross-layer optimization of transport, link and physical layers must be investigated and the theoretical results must be applied to develop new cross-layer communication protocols for reliable transport in WSN.

VII. Network Layer

Since sensor networks have been an attractive area for research due to its potential applications as described in Section II [3], many researchers have proposed routing solutions to enable such networks. The routing protocols are broken down into four groups: (1) data-centric and flat-architecture, (2) hierarchical, (3) location-based, and (4) QoS-based. They are described in the following subsections.

A. Data-centric and flat-architecture protocols

Since sensor nodes are deployed randomly in large number, it is hard to assign specific IDs to each of the sensor nodes. Without an unique identifier, gathering data may become a challenge. To overcome this challenge, some routing protocols gather/route data based on the description of the data, i.e., data-centric.

The data-centric routing requires attribute based naming [45], [50], [123] [175] . 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^oF” 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 multi-casting, 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 [69]. In this technique, a sensor network is usually perceived as a reverse multicast tree as shown in Figure 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 Figure 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 [68]. With this respect, data aggregation is known as data fusion [69]. Also, care must be taken when aggregating data, because the specifics of the data, e.g., the locations

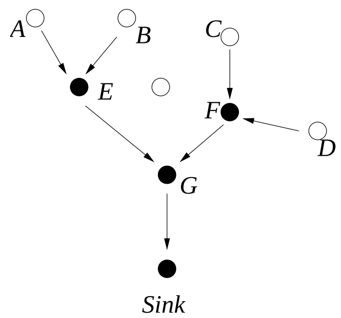

Fig. 5. Example of data aggregation.

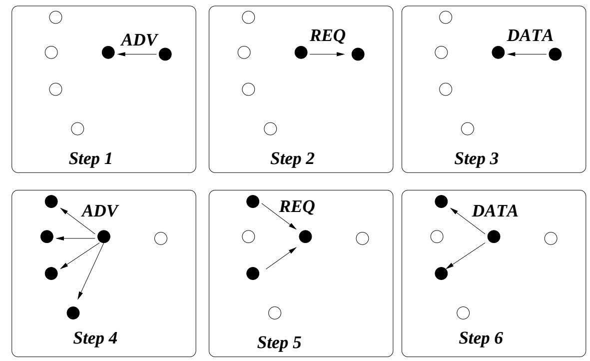

Fig. 6. The SPIN protocol [69].

of reporting sensor nodes, should not be left out. Such specifics may be needed by certain applications.

Some of the protocols that may apply data-centric principles are flooding [67], gossiping [67], SPIN [69], directed diffusion [83], [51], energy-aware routing proposed by Shah and Rabaey [171] , rumor routing [15], gradient-based routing [164], CADR [32], COUGAR [211], ACQUIRE [157], Shortest Path Minded SPIN (SPMS) [93], and Solar-aware routing [198].

To provide insight into the current research, we discuss some of the proposed schemes that may use data-centric techniques.

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 [69]:

- *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 [67] 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 [69] 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 message, the sensor broadcasts an ADV message containing a descriptor, i.e., meta-data, of the DATA as shown in Step 1 of Figure 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 Figure 6, respectively. The neighbor sensor node then repeats this process as illustrated in Steps 4, 5, and 6 of Figure 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 [69] where the sensor nodes broadcast an advertisement for the available data and wait for a request from interested sinks.

Directed Diffusion - The *directed diffusion* data dissemination paradigm is proposed in [83] where the sink sends out $interest$, which is a task description, to all sensors as shown in Figure 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

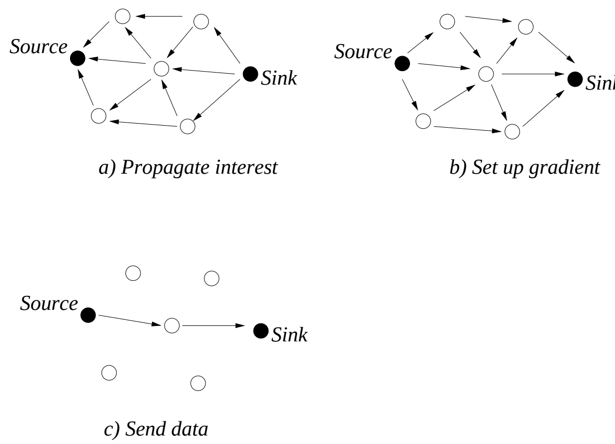

Fig. 7. An example of directed diffusion [83].

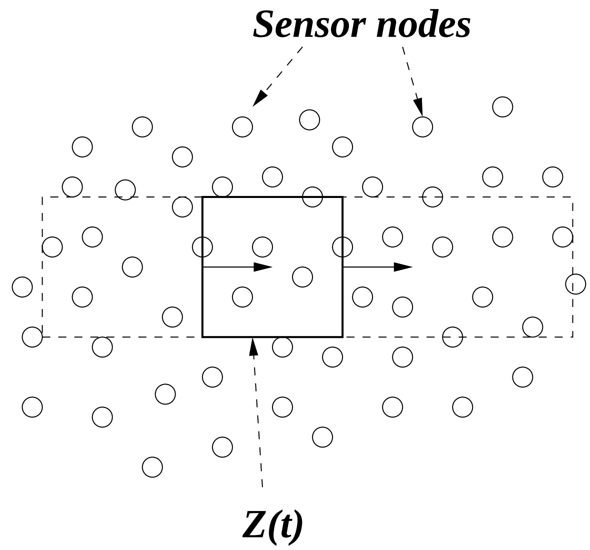

Fig. 8. Spatiotemporal Multicast Protocol

throughout the sensor network, the gradients from the source back to the sink are set up as shown in Figure 7(b). When the source has data for the interest, the source sends the data along the interest's gradient path as shown in Figure 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.

Energy-aware routing - Shah and Rabaey [171] proposed a routing protocol in which the paths between the source and sink are determined by means of a probability function. The purpose is to increase the lifetime of the network without depleting the energy of nodes that lie on the minimum energy path. The probability function in choosing the path is based on the energy consumption of each path.

Gradient-based routing - Schurgers et al. [164] proposed an enhanced version of the Directed Diffusion that includes the hop-number when the interest is diffused to the network. As a result, the nodes in the network know the minimum number of hops away from the sink. In addition, nodes relaying data for multiple paths may spread the data trying to achieve an even distribution of the traffic throughout the network.

Besides data-centric, some routing protocols that are based on a flat-architecture are proposed [72], [76], [77], [219]. The spatiotemporal multicast protocol [76] provides an interesting way to support an application information delivery request. A request session is specified by a tuple, (m, $Z(t)$, T_s, T). m is the request message and $Z(t)$ is the mobile area where the message m should disseminate. T_s is the sending time, and T is the duration that the request is valid. Since $Z(t)$ is the mobile area at time t, the sensor nodes that receive the message m change as well over time. As shown in Figure 8, the solid-rectangle is the mobile area $Z(t)$. It can slide to the right as time t changes. As a result, the sensor nodes that receive the message m changes.

B. Hierarchical protocols

Sensor nodes are deployed with a limited amount of energy. Hierarchical-architecture protocols are proposed to address the scalability and energy consumption challenges of sensor networks. Sensor nodes form clusters where the cluster-heads aggregate and fuse data to conserve energy. The cluster-heads may form another layer of clusters among themselves before reaching the sink. Some of the hierarchical protocols proposed for sensor networks are Low-Energy Adaptive Clustering Hierarchy (LEACH) [68], Power-efficient GAthering in Sensor Information Systems (PEGASIS) [103], [104], Threshold sensitive Energy Efficient sensor Network protocol (TEEN) [111], and AdaPtive Threshold sensitive Energy Efficient sensor Network protocol (APTEEN) [112].

LEACH - LEACH is a clustering-based protocol that minimizes energy dissipation in sensor networks [68]. 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:

$$T(n) = \begin{cases} \frac{P}{1-P*[r \ mod(1/P)]} & if \ n \ \in \ G \\ 0 & otherwise \end{cases}$$

where P is the desired percentage to become a cluster-head, r is the current round, and G is 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 Time Division Multiple Access (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.

PEGASIS - PEGASIS requires the nodes in the network to form chains. Each node within a chain aggregates data from its neighbor until all the data is aggregated at one of the sensor nodes. Only one node within a chain is allowed to communicate with the base station. By using this method, the number of transmissions with the base-station is reduced but at the expense of long-propagation delay.

TEEN and APTEEN - The TEEN protocol organizes the sensor nodes into multiple levels of hierarchy, where data is transmitted by the cluster heads until the base station is reached. The sensor nodes are programmed to respond to sensed-attribute changes, e.g., temperature or magnetic flux, by comparing the measured value with the hard and soft thresholds. If the measured value exceeds the hard and soft threshold limits, the data is sent to upper level hierarchy toward the base station. Since TEEN is based on fixed threshold limits, it is not suitable for periodic reports required by some applications. An advancement of TEEN is APTEEN, which aims at both servicing periodic inquiries and responding to sensed-attribute changes.

In addition, Younis et al. [215] proposes to use the cluster heads as gateways. The cluster heads are assumed to know the location of the sensor nodes to schedule data delivery and route setup. After sensor nodes collect the data, the data is passed to the cluster-head where the data may be fused or aggregated before sending to the sink or user. Furthermore, an architecture is proposed by Subramanian and Katz [189] to self-organize the sensor nodes. In this architecture, all the sensor nodes are assigned an address, and nodes that act as routers are stationary and form a backbone where collected data is routed.

Although a hierarchical-architecture is an easy way to manage and organize the sensor nodes, it faces robustness issues such as failure of the cluster heads. In addition, the hierarchical-structure may not be evenly spread out causing congestion at some cluster-heads.

C. Location-based protocols

Another class of routing protocols is based on location. For example, these protocols are MECN [155], SMECN [97], and GAF [210]. If the locations of the sensor nodes are known, the routing protocols can use this information to reduce the latency and energy consumption of the sensor network. Although GPS is not envisioned for all types of sensor networks, it can still be used if stationary nodes with large amount of energy are allowed. In addition, it simplifies the routing protocols.

On the other hand, the error in location detection can cause error in routing. For example, sensor nodes are prone to failure, and they may be deployed in a hostile environment. If the GPS or the location device is broken/damaged, sensor nodes that depend on the GPS/location device are rendered useless. In addition, the monetary cost for the GPS may be expansive for some applications. Also, the power consumption and size of the GPS may not be appropriate if sensor nodes are operated by batteries and deployed in thousands.

Small Minimum Energy Communication Network (SMECN) - A protocol is developed in [155], which 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 [97] 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 *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 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 modeled as $p(u, v) = td(u, v)^n$, where t is a constant, $d(u, v)$ is the distance between node u and v, and $n \geq 2$ is the path-loss exponent experienced by radio transmission. Also, the power needed to receive data is c. Since $p(u, v)$ increases by n^{th} 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 $r = (u_0, u_1, ..., u_k)$ 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 is the power required to receive data. A path r is a *minimum-energy path* from u_0 to u_k if $C(r) \leq C(r')$ for all paths r' between node u_0 and u_k in G'. As a result, a subgraph G has the minimum-energy property if for all (u,v) $\in V$, there exists a path r in G, which is a minimum-energy path in G' between node u and v.

D. QoS-based protocols

Some of the routing protocols [1], [6], [23], [32], [66], [90], [91], [97], [98], [185] aim to minimize the energy consumption of the network by using the remaining energy of the sensor nodes as a metric of optimization.

Minimum cost path **-** Chu et al. [32] proposes a protocol that tries to find the minimum cost path to route the data. The cost function captures the delay, throughput, and energy consumption of the node. The protocol has two phases. The first phase requires all the nodes in the network to calculate the cost to the sink. Initially, the sink sends a message. The neighbors that receive this message adjust their cost by summing the cost of the link and the cost of the node that has sent the message. Afterwards, this message is broadcast to the neighbors. At the end of the first phase, all the sensor nodes know the cost to send a message to the sink. In the second phase, the source broadcasts the data message to its neighboring nodes. The neighboring nodes check the remaining cost of the message. If the cost is not sufficient to reach the sink, the message is dropped; otherwise, the message is forwarded until it has reached the sink.

Stateless protocol **-** In addition to the protocols that use energy consumption as a metric, SPEED [66] aims to provide soft real-time end-to-end guarantees. It uses location-based schemes to find the routes to the sink, and the end-to-end delay of the packet is determined prior to admission. The SPEED protocol tries to ensure the end-to-end delay of the packets that may be critical for certain applications.

Sequential Assignment Routing (SAR) **-** In [185], a set of algorithms, which perform organization, management and mobility management operations in sensor networks, are proposed. Self organizing medium access control 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 (SWR) and multi winner election (MWE) handle the necessary signaling and data transfer tasks in local cooperative information processing.

E. Open research issues

In summary, designing routing protocols for sensor networks is a challenging problem. The size, energy, and robustness constraints of the sensor nodes have a significant impact in routing that traditional ad-hoc networks do not have [3]. Although many protocols are proposed, the need to have robust yet efficient routing protocols is still there. For example, different QoS protocols are needed. Instead of just using energy consumption as a metric, end-to-end delay and packet-loss ratio may be used.

VIII. Data Link Layer

WSN applications rely on multiple sensor feedback for interaction with the environment. The main objectives of the data link layer in this interaction are *multiplexing/ demultiplexing of data, data frame detection, medium access,* and *error control*. Contrary to traditional networks, WSNs, however, are characterized by low energy requirements and collaborative nature of sensors. Hence, the design of data link layer protocols encounter unique challenges as opposed to traditional networking protocols. In the following two subsections, the data link layer issues are explored within the discussion of the medium access and error control strategies and recently proposed solutions in the WSNs are explained.

A. Medium Access Control (MAC)

Each sensor node shares the same physical wireless medium with other nodes inside their transmission region. Since the nodes communicate through a common wireless multiple access channel, the design of *Medium Access Control* (MAC) layer is of crucial importance. The MAC layer protocols ensure communication in the wireless medium such that communication links between nodes should be established in order to provide connectivity throughout the network. Moreover, the access to the channel should be coordinated such that collisions are minimized or eliminated.

In addition to the traditional requirements of the MAC layer, the distributed nature of the WSN and the application-oriented traffic properties of sensor applications pose additional unique challenges to MAC layer for WSN. Thus, traditional MAC protocols are deemed impractical. The most important properties of the WSN that is crucial to the design of new MAC protocols are discussed as follows:

- *Energy Consumption:* The low cost requirements and the distributed nature of the sensor nodes constrain the energy consumption of all the layers [3]. Hence, energy efficiency is of primary importance for the MAC layer protocol design. The MAC layer protocol should ensure that nodes transmit their information with minimum energy consumption which can be achieved by minimizing idle listening times and collisions among sensor nodes.
- *Application-oriented Traffic:* The application-oriented nature of the WSN should be exploited in order to increase the performance of the MAC protocol. In traditional networks, per-node fairness is an important aspect of the MAC layer protocol due to the competitive nature of the nodes. In WSN, however, the system is interested in the collective information provided by the sensors instead of the information sent by each node. Hence, MAC layer protocols should take a collaborative approach so that the application specific information is exploited to enhance the performance. As an example, in monitoring applications, where the traffic follows a periodic pattern, a reservation-based approach can be used to exploit the periodicity in the traffic. On the other hand, in event based applications, where bursty traffic is generated only during duration of events, an access mechanism that is adaptive to the generated traffic is necessary.
- *Network Topology:* The topological awareness of the network is another property that should be incorporated into MAC protocols. In WSN, large number of sensor nodes can be deployed [3]. The increasing density increases the number of nodes in reach of a sensor node which can be viewed both as a disadvantage and an advantage. Increasing network density increases the number of nodes contending with each other resulting in higher collision probability. On the other hand, the connectivity of the network can be provided without compromising from the increased transmission power due to the high number of neighbor nodes. Moreover, the multi-hop nature of the network needs to be exploited in the MAC layer for improved delay and energy consumption performance.
- *Spatial Correlation:* Due the high density of the sensor nodes, the information gathered by each node is highly correlated [199]. Intuitively, data from spatially separated sensors is more useful to the sink than highly correlated data from closely located sensors. Hence, it may not be necessary for every sensor node to transmit its data; instead, a smaller number of sensor measurements might be adequate to communicate the event features to the sink. Exploiting the correlation between sensor nodes in the MAC layer protocol can be a promising approach to further improve overall network performance.

In order to address the challenges presented above, significant number of MAC protocols have been devel-

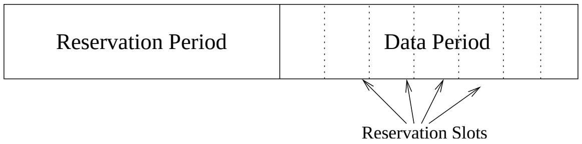

Fig. 9. General frame structure for TDMA-based MAC protocols.

oped recently. The approaches taken in these works can be classified into two main schemes, i.e., *reservation-based medium access* and *contention-based medium access*. Moreover, there exists hybrid solutions that merge these two schemes along with cross-layer approaches, which incorporate information from other layers into the MAC layer functionalities. In the following sections, the fundamental MAC approaches, the hybrid solutions and the cross-layer approaches are discussed based on their applicability in WSN along with the proposed MAC solutions.

1) Reservation-based Medium Access: Reservation-based protocols have the advantage of collision-free communication since each node transmits data to a central agent during its reserved slot. Hence, the duty cycle of the nodes is decreased resulting in further energy efficiency. Recently, *time-division multiple access* (TDMA)-based protocols have been proposed in the literature. Generally, these protocols follow common principles, where the network is divided into clusters and each node communicates according to a specific *super-frame* structure. The super-frame structure which generally consists of two main parts is illustrated in Fig. 9. The *reservation period* is used by the nodes to reserve their slots for communication through a central agent, i.e., *cluster-head*. The *data period* consists of multiple slots, that is used by each sensor for transmitting information. Among the proposed TDMA schemes, the contention schemes for reservation protocols, the slot allocation principles, the frame size and clustering approaches differ in each protocol. We explain each protocol along these common features in the following.

In [5], an energy-aware TDMA-based MAC protocol is presented. In the paper, sensor network is assumed to be composed of clusters and gateways, hence implicit clustering algorithm is not provided. Each gateway acts as a cluster-based centralized network manager and assigns slots in a TDMA frame based on the traffic requirements of the nodes.

In [152], energy efficient collision-free MAC protocol is presented. The protocol is based on a time-slotted structure and uses a distributed election scheme based on traffic requirements of each node to determine the time slot that a node should use. Each node gets information about its every two-hop neighbor and the traffic information of each node during a random access period, i.e., the reservation period. Based on this information, each node calculates its priority and decides on which time slot to use. Nodes sleep during their allocated slots if they do not have any packets to send or receive .

An intra-cluster communication bit-map-assisted (BMA) MAC protocol is proposed in [101] with an energy efficient TDMA (E-TDMA) scheme. The protocol consists of *cluster set-up phase* and *steady state phase*. In the cluster set-up phase, cluster head is selected based on the available energy in each node. Accordingly, an E-TDMA MAC scheme is used in each of the clusters formed by the cluster-heads. In each superframe, the reservation period is slotted for contention and the data period is divided into two periods, i.e., data transmission period and idle period. The duration of the data period is fixed and the data transmission period is changed based on the traffic demands of the nodes.

In [124], an adaptive low power reservation based MAC is proposed. The authors propose a clustered hierarchical organization, where the cluster-head is chosen as a result of contention. The reservation period is composed of three parts. In *control slot*, the cluster-head broadcasts control info such as frame length and the end of clustership info. In the *reservation request window* and *reservation confirmation slot*, slot allocations are performed. The frame size is determined according to the probability of transmission failures of request packets.

Moreover, in [38] and [107] TDMA-based MAC protocols are also proposed for WSN. However, since the main contribution of these protocols are cross-layer optimization techniques, we explore these protocols in Section VIII-A.4.

Overall, TDMA-based protocols provide collision-free communication in the WSN, achieving improved energy efficiency. However, such TDMA-based protocols require an infrastructure consisting of cluster heads which coordinate the time slots assigned to each node. Although many clustering algorithms have been proposed with these protocols, the optimality and the energy efficiency of these algorithms still need to investigated. In addition, TDMA-based protocols cause high latency due to the frame structure. Hence, TDMA-based MAC protocols may not be suitable for WSN applications where delay is important in estimating event features and the traffic has bursty nature. Moreover, since a time slotted communication is performed in the clusters, inter-cluster interference has to be minimized such that nodes with overlapping schedules in different clusters do not collide which each other. Finally, time synchronization is an important part of the TDMA-based protocols and synchronization algorithms as explained in Section XI are required.

2) Contention-based Medium Access: The contention-based protocols generally do not require any infrastructure such as clusters since every node tries to access the channel based on carrier sense mechanism. Although the reservation periods of TDMA-based protocols can be classified as contention-based medium access, here we refer to the actual transmission of data. Contention-based protocols provide robustness and scalability to the network. However, the collision probability increases with increasing node density. In addition, contention-based protocols can support variable, but highly correlated and dominantly periodic traffic.

The most common contention-based protocol which also constitutes a ground for other protocols is the IEEE 802.11 MAC protocol [81], [82]. However, IEEE 801.11 performs poorly in terms of energy efficiency, since nodes have to listen to the channel for contention and before transmission, Nodes also consume energy during the idle listening period [213]. In addition, as the density of the network increases, the collision avoidance mechanism becomes ineffective due to increased number of hidden nodes [201]. Hence, appropriate enhancements are required in the WSN scenario.

An energy-efficient MAC protocol for WSN is introduced in [213], where the authors aim to decrease the energy consumption while trading off throughput and latency. While the protocol is based on the IEEE 802.11 RTS/CTS/DATA/ACK scheme [82], the authors introduce periodic sleep and listen cycles to reduce idle listening. Nodes that are in the transmission range of each other synchronize themselves according to a sleep schedule. Moreover, overhearing avoidance procedure is introduced to further improve energy efficiency. In addition, a message passing feature is proposed which enables transmitting a message in a burst. In order to decrease the delay performance in the multi-hop architecture, adaptive listening procedure is introduced in [214]. The adaptive listening procedure notifies nodes two hop away from the transmission such that potential next hop nodes wait for the transmission. This decreases the dependence of latency on the number of hops by two.

One of the disadvantages of S-MAC is that it can not provide adaptivity to bursty traffic since the sleep schedules are fixed length. In [40], T-MAC is presented which introduces an adaptive duty cycle. The nodes listen to the channel only when there is traffic which reduces the amount of energy wasted on idle listening. Both S-MAC and T-MAC provide significant energy savings compared to IEEE 802.11, however, at the cost of increased latency and throughput degradation.

Generally, contention-based protocols provide scalability and lower delay, when compared to reservation-based protocols. On the other hand, the energy consumption is significantly higher than the TDMA-based approaches due to collisions and collision avoidance schemes. Moreover, contention-based protocols are more adaptive to the changes in the traffic volume and hence applicable to applications with bursty traffic such as event-based applications. Furthermore, the synchronization and clustering requirements of reservation-based protocols make contention-based more favorable in scenarios where such requirements can not be fulfilled.

3) Hybrid Medium Access: While a pure TDMA-based access scheme dedicates the entire channel to a single sensor node, a pure *Frequency-Division Multiple Access* (FDMA) or *Code-Division Multiple Access* (CDMA) scheme allocates minimum signal bandwidth per node. Such contrast brings the tradeoff between the access capacity and the energy consumption. Hybrid schemes in reservation-based protocols aim to leverage the tradeoff introduced in channel allocation by combining TDMA approaches with FDMA or CDMA schemes.

In [177], an analytical formula is derived to find the optimum number of channels for each node, which gives the minimum system *power consumption*. This determines the hybrid TDMA-FDMA scheme to be used. Although the MAC protocol also assumes that clusters are formed in the network, it is a good example of cross-layer optimization where the MAC protocol is designed according to the physical layer properties.

In [64], a low power distributed MAC protocol which uses multiple channels and random access is presented. Spread spectrum CDMA is used for multiple channels and each node share a limited number of channels which are distributed as a result of contention. The channel assignment is modeled as a two-hop coloring problem and an heuristic is used in the protocol. Moreover, each node wakes up its corresponding neighbor by using a wake-up radio, which works separately from the data radio and monitors the channel at a very low power. The most important contribution of the protocol is that node addressing is done according to the channel number.

Hybrid reservation-based solutions, provide performance enhancements in terms of collision avoidance and energy efficiency due to improved channel organization. However, such protocols require sophisticated physical and MAC layer protocols that support CDMA or FDMA communication or unique radio components. Hence, these protocols may not be applicable for high density WSN where sensor node cost is an important factor.

IEEE 802.15.4 is also proposed for low data rate wireless networks which combines reservation-based and contention-based approaches [80]. It introduces a superframe structure with two disjoint periods, i.e. contention access period and contention free period. The network is assumed to be clustered and each cluster head, i.e. PAN coordinator, broadcasts the frame structure and allocates slots to prioritized traffic in the contention free period. In the contention period nodes contend using CSMA/CA or slotted CSMA/CA to access the channel. Although this protocol aims prioritization and energy efficiency up to 1% duty cycles, it requires a cluster-based topology, which may not applicable to some WSN scenarios.

4) Cross-Layer Solutions: It has been shown in [137] that multi-hop nature of the WSN introduces a network delay in S-MAC [214]. More specifically, the multi-hop latency increases linearly with the hop count. Although the slope of the linearity is reduced to half by the adaptive listening algorithm [214], the protocol still introduces significant latency compared to pure contention-based protocols. Likewise, the frame structure in TDMA-based protocols along with the multi-hop nature of the WSN architecture, imposes significant network delay. Hence, it is clear that the multi-hop route of the packets should also be considered in the MAC protocols for WSN. Consequently, route-aware protocols have been proposed for satisfactory data delivery in the WSN.

In [107], a route-aware contention-based MAC protocol for data gathering (DMAC) is proposed for WSN where data is collected through a unidirectional tree. The protocol introduces a sleep schedule such that the nodes on a multihop path wake up sequentially as the packet traverses. Moreover, since small sized packets are used, RTS/CTS mechanism is not used. DMAC incorporates local synchronization protocols in order to perform local scheduling and uses data prediction in case a node requires a higher duty cycle for data transmission. Based on these techniques, multi-hop effects on the delay performance is minimized specifically for data gathering applications where a unidirectional tree is used.

In [38], a TDMA-based MAC protocol is used, where the frame length is determined according to the routing requirements. Moreover, the transmit power and the hop number selection for a specific route are jointly optimized based on physical layer, link layer and network layer requirements. Based on the link information between nodes and the topology of the network, the constellation sizes for data encoding in the physical layer is optimized to reduce transmission time and energy consumption for a delivery of a packet.

A converse approach of selecting relays based on contention is used in [224]. In this scheme, the next hop in the network is determined as a result of contention for CTS messages after an RTS message has been sent. Moreover, each node performs periodic sleep in order to save energy and contend for the relay role based on priority-based backoff policy. Consequently, energy consumption and latency is decreased since a specific node is not waited for next hop transmission. Similarly, MAC layer information is used as the basis for achieving energy-efficient routing in [158].

Incorporating physical layer and network layer information into the MAC layer design improves the performance in WSN. Route-aware protocols provide lower delay bounds while physical layer coordination improve the energy efficiency of the overall system. Moreover, since sensor nodes are characterized by their limited energy capabilities and memory capacities, cross-layer solutions provide efficient solutions in terms of both performance and cost. However, care must be taken while designing cross-layer solutions since the interdependence of each parameter should be analyzed in detail.

5) Open Research Issues: In summary, medium access solutions tailored to the unique challenges of WSN paradigm is required for satisfactory transmission of event features to the sink. Although the abovementioned solutions provide appropriate solutions to the many of the challenges in WSN, there still exists many open research issues to be researched for MAC protocols in WSN. We summarize the open research issues as below:

- **Mobility support:** Although efficient MAC protocols have been developed for WSNs, these protocols are tailored to static nodes. However, the developments in MEMS and robotics technology have enabled production of mobile sensor nodes for low cost. Hence, mobility support at the MAC layer is required also for WSN applications.
- **Real-time communication:** As discussed above, both contention-based and reservation-based protocols do not try to provide low-delay medium access. Moreover, the access latency is usually traded off for energy conservation. However, in order for WSNs to provide real-time support for delay crucial applications, low latency MAC protocols are required.
- **Cross-layer optimization:** In order to improve the energy efficiency of medium access in WSN, cross-layer optimization of data link layer with physical, routing and transport layers is crucial. As explained above, there exists some solutions about cross-layer optimization using routing and physical layer information, however more extensive research is required in order to determine the parameters effecting such an integrity as well as transport layer integration.

- **Spatial correlation:** The high density in the WSN pose highly correlated data for spatially close sensor nodes as discussed above. Hence, MAC protocols that collaboratively filter the redundant data before being transmitted to the network is required for improved energy end latency efficiency in WSN.

B. Link Layer Reliability

The main objectives of the data link layer are multiplexing/demultiplexing of data, data frame detection, medium access, and error control. While fulfilling these objectives, data link layer should provide reliable and energy efficient point-to-point and point-to-multipoint communication throughout the network. An overview of the data link components are shown in Figure 10, which is implemented in [221].

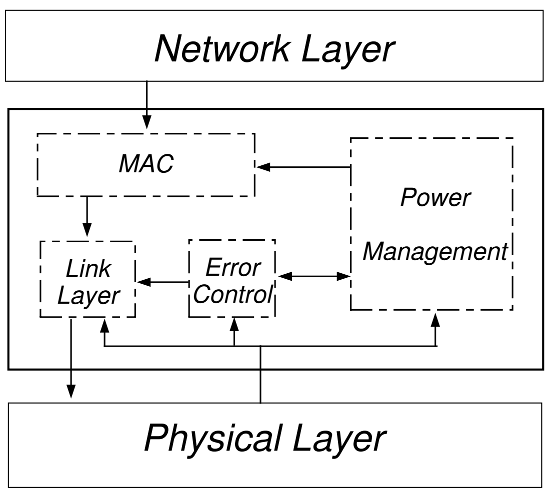

Fig. 10. An overview of data link layer providing reliability in WSN [221].

In WSN, where correlation between sensors can be exploited in terms of *aggregation*, *collaborative source coding*, or *correlation-based protocols*, error control is of extreme importance. Since the abovementioned techniques aim to reduce the redundancy in the traffic by filtering correlated data, it is essential for each packet to be transmitted reliably. Moreover, the multi-hop features of the WSN require a unique definition of reliability other than the conventional reliability metrics which focus on point-to-point reliability. More specifically, in a WSN, when a packet is injected into the network, each node along the path to the sink consumes a certain amount of its scarce resources to relay the packet. Each packet has a different importance due to the path it has already traversed. Hence, packets in different locations in the network, require different reliability measures. Furthermore, in WSN, the applications are interested in the collaborative information from sensors about a specific event, rather than individual readings of each sensor. Consequently, the reliability notion considered in WSN differs from the approach in traditional wireless networks, in terms of both multi-hop reliability and event-based reliability.

In general, the error control mechanisms in communication networks can be categorized into three main approaches, i.e., *Power Control*, *Automatic Repeat reQuest* (ARQ), and *Forward Error Correction* (FEC).

- *Power Control*: Controlling the transmission power can be used to achieve desired error rates. Higher transmission power reduces the packet error rate by improving the signal-to-noise ratio. As a result, however, the energy consumption is increased in addition to increased interference with other nodes. Power control requires sophisticated protocols to be implemented which requires additional memory footprint for the implementation. Another drawback of power control in error control is that the radio should support different power levels, which may not be applicable to many WSNs where low node cost is of critical importance.
- *Automatic Repeat Request (ARQ)*: ARQ-based error control mainly depends on the retransmission for the recovery of the lost data packets/frames. ARQ protocols enable transmissions of failed packets by sending explicit acknowledges upon reception and detection of missing acknowledgments. The main ARQ strategies can be summarized as *Go-Back-N*, *Selective Repeat*, and *Stop-and-Wait* [105], [29], [28]. It is clear that such ARQ-based error control mechanisms incur significant additional retransmission cost and overhead. Although ARQ-based error control schemes are utilized at the data link layer for the conventional wireless networks, the efficiency of ARQ in sensor network applications is limited due to the scarcity of the energy and processing resources of the sensor nodes.

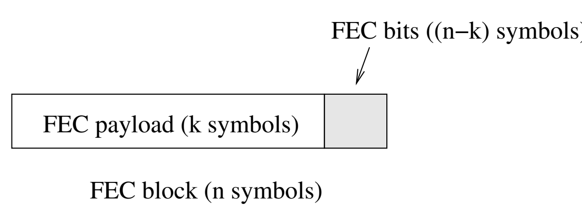

Fig. 11. An illustration of forward error correction (FEC) in WSN.

- *Forward Error Correction (FEC)*: FEC adds redundancy to the transmitted packet such that it can be received at the receiver error-free even if

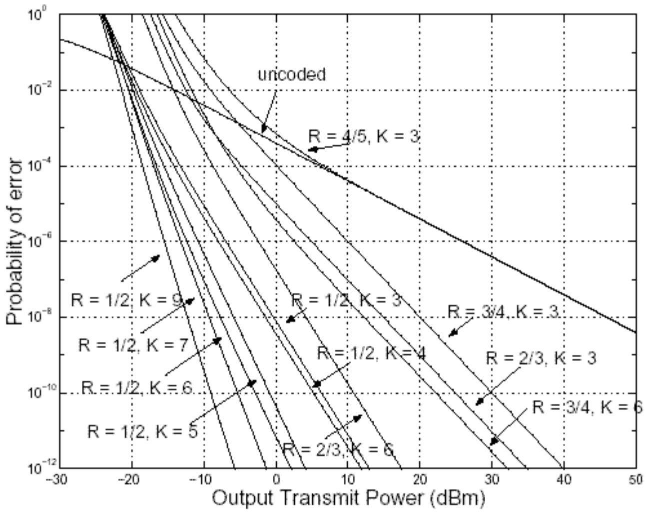

Fig. 12. Probability of error versus transmission power for different convolutional codes.

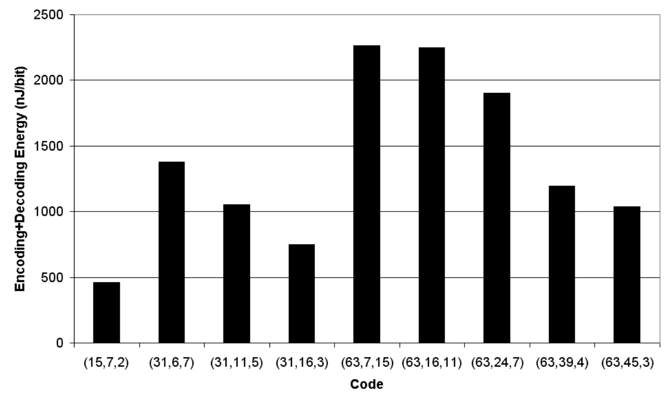

Fig. 13. Total energy consumption for encoding and decoding using BCH codes.

the limited number of bits are received in error. More specifically, in an (n,k) FEC code, as shown in Figure 11, $(n\text{-}k)$ redundant FEC symbols are added to the k bit FEC payload to improve the error resilience of the wireless communication at the cost of increased bandwidth consumption. As a result, the overall probability of error is decreased. There exist various FEC codes such as BCH codes, linear block codes and Reed-Solomon codes, which are optimized for specific packet sizes, channel conditions and reliability notions. On the other hand, for the design of efficient FEC schemes, it is important to have good knowledge of the channel characteristics and implementation techniques.

In WSN, energy consumption is the most important performance metric in the design of communication protocols. Since the sensor nodes have stringent energy capabilities, error control protocols should also consider energy efficiency as the first design goal. The sources of energy consumption in WSN can be mainly classified into two types, i.e., computation power and transmission/receiving power. However, since transmission of a bit is more costly than processing power, protocols that exploit the on-board processing capabilities of sensor nodes are more favorable. Consequently, the use of FEC is the most efficient solution given the constraints of the sensor nodes.

The use of FEC codes can decrease the transmit power due to the increased redundancy in the constructed packets [177]. The performance of convolutional codes in terms of probability of error and output transmit power is shown in Fig. 12 [177]. As shown in Fig. 12, lower transmit power is possible for a specific probability of error using FEC codes. However, the required processing power due to encoding/decoding of the packet increases the overall energy consumption. The required energy during encoding and decoding of BCH codes is shown in Fig. 13(a) along with the incurred encoding/decoding latency in Fig. 14 [120]. Moreover, the increase in packet length also incurs additional energy cost. This additional cost is due to the longer packet transmission times and hence, the increased packet collision rate.

Although the FEC can achieve significant reduction in the *bit error rate* (BER) for any given value of the transmit power, the additional processing power that is consumed during encoding and decoding must be considered when designing an FEC scheme. FEC is a valuable asset to the sensor networks if the additional processing power is less than the transmission power savings. Thus, the tradeoff between this additional processing power and the associated coding gain need to be optimized in order to have powerful, energy-efficient and low-complexity FEC schemes for the error control in the sensor networks. Furthermore, powerful FEC codes incurs additional decoding latency which should also be considered in the choice of error control schemes.

Along with the discussions presented above, an adaptive error control scheme is presented in [121]. The transmit power and the coding rate is increased as the required range between sensor nodes is increased. Given the BER and latency requirements, the lowest power FEC code that satisfies these are continuously chosen. It has been found that using this protocol, energy is scalable over nearly two orders of magnitude, realizing range scalability to well over 100 m and BER scalability across several decades. Moreover in [120], adaptive error control is also discussed as part of a low power WSN protocols.

Although FEC codes has been shown to provide

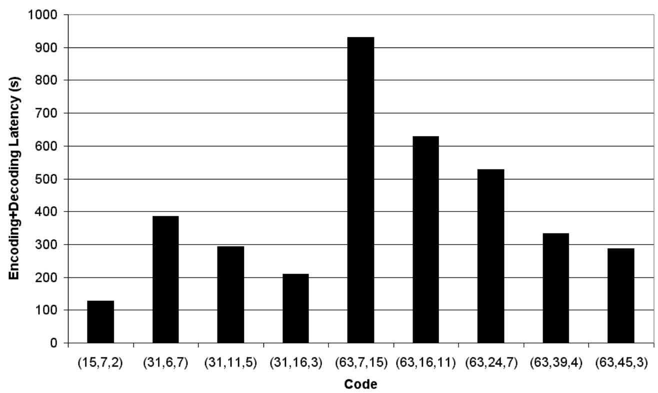

Fig. 14. Total encoding and decoding latency using BCH codes.

flexible error control capabilities over high variety of ranges between nodes, such an advantage is limited in scenarios where limited error probabilities are acceptable. More specifically, for convolutional codes, no coding provides better energy efficiency for probability of error, $P_b > 10^{-4}$ [177]. This is due to the fact that the encoding/decoding energy is small at high P_b and output power is limited. As a result, the transceiver energy dominates the overall energy consumption. Since the packet length is increased due to coding, overall energy consumption increases. Consequently, if lower P_b is not required by an application for individual packets from sensors, FEC coding can be inefficient.

1) Hybrid Solutions: In addition to the various error control schemes explained above, hybrid solutions also exist. Especially, data-aware error control schemes aim to exploit the unique properties of the sensed data such as spatial and temporal correlation [220]. The correlation among individual packets helps implementation of hybrid error control protocols which require less overhead and energy consumption [41]. In [113], the effects of distributed source coding protocols on the reliability and energy efficiency is investigated. Moreover, a channel quality-based error control protocol is also proposed which selects an FEC rate depending on the channel quality [176].

2) Open Research Issues: While link layer error control protocols aim to overcome the errors incurred by the wireless channel, more care can be taken at the link layer through medium access control (MAC) protocols. Since MAC protocols govern the procedures to access the shared wireless channel, the efficiency of the access scheme helps improve the reliability of the WSN. By reducing collisions, less energy can be consumed for a specific communication attempt, preserving the connectivity of the network and hence the overall reliability. The density of the WSN can also be exploited to provide more reliable communication. As the network density of the network increases, the number of nodes contending with each other increases resulting in higher collision probability. On the other hand, the connectivity of the network can be provided without compromising from the total energy consumption due to the high number of neighbor nodes. In addition, due the high density of the sensor nodes, the information gathered by each node is highly correlated. Exploiting the correlation between sensor nodes also at the MAC layer can be a promising approach to further improve overall network reliability.

The data link layer still remains a challenging area to work in since sensor nodes are inherently low-end. Combining the low-end characteristic of the sensor nodes with harsh deployed terrains, collaborative approach and exploiting the correlation between sensor nodes, it calls for new medium access as well as error control schemes.

IX. PHYSICAL LAYER

The physical layer is responsible for the conversion of bit streams into signals that are best suited for communication across the wireless channel. More specifically, the physical layer is responsible for frequency selection, carrier frequency generation, signal detection, modulation and data encryption. The reliability of the communication depends also on the hardware properties of the nodes such as antenna sensitivity, and transceiver circuitry.

The wireless medium used in the WSN is one of most important factors, since the unique properties of different media constraints the capabilities of the physical layer. The unreliability and varying nature of wireless communication channels necessitate efficient error control strategies to be implemented according to the properties of the specified wireless medium. The wireless links can be formed by radio, infrared or optical media. For radio links, one option is to use *Industrial, Scientific and Medical* (ISM) bands, which offer license-free communication in most countries. Some of the ISM frequency bands are already being used for communication in cordless phone systems and wireless local area networks. Much of the current hardware for sensor nodes is based upon *radio frequency* (RF) circuit design. The μAMPS wireless sensor node [177] uses a Bluetooth-compatible 2.4 GHz transceiver with an integrated frequency synthesizer. In addition, the low-power sensor device [208] uses a single channel RF transceiver operating at 916 MHz. The *Wireless Integrated Network Sensors* architecture [148] also uses radio links for communication. Although there exists many advantages in using the ISM bands such as free radio, huge spectrum allocation and global availability, these bands are prone to interference from

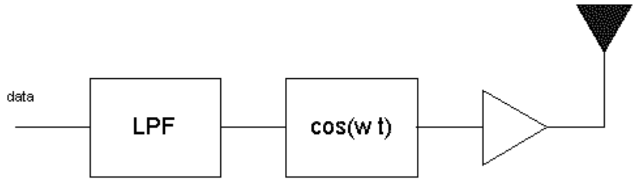

Fig. 15. Binary Modulation Block.

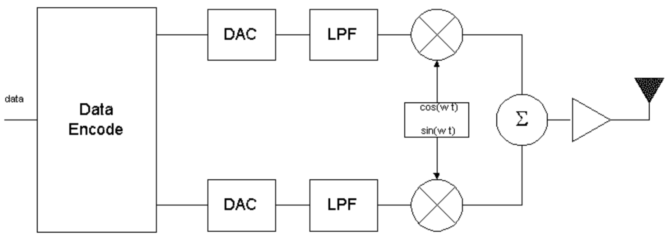

Fig. 16. M-ary Modulation Block.

different sources which operate in the same frequency. Hence, careful selection of operation bands in conjunction with the location of the WSN and sophisticated interference cancellation hardware is required to provide reliable communication.

The *Ultra Wideband* (UWB) or impulse radio has also been used as communication technology in WSN applications, especially in indoor wireless networks [122]. The 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 fading [36], [95]. Hence, increased reliability is possible by exploiting the UWB techniques in sensor networks along with low transmission power and simple transceiver circuitry.

Infrared communication is also used for inter-node communication in sensor networks. Infrared communication is license-free and, in contrast to the RF links, robust to interference from electrical devices. Although the infrared medium provides low error rates and prevents interference, the main drawback is the requirement of a line-of-sight between the sender and receiver. This makes infrared a reluctant choice for transmission medium in the sensor network scenario.

Optical medium can also be used for communication among sensor nodes. An example is the *Smart Dust* mote [89], which is an autonomous sensing, computing, and communication system that uses optical medium for transmission. While optical medium can enable ultra-low power communication with the help of passive devices and mirrors on the sensor nodes, line of sight requirements and robustness problems against node position changes constitute problems in the deployment of WSN.

The main types of technologies used in WSN can be classified as narrow-band techniques, spread spectrum techniques and ultra-wideband (UWB) techniques. Narrow-band technologies aim to optimize bandwidth efficiency by using M-ary modulation schemes in a narrow-band. DSSS and UWB, on the other hand, uses a much higher bandwidth and spreads the information onto the higher bandwidth. While DSSS uses N-chip codes for spreading the spectrum, UWB effects the communication by relative positioning of ultra-wideband pulses with respect to a reference time [222]. Since UWB uses bandwidth modulation, implementation costs are significantly lower than DSSS systems.

In [207], these three technologies are compared in the context of WSN. It is shown that narrow-band technologies perform poorly in WSN since they tradeoff bandwidth efficiency for energy efficiency, while spread spectrum and UWB enable low-power communication with robustness against multipath effects. Moreover, a comparative study between UWB pulse position modulation (UWB-PPM) and DSSS technologies is presented for secure WSN in [222].In equal bandwidth occupancies, packet error probabilities of the two technologies are investigated. It is shown that, for binary modulation, DSSS outperforms UWB. UWB performance is comparable to DSSS only for higher modulation schemes, which however, degrades the advantage of UWB in terms of low cost. On the other hand, when multipath effects are considered, UWB provides higher resilience when compared to DSSS.

The requirements of specific applications of WSN also constraint the capabilities of sensor nodes. For instance, marine applications may require the use of the underwater transmission medium. Hence, acoustic waves that can penetrate through the water is a favorable choice. However, the high error rates and the low data rates make underwater channels challenging to provide reliability. Inhospitable terrain or battlefield applications might encounter error prone channels and greater interference. Moreover, due to the low cost requirements, antenna of the sensor nodes might not have the height, sensitivity and radiation power of those in traditional 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.

Channel coding schemes have for long been investigated in the context of wireless communication theory. There exists many powerful channel codes such as Reed Solomon (RS) codes, convolutional codes, and BCH codes. However, recently, the efficiency of distributed source-channel coding has been investigated in the context of WSN [58]. Since the information gathered by sensor nodes follow physical properties of the sensed phenomenon, the characteristics of the source can be closely matched with the channel characteristics. It has been shown that in distributed networks, where the information about an event is more important than the individual readings of each sensor, source-channel coding results in optimal results [57]. Moreover, in a recent work, it has been proved that uncoded transmission achieves a scaling-law optimal performance. Hence, exploiting the intrinsic properties of the sensed phenomenon provides additional advantages to channel coding. Based on the joint source-channel coding strategies and uncoded transmission principles, many networking protocols extending the physical layer have also been proposed in the literature. In [199] possible approaches to transport and MAC layer protocols exploiting the spatial and temporal correlation and uncoded transmission in WSN have been discussed. The distributed source-channel coding has been exploited in [113] in order to investigate the reliability vs. efficiency in data gathering. Furthermore, an application level error correction algorithm is presented which exploits the spatio-temporal properties of the physical phenomenon in [41] as an alternative to RS codes.

The choice of a good modulation scheme is critical for reliable communication in a sensor network. Generally, binary or M-ary modulation schemes are used in WSN. The general structure of binary modulation is given in Figure 15. In this figure, the frequency synthesizer is integrated with the modulation circuitry. In binary modulation, the VCO can be directly or indirectly modulated [177]. Moreover, the M-ary modulation is illustrated in Figure 16. Using M-ary modulation multiple bits can be sent through the channel. This accomplished by parallelizing the input data and using these parallel data as inputs to a digital-to-analog converter (DAC). As a result, the parallel input levels provide the in-phase and quadrature components of the modulated signal. Binary and M-ary modulation schemes are compared in [177]. 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. The authors of [177] formulate these trade-off parameters and conclude that under startup power dominant conditions, the binary modulation scheme is more energy efficient. Hence, M-ary modulation gains are significant only for low startup power systems. A low-power direct-sequence spread-spectrum modem architecture for sensor networks is presented in [25]. This low power architecture can be mapped to an ASIC technology to further improve efficiency.

In [31], a 6.5 GHz energy efficient BFSK modulator for WSN is implemented. The authors use CMOS technology to implement high-data-rate, low-power modulator scheme. It is shown that, in WSN applications where nodes have low duty cycle, small packets and short distances, startup times of nodes effect energy consumption significantly. In order to provide faster startup times, a multiple stage low switching mechanism is incorporated into the circuit. The FSK modulator achieves significant energy efficiency compared to existing designs.

In addition to modulation schemes, complete physical layer designs tailored to the specific requirements of WSN paradigm is also investigated. An adaptive smart antenna model is used for data collection in sinks in WSN [125], [126]. The proposed multifunctional retrodirective/smart antenna array acts as a transponder between sensors and data collectors. While collecting data, the array system works as a smart antenna, while in transponder mode, the sink sends data to an interrogator.

Although many sensor nodes used today consists of commercial of the shelf (COTS) components, a high-quality, integrated wireless sensor node design is presented in [16]. The nodes are used for very high sensitivity detection in chemical and biological sensing. The RF chip designed for this node uses spread spectrum encoding due to the highly resistivity against interference and multipath effects. The implemented prototype *Wirtx1* includes programmable spread-spectrum generator.

It is well known that long distance wireless communication can be expensive, both in terms of energy and cost. 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. 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. Moreover, network layer protocols are usually developed to provide shortest hop count routes to the packet. Although these routes may seem optimal in the network layer, due to high error rates due to increased transmission range a penalty will be paid [35]. However, with the aid of physical layer implications, less error prone links can be chosen providing a cross-layer energy efficient optimization in the WSN. Energy efficient reliable 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 network especially in terms of power efficient transceiver design,

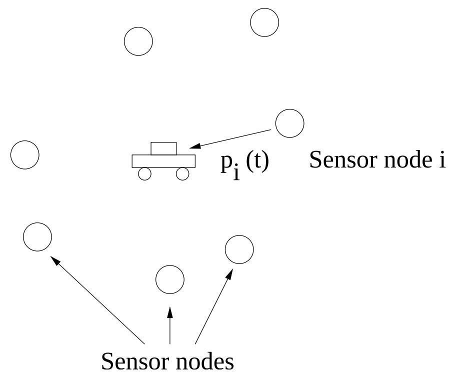

Fig. 17. Use of mobile robots in sensor networks

new modulation techniques, and the efficient implementations of UWB for sensor network applications.

X. LOCALIZATION

In the last few years, many localization techniques have been proposed for the wireless sensor networks. They fall into two categories, range-based and range-free. Range-based protocols require distance/range or angle estimations to determine the locations of the sensor nodes. On the other hand, range-free does not while it still requires beacons/seeds to have known locations. In the following Subsections X-A and X-B, some of the protocols in both categories are described in detail. In addition, Subsection X-C discusses about current research works that provides valuable foundations for the localization problem.

A. Range-based

There is a large number of protocols being proposed in the range-based category. Some protocols borrow ideas from the robotics area [17], [75], [139].

- ***Mobile robots for delay-tolerant sensor networks*** - Mobile robots [139] move around in the sensor field measuring/estimating the locations of the sensor nodes. These robots have high computational capabilities and GPS. As shown in Figure 17, the mobile robot estimates the locations of the sensor nodes by the received signal strength (RSS). The RSS from sensor node i is represented by $p_i(t)$, which is formulated as

$$p_i(t) = p_{oi} - 10\varepsilon log d_i(t) + v_i(t), \quad (6)$$

where p_{oi} is a constant due to the transmitted power and the antenna gain of the mobile robot, ε is the slope index (e.g., 2 or 4), and $v_i(t)$ is the uncertainty factor due to shadowing.
- ***Mobile robots and mobile sensor nodes*** - On the other hand, the work proposed by [75] uses seeds just like robots to observe the locations of mobile sensor nodes. Afterwards, the observations are sent back to the central processor to predict the locations of the nodes via Monte Carlo methods. Let l_t be the position distribution of sensor nodes at time t. It is computed by using the previous observations L_{t-1} and current observation o_t.

Besides using robots, multidimensional scaling (MDS) technique [87], [173], [174] is used to determine the locations of the sensor nodes. It relies on seeds with known locations to create local maps of neighboring nodes. After these local maps are created, they are merged at a central processor to provide a network-wide view of the sensor nodes' locations.

In addition, some protocols [11], [19], [24], [101], [128], [132], [140], [153], [160], [161], [162], [179], [180], [226] rely on the sensor nodes to determine their own locations by received signal strength, time-of-arrival, or time-difference-of-arrival between them and the known-location beacons. The protocols range from single-hop location estimation to multi-hops. In addition, known-location beacons are used for trilateration or multilaterally location estimations.

- ***Relative location estimation*** - Authors in [140] studied the Cramér-Rao bound (CRB) of relative location estimations. Some sensor nodes are assumed to have known locations, and the rest determines its relative locations from these sensor nodes by using received signal strength or time of arrival.
- ***Ad hoc positioning system*** - Ad hoc positioning system (APS) [132] proposes that some sensor nodes have GPS capabilities. Sensor nodes in the sensor field contact these GPS enabled sensor nodes via hop-by-hop communications to obtain their locations. With this GPS requirement, all sensor nodes are mapped into a GPS coordinate system.

Another set of protocols looks into the coverage problem in sensor networks [114], [154], [225], [227]. These protocols try to maximize the coverage area while maintaining a low number of sensor nodes. For example, the virtual force algorithm [225] enables the randomly-placed sensor nodes to move away or toward each other providing the maximum coverage area in the sensor field.

B. Range-free

Range-free protocols [18], [42], [66], [132], [142] do not depend on the receive signal strength, time-of-arrival, or time-difference-of-arrival to determine the location from the known-location beacons.

- ***APIT*** **-** Some portion of sensor nodes are assumed to have high-powered transmitters and location information from GPS. These sensor nodes are called beacons, and APIT [66] partitions the sensor field into triangular regions between beaconing nodes. The triangular regions can overlap each other allowing sensor nodes to calculate their own locations by determining the overlapping region of where they reside.
- ***Convex position estimation*** **-** The position estimation problem is solved by using convex optimization. Some sensor nodes are assumed to have known locations and can communicate with neighboring nodes. All sensor nodes in the sensor field determine their connectivity with the neighboring nodes and report them back to a centralized computer for position estimation. The connectivity provides a proximity constraint parameter. For example, if a node can communicate with another sensor node and the transmission radius is 20 meters, the separation between the two nodes must be less than 20 meters.

C. Localization foundations

Besides designing range-based and range-free localization techniques, some researchers [7], [26], [49], [94], [141] provide valuable foundations for the localization problem. For example, authors in [49] provide computation and complexity analysis of range-based scheme where sensor nodes determine their locations by measuring the distances to their neighbors. In [7], Aspnes show the computational complexity using graph theory.

D. Open research issues

Although many localization protocols are proposed, there is still room for development. For example, researchers should focus on protocols that are robust to beacon/seed failures. In addition, a distributed beacon/seed free localization technique may be a challenge for future types of sensor networks.

XI. Time Synchronization

There are three types of timing techniques as shown in Table II, and each of these types has to address the design challenges and factors affecting time synchronization, such as *robust, energy aware, server-less, light-weight, tunable service, temperature, phase noise, frequency noise, asymmetric delay, and clock glitches*. In addition, the timing techniques have to address the mapping between the sensor network time and the Internet time, e.g., universal coordinated time. In the following, examples of these types of timing techniques are described, namely the *Network Time Protocol* (NTP) [118], *Timing-sync Protocol for Sensor Networks* (TPSN) [56], *Reference-Broadcast Synchronization* (RBS) [47], and *Time-Diffusion Synchronization Protocol* (TDP) [188].

In Internet, the NTP is used to discipline the frequency of each node's oscillator. The accuracy of the NTP synchronization is in the order of milliseconds [79]. It may be useful to use NTP to disciple the oscillators of the sensor nodes, but the connection to the time servers may not be possible because of frequent sensor node failures. In addition, disciplining all the sensor nodes in the sensor field maybe a problem due to interference from the environment and large variation of delay between different parts of the sensor field. The interference can temporarily disjoint the sensor field into multiple smaller fields causing undisciplined clocks among these smaller fields. The NTP protocol may be considered as type (1) of the timing techniques. In addition, it has to be refined in order to address the design challenges presented by the sensor networks.

As of now, the NTP is very computational intensive and requires a precise time server to synchronize the nodes in the network. In addition, it does not take into account of the energy consumption required for time synchronization. As a result, the NTP does not satisfy the energy aware, server-less, and light-weight design challenges of the sensor networks. Although the NTP can be robust, it may suffer large propagation delay when sending timing messages to the time servers. In addition, the nodes are synchronized in a hierarchical manner, and some time servers in the middle of the hierarchy may fail causing unsynchronized nodes in the network. Once these nodes fail, it is hard to reconfigure the network since the hierarchy is manually configured.

Another time synchronization technique that adopts some concepts from NTP is TPSN [56]. The TPSN requires the root node to synchronize all or part of the nodes in the sensor field. The root node synchronizes the nodes in a hierarchical way. Before synchronization, the root node constructs the hierarchy by broadcasting a *level_discovery* packet. The first level of the hierarchy is level 0, which is where the root node resides. The nodes receiving the *level_discovery* packet from the root node are the nodes belonging to level 1. Afterwards, the nodes in level 1 broadcast their *level_discovery* packet, and neighbor nodes receiving the *level_discovery* packet for the first time are the level 2 nodes. This process continues until all the nodes in the sensor field has a level number.

The root node sends a *time_sync* packet to initialize

TABLE II
THREE TYPES OF TIMING TECHNIQUES

Type	*Description*
(1) Relies on fixed time servers to synchronize the network	-The nodes are synchronized to time servers that are readily available. These time servers are expected to be robust and highly precise. [118], [63], [179], [13], [39], [74], [56], [115], [196]
(2) Translates time throughout the network	-The time is translated hop-by-hop from the source to the sink. In essence, it is a time translation service. [47], [59], [135], [202], [46], [44]
(3) Self-organizes to synchronize the network	-The protocol does not depend on specialized time servers. It automatically organizes and determines the master nodes as the temporary time-servers. [188], [101]

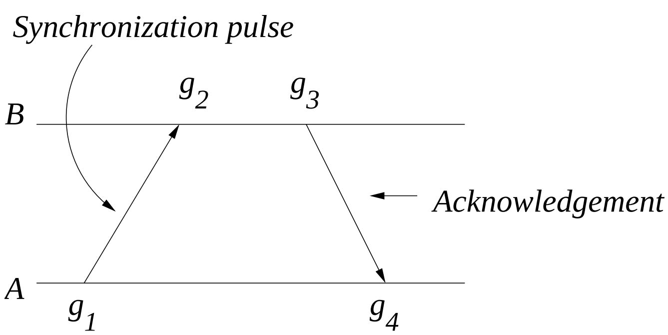

Fig. 18. Two-way message handshake

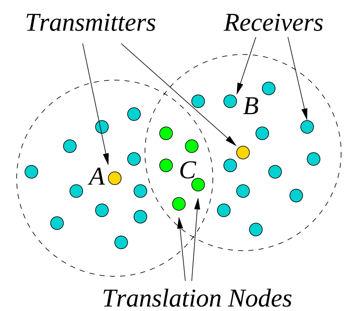

Fig. 19. Illustration of the RBS

the time synchronization process. Afterwards, the nodes in level 1 synchronize to level 0 by performing the two way handshake as shown in Figure 18. This type of handshake is used by the NTP to synchronize the clocks of distributed computer systems. At the end of the handshake at time g_4, node A obtains the time g_1, g_2, and g_3 from the acknowledgment packet. The time g_2 and g_3 are obtained from the clock of sensor node B while g_1 and g_4 are from the node A. After processing the acknowledgment packet, the node A readjusts its clock by the clock drift value Δ, where $\Delta = \frac{(g_2-g_1)-(g_4-g_3)}{2}$. At the same time, the level 2 nodes overhear this message handshake and wait for a random time before synchronizing with level 1 nodes. This synchronization process continues until all the nodes in the network are synchronized. Since TPSN enables time synchronization from one root node, it is type (1) of the timing techniques.

The TPSN is based on a sender-receiver synchronization model, where the receiver synchronizes with the time of the sender according to the two-way message handshake as shown in Figure 18. It is trying to provide a light-weight and tunable time synchronization service. On the other hand, it requires a time server and does not address the robust and energy aware design goal. Since the design of TPSN is based on a hierarchical methodology similar to NTP, nodes within the hierarchy may fail and cause nodes to be unsynchronized. In addition, node movements may render the hierarchy useless, because nodes may move out of their levels. Hence, nodes at level i can not synchronize with nodes at level $i-1$. Afterwards, synchronization may fail throughout the network.

As for type (2) of the timing techniques, the RBS provides an instantaneous time synchronization among a set of receivers that are within the reference broadcast of the transmitter [47]. The transmitter broadcasts m reference packets. Each of the receivers that are within the broadcast range records the time-of-arrival of the reference packets. Afterwards, the receivers communicate with each other to determine the offsets. To provide multi-hop synchronization, it is proposed to use nodes that are receiving two or more reference broadcasts from different transmitters as translation nodes. These translation nodes are used to translate the time between different broadcast domains.

As shown in Figure 19, nodes A, B, and C are the transmitter, receiver, and translation nodes, respectively. The transmitter nodes broadcast their timing messages, and the receiver nodes receive these messages. After-

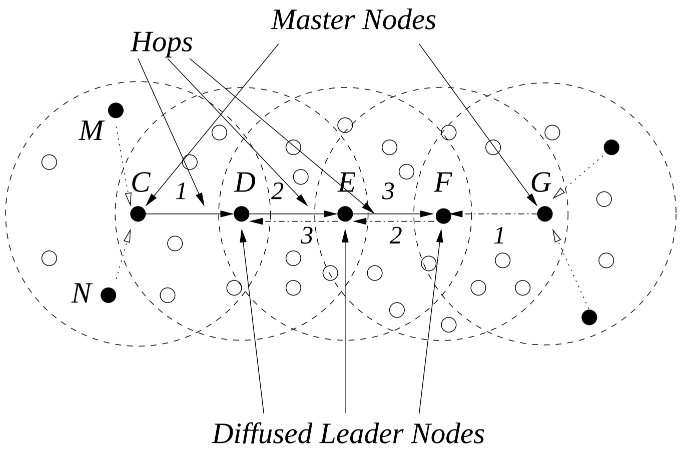

Fig. 20. TDP concept

wards, the receiver nodes synchronize with each other. The sensor nodes that are within the broadcast regions of both transmitter nodes A and B are the translation nodes. When an event occurs, a message describing the event with a time-stamp is translated by the translation nodes when the message is routed back to the sink. Although this time synchronization service is tunable and light-weight, there may not be translation nodes on the route path that the message is relayed. As a result, services may not be available on some routes. In addition, this protocol is not suitable for medium access scheme such as TDMA since the clocks of all the nodes in the network are not adjusted to a common time.

Another emerging timing technique is the TDP [188]. The TDP is used to maintain the time throughout the network within a certain tolerance. The tolerance level can be adjusted based on the purpose of the sensor networks. The TDP automatically self-configures by electing master nodes to synchronize the sensor network. In addition, the election process is sensitive to energy requirement as well as the quality of the clocks. The sensor network may be deployed in unattended areas, and the TDP still synchronizes the unattended network to a common time. It is considered as a type (3) of the timing techniques.

The TDP concept is illustrated in Figure 20. The elected master nodes are nodes C and G. First, the master nodes send a message to their neighbors to measure the round-trip times. Once the neighbors receive the message, they self-determine if they should become diffuse leader nodes. The ones elected to become diffuse leader nodes reply to the master nodes and start sending a message to measure the round-trip to their neighbors. As shown in Figure 20, nodes M, N, and D are the diffused leader nodes of node C. Once the replies are received by the master nodes, the round-trip time and the standard deviation of the round-trip time are calculated. The one-way delay from the master nodes to the neighbor nodes is half of the measured round-trip time. Afterwards, the master nodes send a time-stamped message containing the standard deviation to the neighbor nodes. The time in the time-stamped message is adjusted with the one-way delay. Once the diffuse leader nodes receive the time-stamped message, they broadcast the time-stamped message after adjusting the time, which is in the message, with their measured one-way delay and inserting their standard deviation of the round-trip time. This diffusion process continues for n times, where n is the number of hops from the master nodes. From Figure 20, the time is diffused 3 hops from the master nodes C and G. The nodes D, E, and F are the diffused leader nodes that diffuse the time-stamped messages originated from the master nodes.

The nodes, which have received more than one time-stamped messages originated from different master nodes, use the standard deviations carried in the time-stamped messages as weighted ratio of their time contribution to the new time. In essence, the nodes weight the times diffused by the master nodes to obtain a new time for them. This process is to provide a smooth time variation between the nodes in the network. The smooth transition is important for some applications such as target tracking and speed estimating.

The master nodes are autonomously elected, so the network is robust to failures. Although some of the nodes may die, there are still other nodes in the network that can self-determine to become master nodes. This feature also enables the network to become server-less if necessary and to reach an equilibrium time. In addition, the master and diffusion leader nodes are self-determined based on their own energy level. Also, the TDP is light-weight, but it may not be as tunable as the RBS.

In summary, these timing techniques may be used for different types of applications; each of them has its own benefits. All of these techniques try to address the factors influencing time synchronization while design according to the challenges. Depending on the types of services required by the applications or the hardware limitation of the sensor nodes, some of these timing techniques may be applied.

XII. Topology Management

Topology management is a crucial part of WSN communication protocols, since the topology of the network directly effects the performance of each individual protocol as well as the overall performance of the network. In WSNs, *topology* does not only refer to the locations of the nodes. Since the sensor nodes are turned off and on to increase the energy efficiency, the duty cycles of the nodes are also important. When a node is turned off it is essentially disconnected from the network, hence effecting the network performance. In this section, we investigate topology management in three subsections, i.e., sensor deployment, topology control and clustering.

A. Sensor Deployment

The physical locations of the nodes in a WSN is crucial in terms of both communication and sensing. Since sensor nodes are equipped with radios with limited range, the communication is performed in a multi-hop fashion [3]. Hence, connectivity is an important factor considered for sensor deployment. Moreover, since a physical phenomenon with spatio-temporal characteristics are observed via the WSN, the deployment of the nodes also effects the accuracy of the samples collected regarding the phenomenon. Hence, coverage is also important for sensor deployment.

In [172], a wireless sensor grid-network is investigated in terms of coverage and connectivity of the network. The authors provide methods for determining network connectivity and coverage given a node-reliability model. The node-reliability refers to the probability that a node is active in the network. Moreover, given a power budget, an estimate of the minimum required node-reliability for meeting a system-reliability objective can be found. Although this work focuses on WSN in a grid, it provides theoretical bounds and insight into deployment of WSN. It is found that as the node-reliability decreases, the sufficient condition for connectivity becomes weaker than the necessary condition for coverage. This implies that connectivity in a WSN does not necessarily imply coverage. Furthermore, the power required per each active node for connectivity and coverage decreases at a rate faster than the rate at which the number of nodes increase. Thus, as the number of nodes increase, the total power required to maintain connectivity and coverage decreases.

The relationship between reduction in sensor duty cycle and redundancy in sensor deployment is investigated in [73]. The authors compare two coordination schemes i.e., random and coordinated sleep algorithms, in terms of two performance metrics, i.e., extensity and intensity. *Extensity* refers to the probability that any given point is not covered, while *intensity* gives the tail distribution of a given point not covered for longer than a given period of time. It is shown that as the density of the network is increased, the duty cycle of the network can be decreased for a fixed coverage. However, beyond a certain threshold increased redundancy in the sensor deployment does not provide same amount of reduction in the duty cycle. Moreover, it is shown that coordinated sleep schedules can achieve higher duty cycle reduction at the cost of extra control overhead. Using the intensity analysis of the network, the authors propose a random sleeping schedule for a satisfactory coverage.

In [225], a virtual force algorithm (VFA) is proposed for enhancing sensor coverage through moving sensor nodes after an initial random deployment. The algorithm assumes a cluster-based architecture and VFA is executed at the cluster-heads. The VFA algorithm uses virtual positive or negative forces between nodes based on their relative locations. Moreover, the authors also propose a target localization algorithm that can be used in this cluster-based architecture. The simulation results reveal that VFA algorithm improves the coverage of the sensor network and increases the accuracy in the target localization. However, the algorithm requires either mobile sensor nodes or redeployment of nodes according to the algorithm, which is not applicable to all WSNs.

B. Topology Control

In WSN, it is clear that during operation, it would be difficult or even impossible to access the individual sensor nodes [92]. Moreover, the sensor topology changes due to node failures and energy depletion. Hence, even when an efficient deployment is in place, the WSN topology should be controlled for longer network lifetime and efficient communication.

In [92], a distributed self-organization scheme is presented for topology control. The authors assume a random topology with a time slotted medium access scheme where each nodes access the wireless channel with an attempt probability α_i. The optimal self-organization is performed in order to maximize the communication throughput. The nodes transmit with probability α_i and receive otherwise. It is observed that the saturation throughput of the network decreases as the transmission range of a node increases. Moreover, increasing the arrival rate of the measurements also decreases the saturation throughput. Based on this observation, the authors propose an algorithm to form the topology by constructing directed trees rooted at each sensor. Consequently, each node decides its attempt probability based on local measurements. The results show that the optimal attempt probability is reached by the distributed algorithm leading to maximum saturation throughput.

A topology management protocol is presented in [165]. The Sparse Topology and Energy Management

(STEM) protocol aims to coordinate the sleep transitions of all the nodes. The sensor nodes are assumed to be in two states, i.e., *transfer state* where they forward data, and *monitoring state* where they sample event information. Moreover, the sensors are assumed to be equipped with two radios, for listening to the channel and for actual data communication. The authors aim to optimize the energy efficiency of the network in the monitoring state by trading off energy consumption in the monitoring state, versus latency of switching back to the transfer state. In event based applications, WSN is usually in the monitoring state, and communication is only initiated when an event occurs. Hence, in STEM, nodes turn their radio off and periodically listen to the channel to check if any node is trying to communicate. In the case of a communication attempt, the data radio is turned on and the communication takes place. However, since the radio is turned off for the majority of the time, route setup latency increases as a penalty for energy conservation. The simulation results shows that STEM combined with GAF can reduce the network energy consumption to 7%. Nevertheless, STEM protocol is only applicable to WSNs where the application is monitoring oriented and event-based.

An adaptive self-configuring topology management scheme is presented in [22]. In ASCENT, the redundancy provided by the high density in deployment is exploited in order to extend overall system lifetime. Only a small number of nodes participate in forming a backbone for the whole network, while the remaining nodes periodically check the medium to adapt to the network changes. The management of the nodes is performed by the sink. When a node receives a high packet error rate, the sink signals the nodes in the proximity to participate in multi-hop communication. As a result, more nodes become active until the error rate is decreased. Moreover, the nodes also adapt their duty cycle based on the error rate in order to decrease collisions. The performance evaluations and testbed experiments show that ASCENT achieves energy efficiency and high throughput even when the network density is increased. On the other hand, latency is increased since a fixed number of nodes is used for data forwarding in ASCENT.

C. Clustering

In WSN, high density is one of the major differences between traditional networks. In the wireless domain, high density has both advantages in terms of connectivity and coverage as well as disadvantages in terms of increased collision and overhead for protocols that require neighborhood information. As a result, scalability is an important problem in WSN protocols as the node numbers increase. Recently, this problem is addressed through clustering algorithms, which limit the communication in a local domain transmitting only necessary information to the whole network. Overall, clustering protocols have the following advantages in WSNs:

- *Scalability:* Cluster-based protocols limit the number of transmissions between nodes, thereby enabling higher number of nodes to be deployed in the network.
- *Collision Reduction:* Since most of the functionalities of nodes are carried out by the cluster-heads (CHs), less number of nodes contend for channel access, improving the efficiency of channel access protocols.
- *Energy Efficiency:* In a cluster, the CH is active most of the time, while other nodes wake-up only in a specified interval to perform data transmission to the CH. Further, by dynamically changing the CH functionalities among nodes, the energy consumption of the network can be significantly reduced.
- *Local Information:* Intra-cluster information exchange between nodes and the CH helps summarize the local network state and sensed phenomenon state information at the CH [216], [217].
- *Routing Backbone:* Cluster-based approaches also enable efficient building of routing backbone in the network, providing reliable paths from sensor nodes to the sink. Since the information to the sink is initiated only from CHs, route-thru traffic in the network is decreased.

In [10], an energy efficient hierarchical clustering algorithm is proposed. The authors aim to minimize the overall energy consumption of the network as a clustering metric instead of the minimum number of clusters or minimum number hops in a cluster metrics used before. The performance of the protocol depends on two parameters, i.e., p, the probability that a node assigns itself as a clusterhead (CH), and k, the maximum number of hops this CH information propagates. Each node becomes a CH with a probability of p and notifies this decision up to k hops forming clusters. The nodes outside the clusters also become CHs. The authors provide the optimal values of p and k for minimum energy consumption in a network with randomly deployed nodes. Moreover, the clustering algorithm is also extended to form multiple layers of hierarchical clusters. However, the protocol parameters are calculated based on only the density of the network. Since, a homogeneous distribution is assumed, the energy efficiency of the clustering protocol may not be optimal in the case of non-uniform distribution of nodes.

In [216], a hybrid energy-efficient distributed (HEED) clustering protocol for WSN is presented. HEED aims to form one-hop clusters through use of multiple transmit power levels at the sensor nodes. Each node becomes a CH based on CH probability, CH_{prob}, determined according to the residual of the specific node and the intra-cluster communication cost of the node, had that node become the CH. The clustering process is performed in a limited number of steps. In each step, each node becomes CH based on it CH_{prob}, and doubles its CH_{prob} after each step. The protocol terminates once the CH_{prob} reaches 1. As a result, nodes with higher residual energy and lower intra-communication cost become CH. Moreover, the calculation of CH_{prob} enables heterogeneous nodes with different batteries to participate in the network. HEED protocol is shown to terminate in a limited number of steps and outperforms generic weight-based clustering protocols.

XIII. Evaluation of WSN Protocols

Due to the application-oriented nature of WSN, the ultimate goal of any sensor network deployment is to fulfill the specific requirements and objectives of the application in place. The realization of these goals, however, directly depends on the efficient communication between the wireless sensor network entities, i.e., the sensor nodes and the sink. With this regard, the efficiency and performance of the overall communication in WSN become one of the most significant factors influencing the performance of the entire sensor network. Consequently, exhaustive evaluation of communication protocols developed for WSN is crucial for efficient sensor network deployments. In this section, different methodologies for the evaluation of WSN protocols are described in detail.

A. Physical Sensor Network Testbeds

As the WSN paradigm is tightly related to the physical environment and its main objective is to extract information about physical phenomenon, physical testbeds are the most useful tools for the evaluation of the sensor network communication protocols. Furthermore, they also greatly help assess the performance of communication protocols in addressing the certain application-specific requirements and objectives in a real sensor network deployment scenario.

There exist considerable number of physical testbeds developed in order to perform experimental evaluation of sensor networks and devised communication protocols in the literature. Some of the major testbed development efforts for sensor network research are pointed out here.

A wireless sensor network testbed called *MoteLab* is deployed [129], which provides a public, permanent testbed for development and testing of sensor network applications via an intuitive web-based interface. MoteLab enables users to upload their own executables and communication protocols to be run on the deployed Mica2 motes sensor nodes, which helps evaluate sensor network programming environments, communication protocols, system design, and applications in a physical experimentation scenario. Several different testbeds for wireless sensor network experiments have been developed using Mica motes by SCADDS (Scalable Coordination Architectures for Deeply Distributed Systems) project [163]. In this testbed environment, sensor nodes are heterogeneous, with a diverse range of sensing, actuation and communication capabilities. The objective of SCADDS testbed is to evaluate coordination and communication protocols developed for sensor networks with heterogeneous sensor nodes.

Extensible Sensing System (ESS) is developed as a physical sensor network testbed for microclimate monitoring in support of a wide range of ecophysiology studies [192]. The ESS testbed provides a wide range of scalability and flexibility with a physical sensor network deployment in the scale of hundreds of nodes. It is designed to be a testbed for sensors, interface hardware, RF communication hardware, communication protocols, databases and user interfaces to be used in habitat sensing network. SensorScope is another wireless sensor network testbed deployed with around 20 mica2 and mica2dot motes, equipped with a variety of sensors (such as light, temperature or acoustic) [170]. Its objective is to provide a realistic prototype deployment (motes run on batteries, no wired backchannel) for research activities in sensor networks. The design and development of GNOMES, a low-cost hardware and software heterogeneous wireless sensor network testbed, is presented in [205]. GNOMES testbed is designed to investigate the properties of heterogeneous wireless sensor networks, to test theory in sensor networks architecture, and be deployed in practical application environments. Furthermore, it is also used to investigate the design tradeoffs for different architectures extending the lifetime of individual nodes in the network.

The Smart Sensor Networks (S-Nets) testbed is introduced in [70] as an architecture and set of distributed algorithms to extract, interpret and exploit networked sensor devices. Two complementary implementations of S-Nets are described as the first one using a set of Berkeley motes comprised of low-power 8-bit, 128Kb memory processors, communication devices and sensors, and the second on a set of JStamps having 32-bit controllers, 2Mb of memory and native execution Java hardware.

A distributed sensor network testbed and a target surveillance experiment are described in [12], which are used to demonstrate the integration of distributed tracking algorithms with strategies for location estimation, energy management and mobility management of sensor nodes. The testbed incorporates both real sensor nodes and a simulation environment. Data from real world tracking experiment is provided to the simulation environment, where it is used to self-organize the sensor network in an energy-efficient way [12]. Then the simulation results are provided back to the physical testbed in order to enable enable the sensor network to reorganize for reinforced tracking.

A testbed for sensor networks is developed for evaluating communication protocols in the SENSONET project at Broadband and Wireless Networking Laboratory, Georgia Institute of Technology [169]. The testbed is composed of three parts: core network, core access network, and sensor field. The core network is the backbone of the overall sensor network. It consists of the wireless local area network (WLAN), Internet, and/or satellite networks. The core access network is made up of NSAPs, i.e., sinks of the sensor network, which are emulated by the laptops. The NSAPs integrate the protocols used in the core network with the ones used in the sensor network. The sensor field is the area, where the RAS (route, access, and sense) nodes are deployed. Each RAS node can be either mobile or static with the following combination of components: (i) MPR300CA MICA process/radio board, (ii) MTS310CA MICA light, temperature, acoustic actuator, magnometer, and accelerometer sensors, (iii) laptops with WLAN and 916 MHz radio transceiver, (iv) video and audio capturing devices, (v) differential Global Positioning System (GPS), and (vi) remote control cars or brownian motion cars.

B. Software Environments

In addition to the physical testbeds described in the previous section, there exist many software simulation and emulation environments developed for the evaluation of the sensor networks and communication protocols. These toolsets are extremely useful especially in cases where either physical testbeds are not present or not feasible to be deployed for certain sensor network applications.

In [146], the design and implementation of ATEMU, a fine grained sensor network simulator, are introduced. The objective of ATEMU is to fill the gap between actual sensor network deployments and sensor network simulations for performance evaluation of sensor networking protocols. It incorporates both software simulation for interaction between wireless sensor nodes and software emulation for individual sensor node operation for Mica2 sensor nodes. ATEMU can also simulate a heterogeneous sensor network composed of different sensor hardwares as well as different application objectives.

SENSE (Sensor Network Simulator and Emulator) is another software environment developed for sensor network performance evaluation [167]. It incorporates a component-port model to make simulation models extensible, and a simulation component classification approach to solve the problem of handling simulated time. SENSE simulator has many available components such as different battery models, application layer, network, MAC and physical layer functionalities.

In [190], SENS (Sensor, Environment and Network Simulator), which is a customizable sensor network simulator for WSN applications, is presented. SENS consists of interchangeable and extensible components for applications, network communication, and the physical environment. Application-specific environments can be matched with different signal propagation characteristics and users can execute the same source code on simulated sensor nodes as deployed on actual sensor nodes, enabling application portability. Furthermore, SENS provides different performance evaluation tools such as power utilization analysis for development of dependable applications.

A modeling and simulation framework called VisualSense for wireless sensor networks is presented in [9]. This framework supports actor-oriented definition of sensor nodes, wireless communication channels, physical media such as acoustic channels, and wired subsystems [9]. The VisualSense simulator software provides a set of base classes for defining channels and sensor nodes, a library of subclasses for certain specific channel models and node models, and an extensible visualization framework.

In [127], a conceptual pico-radio sensor network system, and a corresponding design simulation and evaluation environment, H-MAS, are presented. H-MAS separates the tasks of processing and storage from the sensor nodes through an agent-based computer simulation software. It also has a visualization functionality, which provides a convenient way to present the design of sensor networks.

SNetSim is another simulation software developed for performance evaluation of wireless sensor network communication protocols [183]. It is an event-driven simulation software which runs on Windows operating system. It provides the user with the flexibility of determining how the nodes/events are deployed in the sensor network by selecting a distribution method and modifying its parameters according to the experiment requirements. SNetSim also allows to implement new communication protocols and incorporate them into the main simulation software. It also provides a graphical user interface which helps to visually observe, alter the sensor network simulation, and provide auto-created graphs using the simulation results.

EmStar [60] is a programming model and software framework for creating Linux-based sensor network applications that are self configuring, reactive to dynamics, and can either be interactively debugged or operate without user interaction. It provides direct interaction between simulation modules and programming models such as routing, retransmissions, node and link failures and the application while also providing the modularity of conventional layering approach. The code and the configuration of EmStar can be also used on the real sensor node hardware both as a pure simulation or in a hybrid mode that combines processing done in simulation and communication, sensing, and actuation on real (physical) channels.

TinyOS [194] is an open-source operating system designed for wireless embedded sensor networks. It incorporates a component-based architecture, which minimize the code size and provides a flexible platform for implementing new communication protocols. Its component library includes network protocols, distributed services, sensor drivers, and data acquisition tools, which can be further modified or improved based on the specific application requirements. It is based on an event-driven execution model which enables fine-grained power management strategies and provides a software platform that is perfectly suitable for the unique characteristics of wireless sensor networks. In [96], a TinyOS mote simulator, TOSSIM, is introduced to ease the development of sensor network applications. TOSSIM allow thousands of nodes in a simulation experiment, and compiles directly from TinyOS code, which enables developers test both their algorithms and implementations. It simulates the TinyOS network stack at the bit level, allowing experimentation with low-level protocols in addition to top-level application systems. It also provides a graphical user interface tool, TinyViz, in order to visualize and interact with running simulations.

In [195], a cycle-accurate instruction-level sensor network simulator called Avrora is presented. Avrora allows simulation experiments with sensor networks of up to 10,000 nodes and performs as much as 20 times faster than previous simulators with equivalent accuracy, handling as many as 25 nodes in real-time [195]. An event queue is used to realized an instruction-level simulation of microcontroller programs. It also enables developers to perform evaluation experiments for time-critical application scenarios in large-scale sensor networks.

SWANS [191] is another wireless network simulator developed based on the JiST discrete event simulation engine which runs over standard Java virtual machine. It is organized as a set of independent software components that can be composed to form complete wireless network or sensor network configurations. It allows users to simulate sensor networks with significantly large number of nodes.

In addition to the simulation softwares specifically developed for sensor network evaluation purposes, there exist many other general-purpose network simulation softwares such as *ns-2* [193], *OMNET++* [134], *GloMoSim* [61], *J-SIM*, and [88]. These software simulators are also largely used in sensor network research. However, mostly, additional functionalities and libraries need to be developed and integrated in order to use these general-purpose network simulators for sensor network evaluation. In [136], SensorSim, which is a set of additional functionalities to ns-2, is presented. SensorSim is a simulation framework for modeling sensor networks. It builds up on the ns-2 simulator and provides additional features for modeling sensor networks including sensing channel and sensor models, battery models, lightweight protocol stacks for wireless microsensors, scenario generation and hybrid simulation. Similarly, *nsrlsensorsim* [133] is another set of *ns-2* extensions developed by the Naval Research Laboratory (NRL) in order to enable sensor network experiments using *ns-2* libraries.

XIV. Conclusion

Wireless Sensor Networks have enabled human interaction with the physical environment through the use of fault-tolerant, low-cost sensor nodes. In this paper, we survey the improvements in the WSN phenomenon in terms of application areas and protocol developments after the first and most comprehensive survey on WSN which was published three years ago [3]. The extensive research efforts developed throughout the last three years made realization of such networks possible. Furthermore, more improved protocols have been proposed using the experience gained from the realization of WSN in different scenarios. The discussions carried throughout this paper reveal that the research in each specific layer of the WSN stack has provided satisfactory results. However, WSN phenomenon demands further improvement in overall network performance which can only be achieved by incorporating novel techniques such as cross-layer integration and application-aware tailoring such as spatio-temporal correlation exploitation. Hence, we believe that more development to the open research issues is possible which will lead to the ultimate goals of the WSN phenomenon discussed in detail in this paper and in [3].

REFERENCES

[1] K. Akkaya and M. Younis, An Energy-Aware QoS Routing Protocol for Wireless Sensor Networks, *Proceedings of the IEEE Workshop on Mobile and Wireless Networks (MWN 2003)*, Providence, Rhode Island, May 2003.

[2] K. Akkaya and M. Younis, A Survey On Routing Protocols For Wireless Sensor Networks, *to Appear in Computer Networks (Elsevier) Journal*, 2004.

[3] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, “Wireless sensor networks: a survey,”, *Computer Networks (Elsevier) Journal*, vol. 38, no. 4, pp. 393-422, March 2002.

[4] G. Amato, A. Caruso, S. Chessa, V. Masi and A. Urpi, “State of theart and future directions in wireless sensor network’s datamanagement,” *2004-TR-16, published by ISTI, 2004*, May 2004.

[5] K. A. Arisha, M. A. Youssef, M. Y. Younis, “Energy-Aware TDMA-based MAC for Sensor Networks,” *Computer Networks Journal (Elsevier)*, vol. 43, no. 5, pp. 539 -694, Dec. 2003.

[6] J. Aslam, Q. Li, and D. Rus, Three Power-Aware Routing Algorithms for Sensor Networks, *Wireless Communications and Mobile Computing*, Vol. 3, pp. 187-208, 2003.

[7] J. Aspnes, D. Goldenberg, and Y. Yang, On the ComputationalComplexity of Sensor Network Localization, *Proceedings ofALGOSENSORS 2004*, pp. 32-44, Turku, Finland, July 2004.

[8] H. Balakrishnan, V. N. Padmanabhan, S. Seshan, and R. H. Katz, “A Comparison of Mechanisms for Improving TCP Performance over Wireless Links”, *IEEE/ACM Trans. Networking*, Vol. 5, No. 6, pp. 756-769, December 1997.

[9] P. Baldwin, S. Kohli, E. A. Lee, X. Liu, and Y. Zhao, “VisualSense: Visual Modeling for Wireless and Sensor Network Systems,” *Technical Memorandum UCB/ERL M04/08, University of California, Berkeley,* CA 94720, USA, April 23, 2004.

[10] S. Bandyopadhyay, and E. J. Coyle, “An energy efficient hierarchical clustering algorithm for wireless sensor networks,” in *Proc. IEEE INFOCOM 2003*, vol. 3, pp. 1713 - 1723, March 2003.

[11] P. Bergamo and G. Mazzini, Localization in Sensor Networks WithFading and Mobility, *IEEE PIMRC 2002*, Lisbon, Portugal,September 2002.

[12] P. K. Biswas and S. Phoha, “A Sensor Network Test-bed for an Integrated Target Surveillance Experiment,” in *Proc. IEEE International Conference on Local Computer Networks (LCN’04)*, pp. 552-553, November 2004.

[13] P. Blum, L. Meier, and L. Thiele, Improved Interval-Based ClockSynchronization in Sensor Networks, *IPSN’04*, pp. 349-358,Berkeley, CA, April 2004.

[14] P. Bonnet, J. E. Gehrke, and P. Seshadri, “Towards Sensor Database Systems,” in *Proc. Second InternationalConference on Mobile Data Management*, Hong Kong, January 2001.

[15] D. Braginsky and D. Estrin, Rumor Routing Algorithm for Sensor Networks, *Proceedings of the First Workshop on Sensor Networks and Applications (WSNA)*, Atlanta, GA October 2002.

[16] C. L. Britton, *et.al.* “Battery-powered, wireless MEMSsensors for high-sensitivity chemical and biological sensing, ” in*Proc. Conference on Advanced Research in VLSI, 1999*, pp. 359- 368, March 1999.

[17] A. Brooks, S. Williams, and A. Makarenko, Automatic OnlineLocalization of Nodes in an Active Sensor Network, *Int’l Conf.on Robotics and Automation,* New Orleans, LA, April 2004.

[18] N. Bulusu, J. Heidemann, and D. Estrin, GPS-less Low Cost OutdoorLocalization for Very Small Devices, *IEEE Personal-Communications, Special Issue on Smart Spaces and Environments,*Vol. 7, No. 5, pp. 28-34, October 2000.

[19] N. Bulusu, J. Heidemann, and D. Estrin, Adaptive Beacon Placement,*Proceedings of the Twenty First International Conference onDistributed Computing Systems (ICDCS-21),* Phoenix, Arizona, April 2001.

[20] N. Bulusu, D. Estrin, L. Girod, and J. Heidemann, “Scalable Coordination for Wireless Sensor Networks: Self-Configuring Localization Systems,” *International Symposium on Communication Theory and Applications (ISCTA 2001),* Ambleside, UK, July 2001.

[21] A. Cerpa, J. Elson, M. Hamilton, and J. Zhao, ”Habitat Monitoring: Application Driver for Wireless Communications Technology,” *ACM SIGCOMM’2000,* Costa Rica, April 2001.

[22] A. Cerpa, and D. Estrin, “ASCENT: adaptive self-configuring sensor networks topologies,” *IEEE Transactions on Mobile Computing*, vol. 3, no. 3, pp. 272-285, July 2004.

[23] J. H. Chang and L. Tassiulas, Maximum Lifetime Routing in Wireless Sensor Networks, *Proceedings of the Advanced Telecommunications and Information Distribution Research Program (ATIRP’2000)*, College Park, MD, March 2000.

[24] X. Cheng, and et al., TPS: A Time-Based Positioning Scheme forOutdoor Wireless Sensor Networks, *IEEE INFOCOM 2004,* HongKong, March 2004.

[25] Chien, C., Elgorriaga, I., and McConaghy, C., “Low-Power Direct-Sequence Spread-Spectrum Modem Architecture For Distributed Wireless Sensor Networks,” *in ISLPED ’01,* Huntington Beach, California, USA, August 2001.

[26] K. K. Chintalapudi, et al., Ad-Hoc Localization Using Ranging andSectoring, *IEEE INFOCOM 2004,* Hong Kong, March 2004.

[27] Available at http://www.chipcon.com.

[28] Chlamtac I., Petrioli C., Redi J., “Energy-conserving go-back-N ARQ protocols for wireless data networks,” in *Proc. IEEE ICUPC’98*, Oct. 1998.

[29] Chlamtac I., Petrioli C., “Energy-conserving selective repeat ARQ protocols for wireless data networks,” in *Proc. IEEE PIMRC’98*, vol. 3, pp. 836 -840, Sep. 1998.

[30] S. Cho, and A. Chandrakasan, ”Energy-Efficient Protocols for Low Duty Cycle Wireless Microsensor,” *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences,* Vol. 2, pp. 10, Maui, HI, January 2000.

[31] S. Cho; A. P. Chadrakasan, “A 6.5-GHz energy-efficient BFSKmodulator for wireless sensor applications,” *IEEE Journal ofSolid-State Circuits*, vol. 39, no. 5, pp. 731 -739, May 2004.

[32] M. Chu, H. Haussecker, and F. Zhao, Scalable Information-Driven Sensor Querying and Routing for Ad Hoc Heterogeneous Sensor Networks, *International Journal of High Performance Computing Applications*, Vol. 16, No. 3, 2002.

[33] S. Chugh, S. Dharia, D. P. Agrawal, “An energy efficient collaborative framework for event notification in wireless sensor networks,“ in *Proc. IEEE LCN 2003*, pp. 430 -438, Oct. 2003.

[34] Available at http://www.ccalmr.ogi.edu.

[35] De Couto D. S. J., Aguayo D., Bicket J., Morris R., “A High-throughput path metric for multi-hop wireless routing,” in *Proc. Mobicom 2003,* vol. 1, pp. 134 -146, September 2003.

[36] Cramer, R.J., Win, M. Z., and Scholtz, R. A., “Impulse radio multipath characteristics and diversity reception,” in *Proc. IEEE ICC 1998*, vol. 3, pp. 1650-1654, 1998.
[37] Available at http://nms.lcs.mit.edu/projects/cricket.
[38] S. Cui, R. Madan, A. J. Goldsmith, S. Lall, “Joint routing, MAC, and link layer optimization in sensor networks with energy constraints,“ *Submitted for publication to IEEE ICC 2005*, May 2005.
[39] H. Dai and R. Han, TSync: A Lightweight Bidirectional TimeSynchronization Service for Wireless Sensor Networks, *ACMSIGMOBILE Mobile Computing and Communications Review, Special issueon wireless pan & sensor networks*, Vol. 8, No. 1, pp. 125-139,January 204.
[40] T. van Dam, K. Langendoen, “An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks,” in *Proc. ACM SenSys 2003*, Los Angeles CA, November 2003.
[41] Mukhopadhyay S., Panigrahi D., Dey S., “Data aware, low cost error correction for wireless sensor networks,” *IEEE WCNC 2004*, Atlanta, GA, March 2004.
[42] L. Doherty, K. Pister, and L. Ghaoui, Convex Position Estimation inWireless Sensor Networks, *IEEE INFOCOM 2001*, Vol. 3, pp.1655-1663, Anchorage, Alaska, April 2001.
[43] Available at http://www.dust-inc.com.
[44] J. Elson and D. Estrin, Time Synchronization for Wireless Sensor Networks, *Parallel and Distributed Processing Symposium*, SanFrancisco, CA, April 2001.
[45] J. Elson, and D. Estrin, “Random, Ephemeral Transaction Identifiersin Dynamic Sensor Networks,” *Proceedings 21st InternationalConference on Distributed Computing Systems*, pp. 459-468, Mesa, AZ,April 2001.
[46] J. Elson and K. Romer, Wireless Sensor Networks: A New Regime forTime Synchronization, *Proceedings of the First Workshop on HotTopics in Networks (HotNets)*, Princeton, New Jersey, October 2002.
[47] J. Elson, L. Girod, and D. Estrin, Fine-Grained Network TimeSynchronization using Reference Broadcasts, *Proceedings of theFifth Symposium on Operating Systems Design and Implementation (OSDI2002)*, Boston, M.A. December 2002.
[48] Available at http://www.ensco.com.
[49] T. Eren, and et al., Rigidity, Computation, and Randomization inNetwork Localization, *IEEE INFOCOM 2004*, Hong Kong, March2004.
[50] D. Estrin, L. Girod, G. Pottie, and M. Srivastava, “Instrumentingthe World With Wireless Sensor Networks,” *InternationalConference on Acoustics, Speech, and Signal Processing (ICASSP2001)*, Salt Lake City, Utah, May 2001.
[51] D. Estrin et al., Next Century Challenges: Scalable Coordination in Sensor Networks, *Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom’99)*, Seattle, WA, August 1999.
[52] P. Favre et al., “A 2V, 600μA, 1 GHz BiCMOS Super Regenerative Receiver for ISM Applications,” *IEEE J. Solid-State Circuits*, Vol. 33, pp.2186-2196, December 1998.
[53] S.D. Feller, et al., “Tracking and imaging humans on heterogeneous infrared sensor arrays for law enforcement applications,” *SPIE Aerosense 2002*, April, 2002.
[54] S.D. Feller, et al., “Tracking and imaging humans on heterogeneous infrared sensor array for tactical applications,” *SPIE Aerosense 2002*, April, 2002.
[55] S. Floyd, V. Jacobson, C. Liu, S. Macanne, and L. Zhang, “A Reliable Multicast Framework for Lightweight Sessions and Application Level Framing,” *IEEE/ACM Trans. Networking*, Vol. 5, No. 6, pp.784-803, Dec. 1997.
[56] S. Ganeriwal, R. Kumar, and M. B. Srivastava, Timing-Sync Protocolfor Sensor Networks, *SenSys’03*, Los Angeles, CA, November2003.
[57] M. Gastpar, and B. Rimoldi, “Source-channel communication with feedback,” in *Proc. IEEE Information Theory Workshop 2003*, pp. 279-282, March 2003.
[58] M. Gastpar, “Distributed source-channel coding for wireless sensor networks,” in *Proc. IEEE ICASSP 2004*, vol. 3, pp. 829-832, May 2004.
[59] Q. Gao, K. J. Blow, and D. J. Holding, Simple Algorithm forImproving Time Synchronizaation in Wireless Sensor Networks,*Electronics Letters 40*, pp. 889, 2004.
[60] L. Girod, J. Elson, A. Cerpa, T. Stathopoulos, N. Ramanathan, and D. Estrin, “EmStar: a Software Environment for Developing and Deploying Wireless Sensor Networks”, to appear in *Proc. USENIX 04*, (CENS Technical Report 34), 2004.
[61] GloMoSim, Global Mobile Information Systems Simulation Library, [online], *http://pcl.cs.ucla.edu/projects/glomosim/*.
[62] K. Govil, E. Chan, and H. Wasserman, “Comparing Algorithms for Dynamic Speed-Setting of a Low-Power CPU,” *in Proc. of ACM MobiCom ’95*, pp. 13-25, Berkeley, CA, November 1995.
[63] J. V. Greunen and J. Rabaey, Lightweight Time Synchronization forSensor Networks, *Proceedings of the 2nd Int’l ACM Workshop onWireless Sensor Networks and Applications (WSNA)*, pp. 11-19, SanDiego, CA, September 2003.
[64] C. Guo, L. C. Zhong, J. M. Rabaey, “Low power distributed MAC for ad hoc sensor radio networks,” in *Proc. IEEE GLOBECOM 2001*, vol. 5, 2944 -2948, Nov. 2001.
[65] T. He, and et al., Range-Free Localization Schemes for Large ScaleSensor Networks, *ACM MobiCom 2003*, pp. 81-95, San Diego, CA,September 2003.
[66] T. He et al., SPEED: A Stateless Protocol for Real-time Communication in Sensor Networks, *Proceedings of International Conference on Distributed Computing Systems*, Providence, RI, May 2003.
[67] S. Hedetniemi and A. Liestman, A Survey of Gossiping and Broadcasting in Communication Networks, *Networks*, Vol. 18, No. 4, pp. 319-349, 1988.
[68] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, Energy-Efficient Communication Protocol for Wireless Sensor Networks, *Proceeding of the Hawaii International Conference System Sciences*, Hawaii, USA, January 2000.
[69] W. Heinzelman, J. Kulik, and H. Balakrishnan, Adaptive Protocols for Information Dissemination in Wireless Sensor Networks, *Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom’99)*, Seattle, WA, August 1999.
[70] T. C. Henderson, J.-C. Park, N. Smith, and R. Wright, “From Motes to Java Stamps: Smart Sensor Network Testbeds,” in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems 2003*, pp. 799-803, Las Vegas, Nevada, October 2003.
[71] G. Hoblos, M. Staroswiecki, and A. Aitouche, ”Optimal Design of Fault Tolerant Sensor Networks,” *IEEE International Conference on Control Applications*, pp. 467-472, Anchorage, AK, September 2000.
[72] X. Hou, D. Tipper, and J. Kabara, “Label-based Multipath Routing (LMR) in Wireless Sensor Networks,” *ISART 2004*, Boulder, CO, March 2004.
[73] C. Hsin, M. Liu, “Network coverage using low duty-cycled sensors: random and coordinated sleep algorithms,” in *Proc. ACM IPSN ’04*, vol. 1, pp. 433 - 442, April 2004.
[74] A. Hu and S. D. Servetto, Asymptotically Optimal TimeSynchronization in Dense Sensor Networks, *Proceedings of the2nd Int’l ACM Workshop on Wireless Sensor Networks and Applications(WSNA)*, pp. 1-10, San Diego, CA, September 2003.
[75] L. Hu and D. Evans, Localization for Mobile Sensor Networks,*ACM MobiCom 2004*, Philadelphia, September 2004.

[76] Q. Huang, C. Lu and G. Roman, Spatiotemporal Multicast in Sensor Networks, *SenSys 2003*, pp. 205-217, Los Angeles, CA, November 2003.

[77] Q. Huang, C. Lu and G. Roman, Reliable Mobicast via Face-Aware Routing, *INFOCOM 2004*, Hong Kong, March 2004.

[78] K. Hung, Y. T. Zhang, "Usage of Bluetooth$\sup TM$ in wirelesssensors for tele-healthcare," in *Proc. Second Joint EMBS/BMESConference, 2002*, vol. 3, pp. 1881 - 1882, Oct. 2002.

[79] IEEE 1588, Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems, 2002.

[80] IEEE 802.15.4, "Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs), " October 2003.

[81] IEEE 802.11g, "Wireless MAC and PHY Specifications: Further Higher- Speed Physical Layer Extension in the 2.4 GHz Band," June 2003.

[82] IEEE 802.11, "Wireless LAN medium access control (MAC) and physical layer (phy) specifications," 1999

[83] C. Intanagonwiwat, R. Govindan, and D. Estrin, Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks, *Proceedings of the 6th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom'00)*, Boston, MA, August 2000.

[84] Available at http://www.intel.com/research/exploratory/ heterogeneous.htm.

[85] Available at http://www.intel.com/research/exploratory/ deep_networking.htm.

[86] S. Tilak, N. B. Abu-Ghazaleh, and W. Heinzelman, "Infrastructure Tradeoffs for Sensor Networks," in *Proc. ACM WSNA 2002*, September 2002, Atlanta, GA, USA.

[87] X. Ji and H. Zha, Sensor Positioning in Wireless Ad-hoc SensorNetworks Using Multidimensional Scaling, *IEEE INFOCOM 2004*,Hong Kong, March 2004.

[88] J-SIM Simulation Software, [online], *http://www.j-sim.org/*.

[89] J. M. Kahn, R. H. Katz, and K. S. J. Pister, "Next Century Challenges: Mobile Networking for Smart Dust," *Proc. of the ACM MobiCom'99*, pp.271-278, Washington, USA, 1999.

[90] K. Kalpakis, K. Dasgupta, and P. Namjoshi, Maximum Lifetime Data Gathering and Aggregation in Wireless Sensor Networks, *Proceedings of IEEE International Conference on Networking (NETWORKS'02)*, Atlanta, GA, August 2002.

[91] R. Kannan et al., Max-Min Length-Energy-Constrained Routing in Wireless Sensor Networks, *1st European Workshop on Wireless Sensor Networks*, Berlin, Germany, January 2004.

[92] A. Karnik, and A. Kumar, "Distributed optimal self-organisation in a class of wireless sensor networks," in *Proc. IEEE INFOCOM 2004*, Hong Kong, March 2004.

[93] G. Khanna, S. Bagchi, and Y. Wu, Fault Tolerant Energy Aware Data Dissemination Protocol in Sensor Networks, *DSN 2004*, Florence, Italy, June 2004.

[94] K. Langendoen and N. Reijers, Distributed Localization in WirelessSensor Networks: A Quantitative Comparison, *Computer Networks(Elsevier), Special issue on Wireless Sensor Networks*, November2003.

[95] Lee, H., Han, B., Shin, Y., and Im, S., "Multipath characteristics of impulse radio channels," in *Proc. IEEE VTC 2000*, vol. 3, pp. 2487-2491, Tokyo, Japan, May 2000.

[96] P. Levis, N. Lee, M. Welsh, and D. Culler, "TOSSIM: Accurate and Scalable Simulation of Entire TinyOS Applications," in *Proc. ACM SENSYS 2003*, pp. 126-137, November 2003.

[97] L. Li and J. Y. Halpern, Minimum Energy Mobile Wireless Networks Revisited, *Proceedings of IEEE International Conference on Communications (ICC'01)*, Helsinki, Finland, June 2001.

[98] Q. Li, J. Aslam, and D. Rus, Distributed Energy-conserving Routing Protocols, *The 36th Hawaii International Conference on System Science*, January 2003.

[99] Q. Li and D. Rus, Global Clock Synchronization in Sensor Networks,*IEEE INFOCOM 2004*, Hong Kong, March 2004.

[100] T. Li, A. Ekpenyong, and Y. Huang, A Location System UsingAsynchronous Distributed Sensors, *IEEE INFOCOM 2004*, HongKong, March 2004.

[101] J. Li, G. Y. Lazarou, "A bit-map-assisted energy-efficient MAC scheme for wireless sensor networks," in *Proc. ACM IPSN 2004*, pp. 55 -60, April 2004.

[102] N. Lin, C. Federspiel and D. Auslander, "Multi-sensor Single-Actuator Control of HVAC Systems," *Int. Conf. For Enhanced Building Operations*, Richardson, TX, 2002.

[103] S. Lindsey, C. S. Raghavendra, and K. Sivalingam, Data Gathering in Sensor Networks Using the Energy*Delay Metric, *Proceedings of the IPDPS Workshop on Issues in Wireless Networks and Mobile Computing*, San Francisco, CA, April 2001.

[104] S. Lindsey and C. S. Raghavendra, PEGASIS: Power Efficient Gathering in Sensor Information Systems, *Proceedings of the IEEE Aerospace Conference*, Big Sky, Montana, March 2002.

[105] Liu H., Ma H., Zarki M. E., Gupta S., "Error control schemes for networks," *Mobile Networks and Applications*, vol. 2, no. 2, pp. 167 -182, Oct. 1997.

[106] J. Lorch and A. Smith, "Reducing Processor Power Consumption by Improving Processor Time Management in a Single-User Operating System," *in Proc. of ACM MobiCom '96*, 1996.

[107] G. Lu, B. Krishnamachari, C.S. Raghavendra, "An adaptive energy-efficient and low-latency MAC for data gathering in wireless sensor networks," in *Proc. IEEE International Parallel and Distributed Processing Symposium*, pp. 224 -231, April 2004.

[108] S. Madden and M. J. Franklin, "Fjording thestream: an architecure for queries over streaming sensor data," in*Proc. 18th International Conference on Data Engineering*, pp.555-566, 2002.

[109] S. R. Madden, M. J. Franklin, J. M. Hellerstein, and W. Hong, "TAG: a Tiny aggregation service for ad-hoc sensor networks," in *Proc. OSDI*, December, 2002.

[110] S. R. Madden, M. J. Franklin, J. M. Hellerstein, and W. Hong, "The design of an aquisitional query processor for sensor setworks," in *Proc. SIGMOD*, San Diego,CA, June 2003

[111] A. Manjeshwar and D. P. Agrawal, TEEN: A Protocol For Enhanced Efficiency in Wireless Sensor Networks, *Proceedings of the 1st International Workshop on Parallel and Distributed Computing Issues in Wireless Networks and Mobile Computing*, San Francisco, CA, April 2001.

[112] A. Manjeshwar and D. P. Agrawal, APTEEN: A Hybrid Protocol for Efficient Routing and Comprehensive Information Retrieval in Wireless Sensor Networks, *Proceedings of the 2nd International Workshop on Parallel and Distributed Computing Issues in Wireless Networks and Mobile Computing*, Ft. Lauderdale, Fl, April 2002.

[113] Marco D., Neuhoff D. L., "Reliability vs. efficiency in distributed source coding for field-gathering sensor networks," *ACM IPSN'04*, pp. 161 -168, April 2004.

[114] S. Meguerdichian, and et al., Coverage Problems in Wireless Ad-HocSensor Networks, *IEEE INFOCOM 2001*, Vol. 3, pp. 1380-1387,Anchorage, Alaska, April 2001.

[115] L. Meier, P. Blum, and L. Thiele, Internal Synchronization of Drift-Constraint Clocks in Ad-Hoc Sensor Networks, *In Proc. of the 5th Symp. of Mobile Ad Hoc Networking and Computing (MobiHoc '04)*, May 2004.

[116] T. Melly, A. Porret, C. C. Enz, and E. A. Vittoz, "A 1.2 V, 430 MHz, 4dBm Power Amplifier and a 250 μW Front-End, using

a Standard Digital CMOS Process" *IEEE International Symposium on Low Power Electronics and Design Conf.*, pp.233-237, San Diego, August 1999.

[117] MICA Motes and Sensors, available at http://www.xbow.com/Products/Wireless_Sensor_Networks.htm.

[118] Mills, D. L., Internet Time Synchronization: The Network Time Protocol, *Global States and Time in Distributed Systems,* IEEE Computer Society Press, 1994.

[119] R. Min, T. Furrer, and A. Chandrakasan, "Dynamic Voltage Scaling Techniques for Distributed Microsensor Networks," *in Proc. of ACM MobiCom '95,* August 1995.

[120] Min, R., et.al., "Low-power wireless sensor networks," in *Proc. 14. International Conference on VLSI Design*, pp. 205 -210, Jan. 2001.

[121] Min, R, Chandrakasan A., "A framework for energy-scalable communication in high-density wireless networks," in *Proc. ISLPED'02*, pp. 36 -41, Aug. 2002.

[122] Mireles, F. R. and Scholtz, R. A., "Performance of equicorrelated ultra-wideband pulse-position-modulated signals in the indoor wireless impulse radio channel," in *Proc. IEEE Communications, Computers and Signal Processing '97,* vol. 2, pp 640-644, August 1997.

[123] J. Mirkovic, G. P. Venkataramani, S. Lu, and L. Zhang, "ASelf-Organizing Approach to Data Forwarding in Large-Scale SensorNetworks," *IEEE International Conference on CommunicationsICC'01,* Helsinki, Finland, June 2001.

[124] S. Mishra, A. Nasipuri, "An adaptive low power reservation based mac protocol for wireless sensor networks," in *Proc. IEEE International Conference on Performance, Computing, and Communications*, pp. 731 -736, April 2004.

[125] R. Y. Miyamoto, K. M. K. H. Leong, Seong-Sik Jeon, Y. Wang; T. Itoh,"An adaptive multi-functional array for wireless sensor systems,"*IEEE MTT-S International Microwave Symposium Digest*, vol. 2,pp. 1369 - 1372, June 2002.

[126] R. Y. Miyamoto, K. M. K. H. Leong, Seong-Sik Jeon, Y. Wang; T. Itoh,"Digital wireless sensor server using an adaptivesmart-antenna/retrodirective array," *IEEE Transactions onVehicular Technology*, vol. 52, no. 5, Sept. 2003, pp. 1181 - 1188.

[127] B. C. Mochocki and G. R. Madey, "H-MAS: A Heterogeneous, Mobile, Ad-hoc Sensor-Network Simulation Environment," in *Seventh Annual Swarm Researchers Meeting (Swarm2003),* Notre Dame, IN, 2003.

[128] R. Moses, D. Krishnamurthy, and R. Patterson, Self-LocalizationMethod for Wireless Sensor Networks, *EURASIP Journal onApplied Signal Processing*, Vol. 4, pp. 348-358, March 2003.

[129] MoteLab Sensor Network Testbed, [online], *http://motelab.eecs.harvard.edu/*

[130] D. Nadig, and S. S. Iyengar, "A New Architecture for Distributed Sensor Integration," *Proceedings of IEEE Southeastcon '93*, Charlotte, NC, April 1993.

[131] National Semiconductor Corporation, *LMX3162 Single Chip Radio Transceiver, Evaluation Notes and Datasheet*, March 2000.

[132] D. Niculescu and B. Nath, Ad Hoc Positioning System (APS),*IEEE Globecom 2003*, San Francisco, USA, December 2003.

[133] NRL's Sensor Network Extension to NS-2, [online], *http://nrlsensorsim.pf.itd.nrl.navy.mil/*.

[134] OMNET++ Discrete Event Simulator, [online], *http://www.omnetpp.org/*.

[135] S. PalChaudhuri, A. K. Saha, and D. Johnson, Adaptive ClockSynchronization in Sensor Networks, *IPSN'04,* Berkeley, CA,April 2004.

[136] S. Park, A. Savvides, and M. B. Srivastava, "SensorSim: A Simulation Framework for Sensor Networks," in *Proc. ACM International Workshop on Modeling, Analysis and Simulation of Wireless and Mobile Systems,* 2000.

[137] W. C. Park, S. H. Lee, D. H. Kim, J. J. Yoo, "Trade-off energy and delay between MAC protocols for wireless sensor networks," in *Proc. International Conference on Advanced Communication Technology*, vol. 1, pp. 157 -160, Feb. 2004.

[138] S. -J. Park, R. Vedantham, R. Sivakumar, and I. F. Akyildiz, "A Scalable Approach for Reliable Downstream Data Delivery in Wireless Sensor Networks," in *Proc. ACM MOBIHOC 2004*, pp. 78-89, Tokyo, Japan, May 2004.

[139] P. N. Pathirana, et al., Node Localization Using Mobile Robots inDelay-Tolerant Sensor Networks, *to appear in IEEE Trans. onMobile Computing,* 2004.

[140] N. Patwari, et al., Relative Location Estimation in Wireless SensorNetworks, *IEEE Trans. on Signal Processing,* Vol. 51, No. 8,pp. 2137-2148, August 2003.

[141] N. Patwari and A. O. Hero III, Using Proximity and Quantized RSS forSensor Localization in Wireless Networks, *Proceedings of the2nd Int'l ACM Workshop on Wireless Sensor Networks and Applications(WSNA),* San Diego, CA, September 2003.

[142] N. Patwari and A. O. Hero III, Manifold Learning Algorithms forLocalization in Wireless Sensor Networks, *IEEE Int'l Conf. onAcoustic, Speech, and Signal Processing,* Montreal, Quebec, May2004.

[143] T. Pering, T. Burd, and R. Brodersen, "The Simulation and Evaluation of Dynamic Voltage Scaling Algorithms," *in Proc. of International Symposium on Low Power Electronics and Design ISLPED '98,* pp. 76-81, August 1998.

[144] A. Perrig, R. Szewczyk, V. Wen, D. Culler, and J. D. Tygar, "SPINS: Security Protocols for Sensor Networks," *Proc. of ACM MobiCom'01,* pp. 189-199, Rome, Italy, 2001.

[145] E. M. Petriu, N. D. Georganas, D. C. Petriu, D. Makrakis, and V. Z. Groza, "Sensor-Based Information Appliances," *IEEE Instrumentation & Measurement Magazine,* pp. 31-35, December 2000.

[146] J. Polley, D. Blazakis, J. McGee, D. Rusk, J. S. Baras, and M. Karir, "ATEMU: A Fine-grained Sensor Network Simulator," in *Proc. IEEE International Conference on Sensor and Ad Hoc Communication Networks (SECON'04),* Santa Clara, CA, October 2004.

[147] A. Porret, T. Melly, C. C. Enz, and E. A. Vittoz, "A Low-Power Low-Voltage Transceiver Architecture Suitable for Wireless Distributed Sensors Network," *IEEE International Symposium on Circuits and Systems '00,* Volume 1, pp.56-59, Geneva, 2000.

[148] G. J. Pottie and W. J. Kaiser, "Wireless Integrated Network Sensors," *Communications of the ACM,* vol. 43, no. 5, pp. 551-8, May 2000.

[149] C. -Y. Wan, A. T. Campbell, and L. Krishnamurthy, "PSFQ: A Reliable Transport Protocol for Wireless Sensor Networks," in *Proc. ACM WSNA 2002*, September 2002, Atlanta, GA, USA.

[150] J. M. Rabaey, M. J. Ammer, J. L. da Silva Jr., D. Patel, and S. Roundy, "PicoRadio Supports Ad Hoc Ultra-Low Power Wireless Networking," *IEEE Computer Magazine,* pp. 42-48, 2000.

[151] J. Rabaey, J. Ammer, J. L. da Silva Jr., and D. Patel, "PicoRadio: Ad-hoc Wireless Networking of Ubiquitous Low-Energy Sensor/Monitor Nodes," *Proceedings of the IEEE Computer Society Annual Workshop on VLSI (WVLSI'00),* pp. 9-12, Orlanda, Florida, April 2000.

[152] V. Rajendran, K. Obraczka, and J. J. Garcia-Luna-Aceves, "Energy-Efficient, Collision-Free Medium Access Control for Wireless Sensor Networks," in *Proc. ACM SenSys 2003*, Los Angeles, California, November 2003.

[153] V. Ramadurai and M. L. Sichitiu, Localization in Wireless SensorNetworks: A Probabilistic Approach, *ICWN*, pp. 275-281, LasVegas, NV, June 2003.

[154] S. Ray, R. Ungrangsi, and F. D. Pellegrini, Robust Location-Detection in Emergency Sensor Networks, *IEEE INFOCOM 2003*,San Francisco, March 2003.

[155] V. Rodoplu and T. H. Ming, Minimum Energy Mobile Wireless Networks, *IEEE Journal of Selected Areas in Communications*, Vol. 17, No. 8, pp. 1333-1344, 1999.

[156] R. Rugin, G. Mazzini, "A simple and efficient MAC-routing integrated algorithm for sensor network," in *Proc. IEEE ICC 2004*, vol. 6, pp. 3499 -3503, June 2004.

[157] N. Sadagopan et al., The ACQUIRE Mechanism for Efficient Querying in Sensor Networks, *Proceedings of the First International Workshop on Sensor Network Protocol and Applications*, Anchorage, Alaska, May 2003.

[158] A. Safwat, H. Hassanein, H. Mouftah, "ECPS and E2LA: new paradigms for energy efficiency in wireless ad hoc and sensor networks," in *Proc. IEEE GLOBECOM 2003*, vol. 6, pp. 3547 -3552, Dec. 2003.

[159] Y. Sankarasubramaniam, O. B. Akan, and I. F. Akyildiz, "ESRT: Event-to-Sink Reliable Transport for Wireless Sensor Networks," in *Proc. ACM MOBIHOC 2003*, pp. 177-188, Annapolis, Maryland, USA, June 2003.

[160] C. Savarese, J. M. Rabaey, and J. Beutel, Locationing DistributedAd-Hoc Wireless Sensor Networks, *Proc. of Int'l Conf. onAcoustics, Speech and Signal Processing (ICASSP 2001)*, Salt LakeCity, Utah, 2001.

[161] A. Savvides, C. Han, and M. Strivastava, Dynamic Fine-GrainedLocalization in Ad-Hoc Networks of Sensors, *ACM MobiCom 2001*, pp. 166-179, Rome, Italy, July 2001.

[162] A. Savvides, H. Park, and M. Srivastava, The Bits and Flops of theN-hop Multilateration Primitive For Node Localization Problems,*Proceedings of the 2nd Int'l ACM Workshop on Wireless SensorNetworks and Applications (WSNA)*, pp. 112-121, Atlanta, Georgia,September 2002.

[163] SCADDS Sensor Network Testbed, [online], *http://www.isi.edu/scadds/*

[164] C. Schurgers and M. B. Srivastava, Energy Efficient Routing in Wireless Sensor Networks, *The MILCOM Proceedings on Communications for Network-Centric Operations: Creating the Information Force*, McLean, VA, 2001.

[165] C. Schurgers, V. Tsiatsis, M. B. Srivastava, "STEM: topology management for energy efficient sensor networks," in *Proc. IEEE Aerospace Conference 2002*, vol. 3, pp. 3-1099 - 3-1108, March 2002.

[166] L. Schwiebert, S. K. S. Gupta, and J. Weinmann, "Research challenges in wireless networks of biomedical sensors," *in Proc. ACM/IEEE MOBICOM '01*, pp. 151 -165, 2001.

[167] SENSE (Sensor Network Simulator and Emulator), [online], *http://www.cs.rpi.edu/ cheng3/sense/*.

[168] Available at http://www.sensicast.com.

[169] SENSONET Sensor Network Testbed, [online], *http://www.ece.gatech.edu/research/labs/bwn/*

[170] SENSORSCOPE Project, [online], *http://sensorscope.epfl.ch/*

[171] R. Shah and J. Rabaey, Energy Aware Routing for Low Energy Ad Hoc Sensor Networks, *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, Orlando, FL, March 2002.

[172] S. Shakkottai, R. Srikant, N. Shroff, "Unreliable sensor grids: coverage, connectivity and diameter," in *Proc. IEEE INFOCOM 2003*, vol. 1, pp. 1073 -1083, April 2003.

[173] Y. Shang and W. Ruml, Improved MDS-Based Localization, *IEEE INFOCOM 2004*, Hong Kong, 2004.

[174] Y. Shang, J. Meng, and H. Shi, A New Algorithm for Relative Localization in Wireless Sensor Networks, *18th Int'l Parallel and Distributed Processing Symposium (IPDPS'04)*, Santa Fe, NewMexico, April 2004.

[175] C. Shen, C. Srisathapornphat, and C. Jaikaeo, "Sensor Information Networking Architecture and Applications," *IEEE PersonalCommunications*, pp. 52-59, August, 2001.

[176] Shih, E. et al., "Energy-efficient link layer for wireless microsensor networks," in *Proc. IEEE Workshop on VLSI*, Orlando, Florida, April 2001.

[177] Shih, E. et al., Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks, *ACM Mobicom'01*, pp. 272-286, Rome, Italy, July 2001.

[178] M. Sichitiu and C. Veerarittiphan, Simple, Accurate TimeSynchronization for Wireless Sensor Networks, *WirelessCommunications and Networking (WCNC'03)*, Vol. 2, pp. 16-20, March2003.

[179] M. L. Sichitiu, V. Ramadurai, and P. Peddabachagari, SimpleAlgorithm for Outdoor Localization of Wireless Sensor Networks withInaccurate Range Measurements, *Int'l Conference on WirelessNetworks (ICWN 2003)*, pp. 300-305, Las Vegas, NV, June 2003.

[180] S. N. Simic and S. Sastry, Localization in Dense Random SensorNetworks, *Information Processing in Sensor Networks (IPSN2004)*, Berkeley, CA, April 2004.

[181] A. Sinha and A. Chandrakasan, "Dynamic Power Management in Wireless Sensor Networks," *IEEE Design and Test of Computers*, March/April 2001.

[182] F. Sivrikaya and B. Yener, Time Synchronization in Sensor Networks:A Survey, *IEEE Network*, pp. 45-50, July/August 2004.

[183] SNETSIM Wireless Sensor Network Simulator, [online], *http://www.dho.edu.tr/enstitunet/snetsim/index.htm*.

[184] Available at http://www.soflinx.com.

[185] K. Sohrabi et al., Protocols For Self-Organization of a wireless sensor network, *IEEE Personal Communications*, Vol. 7, No. 5, pp. 16-27, 2000.

[186] F. Stann and J. Heidemann, "RMST: Reliable Data Transport in Sensor Networks," in *Proc. IEEE SNPA 2003*, pp. 102-112, Anchorage, Alaska, May 2003.

[187] D. Steere, A. Baptista, D. McNamee, C. Pu, J. Walpole, "Research challenges in environmental observation and forecasting systems," *in Proc. ACM/IEEE MOBICOM '00*, Boston, August 2000.

[188] W. Su and I. F. Akyildiz, Time-Diffusion Synchronization Protocol for Sensor Networks, *to Appear in IEEE/ACM Trans. on Networking*, February 2005.

[189] L. Subramanian and R. H. Katz, An Architecture for Building Self Configurable Systems, *Proceedings of IEEE/ACM Workshop on Mobile Ad Hoc Networking and Computing*, Boston, MA, August 2000.

[190] S. Sundresh, K. WooYoung, and A. Gul, "SENS: A Sensor, Environment and Network Simulator," in *Proc. 37th Annual Simulation Symposium (ANSS37)*, pp. 221-230, Arlington, VA, April 2004.

[191] SWANS, Scalable Wireless Ad hoc Network Simulator, [online], *http://jist.ece.cornell.edu/*.

[192] R. Szewczyk, E. Osterweil, J. Polastre, M. Hamilton, A. Mainwaring, and D. Estrin, "Habitat Monitoring with Sensor Networks," *Communications of the ACM*, vol. 47, no. 6, pp. 34-40, 2004.

[193] The Network Simulator (ns-2), [online], *http://www.isi.edu/nsnam/ns/*.

[194] TinyOS, [online], *http://www.tinyos.net/*.

[195] B. L. Titzer and D. K. Lee, "Avrora: Scalable Sensor Network Simulation with Precise Timing," [online], *http://www.cs.ucla.edu/ palsberg/sns/TitzerLeePalsberg04.pdf*, 2004.

[196] D. Tulone, A Resource-Efficient Time Estimation for Wireless Sensor Networks, *Proceedings of the 2004 Joint Workshop on Foundations of Mobile Computing,* pp. 52-59, 2004.

[197] S. Vardhan, M. Wilczynski, G. Pottie, and W. J. Kaiser, “Wireless Integrated Network Sensors (WINS): Distributed in Situ Sensing for Mission and Flight Systems,” *IEEE Aerospace Conference,* Vol. 7, pp. 459-463, March 2000.

[198] T. Voigt, H. Ritter, and J. Schiller, Solar-aware Routing in Wireless Sensor Networks, *Personal Wireless Communication 2003*, Venice, Italy, September 2003.

[199] M. C. Vuran, ¨ O. B. Akan, I. F. Akyildiz, “Spatio-temporal correlation: theory and applications for wireless sensor networks,” *Computer Networks Journal (Elsevier Science)*, vol. 45, no. 3, June 2004.

[200] C.-Y. Wan, S. B. Eisenman, and A. T. Campbell, “CODA: Congestion Detection and Avoidance in Sensor Networks,” in *Proc. ACM SENSYS 2003*, November 2003.

[201] Y. Wang, J.J. Garcia-Luna-Aceves, “Performance of collision avoidance protocols in single-channel ad hoc networks,” *In Proc. IEEE International Conference on Network Protocols*, pp. 68 -77, 2002.

[202] H. Wang, and et al., A Wireless Time-Synchronized COTS SensorPlatform: Applications To Beamforming, *Proceedings of the IEEECAS Workshop on Wireless Communications and Networking,* Pasadena,CA, September 2002.

[203] B. Warneke, B. Liebowitz, and K. S. J. Pister, “Smart Dust: Communicating with a Cubic-Millimeter Computer,” *IEEE Computer,* pp. 2-9, January 2001.

[204] M.Weiser et al., “Scheduling for Reduced CPU Energy,” *in Proc. of 1st USENIX Symp. on Operating System Design and Implementation*, pp. 13-23, November 1994.

[205] E. Welsh, W. Fish, and P. Frantz, “GNOMES: A Testbed for Low-Power Heterogeneous Wireless Sensor Networks,” in *Proc. IEEE International Symposium on Circuits and Systems (ISCAS) 2003,* Bangkok, Thailand, May 2003.

[206] Available at http://www.wireless4industrial.org.

[207] K. D. Wong, “Physical layer considerations for wireless sensornetworks,” in *Proc. IEEE International Conference on-Networking, Sensing and Control*, vol. 2, pp. 1201 - 1206, March,2004.

[208] A. Woo, and D. Culler, ”A Transmission Control Scheme for Media Access in Sensor Networks,” *Proc. of ACM MobiCom’01,* pp.221-235, Rome, Italy, July 2001.

[209] Available at http://www.xsilogy.com.

[210] Y. Xu, J. Heidemann, and D. Estrin, “Geography-informed Energy Conservation for Ad Hoc Routing,” *Proceedings of the 7th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom’01)*, Rome, Itlay, July 2001.

[211] Y. Yao and J. Gehrke, “The Cougar Approach to In-Network Query Processing in Sensor Networks,” *SIGMOD Record*, September 2002.

[212] Y. Yao and J. Gehrke, “Query processing in sensor networks,”in *Proc. 1st Biennial Conference on Innovative Data SystemsResearch*, Asilomar, CA, Jan. 2003.

[213] W. Ye, J. Heidemann, D. Estrin, “An energy-efficient MAC protocol for wireless sensor networks,” in *Proc. IEEE INFOCOM 2002*, vol. 3, pp. 1567 -1576, June 2002.

[214] W. Ye, J. Heidemann, D. Estrin, “Medium access control withcoordinated adaptive sleeping for wireless sensor networks,”*IEEE/ACM Transactions on Networking*, vol. 12, no. 3, pp. 493-506, June 2004.

[215] M. Younis, M. Youssef, and K. Arisha, Energy-aware Routing in Cluster-Based Sensor Networks, *Proceedings of the 10th IEEE/ACM International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS2002),* Fort Worth, TX, October 2002.

[216] O. Younis, and S. Fahmy, “Distributed clustering in ad-hoc sensor networks: a hybrid, energy-efficient approach,” in *Proc. IEEE INFOCOM 2004*, Hong Kong, March 2004.

[217] O. Younis, and S. Fahmy, “Distributed clustering in ad-hoc sensor networks: a hybrid, energy-efficient approach,” *IEEE Trans. on Mobile Computing*, vol. 3, no. 4, pp. 366 -379, Oct.-Dec. 2004.

[218] Available at http://www.zen-sys.com.

[219] Y. Zhang and L. Cheng, Self-Nominating: A Robust Affordable Routing for Wireless Sensor Networks, *VTC 2003*, Orlando, Fl., October 2003.

[220] Zhao J., Govindan R., “Understanding packet delivery performance indense wireless sensor networks,” in *Proc. ACM SenSys’03*,vol. 1, pp. 1 -13, Nov. 2003.

[221] Zhong, L. C., Rabaey J. M., Wolisz A. “An integrated datalink energy model for wireless sensor networks,” in *Proc. IEEE ICC’04*, Paris, France, June 2004.

[222] R. Ziemer, M. Wickert, T. Williams, “A comparison between UWB andDSSS for use in a multiple access secure wireless sensor network,”in *Proc. IEEE Conference on Ultra Wideband Systems andTechnologies, 2003*, pp. 428 - 432, Nov. 2003.

[223] Available at http://www.zigbee.com.

[224] M. Zorzi, “A new contention-based MAC protocol for geographicforwarding in ad hoc and sensor networks,” in *Proc. IEEE ICC2004*, vol. 6, pp. 3481 -3485, June 2004.

[225] Y. Zou and K. Chakrabarty, Sensor Deployment and Target LocalizationBased on Virtual Forces, *IEEE INFOCOM 2003,* pp. 1293-1303,San Francisco, CA, March 2003.

[226] Y. Zou and K. Chakrabarty, Energy-Aware Target Localization inWireless Sensor Networks, *IEEE International Conf. onPervasive Computing and Communications,* Fort Worth, Texas, March2003.

[227] Y. Zou and K. Chakrabarty, Sensor Deployment and Target Localization in Distributed Sensor Networks, *ACM Transactions on Embedded Computing Systems (TECS),* Vol. 3, pp. 61-91, 2004.