We are IntechOpen,
the world's leading publisher of
Open Access books
Built by scientists, for scientists

6,900
Open access books available

186,000
International authors and editors

200M
Downloads

Our authors are among the

154
Countries delivered to

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

CLARIVATE ANALYTICS
BOOK CITATION INDEX
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

6

Power Considerations for Sensor Networks

Khadija Stewart[1] and James L. Stewart[2]
[1]*DePauw Universtity*
[2]*Purdue University*
USA

1. Introduction

Wireless sensor networks (WSNs) are networks composed of small, resource-constrained and collaborative devices. WSNs are used in a plethora of domains including environmental and agricultural monitoring, military operations, in the health care field and in building automation. The three main functions of wireless sensor nodes (also called motes) are to sense the environment, perform computations, store intermediate results and communicate with other motes in the network.

This chapter focuses on power considerations for all aspects of wireless sensor networks. It covers software, hardware and networking aspects of the motes. The main limitation of wireless sensor motes is that they operate on battery power. In many WSN applications, the motes are placed in remote areas and deployed for the lifetime of the network. During this time the only power resource the motes have access to is their battery. An example of such a deployment is the Mount St. Helens project developed to study volcanic activities on Mount St. Helens (were volcanic eruptions can occur at any time with very little warning). The sensors were placed on the mountain using helicopters and work at length to continually sense seismic activity and relay information to a data center. For such applications, the battery lifetime is the main factor that dictates the lifetime of the network. It is therefore imperative to develop wireless sensor mote platforms that minimize the power consumption and/or maximize the lifetime of the network as a whole.

Several works in the literature address one or two aspects of the mote's architecture and/or functionality but to the authors' knowledge, no work has combined all said aspects and addressed them as a homogeneous unit. This chapter studies and analyzes each hardware component of the mote's architecture, all the main protocols used in the mote's stack layer, discusses the work that has been done in terms of reducing the power consumption, increasing the battery lifetime and or increasing the lifetime of the entire network as a whole.

The chapter is organized as follows: Section 2 gives an overview of wireless sensor networks, their applications and general architecture. Section 3 focuses on the hardware architecture of the motes (the CPU, communication infrastructure, memory and sensors). Section 4 introduces the layered protocol stack of the sensor motes (application, transport, network, link and physical layers). Section 5 summarizes the chapter and suggest paths forward.

2. Preliminaries

Wireless sensor networks are composed of small, inexpensive devices that are designed to sense some phenomena, perform light computations and communicate with one another. These devices are usually scattered over some area. This technology has seen a wide range of applications ranging from military use to personal security. In the following, we discuss the history of WSNs and some of their most pertinent applications.

Wireless sensor networks evolved form the Smartdust project, which was developed and funded by DARPA in the late 1990s. The Smartdust project was designed to show that "a complete sensor/communication system can be integrated into a cubic millimeter package" (Pister, 2001). The Smartdust motes were engineered to be power efficient. This and other similar projects have led to the explosion of research in the area of wireless Ad Hoc and sensor networks, which was and still is heavily supported by US government agencies including the National Science Foundation. While working on the Smartdust project, the researchers recognized the variety of applications for their work both in the military field and elsewhere.

Some of the applications for the Smartdust projects are virtual keyboard, inventory control, product quality monitoring and smart office spaces among others (Pister, 2001). In the virtual keyboard application, dust motes would be glued into fingernails to sense the orientation and motion of the fingertips and communicate with a computer. This could be used in sign language translations, piano play, etc... In the inventory and quality control applications, a system of communication could be implemented and deployed in all aspects of the production process in order to monitor the location of the product and control and monitor its quality (from temperature, to humidity exposure etc...). In the smart office spaces application, the person's preferred temperature, humidity settings could be directly communicated to the environment they walk into. Some of the military applications that the Smartdust project was developed for include battlefield surveillance, transportation monitoring and missile monitoring.

In the past few year, Wireless Sensor Networks made the transition from the Berkeley research centers to the production arena with the creation of companies, such as Crossbow Technologies (Crossbow Technologies, n.d.) that started manufacturing them. The appeal of Wireless Sensor Networks stems from the fact that you can deploy them and just leave. We discuss in the remainder of this section the main classes of applications for the general WSNs.

WSN applications can be categorized into habitat and environmental monitoring, heath applications, commercial applications, military applications among others.

One of the most prevalent uses of WSNs is in habitat and environmental monitoring. It has been shown that direct human contact with some plant or animal colonies can result in disastrous consequences. For example, (Mainwaring et al., 2002) describe the use of a sensor network to monitor Seabird colonies because of their sensitivity to human disturbance. In fact, a 15 minute visit to the colony could result in up to 20% rate of mortality among eggs. Not only are WSNs useful in monitoring colonies without causing any disturbances but they also represent a more economic method of monitoring for long periods of time.

Another example of the environmental use of WSNs is in forecasting systems. WSNs are now scattered around large areas to forecast pollution, flooding and seismic activity. The Automated Local Evaluation in Real Time (ALERT) was developed in the 70s by the National Weather Service. It has been used by several government and state agencies and international

organizations to provide a real time data collection system that can forecast floods (ALERT, n.d.).

Another use for WSNs is in intelligent building management. In fact, they have been used in HVAC, lighting, climate control, fire protection, energy monitoring and security applications among others. In Canada for example, the National Research Council launched a three-year project to develop wireless sensor networks to do just that. The project started in 2008 and is anticipated to continue through 2011.

A very important application of WSNs is in the healthcare field. WSNs can be used to provide continuous, remote, inexpensive, instantaneous and non-invasive monitoring of a patient's vital signs. This technology can be used to allow the elderly to remain in their own residences but still be able to continuously check their vitals.

All these WSN applications consist of deploying the network for an extended period of time on a single battery charge. It is therefore imperative that the motes be power efficient and that the lifetime of the network as a whole be as long as possible.

3. The WSN hardware architecture

The hardware of wireless sensor motes consists of sensors (analog and/or digital), a microcontroller, also referred to as a microprocessor or Central Processing Unit(CPU), memory, RF communication module (transceiver) and battery. The design of each component of a WSN mote should take into consideration the power metrics (power consumption and voltage requirements) of the component. Additionally, the integration/interface of all the components as a whole should be studied for power consumption (having analog sensors means that an ADC component in the CPU should be required to convert the sensor readings to a digital format etcÉ)

To reduce power consumption, several works suggest the introduction of sleep and wake up cycles for the motes. Other schemes suggest a better integration of the functionality of hardware components (using cross-layer principles). Another consideration in the design of the CPU is the clock component. Several applications of WSNs require some level of time synchronization. Clock choices and designs affect the amount of drift that a sensor mote's clock can experience requiring more or less time synchronization operations when the mote is deployed (Akyildiz et al., 2002).

3.1 Sensors

Of the five main units, the sensing unit is the most application specific. Meaning the type of sensor used will depend on the application. For instance, wireless sensors used for structural health monitoring may consist of materials apt for monitoring strain, acceleration (accelerometer) and linear and angular displacement. Other application specific sensors may measure, vehicular movement, soil consistency, blood alcohol levels, humidity, noise levels and so on. These sensors should then report some signal indicative of their acquisition. Temperature (thermo-coupler outputting voltage or thermistor outputting resistance), force or pressure (piezoelectric outputting voltage, strain gauge outputting resistance), position (linear variable differential transformers (LVDT) outputting alternating current) or light intensity (photodiode outputting current) all need to report information regarding their surroundings to a processing unit (Wilson, 2004).

The development of an efficient method for acquiring and converting conventional energy from the sensors such as solar and wind has seen an exponential growth over the last few years. The sensing development has been referred to as energy harvesting. One factor contributing to the enjoyment of such an increase has been the threat of rapid decreases projected in our global and national energy reserves based on utilization rates and trends. Such a premonition has spurred funding for research in various fields including materials or more specifically metamaterials.

Metamaterials have been defined by most associated scientist as materials made by man which exhibit non-natural properties and characteristics, particularly EM or electromagnetic properties not known to exist with any other materials found in nature. Regarding electromagnetism, metamaterials which exhibit propagating electromagnetic waves (both the permittivity and permeability are negative as seen in Figure 1 have seen much attention in recent years as well as when both permittivity and permeability are very close to 1.
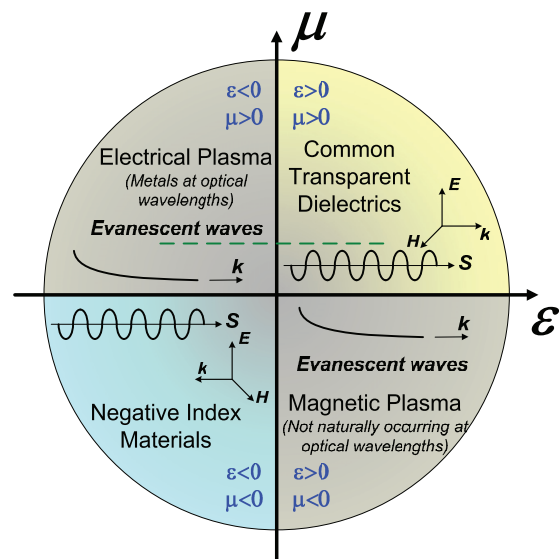

Fig. 1. The parameter space for ϵ and μ. The two axes correspond to the real parts of permittivity and permeability, respectively. The dashed green line represents non-magnetic materials with $\mu = 1$ Cai &shaleav (2010).

The reaction or response of a material (as in a sensor for WSNs) to external fields is largely determined by only the two material parameters ϵ and μ, permittivity and permeability respectively. As shown in Figure 2, the real part of permittivity ϵ_r is plotted to the horizontal axis of the parameter space, while the vertical axis corresponds to the real part of permeability μ_r. A negative value of ϵ (μ) indicates that the direction of the electric (magnetic) field induced inside the material is in the opposite direction to the inbound incident field. Noble metals at optical frequencies, for example, are materials with negative ϵ, and negative μ and can be found in ferromagnetic media near a resonance. Waves can not propagate in material in the second and fourth quadrants, where one of the two parameters is negative and the index of refraction becomes purely imaginary. In the domain of optics, all conventional materials are confined to an extremely narrow zone around a horizontal line at $\mu = 1$ in the space, as represented by the dashed line in Figure 2.

Scores of such materials are designed to manipulate EM waves, many passively, by creating an alternate propagation path. Metamaterials have been designed to redirect, not absorb or
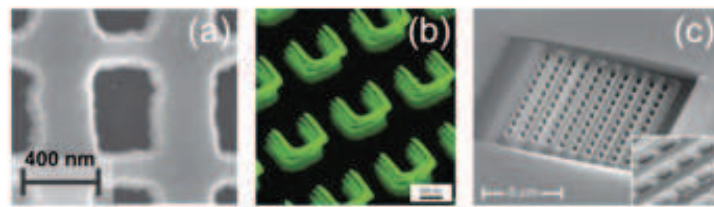
Fig. 2. Examples of a 3D optical metamaterials fabricated in a layer-by-layer manner. (a) A near-infrared NIM (Negative Index Material) with three functional layers made by EBL (Electron Beam Lithography); (b) Four layers of SRRs (Split Ring Resonators) based on EBL with patterning-and-flattening approach; (c) A NIM wedge exhibiting negative refraction for visible light made by an advanced FIB technique Cai &shaleav (2010).

reflect but to divert the energy through a desired path. It is no wonder as to the attention metamaterials have seen for energy harvesting. Research is currently being conducted to develop sensors (both photon and electron based) that extract atmospheric energy regardless of the incident angle such that no energy is reflected back out of the sensor rather, it's reflected down toward the detector. This will lead to the creation of ultra-efficient sensors for wireless networks, see (Narimanov & Kildishev, 2009; Shalaev et al., 2005) for more information on Metamaterials.

3.2 Microcontroller

The component responsible for doing the bulk of the switching and decision making for the WSN at the remote site is the processor or microcontroller. When selecting the processor for specific WSN applications, the engineer must make many considerations. These considerations include, but are not limited to, cost, power requirements, physical size, weight and speed, some of which are elaborated upon below.

Depending on the microcontroller, the power requirement could range from .25 mA to 2.5 mA per MHz for either 8 or 16 bit processors. Again, the application will determine if a processor consuming relatively high amounts of energy is acceptable or if .25 mA per MHz is needed. A common misconception is that by putting the processor in "sleep" mode, the sensor utilizes less power thus is more efficient. It has been shown that this is not always true as while in "sleep mode", sensors still maintain synchronization and memory functionalities necessary to perform expeditiously upon awakening (Hu & Cao, 2010).

In fact a more prudent approach to saving energy would include completely shutting the processor off, entirely, and ensuring the sensor can rapidly recover from a "dead" state or at the very least rapidly jump from "sleep" mode to "awake" mode. As the processor needs to synchronize native clocks and stabilize, the transition time or delay can be as long as 10 ms which is a relative eternity. Another parallel approach involves varying the speed depending on the time allotted for a specific task.

In other words, only using the minimum power required for a task at a given time by dynamically ramping up or down the power accordingly versus drawing full power for all "awake" states. This approach may benefit from an algorithm in which the speed is a function of the power. If the required task and itÕs effort expended is known before the task is given, an absolute "finish time" can be maintained without necessarily completing the task as fast

a possible rather as fast as necessary. Researchers from the University of California, Irvine (Irani et al., 2007) developed an algorithm for optimizing power consumption by varying speed below:

$$g(z, z') = \frac{\sum_j \, such that [r_j, dj] \subseteq [z, z'] R_j}{l(z, z')} \tag{1}$$

where g(z,z') defines the intensity of the interval [z,z'], l[z,z'] defines the length of the interval, R_j is the required work needed to complete the job and d_j denotes the deadline for job j. This would allow energy and speed to be spent where it's needed most creating a dynamic fluid speed variance throughout the CPU for maximum overall efficiency. One might say, 'losing a battle here and there but winning the war'.

3.3 Memory

Memory is a crucial factor in WSNs. Particularly non-volatile memory. Non- volatile memory is defined as various forms of solid state memory which doesn't need to be refreshed or powered to maintain it's information. Examples include flash, electrically erasable programmable read-only memory (PROM) read only memory (ROM), optical discs and magnetic disks (Postolache et al., 2010).

The memory component is the means at which the WSN stores the data it acquires. The speed requirement of the memory unit depends of the nature of the WSN and its intended functionality. A rather fast memory unit may be required for certain military applications where the data acquisition speed from the memory may dictate whether or not a target is detected in time for acquisition and lock. On the other hand, a relatively slow memory unit may be acceptable for soil monitoring WSN utilized by farmers. In either case the security and reliability of the memory unit is important and both require additional power demands on the WSN. To this end, researchers have been developing ways to more efficiently processing and storing the acquired data including virtual memory protocols. Virtual memory has been shown to reduce compile-time optimizations regardless of the limitations in memory on site. One approach which generates a memory layout optimizes to the memory access patterns and attributes for a given WSN. In other words, the protocol optimizes the memory map based on the application, effectively reducing overhead (Lachenmann et al., 2007).

3.4 Transceiver module

All WSN motes will possess a transceiver or TR modules as they allow the motes to communicate in WSNs. They present the capability to transmit and receive data packets, information or signals in a relatively small package. One of the main factors which allows for such a diminutive size lies in the RF architecture. Because the TR modules transmit and receive in the same RF component there is no need for a separate architecture for each transmission or reception. Thus the isolation of incident energy to transmitted energy must be great to ensure against destructive cross modulation, unwanted dispersion and various other resultant noise, all of which would inherently degrade the efficiency of the WSN either directly or indirectly. Signal loss is of particular concern in the input/output portion of the TR module and precautions must be taken to ensure signal degradation is tolerable from a minimum threshold point of view.

Within the TR package, a typical TR module will consist of and follow this RF path for transmission: a common attenuator for signal suppression, a common phase shifter (depending on the application. For example, phase shifter could be used to shape the transmission pattern or radiation pattern leaving a WSN (also known as beam-steering), a driver and a high power amplifier (HPA) to boost the signal amplitude for propagation from the aperture or antenna for transmission. When receiving a signal within the TR module frequency range, which varies per application, the signal passes through a limiting filter and low noise amplifier (LNA) before coursing through a common attenuator to suppress the signal's magnitude and possibly a common phase shifter (depending on the application. For example the phase shifter can be utilized as a directional finder or filter for incident signal in a WSN). Outbound and incident signals are typically discerned by a circulator at the output/input of the module. The attenuator and phase shifters are termed "common" due to the fact that these components are used for both reception and transmission. In the following, we elaborate on a few of the key components of the TR module from Figure 3.

The attenuator is implemented to ensure the unwanted side-lobes are suppressed, sufficiently reducing the noise in the system. It also keeps the amplifiers down stream from prematurely reaching saturation and causing unwanted non-linearities. Typically this is done only for the receiver as during transmissions, it is usually desirable to propagate as much energy from the antenna as possible. Since the attenuator basically performs the exact opposite function of the amplifier, they are typically not conjoined in series unless, in some cases, it's needed for filtering purposes. Note that all the components within the TR module are frequency matched meaning they are optimized for specific frequency ranges. Due to this inherent characteristic, attenuators can be used to suppress frequency bands without distorting the fundamental waveform. This is important for the energy efficiency of the system as the modulator can maintain relative simplicity without the need to effectively recreate a waveform which would subsequently cost more power.

The phase shifter allows multiple RF signals to be controlled by way of an external stimulation such that the output of the phase shifter is of the desired phase without effecting the frequency. The phase shifter may or may not be present in the TR module. It depends on whether or not the WSN calls for a beam-forming or shaping capability which can aid in power efficiency if multiple sensors are synchronized in receive and or transmission mode for power/amplitude coupling. The amplifiers (driver and high power amplifiers) boost the signal for transmission from the antenna. The level of amplification needed depends on the efficiency of the system, particularly the aperture or antenna. A poorly matched antenna or one which has a high Voltage Standing Wave Ratio (VSWR) will demand a higher amplitude or stronger signal to propagate to a given target.

The application and placement availability of WSN will greatly affect which antenna is more suitable and efficient. Most WSN antennas are omni-directional fundamentally but are shaped by various ground effects. This crucial aspect of antenna propagation has prompted many researchers to develop accurate prediction models specifically for WSNs.

3.5 Power source

Considering that many WSNs rely on portable energy or power sources to power sensors, the capacity and efficiency of both the power source and the WSN is crucial in the overall effectiveness of the WSN. For most of the WSN applications, when the power source drains,
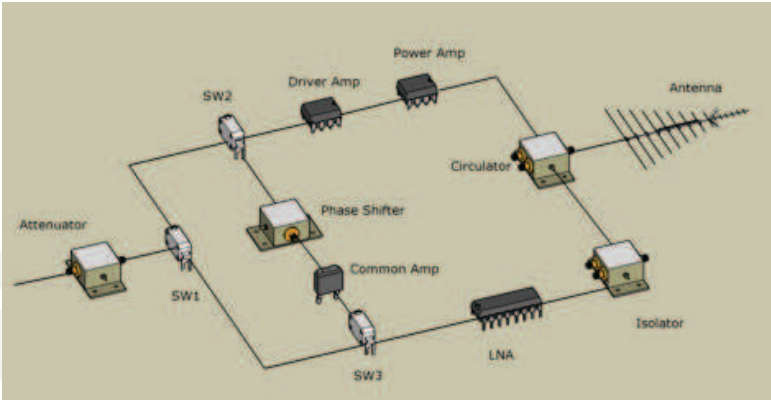
Fig. 3. Transceiver

the WSN is inoperable. For many applications various protocols for maximizing the lifetime of the WSN are adequate while many other applications require WSNs to remain in remote areas for several months or years without opportunities for manual power replenishment. Many research centers have developed models to efficiently harvest energy for power as for sensing previously mentioned. A WSN which can obtain its power requirements from its surrounding environment essentially has an infinite lifetime. Various approaches from mechanical vibrational energy harvesting to photon collection schemes are being considered in an effort to self-generate power needs.
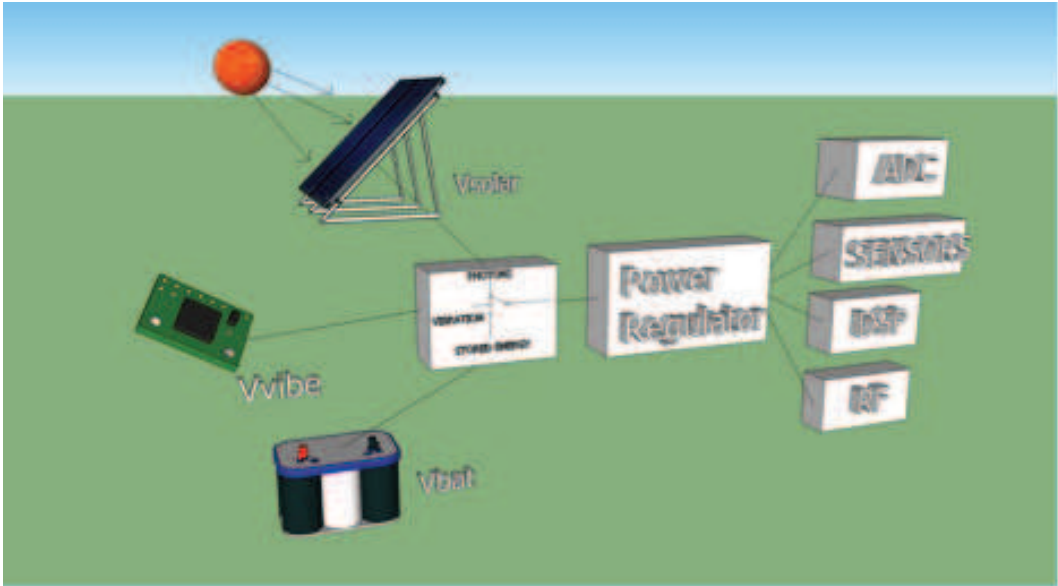

Fig. 4. A low power wireless sensor node system powered from energy scavengers or harvesters and a battery. Guilar et al. (2006).

Figure 4 is a schematic of a low power WSN system that uses energy scavengers. In Figure 4, the energy sources are labeled Vsolar, Vvibe and Vbat for the solar, mechanical vibration and battery, respectively. A mutiplexer switches between the unregulated energy sources. ADC denotes the Analog to digital converter, DSP denotes the Digital signal processors and RF denotes Radio frequency.

4. The WSN layered protocol stack

The WSN layered protocol stack consists of the Application layer, the Transport layer, the Data link layer and the Physical layer. This section will cover the role of each layer and study its power consumption. The section will survey the current literature and analyze it with respect to power consumption.

4.1 Application layer

The application layer is in charge of collecting and processing sensor readings (including the use of data aggregation), performing time synchronization, implementing a security protocol (as needed) etc... Each one of these tasks uses one or more hardware modules and each task results in power being consumed.

4.1.1 Information fusion

Traditionally, sensor motes were designed to perform very little to no processing. They would sense the environment and send the sensing data to the base station for processing. This resulted in large amounts of packets being sent from the motes to the base station. In addition, in several sensor network applications, the motes are exposed to conditions (such as very high/low temperatures, pressure and noise) that might sabotage their measurements. It was then proposed to use information fusion (also referred to as data aggregation) techniques at the motes in order to decrease the network traffic, save energy, remove outlier data, make predictions about future measurements and in general obtain better information quality by combining data from multiple sources. Data aggregation requires some amount of processing to be carried out at the motes. Data fusion can be used at different layers of the WSN protocol stack. For example, it can be used at the application layer to process sensor readings as well as at the network layer to consolidate routing information. In the following, we survey and analyze the work that has been done on data aggregation and information fusion.

Information fusion can be categorized into three classes. Complementary, redundant, and cooperative. This classification depends on the particular application and the relationship between the motes that gather the data. In the case of complementary information, sources gather different types of data and information fusion is applied to obtain a more complete picture from data. In the case of redundant information, one or more sources gather the same type of data and information fusion is used to discard the outlier measurements and filter the data for accuracy, reliability and confidence. In cooperative information fusion, two sources gather information that is fused to produce information that better represents the reality. Information fusion is performed for different purposes. In the following, we present a classification of data fusion algorithms based on the purpose of the information fusion.

Information fusion techniques could be either centralized or distributed. Centralized techniques have a single point that controls the fusion process but are simple to implement. However, all the sensor motes send their data to the central point, which overwhelms the central data point and floods the network with messages. Distributed techniques on the other hand are more complex to implement but are more energy efficient because the information is exchanged locally, which reduces the number of messages exchanged in the network. Several methods have been proposed for information fusion including inference, estimation, aggregation, and compression.

Inference methods consist of making a decision based on previous knowledge. Protocols that have been proposed for inference include Bayesian inference algorithms (Coue et al., 2002; Tsymbal et al., 2003), Dempster-Shafer inference algorithms (Dempster, 1968; Shafer, 1976) and fussy logic algorithms (Gupta et al., 2005) among others.

Estimation methods use probabilistic theory to estimate a state based on a sequence of measurements. Estimation algorithms include the maximum likelihood algorithm (Xiao et al., 2005), least square, Kalman filter and particle filter (Kalman, 1960).

Data aggregation methods are used to overcome implosion and overlap and compression is used to reduce the amount of data by exploiting spatial correlation among the motes. Techniques for compression include distributed source coding (Xiong et al., 2004) and coding by ordering (Petriovic et al., 2003).

The implementation of these algorithms comes at a cost involving hardware complexity, CPU time and energy.

4.1.2 Time synchronization

Time synchronization consists of synchronizing the local clocks of all the members of a distributed network. In WSNs, it consists of synchronizing the clocks of all the motes in the network. Time synchronization is essential for all networked systems and is a requirement in most WSN applications and protocols. Example applications include environmental monitoring and target tracking among others. In these applications, the order of events is usually important. For example, in target tracking, sensors need to continuously report the location of a moving target, which could be time sensitive. Example protocols that require time synchronization are some MAC protocols (Demirkol et al., 2006) (such as the ones based on TDMA, where each node is assigned a time slot) in addition to several routing and security protocols.

In this section, we review the time synchronization algorithms proposed in the literature and analyze their power saving properties. In addition to being energy efficient, time synchronizations schemes for WSN need to be accurate and scalable.

When a packet is sent from node A to node B, node A can append a time stamp to the packet. Node B can then extract the time stamp from the packet, add the time it took the packet to travel from node A to node B (transmission time) in order to estimate its local clock's drift from node A. The packet delay consists of send time, access time, propagation time and receive time. Send time is the time interval between when the node issues the send command until the node is ready to send the packet.

The medium access times is the duration from when the node is ready to send until the time when the transmission starts. This is the step that makes time synchronization such a difficult problem. It is not possible to accurately estimate this time. The propagation time is the time it takes the packet to reach to the destination, and the receive time is the time it takes to receive the frame.

The Network Time Protocol (NTP) described in (NTP, n.d.), is the protocol that synchronizes the clocks in wired networked systems by estimating the roundtrip time of packets. It is the standard used on the Internet. NTP maintains a universal time (UTC) across the network. NTP is not suitable for WSNs because of its centralized nature and prohibitive cost. In fact

in NTP, clients synchronize their clocks to the server and servers are synchronized to using external time sources (using a GPS). NTP is not suitable for WSNs for a number of reasons. First, NTP is centralized. 2. In WSNs, it is impossible to accurately estimate the roundtrip time. 3. GPS is too expensive to use or is not an option for most WSN applications (for example, indoor applications will not have access to GPS signal).

Most time synchronization protocols are sender to receiver. The sender time stamps a packet and the receiver extract the time stamp and tries to extrapolate its clock drift compared to the sender (Romer, 2001), (Ganeriwal et al., 2003). However, the Reference Broadcast Scheme (RBS) (Elson et al., 2002) is different. It is a receiver-to-receiver synchronization protocol. In RBS, a sender broadcasts a beacon without any time information. The receivers then exchange Acknowledgement messages with the time they received the beacon. Receivers can then extrapolate their own clock drift relative to each other. RBS works with two receivers and is easily extended to more than two receivers. In addition, increasing the number of broadcasts increases the accuracy of the scheme. Note that in RBS, the uncertainty of access time is removed (since the sender is removed from the drift calculations) and since the propagation time is assumed to be negligible in WSNs, the only uncertainty factor and potential error margin in this protocol is the receive time.

The Timing sync Protocol for Sensor Networks (TPSN) (Romer, 2001), (Ganeriwal et al., 2003) is a sender-receiver protocol. In TPSN, the sender sends a packet to a receiver, which uses the TPSN equation to extract its local clock drift compared to the sender. TPSN then uses a tree hierarchy to propagate the synchronization, it categorizes the nodes in the network into levels during the discovery phase. During the synchronization phase, the root node (level 0) synchronizes all level 1 nodes. After this first phase of synchronization, level 1 nodes synchronize level 2 nodes and so on, until synchronization has been propagated through the entire network. TPSN achieves better accuracy than RBS when using MAC layer time stamps because RBS is limited by the transmission range and would require more beacons in order to perform synchronization.

In (Greunen & Rabaey, 2003), the authors claim that most sensor network applications do not require very precise synchronization. In fact, they claim that most applications only require synchronization in the order of a fraction of a second. The authors therefore propose a different approach where the required accuracy is taken as a constraint and then a synchronization algorithm with minimal complexity is devised so that the requested accuracy can be achieved. In this work, the synchronization is propagated in a centralized manner where a spanning tree is created and synchronization is conducted along the edges of the tree.

Centralized approaches to time synchronization are not energy efficient and often result in depleting the energy reserves of the root node. The authors in (Maroti et al., 2004) propose the Flooding Time Synchronization Protocol (FTSP). FTSP uses periodic flooding of synchronization messages. This approach makes the algorithm de-centralized, scalable and topology independent. In FTSP, the synchronization root is elected dynamically and re-elected periodically. The root is responsible for keeping the global time of the network. In this work, the nodes form a dynamic mesh like structure to propagate the time synchronization throughout the network (unlike TPSN). This work saves on the energy required to create an initial spanning tree (as in TPSN) and is therefore more energy efficient than TPSN. In addition, this protocol is not topology dependent and can perform synchronization even when

the topology of the network changes. However, the synchronization error in FTSP can grow exponentially with the size of the network (Lenzen et al., 2009).

Similar to FTP, the Novel Algorithm for Time Synchronization (NATS) is a decentralized time synchronization protocol. Unlike FTSP, NATS is a receiver-sender protocol because the receiver requests synchronization from the sender. This reduces the amount of messages exchanged for the purpose of time synchronization and therefore, reduces the amount of energy consumed during synchronization. NATS was designed at DePauw University by Peter Terlep [1], Steven Klaback [2] and Khadija Stewart. NATS does not need to meet any specific topology prerequisites, it can adjust to topology changes. It accomplishes the following: 1) it does not need a third party device that is within radio communication range of all motes, 2) it does not need any one mote to be within range of all motes, 3) it is scalable, 4) it allows for deep sleep between synchronization activities, 5) it handles receiver-side medium access control (MAC) buffer latency uncertainty, 6) it addresses the inability to acquire a real-time sender-side MAC timestamp, 7) and it uses a distributed energy efficient algorithm for multi-hop synchronization.

Pair-wise synchronization in NATS starts when the root node receives a sync request. The root then sends two consecutive packets to the requesting node, each containing a timestamp at the MAC layer. The receiving node uses these two packets along with its receive time stamp to extrapolate the propagation and channel access times. It uses that information to estimate its clock drift from the root node. Time synchronization is then propagated throughout the network in a distributed manner, similar to FTSP, by having each synched node act as a potential root node for synchronization. Experimental results show that NATS provides better synchronization accuracy than TPSN. In fact, using the Sun Spots platform, the Mean Sync Error for NATS was 1.74ms versus 2.63ms for TPSN.

The Gradient Time Synchronization Protocol (GTSP) is completely distributed (Sommer & Wattenhofer, 2009), where the nodes periodically broadcast synchronization beacons to their neighbors and agree on a common clock. It is proven that after multiple beacon exchanges, the clock of the nodes converges to a common value. This algorithm is completely distributed and nodes only exchange beacons locally. GTSP is proven to achieve better time synchronization accuracy as compared to tree-based methods.

In PulseSync (Lenzen et al., 2009), the root node floods a "pulse" through the network in a breadth-first search tree manner. The nodes receiving the pulse then compensate for the drift relative to the root node. The authors note that the flooding of the pulse needs to be scheduled in order to avoid collisions. This protocol is proven to be accurate when used in sensor network applications where the topology does not change. In fact, it is proven to outperform FTSP by a factor of 5 on mid-size networks.

The authors in (Li et al., 2011), propose a new direction in time synchronization where the Radio Data System (RDS) of FM radios is used to synchronize the nodes' clocks. In this work, each node is equipped with an FM receiver and programmed to receive the same RDS signal. The mote's clock then uses a calibration component to calibrate itself to the RDS clock. The drawbacks of this method stem from the fact that the FM interface is not power efficient and

---

[1] Peter Terlep is currenty a Ph.D student at Michigan University
[2] Steven Klaback is currently with Digital Knowledge

that not all WSN applications can have access to FM signals especially for the applications deployed in remote areas.

In summary, in order for a time synchronization protocol to be appropriate for a wide range of WSN application, it needs to accurately compute the clock drifts, be distributed, scalable, adapt to any topology and be able to propagate the synchronization instantaneously and without flooding the network.

4.2 Transport layer

The transport layer is mainly used to communicate with external networks (such as the Internet) and is therefore rarely implemented in sensor motes.

4.3 Network layer

The network layer is in charge of all routing functions. Routing is the function that is used the most in multi-hop WSNs. It is the routing algorithm that allows nodes that are more than a hop away to communicate with each other and form a connected network. Because routing is used extensively in most WSN applications, it is the function that should be the most power efficient. A variety of routing protocols have been proposed in the literature, some of which are designed to be 'power aware' and use the battery level or the network lifetime as a routing constraint. This Section reviews these works and studies the effect of clustering on power consumption.

Initially, research on routing algorithms focused on Mobile Ad hoc NETworks (MANETs). In these networks, the nodes were designed to be highly mobile, which resulted in the development of on-demand routing algorithms. These algorithms use flooding to compute routes (see the Reliable Ad-Hoc On-Demand Distance Vector Routing Protocol (RAODV) (Khurana et al., 2006), and the Ad hoc On-demand Multipath Distance Vector (Marina & Das, 2001) among others). The traditional flooding method consists of every node broadcasting the data to all its neighbors, the neighbors broadcasting the data to their neighbors etc... Ultimately, the sink will overhear the data. Flooding-based protocols suffer from several inefficiencies including overwhelming the network with unnecessary transmissions, excessive energy consumption, implosion, overlap, among others see (Heinzelman et al., 1999). Routing in MANETs is a tedious problem because of their dynamic nature. Adding power efficiency to the equation renders the problem even more tedious.

In (Mleki et al., 2002), the authors propose a reactive Power-aware Source Routing (PSR) protocol for MANETs. This protocol was based on the Dynamic Source Routing protocol (RFC4728, n.d.). PSR computes the cost of routes while taking into consideration both transmission power and remaining battery power. In PSR, the source broadcasts a message and intermediate nodes compute the path cost and add it to the header of the broadcast message. The destination then adds the least cost path to the reply and sends it back to the source. This solution fits the needs of MANETs but because of its broadcast nature, it is not suitable for the more resource constrained sensor networks. Since most sensor network applications require static sensors and are more resource constrained than MANETs, the routing solutions that were developed for MANETs are not suitable for the low power sensor networks. As a result, the Routing Over Low power and Lossy networks (ROLL) group was created as part of IETF in 2008 (Watteyne & Richichi, 2010) to help develop a standardized routing solution for sensor networks.

In (Watteyne & Richichi, 2010), the authors define a set of criteria that routing protocols must possess for routing in low-power and lossy networks. These criteria consist of satisfactory performance in: 1. Routing state. 2. Loss response. 3. Control cost. 4. Link cost. 5. Node cost. The authors then conclude that none of the mature IETF protocols, that were developed for MANETs, fulfill those requirements. The protocols examined in this work are: OSPF (RFC2328, n.d.), IS-IS (RFC1142, n.d.), OLSR (RFC3626, n.d.), OLSRv2 (draft-ietf-manet-olsrv2-12, n.d.), TBRPF (RFC3684, n.d.), RIP (RFC2453, n.d.), AODV (RFC3561, n.d.), DYMO (draft-ietf-manet-dymo-mib-04, n.d.), DSR (RFC4728, n.d.), IPv6 Neighbor Discovery (RFC4861, n.d.) and MANET-NHDP (draft-ietf-manet-nhdp-15, n.d.). In (Watteyne & Richichi, 2010), the authors suggest that a new protocol specification document needs to be created for routing in low-power and lossy networks. The discussion in (Watteyne & Richichi, 2010) was limited to mature and well documented IETF protocols, in the remaining of this section, we examine "energy aware" routing protocols designed for wireless sensor networks that have not been included in this review.

Routing algorithms with energy considerations aim to either minimize the energy consumption of the networks as a whole or increase the lifetime of the network. Protocols that attempt to minimize the energy consumption of the network usually compute and use the shortest paths in the network. As a consequence, a few select motes are usually overused and their energy reserve is depleted earlier than the rest of the motes. This could result in the network becoming partitioned and could therefore end its useful lifetime prematurely.

Most applications of WSNs are deployed in remote areas and are scheduled to monitor the area for long periods of time. In this case, extending the useful lifetime of the network is of at most importance. The concept of 'lifetime of the network' is difficult to define in WSNs (Dietrick & Dressler, 2009). For practical purposes, we define the useful lifetime of the network as: 'The total amount of time that the network is able to do useful work'. If for example the purpose of the network is to record sensor readings from ten different areas for as long as possible, the useful (operational or functional) lifetime of the network will be the total amount of time that at least one sensor is functional in each of the ten different areas and that there exists a path between each of those senors to the sink, i.e., those sensor motes are able to relay their readings to the sink. The useful lifetime of the network is therefore application specific and a uniform definition may not apply to all types of WSN applications.

The shortcomings of the broadcast-based protocols have led to the design of data-centric routing mechanisms. One of the earliest works on this type of protocols is SPINS (Heinzelman et al., 1999) where the data is named using high-level descriptors (meta-data). In this case, sensors exchange meta-data. The protocol relies on three types of messages: 1. ADV message, which is used to advertise particular meta-data, 2. REQ message used to request specific data, and 2. DATA message used to deliver the actual data. Spins achieves significant energy savings over traditional broadcast-based protocols (a factor of 3.5) and reduces the data redundancy in half. However, Spins does not guarantee the delivery of data to the requesting node, which makes this protocol unpractical for several applications of WSNs (Akkaya & Younis, 2003).

In data-centric routing algorithms, regions of sensors are queried to send their sensed readings to the sink. Because of the redundancy in sensors in each region, the data needs to be aggregated before it is forwarded to the sink. Several algorithms have been proposed to perform data aggregation to disregard the redundant information. Sensor Protocols for

Information via Negotiation (SPIN) (Kulik, 1999) was the first work to suggest eliminating redundant information to save energy. Later, a series of protocols that use directed diffusion were proposed (Intanagonwiwat et al., 2000), (Braginsky & Estin, 2002), (Schurgers & Srivastava, 2001), (Chu et al., 2002).

An important step in routing in wireless sensor networks was the creation of routing algorithms based on directed diffusion, the first introduction is described in (Intanagonwiwat et al., 2000). In directed diffusion, a node sends a query for some particular data (data here is identified using an attribute-value pair). As a result, data matching the query description is "drawn" towards the querying node. The data can be aggregated by intermediate nodes and all the communication is only neighbor-to-neighbor. These types of algorithms achieve significant energy savings over the traditional broadcast-based algorithms. Despite the energy saving properties of the directed diffusion algorithms, they are not suitable for all sensor network applications. Some sensor network applications require continuous data flow from the sensors to the sink, as a consequence, query based algorithms will not be suitable for such applications since the sink would need to continuously query each sensor for data (Akkaya & Younis, 2003).

An alternate way of relaying information in WSNs, other than flooding, is gossiping (Kyasanur et al., 2006). In gossiping, the source node selects a random neighbor and forwards the data to them. The process continues until the destination is reached or a maximum number of hops is achieved. Similar to flooding protocols, gossiping protocols also waste energy by sending messages by sensors that cover overlapping areas. In addition, gossiping algorithms can suffer from excessive delays because the next hop node is selected randomly.

An improvement to the traditional gossiping protocols is the location-based protocols. In these protocols, location information is used to direct the routing in order to reduce the number of transmissions and therefore save energy. One such protocol is SPEED (He et al., 2002). This protocol uses a combination of feedback control and non-deterministic geographic forwarding to provide real-time unicast, area-multicast and real-time area-anycast.

In (Li et al., 2001), the authors propose an energy saving routing scheme called the adaptive max-minzPmin scheme. This routing algorithm selects a route that maximizes the minimum residual energy as long as it consumes no more than zPmin energy (Pmin energy is he amount of energy consumed by the minimum-energy route). This algorithm also computes the minimum node lifetime of the network and adjusts its routing criterion accordingly. While this method is hard to implement (keeping track of the lifetime of the nodes in a central location), it is more practical for ad hoc networks than it is for sensor networks.

Another family of protocols is the hierarchical routing protocols. The main purpose of creating a hierarchy within a sensor network is to achieve scalability, i.e., the network performance should decrease slowly in response to an increase in the network size. The main form of hierarchical routing in WSNs is clustering, which consists of organizing the nodes into clusters where each cluster has a cluster head. The cluster head is then in charge of performing data aggregation or forward the packets on to the next hop. This leads to a smaller amount of data being transmitted to the sink, which intrinsically saves energy.

One of the first clustering protocols, LEACH is described in (Heinzelman et al., 2000). LEACH randomly rotates the head cluster in order to balance the energy consumption amongst the nodes in the cluster and uses data fusion in order to reduce the amount of data sent to the sink.

As a result, LEACH achieves significant energy savings compared to conventional routing protocols. Several other hierarchical protocols have been proposed in the literature who build up on LEACH such as TL-LEACH (Loscri et al., 2005) which proposes a two-level hierarchy to LEACH, EECS (Ye et al., 2006) where nodes compete for the position of cluster head, HEED (Yonis & Fahmy, 2004) where cluster heads are selected based on the distance between nodes, among others.

In (Iwanicki & Steen, 2009), the authors develop a framework to test the various hierarchical routing protocols proposed for WSNs. The authors state that hierarchical routing is a promising solution for the resource constrained WSNs and caution that the theoretical results presented in most hierarchical work can be very different from the results obtained using a more realistic framework. The proposed framework dismisses the idea of rotating the cluster head to save energy because this change complicates route computation by changing the routing addresses. The authors conclude that there is no one optimal hierarchical routing protocol for all WSN applications, rather protocols are application and requirement dependent.

In conclusion, there still exists the need to develop a low-frills, low-power, manageable and adaptable protocol for routing in the resource constrained sensor networks. The ROLL working group is still working on a requirement specification document. They may in fact, not be able to propose a single protocol for all or most WSN applications and could end up proposing or extending more than one protocol.

4.4 Medium access control layer

The main duties of sensor motes are communication, sensing and computing. Amongst these three tasks, communication consumes the most energy. It is therefore imperative to make sure that the communication task is as efficient as possible in order to prolong the energy lifetime of the motes. It is the data link layer that is responsible for establishing communication links between the motes, allowing the motes to share the wireless medium fairly and detecting/correcting transmission errors. Power considerations at the data link layer involve studying the hardware of the communication module (see Section 3) , the implementation of protocols such as the power management protocol and manipulating the power level of the transceiver.

The most energy waste occurs when a mote receives multiple frames at the same time. In this case all the frames that collide need to be discarded which results in wasted transmissions and receptions and increased latency. Other causes of energy waste are control packet overhead, overhearing unnecessary traffic and the long idle time in WSNs. In fact, in WSNs, idle listening consumes more than half the amount of energy required for reception (Ye et al., 2004). The Medium Access Control (MAC) layer is the sublayer of the data link layer that is responsible for handling the contention over the medium (in this case, the wireless medium). The main media access protocols used in wireless networks are Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), Carrier Sense Multiple Access (CSMA), Request To Send/Clear To Send (RTS/CTS) protocols, and the IEEE 802.11 protocol. The purpose of these schemes is to avoid channel contention. In the following, we review the most relevant MAC protocols that are proposed for use with wireless sensor networks. The channel contention scheme in these protocols is based on the above described contention

prevention mechanisms. In the rest of this Section, we study the main MAC layer protocols that are proposed in the literature and analyze their power-saving properties.

In this work, we consider energy efficiency to be the most important attribute in a MAC protocol. Other important attributes for a MAC protocol consist of providing fair and efficient access to the medium, scalability and adaptability to change.

Most ad hoc network and WSN applications require the network to be deployed for an extended period of time. During their deployment, the motes are programmed to sense the environment and relay sensor readings to the sink. Several MAC protocols have been proposed for these applications where the motes are periodically scheduled to be in a power-saving state (a sleep state or an off state) in order to save their battery power and extend their deployment lifetime, see (Singh & Raghavendra, 1998; Stewart & Tragoudas, 2007; Ye et al., 2004) among others.

PAMAS (Singh & Raghavendra, 1998) is a MAC protocol based on RTS/CTS. PAMAS schedules sleep intervals for sensor nodes to avoid overhearing and uses separate channels for data and control frames. In PAMAS, nodes probe their neighbors for transmission time in order to avoid collision as well. PAMAS reduces energy consumption by avoiding collision and transmission overhearing at the expense of increased hardware complexity, which in turn affects the power consumption.

The S-MAC (Ye et al., 2004) protocol reduces the energy consumption of the nodes by implementing the following mechanisms. First, it reduces idle listening by scheduling sleep intervals for nodes, in fact, S-MAC coordinates sleep intervals amongst neighboring nodes. Second, it divides long messages into smaller packets and transmits them back to back. As a result, nodes with longer messages occupy the wireless medium for longer periods of time. The authors show that this seemingly "unfair" advantage results in energy savings over traditional "fair" methods. Third, it implements a low-duty-cycle that reduces idle listening. Finally, it uses in-channel signaling to reduce overhearing by extending the work from PAMAS (Singh & Raghavendra, 1998).

S-MAC's mechanisms do reduce energy consumption at the expense of increased message latency. However, the predefined sleep intervals limit the flexibility of the protocol and the broadcast mechanism increases the probability for collision because S-MAC does not use RTS/CTS (Demirkol et al., 2006).

TMAC (Van & Langendoen, 2003) is similar to SMAC except that each node is equipped with a timer. In TMAC, a node is put on the low-power/sleep state if it does not transmit or receive for the entire duration of the timeout period. TMAC performs significantly better than S-MAC under variable load.

In WiseMAC (El-Hoiydi & Decotignie, 2004), the authors propose a downlink (to be used when the sink transmits packets to sensors). WiseMAC uses non-persistent CSMA (np-CSMA) with preamble sampling in order to decrease idle listening. In this case, a preamble is used to alert the receiving node that a data packet is on its way. The preamble precedes each data packets. All the nodes in the medium listen to the medium for a constant time interval referred to as the sampling period. If a node hears a transmission while it is listening to the medium, it will continue to listen until it receives a frame or until the medium becomes idle. The sink precedes each data frame with a preamble sequence that is equal to the sampling period. This guarantees that the receiving node will be able to detect the transmission. On the downside,

the long preamble sequence results in a low throughput and in increase power consumption. In addition, all the nodes within wireless range of the receiving node are able to hear the transmission. WiseMAC proposes an improvement to this where the sink takes advantage of knowing the sampling schedule of the nodes. The sink therefore, sends a smaller preamble and a frame right when the receiving node is scheduled to start sampling the medium.

WiseMAC suffers from two main drawbacks (Demirkol et al., 2006). The first drawback results from its decentralized sleep schedule where nodes wake up from their sleep cycle at different times. This is inefficient when broadcast communication is used because the broadcasted frames would need to be stored at the neighbors who are awake and end up being transmitted multiple times. The second drawback of the protocol is the fact that it is vulnerable to the hidden terminal problem where collision can happen at a node if it receives transmissions from two nodes that are not within transmission range of each other (Note that this is not a problem if WiseMAC is only used as a downlink protocol)

TRAMA (Rajendran et al., 2003) is a collision-free TDMA based MAC protocol for sensor networks. TRAMA ensures energy efficiency by avoiding collision during unicast, multicast and broadcast transmissions. In addition, in TRAMA, nodes can switch to a low-power state whenever they are not transmitting or receiving frames to save energy. In TRAMA, a node is elected to transmit within a two-hop neighborhood during each time slot. This mechanism avoids the hidden terminal problem.

TRAMA achieves significant energy savings due to: 1. the increased amount of low-power states, 2. the decreased amount of communication since the receiving nodes are indicated a priori, and 3. the significant decrease in collision probability. However, the latency when using TRAMA is longer compared to CSMA as a result of the high percentage of sleep time (Demirkol et al., 2006).

Berkeley MAC (B-MAC) (Polastre et al., 2004) is a low frills protocol based on clear channel assessment, it uses low power listening with preamble sampling. The default mode in B-MAC does not include a mechanism to avoid the hidden terminal problem, which could be implemented by higher layers if needed. B-MAC achieves significant energy savings when varying check time, by making the preamble constant and setting the sample rate. However, since the protocol is bare-bone, additional features would have to be implemented at higher layers when needed, which increases the complexity of the system as a whole.

Even though multiple MAC layer protocols provide adequate performance, no single protocol has been chosen as a standard. This is due to the fact that some protocols perform better than others for particular applications, communication pattern, network infrastructures and or network densities. An ideal energy efficient MAC layer protocol for WSNs would use a local schedule for motes to turn to the low-power/off state as a function of their residual energy as well as their sensing schedule. The schedule should aim to maximize the sleep time of the motes while preserving their sensing schedule, local connectivity and balancing their energy levels in order to increase the lifetime of the network as a whole.

4.4.1 Physical layer

Frequency detection, generation, modulation and coupling are the responsibility of the physical layer and are explained in detail in the hardware section. Note that when an engineer

is charged with designing a physical layer, propagation effects due to the ambient conditions must be considered.

5. Conclusion and future work

This chapter reviews the hardware architecture of wireless sensor motes, as well as their protocol stack focusing on power considerations at every level. We conclude that because of the diversity in WSN applications, it is very difficult to derive a universal power efficient architecture both in terms of hardware and software.

As far as the hardware components in WSNs, many advances have been made over the last few years. These improvements include more efficient apertures with better directivity and lower VSWR. The sensor element has been made to become more resolute while power management has improved due to the accessibility of more exotic materials for energy storage. The future holds near perfect antenna with nearly a 1:1 VSWR ensuring most of the energy leaving the system goes where it's designed to propagate. Researchers at Purdue University are working toward ensuring optical sensors are near perfectly efficient with negative refractive metamaterials and photon collection efforts.

In terms of the WSN protocol stack, no one protocol has been adopted as a WSN standard, rather each protocol is designed to efficiently serve one or more WSN applications. The power efficiency of protocols has become the number one constraint in almost every layer of the protocol stack. More work is needed to design and develop protocols that are less application specific and still power efficient.

6. References

Kemal Akkaya and Mohamed Younis, *A Survey on Routing Protocols for Wireless Sensor Networks*. Elsevier journal of Ad Hoc Networks, Volume 3, pages 325-349.

I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, *Wireless sensor networks: a survey*. Elsevier Computer Networks, Volume 38, pages 393-422, 2002.

ALERT, www.alertsystems.org

S. Basagni, M. Conti, S. Giordano, Iv. Stojmenovic, *Chapter 11: Energy-efficient Communication in ad hoc Wireless Networks*. Mobile ad hoc networking, Wiley-IEEE Press, 2004.

Bontempi, G., and Le Borgne, Y. (2005). *An adaptive modular approach to the mining of sensor network data*. In Workshop on Data Mining in Sensor Networks, SIAM SDM, Newport Beach, CA, USA, April.

D. Braginsky and D. Estin, *Rumor routing algorithm for sensor networks*. Proceedings of the first workshop on Sensor Networks and Applications (WSNA), Atlanta, GA, October 2002.

Wenshan Cai, and Vladmir Shalaev, *Optical Metamatrials: Fundamentals and Applications*. Springer, 2010.

M. Chu, H. Haussecker, and F. Zhao, *Scalable Information-Driven Sensor Querying and Routing for ad hoc Heterogeneous Sensor Networks*. The International Journal of High Performance Computing Applications, Vol. 16, No. 3, August 2002.

C. Coue, T. Franichard, P. Bessiere, and E. Mazer, *Multi-sensor data fusion using Bayesian programming: An automotive application*. Proceedings of the IEEE/RSJ International Coference on Intelligent Robots and Systems. Vol. 1, Lausanne, Switzerland, pages 141-146.

Crossbow Technologies, *http://www.xbow.com/*

Ilker Demirkol, Cem Ersoy, and Fatih Alagoz, *MAC Protocol for Wireless Sensor Networks: a Survey*. IEEE Communications Magazine, 2006.

A. P. Dempster, *A generalization of Bayesian inference*. J. Royal Stat. Soc., Series B 30, pages 205-247, 1968.

Isabel Dietrich and Falko Dressler, *On the lifetime of wireless sensor networks*. ACM Transactions on Sensor Networks, Vol. 5, No. 1, Article 5, February 2009.

Draft-IETF-MANET-DYMO-mib-04: http://tools.ietf.org/html/draft-ietf-manet-dymo-mib-04

Draft-IETF-MANET-NHDP-15: http://tools.ietf.org/html/draft-ietf-manet-nhdp-15

Draft-IETF-MANET-olsrv2-12: https://datatracker.ietf.org/doc/draft-ietf-manet-olsrv2/

A. El-Hoiydi and J.-D. Decotignie, *WiseMAC: An Ultra Low Power Protocol for the Downlink of Infrastructure Wireless Sensor Networks*. Proceedings of the Ninth IEEE Symposium on Computers and Communication, ISCCÕ04, pages 244-251, Alexandria, Egypt, June 2004.

E. H. Elhafsi, N. MItton, D. Simplot-Ryl, *End-to-End Energy Efficient Geographic Path Discovery With Guaranteed Delivery in Ad Hoc and Sensor Networks*. 19th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC). Cannes, France: IEEE, 15-18 Septembr 2008, pp. 1-5.

Jeremy Elson, Lewis Girod, and Deborah Estrin, *Fine-grained network time synchronization using reference broadcasts*. Proceedings of the ACM OSDI'02, Boston, MA, December 2002.

Mehdi Esnaashari and M.R. Meybodi. *Data Aggregation in Sensor Networks using Learning Automata*. Wireless Networks 20

S. Ganeriwal, R. Kumar, and M Srivastava, *Timing Sync Protocol for Sensor Networks*. Proceedings of the ACM SenSys'03, 2003.

J.V. Greunen, and J. Rabaey, *Lightweight Time Synchronization for Sensor Networks*. Proceedings of the 2nd ACM International Conference on Wireless Sensor Networks and Applications (WSNA'03), San Diego, CA, September 2003.

S. Grime, H.F. Durrant-Whyte, *Data fusion in decentralized sensor networks*. Control Eng. Practices, 2(5):849-63, 1994.

N. Guilar, A. Chen, T. Kleeburg, and R. Amirtharajah, *Integrated Solar Energy Harvesting and Storage*. Proceedings of the International Symposium of Low Power Electronics and Design (ISLPED'06), October 2006.

I. Gupta, D. Riordan, and S. Sampalli, *Cluster-head election using fuzzy logic for wireless sensor networks*. Proceedings of the 3rd Annual Communcation Networks and Services Research Conference (CNSR'05). IEEE, Halifax Canada, pages 255-260.

Tian He, John Stankovic, Chenyang Lu, and Tarek Abdelzaher, *SPEED: A Real-Time Routing Protocol for Sensor Networks*.

Heinzelman, W., Chandrakasan, A., and Balakrishnan, H. (2000). *Energy-efficient communication protocol for wireless microsensor networks*. In Proceedings of 33rd Hawaii International Conference on System Science (HICSS Ô00), January.

W.B. Heinzelman, A. P. Chandrakasan, and H. Blakrishnan, *An Application-Specific Protocol Architecture for Wireless Microsensor Neworks*. IEEE Transactions on Wireless Communications, vol. 1, no. 4, pp. 660-670, October 2002.

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 (MobiComÕ99), Seattle, WA, August 1999.

W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, *Energy-Efficient communication protocol for wireless sensor networks*. Proceedings of the Hawaii International Conference System Sciences, Hawaii, January 2000.

Fei Hu, and Xiaojun Cao, *Wireless Sensor Networks: Principles and Practice*. CRC Press, 2010.

C. Intanagonwiwat, R. Govindan and D. Estin, *Directed Diffusion: A scalable and robust communication pradigm for sensor networks*. Proceedings of the 6th annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiComÕ00), Boston, MA, August 2000.

Sandy Irani, Sandeep Shukla, and Rajesh Gupta, *Power Savings* . Proceedings of ACM Transactions on Algorithms, Vol. 3, No. 4, Article 41, November 2007.

Konard Iwanicki, and Maarten van Steen, *On Hierarchical Routing in Wireless Sensor Networks*. Proceedings of IPSN'09, April 13-16, 2009, San Francisco, California, USA.

R. E. Kalman, *A new approach to linear filtering and prediction problems*. Transactions. ASME J. Basic Engin. 82, pages 35-45, 1960.

Mauritus Morne, *Reliable Ad-hoc On-demand Distance Vector Routing Protocol*. Proceedings of the International Conference on Networking, International Conference on Systems and International Conference on Mobile Communications and Learning Technologies (ICNICONSMCL'06).

Joanna Kulik, Wendi Rabiner, Hari Balakrishnan, *Adaptive Protocols for Information Dissemination in Wireless Sensor Networks*. Proceedings of the 5th ACM/IEEE Mobicom Conference, Seattle, WA, August 1999.

P. Kyasanur, R. R. Choudhury, and I. Gupta. *Smart Gossip: An Adaptive Gossip-based Broadcasting Service for Sensor Networks*. Proceedings of MASS'06, 2006.

Andreas Lachenmann, Pedro Jos'e Marr'on, Matthias Gauger, Daniel Minder, Olga Saukh, and Kurt Rothermel, *Removing the Memory Limitations of Sensor Networks with Flash-Based Virtual Memory*. Proceedings of the 2nd ACM SIGOPS/EuroSys European Conference on Computer Systems 2007.

Xu, Y., Lee, W. C., Xu, J., and Mitchell, G. (2006). *Processing window queries in wireless sensor networks*. In IEEE International Conference on Data Engineering (ICDEÕ06), Atlanta, GA, April.

Christoph Lenzen, Philipp Sommer, and Roger Wattenhofer, *Optimal clock synchronization in network*. Proceedings of the the 7th ACM Conference on Embedded Networked Sensor Systems (SenSys'09).

Christoph Lenzen, Philipp Sommer and Roget Wattenhofer, *Optimal Clock Synchronization in Networks*. Proceedings of SensSysÕ09, November 4-9, 2009, Berkeley, CA, USA.

P. Levis, A. Tavakoli and S. Dawson-Haggerty, *Overview of Existing Routing Protocols for Low Power and Lossy Networks*. IETF ROLL, IETF draft, 14 February 2009, Draft-ietf-roll-protocols-survey-07.

Qun Li, Javed Aslam, and Daniela Rus, *Online power-aware routing in wireless ad-hoc networks*. Proceedings of the 7th Annual International Conference on Mobile Computing and Networking, 2001.

Liqun Li, Guoliang Xing, Limin Sun, Wei Huangfu, Ruogu Zhou, and Hongsong Zhu, *Exploiting FM Radio Data System for Adaptive Clock Calibration in Sensor Networks*. Proceedings of the ACM MobiSys'11, Washington DC, June 28, 2011.

Liu, C., Wu, K., and Pei, J. (2005). *A dynamic clustering and scheduling approach to energy saving in data collection from wireless sensor networks*. In Proceedings of the Second Annual

IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks (SECONÕ05), Santa Clara, California, USA, September.

V. Loscri, G. Morabito, and S. Marano, *A Two-Level Hierarchy for Low-Energy Adaptive Clustering Hierarchy*. Proceedings of the Vehicular Technology Conference (VTC'05), September 25-28, 2005.

Lotfinezhad, M., and Liang, B. (2004). *Effect of partially correlated data on clustering in wireless sensor networks*. In Proceedings of the IEEE International Conference on Sensor and Ad hoc Communications and Networks (SECON), Santa Clara, California, October.

Saoucene Mahfoudh, and Pascale Minet. *Energy-aware Routing in Wireless Ad Hoc and Sensor Networks*, Proceedings of the 6th International Wireless Communications and Mobile Computing Conference (IWCMCÕ10). June 2010.

Alan Mainwaring, Joseph Polastre, Robert Szewczyk, David Culler, and John Anderson. *Wireless Sensor Networks for Habitat Monitoring*. Proceedings of WSNA'02, September 28, 2002, Atlanta, Georgia.

M. Marina, and S. Das, *On-demand Multipath Distance Vector Routing in Ad Hoc Networks*. Proceedings of the 2001 IEEE International Conference on Network Protocols (ICNP), pages 14-23, IEEE Computer Society Press, 2001.

M. Maroti, B. Kusy, G. Simon, and A. Ledeczi, *The Flooding Time Synchronization Protocol*. Proceedings of the 2nd ACN Conference on Embedded Networked Sensor Systems (SenSys'04), Baltimore, Maryland, 2004, pages: 39-49.

Morteza Maleki, Karthik Dantu, and Massoud Pedram *Power-aware Source Routing Protocol for Mobile Ad Hoc Networks*. Proceedings of the ISLPED'02, August 12-14, 2002, Monterey, California, USA.

Eduardo Nakamura, and Alejandro Frery. *Information Fusion for Wireless Sensor Networks: Methods, Models, and Classifications*, Computing Surveys (CSUR), Volume 39, Issue 3, 2007.

Evgenii E. Narimanov, and Alexamder V. Kildishev, *Optical black hole: broadband omnidirectional light absorber*. Appl. Phys. Lett. 95, 041106 (2009).

NTP: http://www.ntp.org/

OLSR: RFC 3626

D. Petriovic, R. C. Shah, L. Ramchandran, and J. Rabaey, *Data funneling: Routing with aggregation and compression for wireless sensor networks*. Proceedings of the first IEEE International Workshop on Sensor Network Protocols and Applications (SNPA'03). IEEE, Anchrage, AK, pages 156-162.

Kris Pister, *Autonomous sensing and communication in a cubic millimeter*. Http://www-bsac.eecs.berkeley.edu/ pister/SmartDust/

Joseph Polastre, Jason Hill, and David Culler, *Versatile low power media access for wireless sensor networks*. Proceedings of SenSys'04, 2004.

Octavian Postolache, Pedro Silva Girao, and Jose Miguel Dias Pereira, *Non-Volatile Memory Interface Protocols for Smart Sensor Networks and Mobile Devices*. Data Storage, InTech publishers, April 2010.

V. Rajendran, K. Obraczka, J. J. Garcia-Luna-Aceves, *Energy-Efficient, Collision-Free Medium Access Control for Wireless Sensor Networks*. Proceedings of SenSysÕ03, November 5-7, 2003, Los Angeles, California, USA.

RFC 1142: http://tools.ietf.org/html/rfc1142

RFC 2328:http://www.ietf.org/rfc/rfc2328.txt

RFC 2453: http://tools.ietf.org/html/rfc2453

RFC 3561: http://www.ietf.org/rfc/rfc3561.txt

RFC 3626:http://www.ietf.org/rfc/rfc3626.txt

RFC 3684: http://www.ietf.org/rfc/rfc3684.txt

RFC 4728: http://www.ietf.org/rfc/rfc4728.txt

RFC 4861: http://tools.ietf.org/html/rfc4861

Kay Romer, *Time synchronization in ad hoc networks*. Proceedings of the ACM MobiHoc'01, Long Beach, CA October 2001.

Rosemark, R., and Lee, W. C. (2005). *Decentralizing query processing in sensor networks*. In The Second International Conference on Mobile and Ubiquitous Systems: Networking and Services (MobiquitousÕ05), San Diego, CA, July (pp. 270Ð280).

C. Schurgers and M.B. Srivastava, *Energy efficient routing in wireless sensor networks*. MILCOM Proceedings on Communications for Network-Centric Operations: Creating the Information Force, McLean, VA 2001.

G. Shafer, *A Mathematical Theory of Evidence*. Princelton University Press, Princeton, NJ 1976.

Vladimir M. Shalaev, Wenshan Cai, Uday K. Chettiar, Hsiao-Kuan Yuan, Andrey K. Sarychev, Vladimir P. Drachev, and Alexander V. Kildishev, *Negative index of refraction in optical metamaterials*. Optics Letters, Vol. 30, Issue 24, pages 3356-3358, 2005.

S. Singh and C.S. Raghavendra, *Power aware multi-access protocol with signaling for ad hoc networks*. ACM Computer Communication Review Vol. 28 No. 3 (July 1998) pages. 5-26

Philipp Sommer and, Roger Wattenhofer, *Gradient Clock Synchronization in Wireless Sensor Networks*. Proceedings of the International Conference on Information Processing in Sensor Networks, 2009.

Soro, S., and Heinzelman, W. (2005). *Prolonging the lifetime of wireless sensor networks via unequal clustering*. In Proceedings of the 5th International Workshop on Algorithms for Wireless, Mobile, Ad Hoc and Sensor Networks (IEEE WMAN Ô05), April.

K. Stewart, and S. Tragoudas, *Managing the power resources of sensor networks with performance considerations*. Computer Communications Journal, Volume 30, Number 5, pages:1122-1135, March 2007.

A. Tsymbal, S. Puuronen, and D. W. Patterson, *Ensemble feature selection with the simple Bayesian classification*. Information Fusion 4, 2, June, pages 87-100.

T. van Dam, and K. Langendoen, *An adaptive energy-efficient mac protocol for wireless sensor networks*. Proceedings of the First ACM Conference on Embedded Networked Sensor Systems, November 2003.

Natalia Vassileva, Francisco Barcelo-Arroyo, *A Survey of Routing Protocols for Maximizing the Lifetime of Ad Hoc Wireless Networks*. International Journal of Software Engineering and its Applications, Vol. 2, No. 3, July 2008.

Virrankoski, R., and Savvides, A. (2005). *TASC: Topology adaptive spatial clustering for sensor networks*. In Second IEEE International Conference on Mobile Ad Hoc and Sensor systems, Washington, DC, November.

Thomas Watteyne, Maria Grazia Richichi, *From MANET to IETF ROLL Standardization: A Paradigm Shift in WSN Routing Protocols*, submitted to IEEE Communications Surveys and Tutorials.

Jon Wilson, *Sensor Technology Handbook*. Elsevier, ISBN: 0-7506-7729-5, December 2004.

Winter, J., Xu, Y., and Lee, W. C. (2005). *Energy efficient processing of K nearest neighbor queries in location-aware sensor networks*. In The Second International Conference on Mobile and

Ubiquitous Systems: Networking and Services (MobiquitousÕ05), San Diego, CA, July (pp. 281Ð292).

L. Xiao, S. Boyd, and S. Lall, *A scheme for robust distributed sensor fusion based on average consensus*. Proceedings of the 4th International Symposium on Information Processin in Sensor Networks (IPSN'05), pages 63-70, 2005.

Z. Xiong, A. D Liveris, and S. Cheng, *Distributed source coding for sensor networks*. Proceedings of IEEE Sig. Proc. Mag. 21, 5, September 2004, pages 80-94.

M. Ye, C. Li, G. Chen, and J. Wu, EECS: *An Energy Efficient Clustering Scheme in Wireless Sensor Networks*. Ad Hoc and Sensor Wireless Networks, Vol. 3, Pages 99-119, April 2006.

W. Ye, J. Heidemann, D. Estrin, *Medium Access Control With Coordinated Adaptive Sleeping for Wireless Sensor Networks*. IEEE/ACM Transactions on Networking, Volume 12, Issue: 3, Pages: 493-506, June 2004.

Zhenzhen Ye, Alhussein Abouzed, and Jing Ai. *Optimal Stochastic Policies for Distributed Data Aggregation in Wireless Sensor Networks*, IEEE/ACM Transactions on Networking, VOL. 17, NO. 5, October 2009.

O. Younis and S. Fahmy, *HEED: A Hybrid Energy-Efficient Distributed Clustering Approach for Ad Hoc Sensor Networks* IEEE Transactions on Mobile Computing, vol. 3, no. 4, Oct-Dec 2004.

Younis, O., and Fahmy, S. (2005). *An experimental study of routing and data aggregation in sensor networks*. In Proceedings of theInternational Workshop on Localized Communication and Topology Protocols for Ad hoc Networks (LOCAN), held in conjunction with The 2nd IEEE International Conference on Mobile Ad Hoc and Sensor Systems (MASS-2005), November.
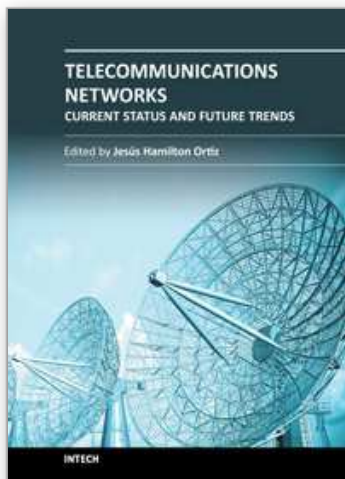
Telecommunications Networks - Current Status and Future Trends

Edited by Dr. Jesús Ortiz

This book guides readers through the basics of rapidly emerging networks to more advanced concepts and future expectations of Telecommunications Networks. It identifies and examines the most pressing research issues in Telecommunications and it contains chapters written by leading researchers, academics and industry professionals. Telecommunications Networks - Current Status and Future Trends covers surveys of recent publications that investigate key areas of interest such as: IMS, eTOM, 3G/4G, optimization problems, modeling, simulation, quality of service, etc. This book, that is suitable for both PhD and master students, is organized into six sections: New Generation Networks, Quality of Services, Sensor Networks, Telecommunications, Traffic Engineering and Routing.

INTECH
open science | open minds