Wireless Sensor Network Energy Conversation Techniques

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Contents

Chapter 1

Introduction to Wireless Sensor Networks

1.1 General Overview

Wireless sensor networks (WSN), which combine advanced sensing and networking techniques, are becoming increasingly more prominent in all fields of today's technology. Just to name a few major applications, wireless sensor networks can be seen in the medical industry, agriculture, the military, and, more recently, in consumer-based applications [1, 2]. For example, the military could take advantage of a WSN for the surveillance of unknown regions [1], while the agriculture industry could take advantage of a WSN that monitors the soil hydration levels in order to optimize watering [3].

A short list [4] of the major fields that wireless sensor networks are involved in, including some of their applications, are listed below. Keep in mind that each of the fields have hundreds more applications for wireless sensor networks than simply what is listed below. After reading the list, this should spark the imagination of the reader to come up with his or her own application ideas.

- Weather, Environment, and Agriculture
  - tracking important weather phenomenon over a region
  - monitoring important environmental parameters
  - tracking and measurement of animal herds
  - tracking soil hydration for sprinkler control
- Factories, Facilities, Buildings, and Homes
  - industrial automation
  - manufacturing and process control
  - heating, ventilation, and air conditioning control for energy savings
- Transportation Systems and Vehicles
  - smart highways with computerized traffic routing
  - smart vehicles with advanced sensing capabilities
  - autonomous vehicles for transportation and housekeeping use
- Safety, Health, and Medical
  - monitoring hazardous working conditions
  - monitoring living conditions
  - monitoring health patients and the elderly
- Security, Crisis Response, and Military Operations

  - surveillance
  - ensuring the integrity of imports and exports
  - fire or flood monitoring
  - unattended ground sensors on the battlefield

- Infrastructure and Other Applications
  - monitoring transportation
  - monitoring water, oil, and electrical power distribution systems
  - monitoring warehouses' and distribution facilities' product inventories via RFID tags

A general wireless sensor network [1], see Figure 1.1, is composed of a various number of sensors, or nodes, distributed throughout an environment or area of interest that will be studied and monitored. The number of nodes distributed throughout the area of interest [5, 1] depends on the application of the WSN, which can range from two nodes all the way up to millions of nodes having node densities as high as 20 $nodes/m^3$ [6]. The hardware composition of a wireless sensor node will be discussed in more detail in Section 1.2.1. In all wireless sensor networks, nodes are distributed either randomly or they are strategically placed by either a human or a robot [7]. One common way to randomly distribute nodes is via an aircraft flying over an environment of interest while dropping the sensor nodes into place.

After all of the sensor nodes are in place in the area of interest, they *must* be able to configure themselves [1] into a network in order to carry

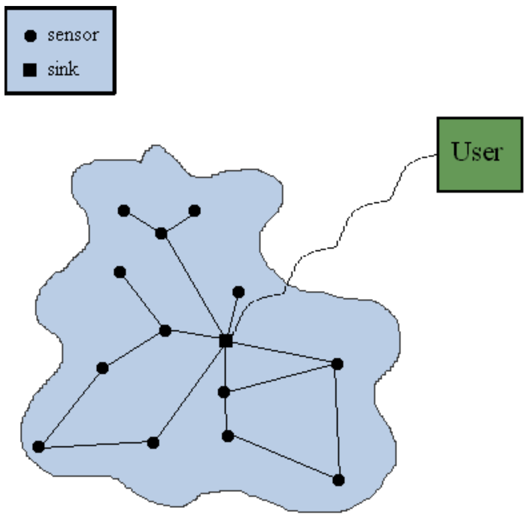


Figure 1.1: A general wireless sensor network.

out their overall task of being a wireless sensor network. A discussion of the major networking algorithms and techniques will be presented in Chapter 2. Once all of the sensors have self-configured into a functioning network, the WSN may then begin to carry out its overall task of sensing and monitoring the environment of interest. Depending on the wireless sensor network's application, the sensing frequency could be as low as months to years or as short as seconds. Most importantly, sensor information must be collected periodically throughout the life of the WSN in one of two ways. Either the sensor nodes may send all of their collected data to a sink or the information can be collected directly at the sensor nodes [7]. A sink [8] is a specialized type of node, such as a satellite or a long range laser communication device, that contains much more computing power and memory than a standard node in order to handle and transfer all of the information it receives to the user(s) of the WSN [8]. Once data is collected by one of the two methods mentioned above, the data can then be processed and used accordingly depending on the WSN's application.

Also, depending on the wireless sensor network's application, it may be necessary for information to be routed to a particular node such that the communication between sensor nodes becomes two-way. An example of the two-way communication feature is most common in wireless sensor network security systems. Say that some node A can sense intruders as well as some node B, which is one mile away. However, say that node B also has the capability to operate the locking mechanism of a door. If node A sensed an intruder, it would have to send that information to node B so that it could lock the door and stop the intruder. Keep in mind that data collection of these two nodes would be important for analysis of the intruder rate, analysis of false alarms for the WSN, etc.

Lastly, a wireless sensor network *must* be adaptable once it is set up. Due to the fact that most wireless sensor networks are completely autonomous, a WSN may have to reconfigure itself to keep the network optimized in case of a loss of node(s), a change in the environment, or even a change of the application for a wireless sensor network. For example, during the spring and summer months, a WSN may need to monitor humidity with respect to the temperature, while during the fall and winter, the WSN may need to monitor the temperature with respect to overall wind velocity.

1.2 The sensor network protocol stack and sensor node hardware

The wireless sensor network protocol stack [1], which can be seen in Figure 1.2, describes the required tasks of a node in order for it to be part

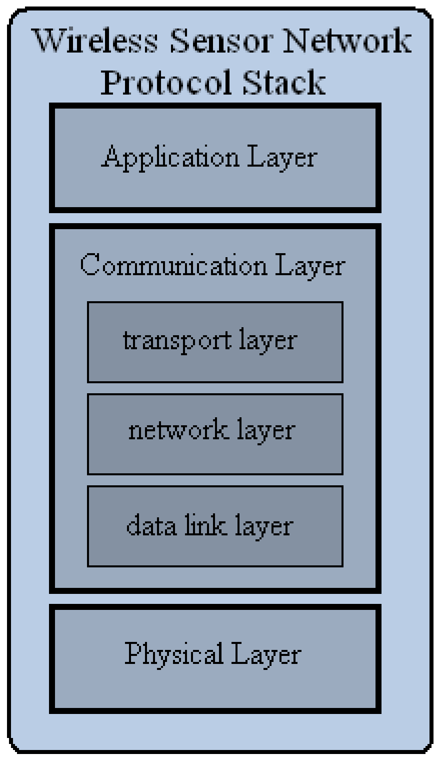


Figure 1.2: The wireless sensor network protocol stack.

of a wireless sensor network. The wireless sensor network protocol stack consists of five layers including the physical layer, data link layer, network layer, transport layer, and application layer as well as the important power management plane. For the remainder of this thesis, the data link layer, the network layer, and the transport layer will be defined as the communication layer. Notice that the power management plane intersects all the protocol layers. When designing a wireless sensor network, the power management plane must be taken into account and must be modified according to the wireless sensor network's application. Each of the five layers will be discussed in detail in the following subsections and an even further and more in depth analysis of the communication stack will be presented in Chapter 2. But first, the major hardware components of a basic wireless sensor node are examined in detail in order to develop a better overall picture of wireless sensor nodes.

1.2.1 Hardware of a sensor node

A basic wireless sensor node consists of four major components [1] which include a power supply, a processor, a transceiver, and at least one sensor. Figure 1.3 illustrates all of these components in a simple block diagram showing how they interact with each other. Note the three other minor components – a location finding system, a mobilizer, and a power generator. These components are very specialized and a sensor node may or may not need to make use of them depending its application. Almost all sensors used in wireless sensor network applications are relatively small [1]. Figure 1.4 [9, 10, 11] shows a variety of wireless sensor nodes to develop an idea of their current size. Notice how small the smart dust [11], is in size relative to the other sensors. In some cases, WSN developers would like to eventually decrease sensors to the size of a nanomachine [11].

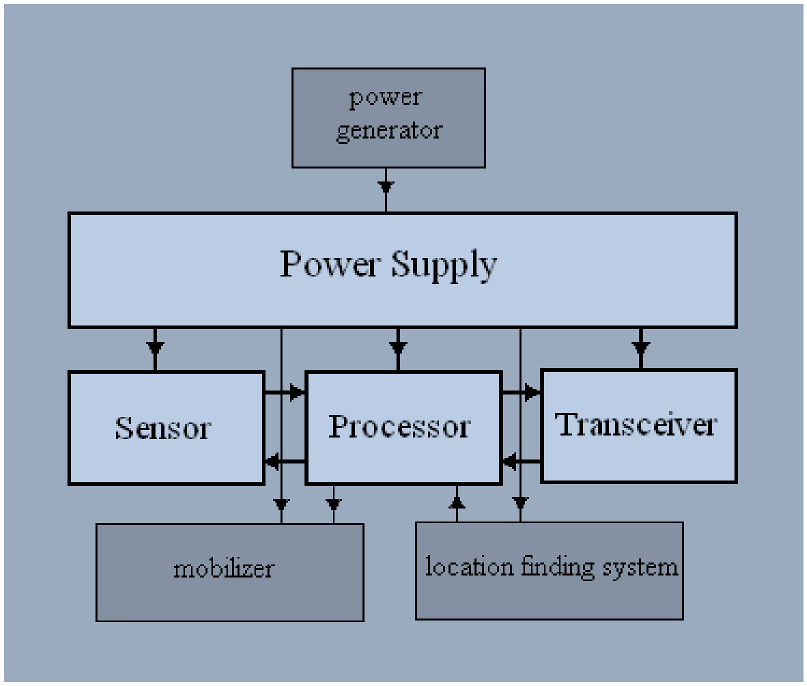


Figure 1.3: A general wireless sensor node.

The power supply is one of the most important components [1] of a sensor node because without power, a node or a collection of nodes will not be able to operate and can render an entire wireless sensor network completely useless. Because energy consumption of WSNs and their nodes is a research topic in and of itself, Chapter 3 is devoted entirely to this subject and is also the major focus of this research. In order for nodes to communicate with each other and their corresponding sinks and collectors, i.e. to create a wireless network, a transceiver unit is another important component of a wireless sensor node. Not having a transceiver in a sensor node would completely defeat the purpose of creating a wireless sensor node for a WSN.

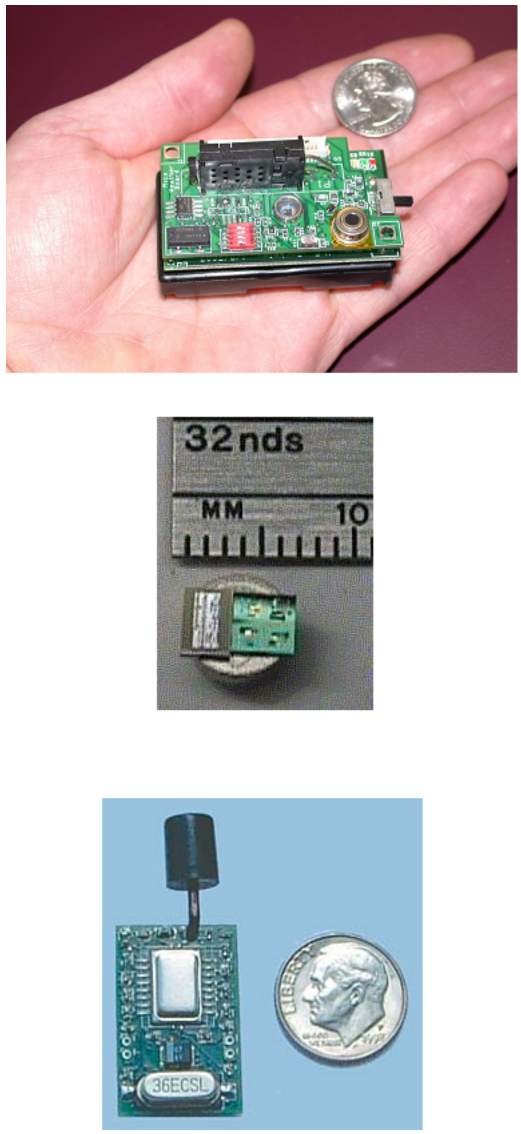


Figure 1.4: [9, 10, 11] A few various types of nodes.

The processing unit of a sensor node must be fast enough and have the right size memory on board in order to coordinate all the tasks that will incorporate the sensor node into the overall network. Lastly, the sensor, or sensors, must be chosen appropriately to suit the needs of the wireless sensor network application.

Depending on the wireless sensor network's application, specialized components, such as the minor components shown in Figure 1.3, may need to be added onto a basic sensor in order for the node to function properly in the WSN. For example, if a wireless sensor network needed to reconfigure and move about quite frequently, i.e. to be a mobile wireless sensor network [12, 13], fixed sensor nodes would not fit the application at hand. Therefore, a mobilizer such as wheels or another means of transportation [14] must be added onto the sensor node in order for it to function properly. Other devices, such as GPS units [15] or power generators [16], may also be added to a wireless sensor node in order to suit the need of the application for the WSN.

Keep in mind that, depending on the WSN application, a sensor may not need all of the components mentioned in this section. If a wireless sensor network required some nodes to take care of routing, then a router node [17] may be implemented by using the major components listed above minus the sensors. An analysis of the energy consumption used to implement a wireless sensor network consisting of sink nodes, sensor nodes, and router nodes is the major topic of discussion in Chapter 4. This type of wireless sensor network that takes advantage of different types of sensors is known as a heterogenous wireless sensor network [18].

1.2.2 Physical layer

The physical layer of the five layer protocol stack is responsible for handling the wireless communications [1] between sensor nodes in a wireless sensor network. The communication aspect of a wireless sensor network not only covers the communications between nodes via radio frequency, usually in the industrial, scientific, and medical (ISM) band, or with other means, such as optical communications [19], but it must also handle any necessary and important encryption techniques [20]. The power management plane plays a very important role in the physical layer because power must be regulated in such a way that the physical communication requirements do not consume all the power resources. Otherwise, a wireless sensor network may be extremely short-lived or may not even be alive after its initial setup in the environment of interest.

1.2.3 Data link layer

The next layer in the five layer wireless sensor network protocol stack is the data link layer. This layer handles the connectivity [1] of the wireless sensor nodes to each other in order to form an operating wireless sensor network. A detailed discussion of the various techniques and algorithms currently used will be presented in Chapter 2. The data link layer is the layer which is responsible for setting up or reconfiguring, if needed, the wirelesssensor network. One major power management problem that occurs in this layer is that sometimes an algorithm will use all the power resources *just* to set up the network. If this is the case and the WSN only gets to this stage, then the WSN is entirely useless.

1.2.4 Network layer

The network layer in the five layer wireless sensor network protocol stack is responsible for the data paths, or routing, of information throughout the entire wireless sensor network [1]. It must also take the responsibility of maintaining a proper network. These routing paths must be energy efficient in order for the wireless sensor network to last a reasonable amount of time. Keep in mind that this layer slightly overlaps with the data link layer and a detailed discussion of the various techniques and algorithms currently used will be given in detail in Chapter 2.

1.2.5 Transport layer

One of the most important layers in the five layer protocol stack is the transport layer. Without it, humans or the central processing machine, (not to be confused with a CPU), for the wireless sensor network would not be able to receive the data [1] picked up by the wireless sensors and to make sense of it. If there is more than one wireless sensor network or different types of networks in any given environment of interest, the transport layer is important for relaying information between two wireless sensor networks or between a wireless sensor network and other networks.

1.2.6 Application layer

The application layer defines the characteristics needed for a wireless sensor node to properly function in the area of interest and for it to correctly work together with the other sensor nodes which will form the wireless sensor network. There are literally thousands, and possibly an endless amount, of applications for a wireless sensor network. The applications that were listed in Section 1.1 are only a minute fraction of all the possible applications for a wireless sensor network. If wireless sensor networks are a long-term technology, then this implies that the research areas for WSN applications will continue to grow over time. When designing a wireless sensor network to study a particular environment of interest, the nodes *must* be chosen accordingly to suite the WSN application. Hence, a general wireless sensor node may not work efficiently, or not even work at all, in any given WSN.

1.3 Conclusions

In this chapter, an introductory presentation of general wireless sensor networks was given. After presenting a few applications in which wireless sensor networks are involved in, the basic functioning of a wireless sensor network was discussed. This was followed by a discussion of the major and minor hardware requirements for a wireless sensor node as well as presenting the wireless sensor network protocol stack. In the next chapter, the data link layer, the network layer, and the transport layer, from the wireless sensor network protocol stack, will be discussed in terms of the current networking algorithms and techniques used for wireless sensor networks.

This discussion will be important for understanding the energy conservation techniques of Chapter 3, since the networking algorithms and techniques are highly correlated with the overall energy consumption in a wireless sensor network.

Chapter 2

Networking Algorithms and Techniques

2.1 Introduction

This chapter presents some of the more important networking algorithms and techniques used for creating a wireless sensor network. There are numerous networking algorithms [1] used in wireless sensor networks which, in most cases, are geared toward specific WSN applications. Networking is one of *the* most important features of a wireless sensor network because it allows the nodes of the WSN to communicate with each other and it also enables the information sensed by the nodes to be transferred to other networks and computers where human interaction or data computation is needed. There are two distinct types of communication patterns in a wireless sensor network. One pattern called convergecast [21] which aggregates a few messages together and then sends off the compound message to the sink. This is quite commonly used in monitoring applications where messages need to be periodically sent. The second communication pattern is known as local gossip where nodes around a general vicinity collectively average out their readings in order to produce more accurate data [21]. Recall that wireless sensor networking is also highly correlated to the energy consumption of a WSN. Therefore, a thorough understanding of the major networking algorithms and techniques is very important for understanding the energy consumption of a WSN.

In the five layer protocol stack of a wireless sensor network [1], see Figure 1.2, the networking algorithms and techniques span three important layers, defined as the communication layer in Chapter 1, which include the data link layer, the network layer, and the transport layer. Each layer will be presented individually in the following sections with a discussion of the algorithms that fit into that particular layer. The data link layer, which is responsible for setting up the network, will be discussed first, followed by a discussion of the network layer, which handles the data paths in a wireless sensor network. Then, there will be a brief discussion of the transport layer, which takes care of the interaction between a WSN with other wireless senor networks and other networks along with handling the congestion control and data loss recovery algorithms [1, 22].

2.2 The data link layer

Recall that the data link layer in the five layer wireless sensor network protocol stack takes care of the connectivity [1] of the wireless sensor nodes in order to form a functioning wireless sensor network. The two most important tasks performed in the data link layer are the medium access control (MAC) and the error control, which can be embedded in the MAC. The MAC takes on the responsibility of regulating the access to the wireless medium [21], which is the the radio channel(s) in most WSN applications, and setting up the wireless sensor network, while the error control handles the error correction algorithms for the transmission of data [1]. Some of the minor, but important, protocols also embedded in the MAC include the multiplexing of data streams as well as data frame detection [21]. The multiplexing of data refers to sending multiple sets of data on a single carrier frequency at one time [23]. Some of the multiplexing methods include carrier division multiple access (CDMA), frequency division multiple access (FDMA), and time division multiple access (TDMA) as well as many other schemes [23]. TDMA is a very important multiplexing technique used in wireless sensor networks and will be further discussed. Data frame detection is simply the detection and the synchronization of a transmitted data signal to its corresponding receiver [24].

2.2.1 Medium access control

In a wireless sensor network, the medium access control (MAC), operating on a local scale, must take care of the creation of the wireless sensor network as well as managing the communication resources [21], throughout the wireless sensor network [1]. Since networking techniques have been around since the 1970s, see [25], why can't these techniques be applied to present day wireless sensor networks? Well, the bottom line is that power consumption was only a secondary consideration, or never considered at all, when creating the networking algorithms [1]. This is due to the assumption that a computer or a device would always have access to a power source or a user would be able to replace the devices' batteries.

In a wireless sensor network, this is definitely not the case. Sometimes, a wireless sensor network must operate for *years* at a time [21] with no means of recharging or replacing the batteries in each and every sensor node. Also, since there is the possibility that a WSN would have nodes on the order of thousands [1], it would just take way too much time to individually replace each node's batteries to make it a feasible option. Because of the high energy constraints, when designing a MAC protocol for a wireless sensor network, the latency, throughput, and fairness of the WSN may not be optimized so data rates are very low and can be on the order of one to two-hundred bytes per second [21]. However, recharging the batteries of a wireless sensor node is definitely a possibility in certain types of wireless sensor networks. This will be discussed in more detail in Chapter 3.

Reference [21] surveys twenty wireless sensor MAC protocols and reveals that there are three major important design considerations when building a MAC for a WSN. They are [21]

1. the type and amount of physical channels used
2. the freedom or organization of the individual nodes
3. how a node knows when to receive a message

Currently there is no unique solution [21] for creating a wireless sensor MAC protocol. This implies that more simulations and actual implementations of wireless sensor networks are needed to help evolve a WSN MAC protocol toward an ideal solution or, possibly, solutions. However, most all wireless sensor MAC protocols use a single or a double radio channel scheme. When using a second radio in the MAC protocol, this radio is used to emit a very low energy and a very simple wake up tone. The organization of the nodes can fall under three categories. There is a contention-based MAC protocol in which nodes must contend for a channel or have random access to the channel. Secondly, there are fame-based TDMA MAC protcols which regulate the access to the medium by assigning nodes when and how long they can have the channel. And finally, there are hybrid algorithms of the two mentioned MAC protocols known as slotted protocols. The final classification is node notification which can take on listening, wakeup, or a schedule based scheme. Scheduled based protocols are used in conjunction with the frame-based TDMA MAC protocols while listening based and wakeup based protocols are used with contention-based protocols [21].

Some of the major draw backs in a contention-based protocol is that there is a lot of energy wasted due to collisions, overhearing, and idle-listening [21]. Collisions occur when there is interference between two nodes' transmission signals. Overhearing occurs when a node receives information not intended for it. And idle listening is when a node has to keep its receiver on since it does not know when its next message will arrive. On the other hand, TDMA-based protocols can be collision-free and any forms of idle listening usually do not exist [21]. However, in a wireless sensor network, it is muchmore difficult to incorporate new nodes, mobile nodes, or restructure the network due to any node failures. The hybrid slotted protocols try to find a middle ground between the contention-based protocols and the TDMA-based protocol.

Contention-based protocols

- Carrier Sense Multiple Access (CSMA) [26]
  - If a node listens to the channel and there is not any traffic then a packet is sent.
- Medium Access with Collision Avoidance (MACA) protocol [27]
  - A node will send a Request-To-Send (RTS) packet to its corresponding receiver node. The receiver node will send back a Clear-To-Send (CTS) packet if the channel is free.
  - This avoids the hidden terminal problem associated with the CSMA algorithm.
    - The hidden terminal problem occurs when two nodes transfer data to a common node but are separated far enough apart where they cannot detect each other's signal. This separation results in the two nodes always thinking the channel clear when in fact it might not be, which then causes network collisions [23].

- MACA Wireless (MACAW) [28]
  - Built off of MACA with an additional ACKnowledgement packet that the receiver sends back to the transmitter node to ensure proper delivery of the information.
- IEEE standard 802.11 MAC protocol [29]
  - Based upon CSMA and collision detection through acknowledgments.
  - A sender checks the channel to see if it free during a time period called the Distributed Inter Frame Space (DIFS). The receiver node then wait a time period called the Short Inter Frame Space (SIFS), which is shorter than a DIFS, before sending the CTS message back to a sender. Next, the sender nodes waits one SIFS and sends the data while the receiver node waits a SIFS before sending the ACK and then waits a DIFS to see if any other nodes wants to send information.
  - Receiver nodes takes precedence of the channel over any other node.
- Low Power Listening and Preamble Sampling [30, 31]
  - A receiver node's radio is cycled on and off for a chosen duty cycle, usually relatively very low. If the receiver picks up a preamble packet, which signals the receiver that a message is coming, then

the receiver's radio will stay on and receive the incoming message.

- There is no collision avoidance.

- WiseMAC [32]

    - Based upon low power listening and preamble sampling.

    - The sender simply waits until it knows when the receiver's channel is on and goes ahead and sends the packet of information.

    - Not very effective for broadcasting messages since the preamble must be increased to account for any clock drift of all the receiving nodes.

- IEEE standard 802.15.4 MAC protocol [33]

    - Based off of a slotted access MACA algorithm which is optimized for low power consumption and low data rates.

Slotted protocols

- Sensor-MAC (SMAC) [34]

    - The nodes of the WSN are first clustered. Then every node regularly sends out a SYNChronization packet at the beginning of a slot. Afterwards every node remains active and then sleeps for a certain period of time.

    - Allows new nodes to join the ad-hoc network.

- Timeout-MAC [35]
    - Based upon SMAC.
    - Uses an adaptive duty cycle which gets rid of the need for pre-programming a duty cycle and allows the network to adapt to traffic fluctuations.
- Data-gathering MAC (DMAC) [36]
    - Staggers the duty cycles of the receive, send, and sleep patterns into a convergecast tree. While a child node is sending information, its parent node will be receiving the information and aggregating the data it receives with its own data. This process is continually repeated until all information arrives at the sink, which is the final parent of the convergecast tree.

TDMA-bases protocols

- Sink-based scheduling [37]
    - The network is partitioned into clusters.
    - Each cluster is then scheduled by the cluster head.
    - The schedule can adapt to changes.
    - The maximum number of nodes in a cluster must be known a priori.

- Static scheduling [38]
    - This protocol uses a fixed schedule for the entire network which removes the need of a scheduler in the network.
    - The node deployment must be deterministic in order for the protocol to work.
- Rotating duties [21]
    - The protocol uses clustering and rotates the cluster head.
- Partitioned scheduling [21]
    - Preset active nodes control a time slot, which is chosen by themselves, in order to allow global communication.
    - Preset passive nodes do not control time slots and can communicate with active nodes.
    - Supports node mobility.
    - Protocols include
        * EnergY Efficient Sensor (EYES) MAC (EMAC) protocol [39]
        * Lightweight Medium ACcess protocol (LMAC) [40]
- Replicated scheduling [41]
    - The scheduling process is replicated to every node in the network so that every node stores information about its one-hop neighbors and knows its two-hop neighbors. Then, collision-free slot assignments are based upon a distributed hash function created from the node information.

2.2.2 Error control

The error control embedded in the wireless sensor network MAC protocol handles the error correction algorithms to ensure reliable data transmission [1]. Research of this topic in wireless sensor networks is not the biggest area as can be seen with the lack of numerous papers compared to the research involved for designing MAC protocols. During the transmission of a bit or bytes, the receiver node may mistake a zero for a one or vice versa [42] and this needs to be handled correctly. Otherwise, serious consequences or errors may occur in the wireless sensor network. Presently, some of the simpler and less complex error correction codes such as forward error correction (FEC) and automatic repeat request (ARQ) [1] seem to be better suited for a wireless sensor network. If the correction algorithms are too complex, then too much time and resources are wasted at the computation end. Remember, a wireless sensor node is not going to have the computational power of a simple laptop or home desktop.

2.3 The network layer

The MAC protocols for wireless sensor networks took care of the local networking needs for the wireless sensor nodes [21]. Now, it is time to move up a layer in the wireless sensor network protocol stack and examine the networking layer, which takes care of the global networking [1]. Wireless sensor network algorithms and techniques are much different than present wireless networking for many reasons. First, and most importantly, wireless sensor nodes are very restricted in terms of there resources and have to be carefully managed. Second, it's not possible to use a global addressing scheme in wireless sensor networks due to the high amount of nodes that are deployed. Lastly, most every application of a wireless sensor network must send data from each of its node to a destined source which may induce a high level of network traffic along with a redundancy of data [43]. These design constraints must be considered when creating networking algorithms for wireless sensor networks. Networking techniques for wireless sensor networks can be grouped into four categories which include data-centric protocols, hierarchial based protocols, location based protocols, and network flow and QoS-aware protocols.

2.3.1 Data-centric protocols

Since the lack of global identifiers in a wireless sensor network, it is quite challenging to select a node or a particular group of nodes [43]. Hence, this creates a significant amount of redundancy in data and in turn wastes a considerable amount of resources. Therefore, data-centric networking algorithms usually take advantage of data aggregation [1]. Data aggregation reduces the number of transmissions by combining similar data packets from multiple nodes and then sending off only one set of data. This would also allow a sink node to transmit one message to a region of nodes and then receive one message back as opposed to several messages.

- Sensor Protocols for Information via Negotiation (SPIN) [44]
    - Uses a meta-data exchange before actual data is sent. A sensor would first advertise, ADV message, that is has a particular type

of data to its one-hop node or nodes. The one-hop node or nodes would then send back a request, REQ message, telling the other node that they need the data and then the actual data is sent.

  - Halves the redundant data transmissions.

- Directed Diffusion [45]

  - Uses a naming scheme of data. The sink will send out an interest for a particular named data throughout all of the nodes. The named interest is compared to the received data and if there is a match, the data is passed back and eventually returns to the sink while creating several paths.

  - Not efficient for continuous data delivery [43].

- Energy-aware routing

  - Variation of directed diffusion.

  - Increases the whole network lifetime by randomly choosing sub-optimal routing paths by means of a probability function.

  - If the minimum energy path was used the entire time, then this path would eventually die out.

- Rumor routing [46]

  - Variation of directed diffusion.

  - Rather than flooding the network, only route queries to any nodes that have made an observation.

  - Performs well with a small number of events.

- Gradient-based routing [47]
  - Based upon directed diffusion.
  - Flood the nodes with a query but store the number of hops it took to reach a node. Then the node can resend the data back using the shortest path.
- Constrained anisotropic diffusion routing (CADR) [48]
  - Tries to generalize directed diffusion.
  - Minimizes the latency and bandwidth while maximizing the amount of information.
- Information-Driven Sensor Querying (IDSQ) [48]
  - Based upon CADR and tries to maximize obtaining the most useful information.
- COUGAR [49]
  - Adds a query layer in between the network layer and application layer in the wireless sensor network protocol stack. The sensor nodes select a data aggregation, or leader, node which sends data to the sink. The sink nodes are in control of the query layer which describes data flow, in-network computation, and also leader selection.
  - Nodes need extra storage and require synchronization as well as dynamically maintaining leaders [43]

- ACtive QUery forwarding In sensoR Networks (ACQUIRE) [50]
  - Suited for complex queries containing sub-queries. Pre-cached information tries to answer a query and is forwarded to the sink by reverse order or the shortest path if it can answer correctly. If not, nodes try to update their cache with their n-hop neighbors – n ranges from one to a preset value and increases until the query can be answered.
- ZigBee [51]
  - Tries to standardize a network protocol for wireless sensor networks such that developers can focus on application development. (Uses the 802.15.4 PHY and MAC standard.)
  - Can support up to 65,535 nodes.

2.3.2 Hierarchical protocols

Because some wireless sensor networks have nodes ranging in the thousands [1], nodes within the same region can be grouped together into clusters [21]. Then nodes will aggregate their data together within a cluster and then a cluster head, basically the leader node of a cluster, will then pass on any information to the sink and vice versa [21].

- Low-Energy Adaptive Clustering Hierarchy (LEACH) [52]
  - The strength of a received signal of a given node determines the clustering. Cluster heads will act as routers to the sink.

- Power-Efficient GAthering in Sensor Information Systems (PEGASIS) [53]
  - Derived from LEACH.
  - Chains are formed between clusters in a such way that cluster heads can only transmit and receive data from their one-hop neighbor clusters heads. Also, data is aggregated at every cluster head so that eventually, only one cluster head will be able to communicate with the sink.
- Threshold sensitive Energy Efficient senor Network protocol (TEEN) [54]
  - Hierarchical approach along with using a data-centric mechanism.
  - The WSN is responsive to sudden changes by using two thresholds. A hard threshold triggers nodes to switch on and transmit data. A soft threshold triggers nodes to switch on again and transmit data once the value is equal to or greater than the hard threshold.
  - Not well suited for periodic data reports.
- Adaptive Threshold sensitive Energy Efficient sensor Network protocol (APTEEN) [55]
  - Extension of TEEN.
  - Reacts to time-critical events as well as capturing periodic data.

- Energy-aware routing for cluster-based sensor networks [56]
  - Allows wireless sensor nodes to change and either sense or relay information, sense and relay information, or be inactive.
- Self-organizing protocol [17]
  - Allows wireless sensor nodes to self organize. The wireless sensor nodes can either be strictly an immobile router node, a mobile or immobile sensor node, or be a sink node.

2.3.3 Location-based protocols

Location-based networking protocols can use the location of nodes to calculate the distance amongst themselves. This information can then be used to efficiently route data. Also, the sink can take advantage of this information, and for example, send data to a particular location in the wireless sensor network as opposed to flooding the information onto the network [21].

- Minimum Energy Communication Network (MECN) [57]
  - A sub-network is created between any two nodes which will find the least power transmission path while using the least number of nodes, thus eliminating the need to consider every node for a single path. This in turn finds all the global minimum power paths between nodes while saving computation costs.
  - This network dynamically adapts to the addition or the removal, failure, of sensors nodes in the network.

- Small Minimum Energy Communication Network (SMECN) [58]

    - An adaptation of MECN which includes the assumption that all nodes may not be able to communicate with each other due to obstacles between any two nodes.

- Geographic Adaptive Fidelity (GAF) [59]

    - The network forms a virtual grid in the environment of interest and if there is more than one node in the same region of the grid, only one node will remain active while the other nodes sleep. The sleeping nodes rotate between being the active node for the grid region in order to distribute energy resources and further increase the lifetime of the network.

    - This algorithm can also be considered a hierarchical-based protocol since node clusters are formed based on the geographic region. However, no data aggregation occurs [21].

- Geographic and Energy Aware Routing (GEAR) [60]

    - This network protocol is based upon GAP and directed diffusion where queries are sent to particular geographic regions.

2.3.4 Network flow and QoS-aware protocols

Network flow and QoS-aware protocols is the last set of protocols to be discussed in the network layer section. Network flow simply refers to the flow of data throughout the network and most of the algorithms using this technique try to regulate the flow of the wireless sensor network so that it is not too much or too little. QoS protocols try to set minimum and maximum standards for certain communication parameters such as delay or error rate [21].

- Maximum lifetime energy routing [61]
  - Maximizes the total time the network lasts by using two network flow cost functions. Namely, the remaining energy of a node and the energy used to complete a transmission. Then, shortest path algorithms can be applied to the above.
- Maximum lifetime data gathering [62]
  - The number of periodic data readings a sensor can take before it dies is defined. Then a scheduling algorithm specifies for each periodic data reading, or round, how to acquire and route the data from each node to the sink. The network lifetime depends on the scheduling lifetime which is maximized.
  - Network algorithms include
    - Maximum Lifetime Data Aggregation (MLDA).
      - Uses the above technique along with data aggregation.
    - Maximum Lifetime Data Routing (MLDR)
      - Uses the above technique along with a network flow technique with energy constraints on the nodes.
    - Clustering Maximum Lifetime Data Routing (CMLDR)
      - Uses MLDR along with a clustering based approach.

- Minimum cost forwarding [48]
  - Finds the minimum cost path using a cost function based upon the effect of delay, throughput, and energy consumption which is updated after each flow.
- Sequential Assignment Routing (SAR) [63]
  - This protocol creates a routing tree based upon the priority of a packet from a sensor, a QoS metric, and energy resources on each possible routing path. From the tree, one path is chosen according to the three above conditions.
  - This protocol has a large overhead of maintaining the routing tables and the states of each sensor.
- Energy-aware QoS routing protocol [43]
  - This protocol is an extension of the energy-aware routing for cluster-based sensor networks, see Section 2.3.2, which finds an energy efficient path that takes into account connection delay as well as using a cost function based upon a node's energy reserve, transmission energy, error rate, and other basic communication parameters.
- SPEED [64]
  - This is a QoS routing protocol that tries to ensure a certain speed, hence the name, of a packet routed throughout the network. Routing paths are accomplished by having the nodes store

information about its neighbors as well as using geographic information.

2.4 The transport layer

The final layer in the wireless sensor network protocol stack, which covers the networking algorithms and techniques, is the transport layer. The transport layer is responsible for the interaction between a wireless sensor network with other wireless senor networks and other external networks, such as the Internet, etc. [1]. In most all present wireless sensor networks, this global interaction of networks is usually taken care of at the sink node [22]. More importantly, the transport layer must also handle the congestion control algorithms as well as the data loss recovery algorithms. If congestion is not controlled, as well as guaranteeing the reliably of data, then this can lead to a drastic increase in energy consumption of the nodes and henceforth completely destroy a wireless sensor network. For example, if there is a lot of network congestion around the sink node, or sink nodes, the one or two-hop neighboring nodes must utilize much more of their energy reserves due to the amount of data flow going through them as compared to the data flow going through nodes which are several hops away from the sink. If these one and two-hop nodes deplete all of their energy and die out, then the nodes that are three or more hops away from the sink have no way to receive or transmit information and hence the wireless sensor network is rendered completely useless or dead.

So why can't any of the current transport protocols, such as TCP or

UDP, be utilized for a wireless sensor network? The basic answer is that current transport protocols do not take into account the energy consideration needs of a wireless sensor network. Designing an energy-aware transport protocol for a WSN can be accomplished by utilizing a congestion control and data reliability mechanism, guaranteeing a certain throughput and transmission delay, avoiding dropped packets, ensuring a fairness throughout the network, and finally, overlapping the transport control protocol with the data link and network layer so that the above energy saving design constraints can be optimized [22]. Furthermore, the current transport protocols for wireless sensor networks can be classified into four major types [22] including upstream congestion control, downstream congestion control, upstream reliability, and downstream reliability. Upstream refers to information flowing from a sensor to a sink and downstream refers to just the opposite. Some of the major transport protocols [22] can be summarized in Table 2.1 below. Some other important definitions that can be seen in

Table 2.1: Transport Protocols for WSNs

Name	**Direction**	**Congestion Detection**	**Reliability Support**
CODA	Upstream	Yes	None
SenTCP	Upstream	Yes	None
ESRT	Upstream	Passive	Application End-to-End
RMST	Upstream	No	Packet Hop-by-Hop
PSFQ	Downstream	No	Packet Hop-by-Hop
GARUDA	Downstream	No	Packet Hop-by-Hop

the table include end-to-end and hop-by-hop reliability [65]. End-to-end reliability refers to the reliability of data from, say, the starting node to the ending node, while hop-by-hop reliability ensures reliability of data at each hop in the network.

2.5 Conclusions

This chapter presented how the data link layer, the networking layer, and the transport layer all work individually and together to form the important and well needed networking algorithms and techniques used in wireless sensor networks. It should be noted that some of the wireless sensor network protocols not only cover one of the three overall networking layers but a combination of the layers. Setting up of the actual wireless sensor network takes place in the MAC protocol, while the the network layer handles the data paths of the network. Finally, the transport layer takes care of the interaction between a WSN with other wireless senor networks and other networks as well as handling the congestion control and data loss recovery algorithms [1, 22]. In all of the layers examined, the algorithms and techniques used for current networks could not be applied, or needed to be adapted, to a wireless sensor network because of the energy limitations of the wireless sensor network itself, which boils down to the energy constraints of the wireless sensor nodes. The energy limitations of a wireless sensor network is very closely tied into the networking algorithms and will be examined in the next chapter.

Chapter 3

Energy Conservation Techniques

3.1 Introduction

In the previous two chapters, a general overview of wireless sensor networks was presented followed by WSN networking algorithms and techniques. A basic overview of energy concepts and energy conservation techniques will be the topic of discussion for this chapter. As mentioned several times in Chapter 1 & 2, energy conservation must be taken into account for a wireless sensor network due to the nodes having an extremely limited supply of energy and the fact that they must be able to operate for up to years at a time [1]. Without the proper attention to conserve the energy of the nodes, an entire WSN may become completely useless, or dead, in only a short period of time. Therefore, energy conservation techniques must be applied throughout every layer in the WSN protocol stack in orderto conserve the maximum amount of energy [1]. First, basic energy concepts will be discussed followed by examining the five layer WSN protocol stack, from the bottom of the stack to the top, with the paradigm of energy conservation.

3.2 Basic energy concepts

So where does a node get all of its energy? Well, in order to keep the nodes autonomous, small, and cheap, batteries are the most common source of energy used [32]. Typically, a wireless sensor node will use either two double-A or two triple-A batteries or a coin-cell battery as can be seen in Figure 3.1. For analysis purposes, assume that all nodes use two double-A batteries. This assumption is used from this point forward. From [68], it states that on average, a typical alkaline long-life double-A battery has 9360 Joules of energy implying that a typical wireless sensor node would have about 18700 Joules of energy. Remember, this energy must be used wisely because it must last the *entire* lifetime of the wireless sensor network [1].

All of the energy dissipation of a wireless sensor node comes from the wireless communication device and the micro-processer unit. [1]. The energy used by the wireless communication device can be split up into three components [69]. Namely, the energy required to transmit a bit over a distance d, the energy required to receive a bit, and the energy required to sense a bit with symbols E_{tx}, E_{rx}, and E_{sense}, respectively. These quantities can be defined as

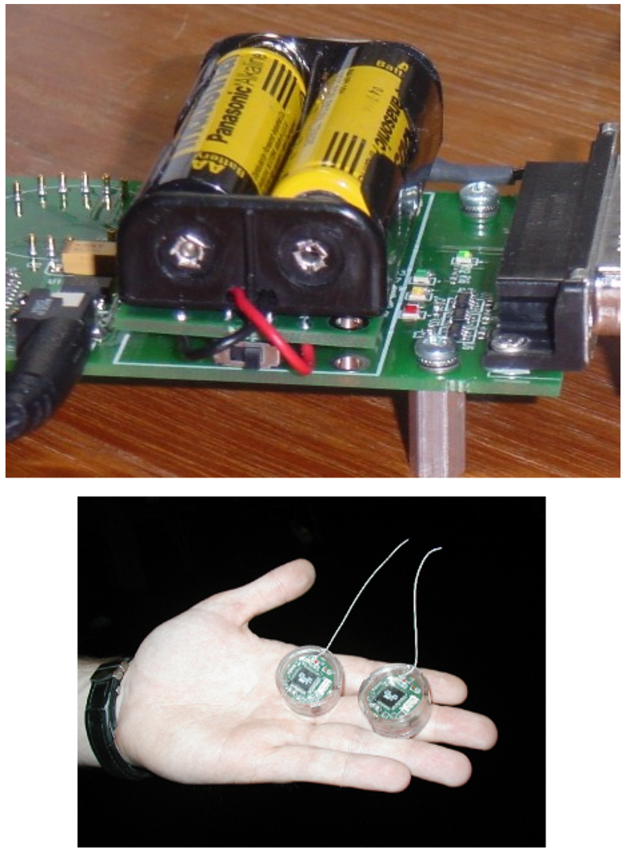


Figure 3.1: [66, 67] Two wireless sensor nodes using two different battery types.

$$E_{tx} = \alpha_{11} + \alpha_2 d^n \tag{3.1}$$

$$E_{rx} = \alpha_{12} \tag{3.2}$$

$$E_{sense} = \alpha_3 \tag{3.3}$$

The d^n in Equation 3.3 accounts for the $1/d^n$ path loss model in the free space electromagnetic wave propagation model [23]. Typically, $\alpha_{11} = 45nJ/bit$, $\alpha_{12} = 135\, nJ/bit$, $\alpha_2 = 10\, pJ/bit/m^2$ (for $n = 2$), and $\alpha_3 = 50\, nJ/bit$ [69].

The energy consumption of the communication device is much greater than the energy consumption of the micro-processor [21], usually, the total energy consumption of a wireless sensor node and its network can be solely based on the energy used for wireless communications. However, this does *not* mean that the energy consumption of the micro-processor can be ignored. It is very important to optimize the wireless sensor node's code in order to conserve energy because every instruction of the micro-processor uses about 80 nJ of energy [70].

3.3 The physical layer

Recall that the physical layer composes the basic hardware composition of the wireless sensor node [1]. One way to improve the energy consumption of the micro-processor is by improving the mico-processor itself. A recent advancement of technology shows that it is possible to create a one molecule transistor [71]. In terms of energy savings, the processor could theoretically use one million times less energy than a present day micro-processor [72]. Just because the micro-processor does not utilize as much energy as the wireless communications does not mean this would result in an insignificant energy savings. Because of the incredible energy savings at the processor, this would imply that extremely complex algorithms could be run at an extremely low energy rate. In turn, this would have a major effect on the other four layers of the WSN protocol stack. Also, the actual battery supply could be improved in terms of the size to energy output ratio [**?**].

Another method to improve the amount of energy available to a wireless sensor node is to use energy harvesting techniques to constantly replenish the node's battery supply [73]. Theoretically, energy harvesting techniques could supply energy to the wireless sensor node for an indefinite amount of time [74]. Some of the current techniques include using solar cells, harvesting vibrations such as acoustic noise, mechanical vibrations, etc., and micro-heat engines that could use various atmospheric gases such as to supply energy to the node [75].

Keep in mind that some of the energy harvesting techniques cannot be used with certain WSN applications. For example, if sensors need to be placed underground, then utilizing solar cells on the nodes would only waste space. Also, the use of an energy harvesting technique does not necessarily mean infinite lifetime of a wireless sensor network. If the communication protocols use too much energy too fast, the output of the energy harvesting may not be able to keep up with the communication protocol demand and render the WSN dead. Unfortunately, the techniques presented in this section are almost all purely theoretical or the energy output, such as using solar cells, is far too little to increase the lifespan of the wireless sensor node and in turn, the wireless sensor network. These techniques need much more research and development before they can become a realizable solution.

3.4 The communication layer

As mentioned in Chapter 2, the communication layer, which composes of the data link layer, the network layer, and the transport layer, uses most of the energy in a wireless sensor network due not to computations in the algorithms used, but due to the energy used for the wireless communication between the nodes [1, 21]. However, it is not impossible, but it is *extremely* difficult to compare the different protocols in each layer of the WSN protocol stack due to the lack of a standard benchmark [21]. The current literature concerning the communication layer states usually states in the abstract that "our protocol is better than some other protocol" but it does not clearly indicate why or how. Surely though, some of the more recent protocols are much more energy-efficient than the early protocols and techniques such as flooding, gossiping [21], and the ALOHA protocol [31] which never even considered the energy limitations posed on wireless sensor networks.

If a standard energy comparison of the protocols were to be made, here are some really important questions that must be taken into account:

- How many nodes are being used?
- How large, or small, is the environment of interest?
    - Are there obstacles in the field?
    - Is the field completely flat or does it have uneven terrain?
    - How were the nodes deployed or placed onto the environment of interest?

- What type of wireless medium is being used?
  - Radio?
  - Infrared?
  - Optical?
- What is the sampling rate that the sensors are using?
- How many sensors are being used per node?
- What combination of the four major types of nodes are being used?
  - Of the combination, which are mobile and which are immobile?
  - Are they utilizing any energy harvesting techniques?
- What size are the data packets being transferred by the nodes?
  - Is the size static or variable?
  - How fast, or slow, are they being transmitted?
- Which combination of the data link, network, and transport protocols are being used?

When comparing communication protocols to each other, *all* of the above questions must be considered in order to make an appropriate decision as to whether the protocol is energy-efficient or not. With the large number of variables to consider, it makes it very difficult to compare the energy-efficiency of one protocol to another. Therefore, more simulations, actual implementation, and testing of wireless sensor networks [21] are needed in order to develop some kind of standard benchmark of not only the energy-efficiency of the communication protocols for a WSN but also, how effectively they function. This information would enable WSN communication protocol developers clearly see a trend of the current communication protocols and be able to improve or create new ones as needed [21].

3.4.1 Energy Analysis of a Heterogenous Wireless Sensor Network

In Section 2.3.2, a self-organizing network protocol [17] was introduced. Like all other papers, the authors of [17] did not include any data concerning how much energy is actually consumed when using this algorithm. Therefore, MATLAB simulations were used to compute the average energy consumed per node per bit of information transmitted under ideal conditions. These ideal conditions include:

- the probability of a radio communication failure is zero
- all nodes distributed throughout the environment of interest are in operation and immobile
- the environment of interest is two-dimensional with no obstructions

The energy consumption taken into account was solely based upon the energy consumption used by the wireless radio communication device, which can be modelled by Equations 3.1, 3.2, and 3.3 for $n = 2$. A node's microprocessor energy consumption was ignored due to the fact that the energy consumption of a node's wireless communication device outweighs the microprocessor's energy use.

The first step towards completing the simulations were to distribute a predefined number of router and sensor nodes along with one sink onto a two-dimensional environment of interest. Nodes were deployed onto a square field of various sizes using a uniform distribution, a normal distribution, and a deterministic distribution, which had x and y-coordinates, in meters, of integer values. Dropping nodes from a plane can be modelled using the uniform distribution with the wingspan of the plane being the dimension of the square field. Figure 3.2 shows an example of how the nodes are distributed on a 50 x 50 field. The field size of 50 x 50 was chosen because the wingspan of a B2-A stealth bomber [76] is 50 meters. The normal distribution models

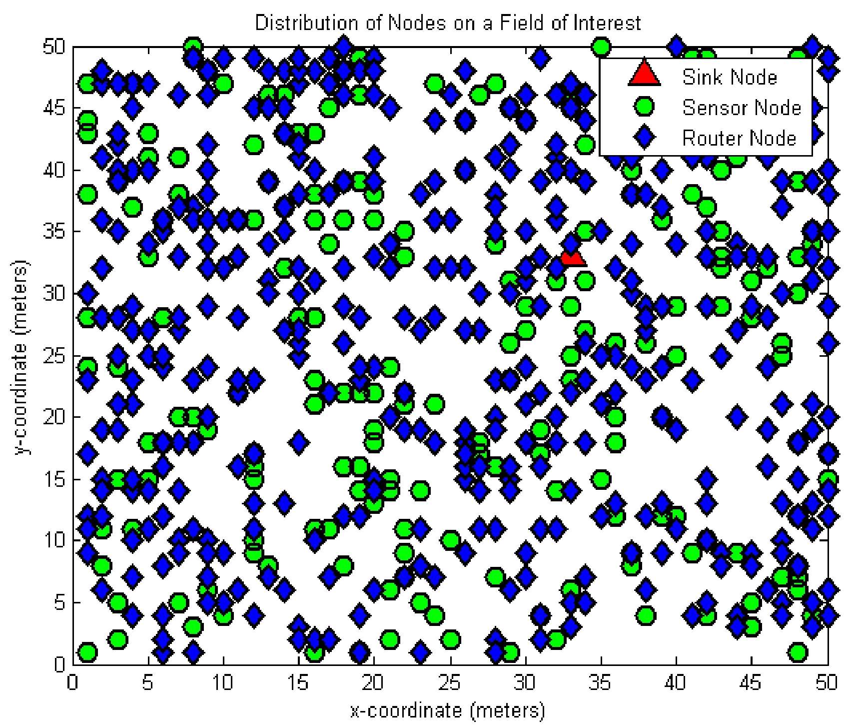


Figure 3.2: Uniform node distribution on a 50 x 50 meter field.

node placement if the nodes were distributed with a bomb and an example can be seen in Figure 3.3. The standard deviation of the normal distribution is correlated to how far, or close, the nodes get distributed on the environment of interest upon impact of the bomb. The last distribution,

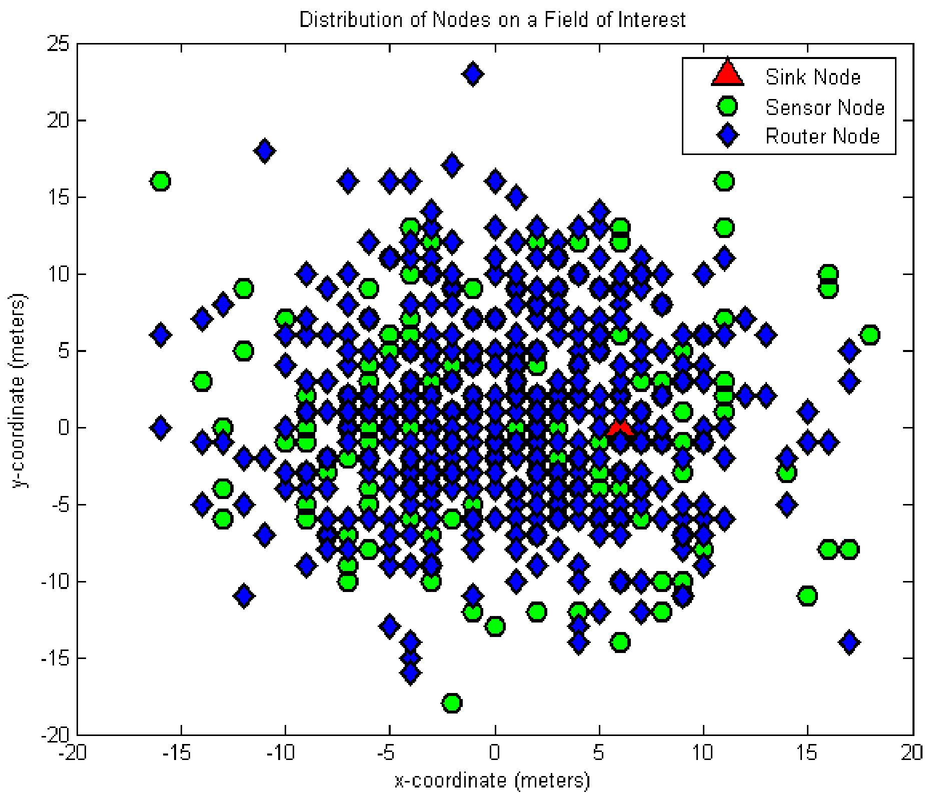


Figure 3.3: Normal node distribution on a 20 x 20 meter field using a moderately dense standard deviation pattern.

the deterministic distribution, models node placement if a human or robot were to place the nodes in an environment of interest. Figure 3.4 shows one possible node placement using a deterministic distribution.

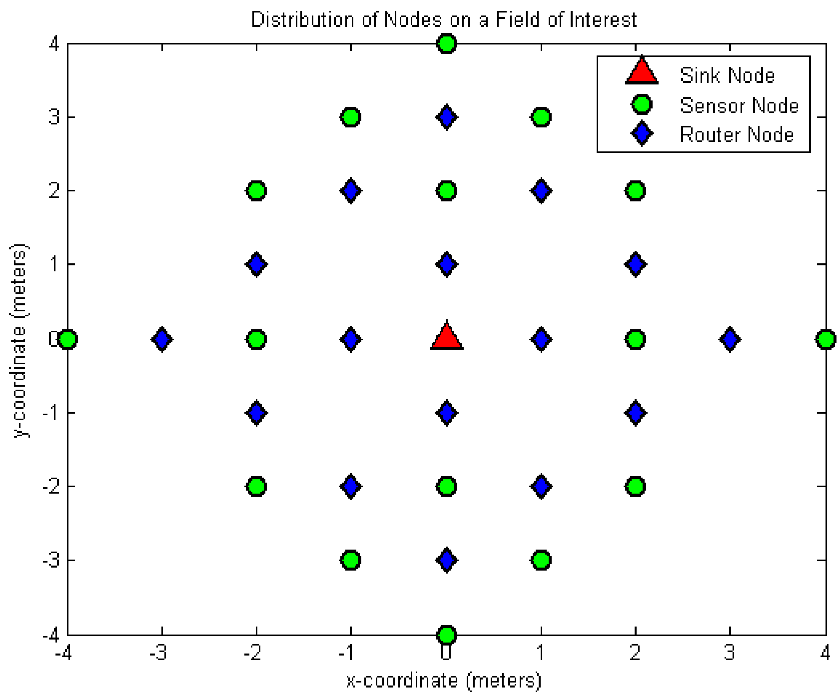


Figure 3.4: Deterministic node distribution on a 8 x 8 meter field.

Because the self-organizing phase in the self-organizing network protocol uses up the most energy [17] compared to sensing and returning data to the sink, examining the energy consumption of this phase will lead to a conclusion as to if this protocol is energy efficient or not. Simulations were run using the three distribution types mentioned above with a various amount of nodes, a various amount of field sizes, and ensuring that nodes find a specified number of neighbors. A node's neighbor(s) is simply defined as the closest surrounding node(s). Ideally, a node will find neighbors that are all very close in proximity. However, depending on the node placement, this is not always the case and some neighbors could be very far from a node.

Also, increasing the number of neighbors reduces the probability of failure of the entire WSN [17].

Figure 3.5 shows the average energy consumption per node per bit of

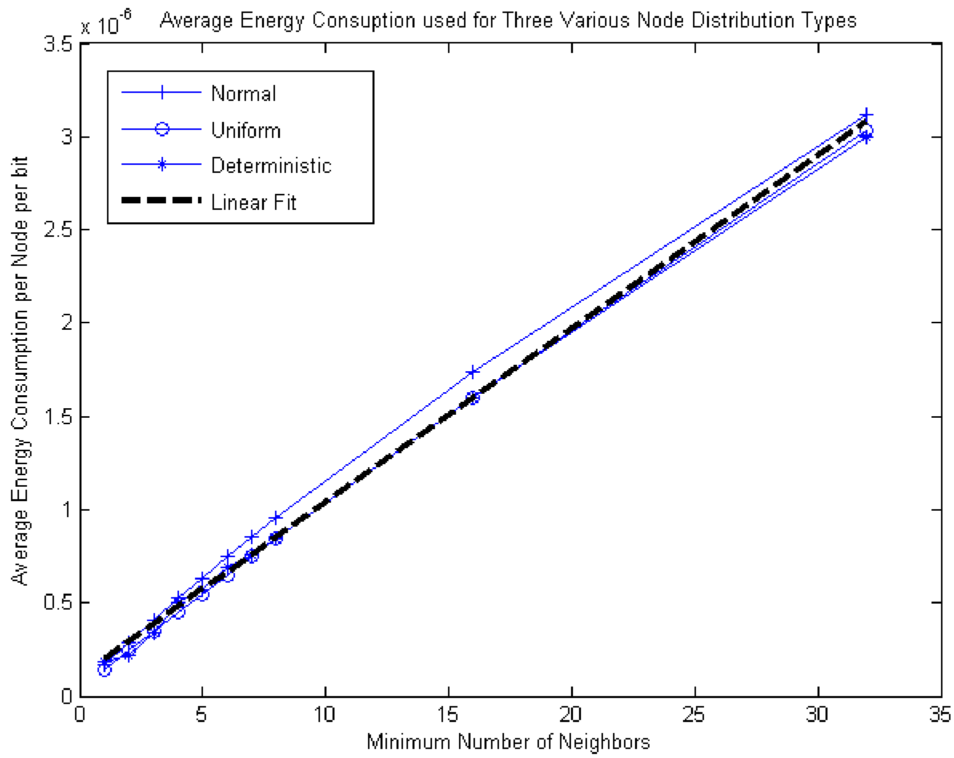


Figure 3.5: The average energy consumption used for three various node distribution types.

information transmitted using the three distribution types on a 50 x 50 field size with a 25% node coverage while varying the number of neighbors from 1 to 32. If a 50 x 50 field is used then this implies that there are 2500 possible locations that a node can fall into and a 25% field coverage implies that there are 625 nodes deployed onto the field. Since, the average energy consumed per node per bit is in the order of micro-Joules, this shows that the algorithm is indeed energy efficient. One could assume that the average energy consumption per node per bit would increase quadratically as the number of neighbors increased due to the d^n factor in Equation 3.1, for which $n = 2$. However, Figure 3.5 shows that the average energy consumption per node per bit increases *linearly* as the number of neighbor's per node increases. This is due to the fact that the probability of having neighbors only a short distance away, zero, one, or two meters, is extremely high. A distance of zero meters refers to nodes having the same x and y-coordinates. In reality, this approximation accounts for nodes being directly on top of each other all the way up to one meter apart minus some epsilon distance.

When using a deterministic distribution, the linearity result always holds true as long as the nodes are placed in a way such that neighboring nodes are only a short distance away and its corresponding probability density function (pdf) of a node having a neighbor some distance, from zero to infinity, is plotted in Figure 3.6. Figure 3.7 shows the probability density function of a node having a neighbor some distance away for a uniform distribution and a normal distribution using a 50 x 50 field with 30% coverage and a 4 as the minimum number of neighbors. Figure 3.8 shows the same results except that a 10% field coverage is used. In both figures, notice that the uniform distribution has a pdf similar to a skewed Weibull distribution and the normal distribution has a pdf very similar to a standard Weibull distribution. In addition, notice that as the field coverage decreases, the probability of having neighboring nodes within a close distance also decreases. This implies that there is a cutoff as to where linearity holds true for the two

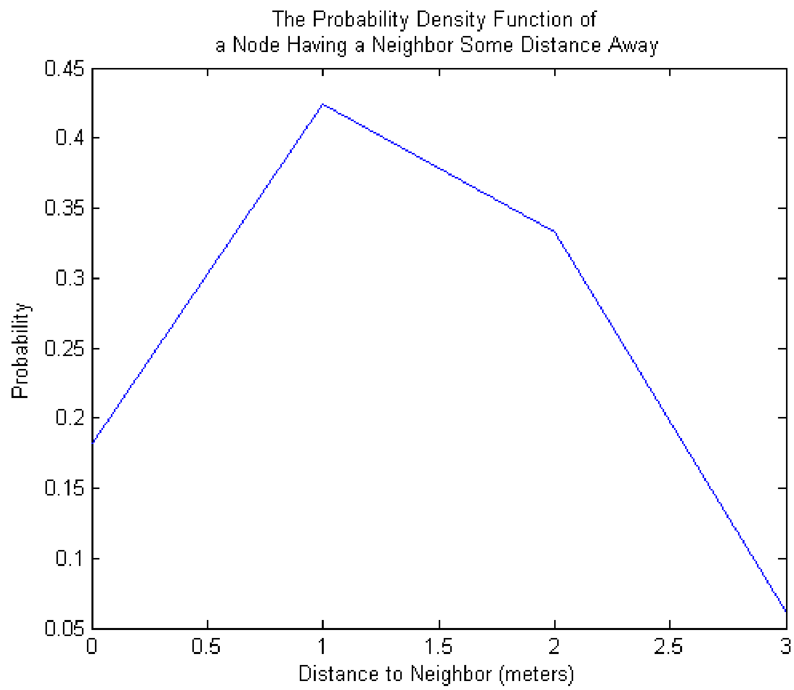
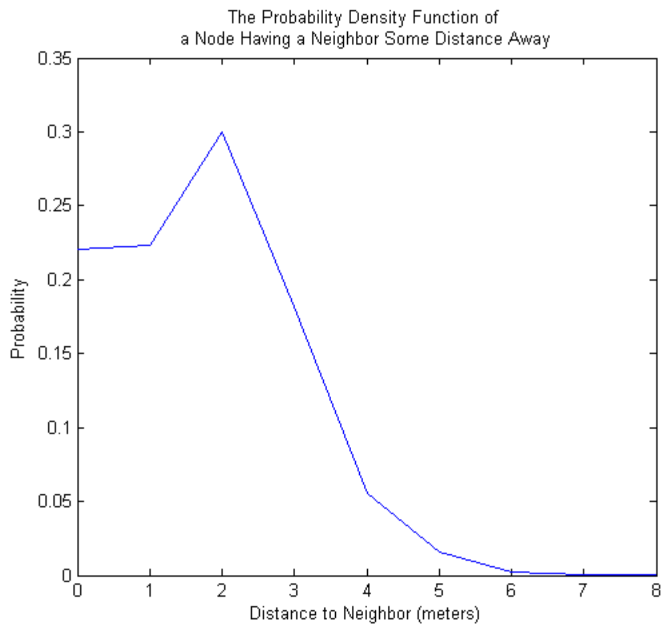


Figure 3.6: The probability density function of a node having a neighbor some distance away for a deterministic distribution.

random distributions. For the uniform distribution, at least 20% of the field must be covered with nodes, and for the normal distribution, at least 4% of the field must be covered with nodes for the above linearity result to hold true. Also, covering the field with greater percentages than above does *not* change the average energy per node per bit no matter what the field size is. However, covering a field with a greater percentage of nodes will obtain more data from the sensor nodes and ensures a greater reliability of the network. Overall, using a normal distribution of nodes is more energy efficient and more cost effective, because less nodes can be used to uphold linearity, as compared to a uniform distribution.



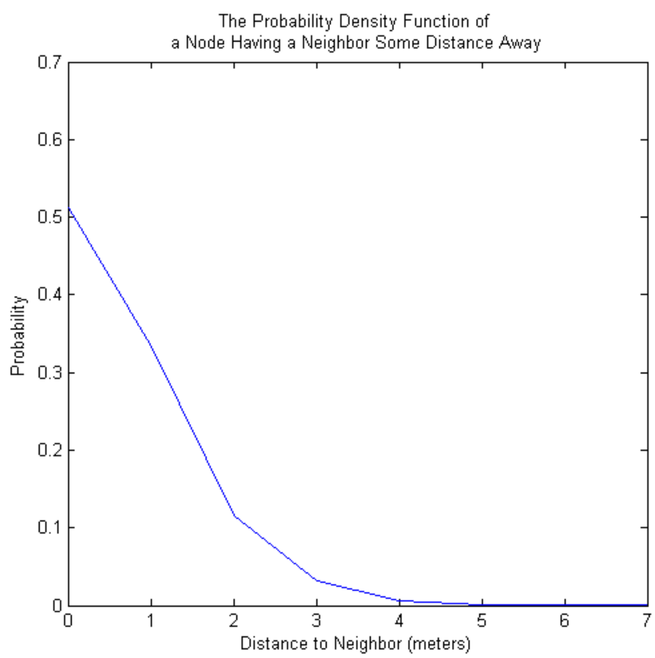
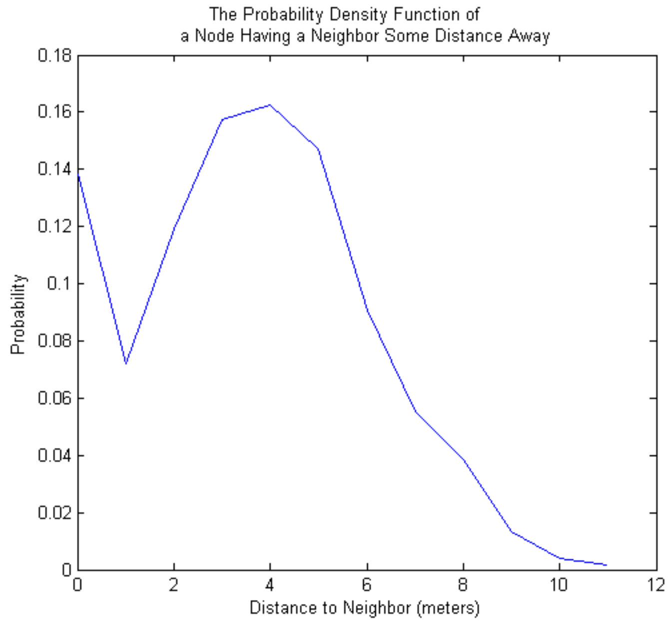


Figure 3.7: The probability density function of a node having a neighbor some distance away for a uniform distribution, top, and a normal distribution, bottom, using a 30% field coverage on a 50 x 50 field.



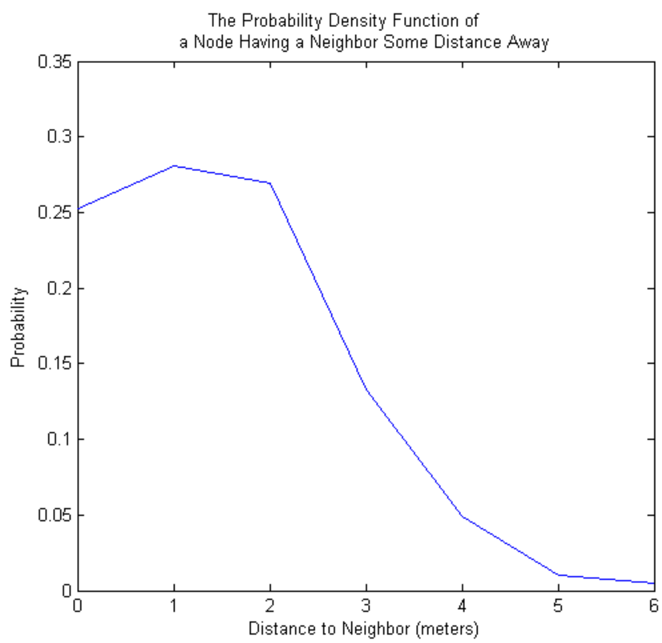


Figure 3.8: The probability density function of a node having a neighbor some distance away for a uniform distribution, top, and a normal distribution, bottom, using a 10% field coverage on a 50 x 50 field.

3.5 The application layer

Recall that the application layer is responsible for handling the wireless sensor network's application instruction code [1]. In terms of energy-efficiency, the application's code should be optimized in order to reduce the number of instructions to a number as low as possible, since every instruction of the micro-processor uses about 80 nJ of energy [70]. The code should also be optimized to the specific WSN application. For example, if the temperature of an environment of interest needed to be measured in terms of weekly averages, then instructing the nodes to record samples every minute would clearly waste energy not only in terms of sensing but also in terms of having to relay that information to the sink.

3.6 Conclusions

This chapter presented basic energy concepts and how the three major layers, the physical layer, the communication layer, and the application layer, of the wireless sensor network protocol stack use up a node's energy. It was shown that the physical and application layer can be improved to increase the energy-efficiency of the node, as well as showing the difficulties in comparing and contrasting the present communication layer protocols in terms of energy-efficiency and how well they work.

Most of the energy conservation mechanisms in the physical layer are only in the theoretical stage and need much research and development to refine, while current code optimization techniques can be utilized by the application layer in order to increase the energy-efficiency of a node. Most importantly, more simulations, actual implementation, and testing of wireless sensor networks [21] are needed in order to develop some kind of standard benchmark of not only the energy-efficiency of the communication protocols for a WSN but also, how effectively they function. The average energy consumption of nodes in an ideal heterogeneous WSN was examined for three node distribution types and the results showed that the average energy consumption per node increases linearly as the number of neighbors increase because the probability of having neighbors only a short distance away is extremely high. This result always holds true if 20% of the field is covered with nodes when using a uniform distribution and if 4% of the field is covered with nodes when using a normal distribution. If a deterministic distribution is used, this result always holds as long as the nodes are placed in a way such that neighboring nodes are only a short distance away. In conclusion, the above results can be combined with other energy saving techniques in order to increase the longevity of the entire wireless sensor network. However, much more research is still needed at all levels of a wireless sensor node in order to increase the overall energy-efficiency and, in turn, the entire wireless sensor network. The next chapter is going to conclude this paper with an overall summary of wireless sensor networks.

Chapter 4

Conclusions

Wireless sensor networks are becoming increasingly more prominent in all fields of today's technology as can be seen by the numerous, and almost endless, applications in which they are involved in. The basic function of a wireless sensor network is to relay information about an environment of interest to a computer or human so that proper data computations and analysis can be made. This in turn will give WSN users, such as researchers, the military, and even consumers, a very detailed understanding of the environment they are studying. Also, the use of a wireless sensor network could dramatically increase quality of living in a number of ways. For example, if a health monitoring WSN application is being used on humans, then certain malignancies could be detected sooner, as compared to current health monitoring techniques, and corrected sooner which could increase the humans' lifespan.

A basic wireless sensor network is composed of a variety number of sensor nodes, router nodes, cluster head nodes, and sink nodes deployed in an environment of interest. Each of these types of nodes can be used in any combination in the environment. Also, the nodes may serve the function of the router and sensor, as seen in early WSN, or any other desired combination such as a sensor cluster head node. Each and every node is composed of three major layers that include the physical layer, the communication layer, and the application layer. The physical layer is the actual hardware components of the node while the communication layer and application layer instruct the node how to communicate and perform depending on the WSN application. Furthermore, the communication layer may be split up into three components of its own consisting of the data link layer, the network layer, and the transport layer.

Due to the autonomous nature of a wireless sensor network, energy resources of each and every node must be carefully managed in order to sustain the entire lifetime of the WSN. Without proper energy management, a wireless sensor network may become completely inactive in only a matter of minutes to hours. Many types of energy conversation techniques, which were discussed in Chapter 3, must encompass all of the three major layers of a node in order sustain a node's energy reserves for a maximum amount of time. Also, the MATLAB simulations in Chapter 3 showed that using a self-configuring network is energy efficient, the average energy consumption of a node increases linearly as the number of neighbors increases, and a deterministic and normal distribution of nodes will yield the most energy savings. In conclusion, because WSNs are a relative new technology, much more research and development is needed in order to improve the energy-efficiency standards of today's present node technology, which will, in turn, improve the quality of wireless sensor networks.

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Appendix A

Wireless Sensor Network Glossary

application layer – defines the characteristics of node in order for it to function according to its intended use in a WSN

bandwidth – the maximum data transmission and or receiving rate of a node; usually measured in bits or bytes per second

broadcast – transmitting data from one node to one or more nodes in a predetermined area

clock drift – the amount of time to shift a node's wireless receiver clock in order for it to properly decipher any received data; occurs due to latency

cluster – a group of nodes

cluster head – the single node that organizes and controls any data flow of its cluster

collision – the corruption of a node's received or transmitted signal due to other nodes sending signals on the same channel at the same time

communication layer – this layer in the five layer WSN protocol stack encompasses the data link layer, the network layer, and the transport layer

contention-based network – a network in which nodes must actively listen in order to send and receive data

control sequence packet – a packet sent out between a node or nodes before or after data is transmitted in order to verify if a node needs data, Request To Send (RTS), the wireless communication channel is clear, Clear To Send (CTS), or the data was properly received, ACKnowledgement (ACK)

convergecast – a communication pattern in which data is aggregated together and then sent

data frame detection – the detection and the synchronization of a transmitted data signal to its corresponding receiver

data link layer – handles the node's connectivity to other nodes in the WSN

downstream data flow – sending data from the sink to the nodes

dynamic node – a node that can change its capabilities

end-to-end reliability – the reliability of data from the starting node to the ending node

energy harvesting – techniques used to replenish a node's battery supply

environment of interest – the area and location which will be studied and monitored by the wireless sensor network

fairness – using a node's resources not too much or too little

flooding – sending data to every node in the network from a single node

heterogenous wireless sensor network – a WSN that uses a variety of nodes; this includes WSNs where more than one type of sensor node is used and where there is a combination of mobile and immobile sensor nodes

hidden terminal problem – network collisions in a contention-based environment that occur from not using control sequence packets

homogenous wireless sensor network – a WSN that uses only one type of node

hop-by-hop reliability – the reliability of data at each hop in a network

idle listening – when a node keeps its transceiver on at all times in order to receive message from other nodes

latency – the amount of time a packet takes to go from one node to another

local gossip – a communication pattern in which data over a local region is averaged together and then sent

medium access control (MAC) – regulates a node's access to the wireless medium and creates the initial network

multiplexing – sending multiple sets of data on a single carrier frequency at one time

network flow – the rate of data coming into or out of a node

network layer – handles the routing and network maintenance of a WSN

node – a hardware device distributed onto an environment of interest which is used in multiple numbers in order to create a WSN; this device may be a sink node, a sensor node, a router node, or any combination of the above

overhead – factors, such as idle listening, overhearing, etc., which cause wasted energy in a wireless sensor network

overhearing – when a node receives a packet in which it was not suppose to receive

physical layer – handles the wireless communication, as well as data encryption, of a node

power management plane – the energy conservation techniques used in each layer of the WSN protocol stack

preamble packet – a transmitted message before data is sent which informs a receiver node of an incoming packet

protocol overhead – the energy used to transmit and receive a control sequence packet

quality of service (QoS) – QoS; a performance measure based upon the latency, throughput, and or fairness of a network

router node – a specialized type of node in a WSN that only receives and sends data to other nodes in the network

schedule-based network – nodes are assigned a certain time period to send and receive data

sensor node – a specialized type of node in a WSN that can sense information about the environment; these nodes must have the capability of router nodes; there may be more than one of sensor on this type of node

sink node – a specialized type of node that contains much more computing power, memory, and a communication device with a longer range compared to a common node used in a WSN

throughput – a rate of the amount of data sent from one node to another

transport layer – handles relaying information of a WSN between two or more wireless sensor networks and other networks

unicast – transmitting data directly from one node to another node

upstream data flow – sending data from nodes to the sink

wireless ad-hoc network – a type of wireless network in which nodes discover themselves

wireless sensor network protocol stack – describes the five required tasks of a node in order for it to be part of a WSN