

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This chapter centres on the various studies that have been conducted in the field of wireless sensor networks (WSN) especially with respect to coverage optimisation. It outlines and evaluates the progress that has been made, in order to highlight the strengths and weakness of approaches or techniques that have been used or proposed for energy management, energy loss problem, and Medium Access Control (MAC) protocols design in WSNs. The chapter evaluates the different approaches that have been employed for power management and coverage methodology and algorithms, highlighting the high merits of these approaches as well as their shortcomings. Furthermore, a review of the concept of WSNs coverage problem, an integral issue of any WSNs, was carried out.

2.1.1 WSN Coverage

The Coverage control problem is one of the most fundamental issues in wireless sensor networks, because it is a measure of the Quality of Service (QoS) in a sensor network (Cardei & Wu, 2006). Sensor nodes in network are usually equipped with batteries with limited power. Therefore, energy conservation operations are critical for extending network lifetime (Zhou, Liang, Xu, & Xie, 2012).

Wireless sensor network has emerged as a promising tool for monitoring the physical world. It utilizes self-organizing networks of battery-powered wireless sensors that can sense, process, and communicate (Ian F Akyildiz, Su,

Sankarasubramaniam, & Cayirci, 2002). The optimal set of active nodes selection has been proved as an NP-complete problem with random WSN network topology (Cardei & Wu, 2006). Heuristic algorithm is an effective way to solve that problem. PEAS is a well-known protocol proposed by (F. Ye et al., 2003). They have developed PEAS, a distributed and randomized energy-saving protocol for sensor networks. PEAS let each node probe its local operating space to maintain desired working node density while avoiding the overhead of keeping per neighbour state. To handle unpredictable node failures, PEAS uses a randomized wakeup algorithm that can self-adapt to node failures. PEAS keeps the working node density approximately constant independent of the node deployment density with roughly the same overhead. As a result, PEAS can prolong the overall system lifetime proportionally to the total number of deployed node. By the protocol, some nodes will become redundant nodes that need not be activated, as long as the other nodes exist within sense area of the inactivated nodes. The centralized and distributed greedy algorithms have been proposed based on randomized algorithm, so that nodes set can cover target area as large as possible (Goel & Plotkin, 2004). The approach of (Tian & Georganas, 2003) effectively extends network lifetime by alternating the active or sleep state of node. The diagram programming method is used to obtain the minimum active nodes set to keep coverage (Chakrabarty et al., 2002). The coverage uniformity is considered simultaneously. PCover protocol is proposed by (L. Wang & Kulkarni, n.d.2008), they present a simple, local protocol, pCover, which provides partial (but high) coverage in sensor networks. Through pCover, they demonstrate that it is feasible to maintain a high coverage ($\sim 90\%$) while significantly increasing coverage duration when compared with protocols that provide full coverage. In particular, they show that are able to maintain 94% coverage for a duration that is 2.3-7 times the duration for which

evolutionary-based mechanism with a distributed query sensor cover algorithm for optimal query execution in self-organized wireless sensor networks (WSN). An algorithm based on an evolutionary technique is proposed, with problem-specific genetic operators to improve computing efficiency. Redundancy within a sensor network can be exploited to reduce the communication cost incurred in execution of spatial queries. Any reduction in communication cost would result in an efficient use of battery energy, which is very limited in sensors. The objective is to self-organize the network, in response to a query, into a topology that involves an optimal subset of sensors that is sufficient to process the query subject to connectivity, coverage, energy consumption, cover size and communication overhead constraints. Query processing must incorporate energy awareness into the system by reducing the total energy consumption and hence increasing the lifetime of the sensor cover, which is beneficial for large long running queries. Experiments have been carried out on networks with different sensors transmission radius, different query sizes, and different network configurations. Through extensive simulations, that have shown that their designed technique result in substantial energy savings in a sensor network. Compared with other techniques, the results demonstrated a significant improvement of the proposed technique in terms of energy-efficient query cover with lower communication cost and lower size.

Authors in (Jia et al., 2009) optimize network coverage and nodes utilization simultaneously by using improved Non-Dominated Sorting Algorithm II(NSGA-II) to obtain the control of WSN network coverage. That algorithm is based on the structure of basic genetic algorithm. Some steps, initialization and reproduction are identical. Moreover, the above discussed multi-objective search techniques, such as non-

equilibrium degree by MOFS algorithm to determine the working status of sensor nodes. Meanwhile, the proposed strategy can adjust weight and coverage threshold to obtain the optimum allocation of different business requirement and then to improve the applicability of WSN network. It is obvious that the coverage control strategy has wide applicability, and the effectiveness of the strategy is verified by the simulated results. (Zhou et al., 2012).

In this case, the search to improve the coverage of wireless sensor networks from the other side to solve this problem in a wireless sensor network through automatic and dynamic techniques high quality in the future. To identify the fitness function for obtaining optimal coverage area in wireless sensor networks and can control the parameters such as energy consumption, radio bandwidth, users and using single fitness function to manage the coverage area problem.

The use of smart sensors has gained considerable recognition in recent times, noticeably in applications such as system surveillance, military applications and other industries. Smart sensors are created by combining tiny sensing materials with electrical circuits (Tseng, Chang, & Bour-Hour, 2004). The combination of smart sensors with the growing application of wireless sensor network has further enhanced its usage. This is made possible with increased wireless communication capability and networking the sensors together each sensor (Intanagonwiwat, Govindan, & Estrin, 2000). While wired communication approach can be used to enable smart sensors, the development of the wireless ad hoc network, or the use of autonomous wireless devices connected using radio waves rather than wired or fixed infrastructure has made a considerable evolvment (Perkins.C.E,2000). The main technology common to both sensor networks and ad hoc networks is the multi-hop communication.

Because of the need to be self-reliant, portable devices are generally powered by batteries. For all applications of portable devices, there is always the question of power efficiency such that the life of a network can be sustained longer. Numerous works have been dedicated to power efficiency and maintenance in wireless sensors or ad hoc networks. For instances, (Huang & Tseng, 2003) examined the use of power control to minimise interference and improve throughput was addressed in Furthermore, (Hu, 1993; Slijepcevic & Potkonjak, 2001; Wattenhofer, Li, Bahl, & Wang, 2001) studied the topology control approach of tuning transmission powers Others such as (Chang & Tassiulas, 2000) (Ryu & Cho, 2000) (Stojmenovic & Lin, 2001) considered Power-aware efficient routing for ad hoc networks.

Devices with IEEE 802.11 or Bluetooth are known to support low-power modes (Haartsen & Mattisson, 2000) and (Woesner, Ebert, Schlager, & Wolisz, 1998). (Tseng, Hsu, & Hsieh, 2002) explored development of low-power modes on 802.11-based multi-hop networks. The approach considered in the particular research considers minimising problem associated with topology control in an ad hoc sensor network. Granted that topology in ad-hoc networks are not necessarily static because changes in the transmission powers of hosts effect changes in the topology, thereby resulting in a dynamic system.

The study considered a scenario where a set of hosts forms a wireless ad hoc network, an initial energy of each host, and the traffic ratio of each host and how best to determine the best transmission power of each host based on the network topology configurations such as 1-edge-, 1-vertex-, 2-edge-, or 2-vertex-connected. From the approach present, the main goal in this instance is to maximize the *lifetime* of the network. By prolonging the lifetime of the network the amount of time when all hosts

remain active is the focus. The work considered two variations of the problem. The first instance is when the powers at each hosts can be fixed while the other instance is when the power is not fixed but rather changing. namely, In the study, they claimed that optimal lifetimes for the mobile nodes is obtainable using an approach of simple *minimum spanning tree* construction under the fixed power assumption.

Other closely related work include that of (Ramanathan & Rosales-hain, 2000). He employed topologies control algorithms to model the 1-vertex and 2-vertex-connected graphs where they regard all the hosts to possess an equal initial energies. This is considered a special case of the model. Furthermore, in (Ramanathan & Rosales-hain, 2000) the approach employed was to ensure that the maximal transmission power of each host in the network was a minimum using a minimum spanning tree construction yielding an optimal result although, the final spanning tree graph may not necessarily always be the same as modelled in their work.. Therefore, this work is an extension of that reported in relating to an environment where hosts' initial energies are not necessarily equal.

The work of (TSENG et al., 2004) claimed the first to attempt an approach that study the topology control problem in adhoc network evaluating the remnant energies at the hosts. They presented algorithms adequate for creating 1-edge-, 1-vertex-, 2-edge-, and 2-vertex-connected networks. Given a fixed power scenario, optimality of the models was achieved, though it is also based on a minimum spanning tree construction. To reduce individual hosts' powers, an approach referred to as the *PerNode Minimize*. This technique can remove some side-effect links, but the network lifetime cannot be improved. The result can be applied to our work under the variable power model since side-effect links may potentially become critical links in the future.

Distributed topology control was also discussed in (Ramanathan & Rosales-hain, 2000). In spite of its desirability, it may not be appropriate to extend the schemes to obtain distributed ones. This is because global information are needed to determine a graph's connectivity. It is often difficult or impossible to recharge or replace the batteries usually used to power hosts in wireless networks when depleted by (Li, Cheng, & Wu, 2005) the energy consumption becomes a great concern in cases where the system is life threatening. This is particularly critical for some systems such as the military where once the power is exhausted during duel, it may not be possible to pause in order to change the battery for another. The lifetime of a network can be regarded as the longest time that the network is fully connected after the deployment without disconnecting any host. Any host that exhausts its energy will thereby lose its communication capability, and hence, disconnected from the network. This therefore signifies the end of such communication connection lifetime. In a situation where other hosts may still have much energy left, the power left would likely be a waste. Therefore, it is of critical necessity that the respective energy at each host should be efficiently utilised in order to maximize the lifetime of a network. Previous approach such as the topology control focuses on how to manage and adjust the transmission power at each host in the communication network to sustain a desired topological property while at the same time satisfying other requirements such as lifetime, throughput, etc. In maintaining the topology of a network, a dynamic approach is employed. This is required in order to obtain the global connectivity where there exists a path between each ordered pair of nodes the work focused on the network connectivity by attempting to propose an energy-efficient approach to maximize the lifetime of a network. The work used total energy consumption as an important metric when evaluating routing algorithms. Some cases were seen where low total energy

consumption which should signify energy-efficiency, however, a minimum total energy does not always produce a prolonged lifetime of a network. The field of wireless sensor networks (WSNs) has witnessed growing interest in recent time, especially in the area of research and commercial development. Wireless sensor networks have seen a remarkable deployment in the monitoring of movement or changes in the environment. Specifically, they have been deployed for surveillance considerably in military, indoor environmental, research and scientific applications and so on. However, a crucial issue for consideration for the deployment of wireless sensor networks is that of coverage. "Coverage in wireless sensor networks is usually defined as a measure of how well and for how long the sensors are able to observe the physical space.

In a given wireless sensor network, there are a number of wireless sensor nodes. Nodes essentially are small size embedded with sensing capability equipped with limited energy usually supplied by a battery, communicating via built-in antennae over radio frequency (RF) signals. The WSNs system are often employed to observe area of interest for intrusion, movement, changes such as temperature, humidity, precipitation, etc.

The coverage of WSNs, which can be regarded as how well and lasting a sensor network sufficiently monitor a field of interest, is the most active research fields in wireless sensor networks. The coverage of WNSs can be thought of as a measure of quality of service. The measurement or bench marking of coverage which could be done in several forms is application dependent. Very closely related to coverage is the crucial need for a WSN to provide and sufficiently sustain connectivity. Connectivity defined as the capacity of the nodes to sustain link to the

data sink, can be impacted when no available route from a sensor node to the data sink is maintained leading to the failure to process the data received by the nodes. For a given node, there is a communication range which encompasses the area that nodes that can receive data be located. Any nodes beyond the communication range are not likely to receive data. There is also the sensing range designates the area a node can observe. Often times sensing range is not equal to communication range but may be equal in some cases.

2.1.2 Current challenges & Issues in WSNs Coverage

Many factors are to be considered in developing WSNs to ensure coverage. These factors as mentioned above are dependent on the application in consideration. Another factor is the consideration for the capabilities of the sensor nodes to be used. There are two approaches previously adopted – the single deployment model as well as many types of deployment. The single deployment model is more common compared to the many types of deployment.

2.1.3 Coverage Types

As mentioned in the preceding section, the application in consideration is the first factor that is of highest priority when deploying a wireless sensor network. In WSNs, the goal is to monitor an entire area, set of targets, or intrusion into an environment or breaking through a barrier. The coverage of a whole area is usually referred to as full or blanket coverage. This is intended to mean that every single point within the field of interest is within the sensing range of at least one sensor node. Ideally you would like to deploy the minimum number of sensor nodes within a field in order to achieve blanket coverage.

There is also the target coverage that is meant to observe a fixed number of targets. Target coverage is very applicable in military applications (Arora. A, P. Dutta, et. Al(2004).It may be required in this type of coverage to monitor targets, as well as classify and track them. Maintaining energy in target coverage is a crucial issue. A comparative analysis of full and target coverage for energy efficiency was carried out by Cardei. M, M. Thai, et al(2005), Cardei. M and D. Du(2005), Cardei. M, J. Wu, M. Lu, and M. Pervaiz (2005),Zhang. H, H. Wang, and H. Feng (2009), and Zhang. H (2009).Another type of coverage is the barrier coverage, which is used to refers to the detection of movement across a barrier of sensors. The barrier coverage is also referred to as the maximal breach path Meguerdichian. S, F. Koushanfar, M. Potkonjak, and M. Srivastava (2001). Various algorithms in barrier coverage have been studies Chen. A, S. Kumar, and T.-H. Lai (2007).

Other forms of coverage include sweep coverage Cardei. M and J. Wu (2006) and Osmani.A, M. Dehghan, H. Pourakbar, and P. Emdadi, (2009). Sweep coverage is a variant of the barrier coverage and usually regarded as moving barrier coverage problem.

2.1.4 Deployment

Another important factor in WSNs is the deployment approach adopted. There are two basic approaches to deployment - a dense deployment or a spars deployment.

A dense deployment, as the name suggests is a deployment that contains a relatively high number of sensor nodes in an area of interest. It is often the deployment of choice when it is very important for every movement or event in an area of interest to be detected. It may also be applicable to a situation where it is imperative to have

multiple sensors cover an area of interest. A sparse deployment on the other hand is used when there are relatively fewer nodes. The sparse coverage approach is often adopted when there is consideration for cost of sensors. That is where it is too expensive to have several sensors to achieve a dense deployment. It is also usually the case when you intend using sensors with long range coverage that can achieve maximum coverage of the target area with minimum number of sensors, rather than several sensors.

Traditional sensors are stationary and most previous work adopt static model for sensors whereby the sensors are assumed to be located in a fixed location after deployment. Some of the recent sensors have the capability to be mobile. This means that they have the ability to relocate after they are deployed. These new sets of sensors are regarded as mobile sensors. Works such as Howard, A. M. J. Matari'c, and G. S. Sukhatme (2002) have sought to propose model for mobile sensors capable of determining the location to which a particular mobile node could relocate to in order to ensure maximum coverage. In other previous attempt, methods were introduced to an optimize coverage while at the same time limiting sensor movements as mentioned by Osmani, A. M. Dehghan et al (2009). The performance in the above arrangement guarantees an excellent coverage provided there are limited amounts of movement. The approach also has another drawback. The algorithm for the set up was very complex algorithm thereby placing critical strain on the sensor nodes. Other authors have also demonstrated the design of three separate deployment protocols that provide a high level of coverage with minimal movement in a short time(Wang, G, G. Cao, and T. La Porta (2004). The simulations show that the protocols hold up with a limited

amount of sensors but there are questions about how scalable the protocols are with larger numbers of sensors.

Sensor network nodes can be deployed in a target area in predetermined configuration or in random fashion. A coverage scheme that adopts a deterministic placement of sensor nodes is often easier than that of random placement. Despite this edge, it is however impractical or impossible to adopt a deterministic scheme for sensor nodes' distribution in prevailing deployments. Figures 2 and 3 describe the two aforementioned placements. Previous works that explored deterministic schemes include Howard. A, et al (2002) and Bai. X, Z. Yun, D. Xuan, P. Lai, and W. Jia (2008). The work in Bai. X, Z. Yun et al (2008) adopts a diamond pattern Voronoi polygon. The approach was reported to have achieved full coverage four way connectivity given that the ratio of the communication range to the sensing range is not less than or equal to the square root of two.

Most deployments that are based on random deployments of sensor nodes are usually dense deployments. This is because more sensor nodes are added to achieve better coverage for stationary sensors. In the case of mobile sensors, are often initially deployed using a random arrangement, but subsequently employ the mobility algorithm to achieve an optimal placement.

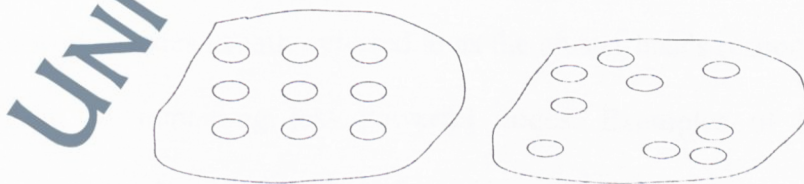


Figure 2. Sensor nodes' placements (a) Deterministic Placement (b) Figure R.

Random Placement [p]

2.1.5 Node Types

Predominantly, there are two groups of nodes in a given WSN, namely, homogeneous or heterogeneous nodes. In a homogenous group of nodes, all nodes within the group are of the same types and capabilities.



Figure 3: Node types (a) Homogeneous Sensors (b) Heterogeneous Sensors

Heterogeneous group on the other hand consists of nodes that are of different capabilities. In heterogeneous nodes, there is often the presence of a smaller group of more powerful nodes usually referred to as the cluster heads responsible for gathering data from the remaining less powerful nodes. Examples of homogeneous and heterogeneous nodes are given in 3, (a) and (b).

2.1.6 Constraints

Any algorithm that will work for a heterogeneous network will also work with a homogeneous network. Several papers attempt to prove their theories first with a homogeneous deployment then show that the findings will hold up for a heterogeneous deployment Kar. K, S. Banerjee(2003), Chen. A, (2007), Howard. A et al(2002), X. Bai, Z. Yun et al(2008), Y-X. Li, P.-J. Wan, and O. Frieder (2002) and Cărbunar. B, A. Grama, J. Vitek, O. Cărbunar (2006). Algorithms in Kar. K, S. Banerjee (2003) and Bai. X, Z. Yun (2008) employ homogeneous set of nodes where the nodes are placed at a precise distance in relation to each other that is dependent on the sensing ranges of every node being identical, may be in rectangular design of homogeneous sensors by Chen. A, et al (2007) or others design such as Voronoi diagram Cărbunar. B, et al (2006) weighted to maintain coverage.

2.2 WSN Energy Loss and Mac Protocol Design

Wireless sensor networks (WSNs) rely on efficient design of hardware to ensure that sensor application deployments are cost effective and sustain a longer lifetime with minimal maintenance. Often, the design of WSN requires an approach that extent the lifetime and balance application-specific throughput and latency requirements. One of the common effective approach adopted is to ensure selective sensor nodes be placed in an available energy-saving approach usually utilizing the sleep period duration and the current state of the radio as the criteria.

Using the WSN MAC protocols design, the network lifetimes can be extended by limiting the activity of the radio, since it is the highest energy-demanding component of the WSN. For effective design of power management system, a good

understanding of how energy in the WSN is depleted is vital. Energy is often depleted in the form of idle listening, frame collisions, protocol overhead, and message overhearing. These key sources of energy loss are discussed below.

2.2.1 Idle listening

The phenomenon of idle listening is used to describe a situation in which a node in the WSN system listens to an inactive medium. The idle listening mode causes power loss in WSN when there are scarce traffic and limited sleep cycles. The ideal thing is to have nodes switch into sleep mode when all network transmissions have been completed during a specific time *frame* until the next transmission period.

2.2.2 Frame collision

In WSN, frame collision refers to a situation where nodes send messages simultaneously leading to collision. The MAC frames from a given node are sent at the same time with another node thereby collides or overlaps in time with another message. When collision occurs, the interfering message of the colliding packet may times sufficiently neutralise the receiving node's signal, thereby corrupting the data at the receiving end. In a situation where the radio possesses a single channel, such collision cannot be reported since it is only possible to either be in the transmit mode or receiving mode at one time. The only way to ensure a successful transmission or a collision is the receipt of a message acknowledgement (ACK) from the receiver or its failure.

Factors that leads to frame collisions include finite radio receive to transmit transition times, otherwise referred to as the capture effect often ranging between 250 μ s - 500 μ s after sensing a clear channel; propagation delays between distant stations;

and hidden nodes which are out of range of the sender, but within range of the receiver. Frame collisions may require resending messages which in turn requires the sending and receiving node to further expend additional energy.

To resolve the problem caused by frame collisions, protocol designers may adopt one of the following approaches: the IEEE 802.11 exponential contention back off, transmission scheduling with TDMA protocols and four-way request to send (RTS) – clear to send (CTS) – data – acknowledgement (ACK) handshaking to reserve the medium before sending data?

Both the RTS and CTS messages contain a duration field which advertises to all surrounding nodes the length of the transmission exchange. By having all nodes set their Network Allocation Vector (NAV) countdown timers for the duration of the exchange, a WSN protocol can significantly reduce frame collisions after the initial RTS-CTS exchange has seized the channel.

2.2.3 Protocol Overhead

Protocol overhead in wireless networks consumes both energy and bandwidth. Networks serve as an integrated system to transfer data between distributed application layer programs, but maintaining a network and providing reliable data delivery requires trade-offs in effective throughput and energy efficiency. For example, adding data message headers and 2-to-1 Manchester encoding to the RF Monolithic TR1001 Monolithics. RF (2005) transceiver reduces the 115.2 kbps physical transmission rate to an effective 46 kbps (Langendoen and Halkes, 2004). This 60% reduction does not yet include the additional network control overhead required to configure the network using neighbour discovery, synchronization time,

and available message route determination. Protocol designers must minimize the protocol overhead while maintaining energy efficiency, latency and throughput requirements.

2.2.4 Message overhearing

Message overhearing is receiving and discarding messages intended for other nodes and is tolerable in networks not constrained by energy. Receiving all messages is an efficient method to increase throughput and decrease latency, but it also causes all of the receiving nodes to expend energy. In many WSN platforms, the radio receive mode actually expends more energy than the transmission. Message passing is an energy-efficient technique to reduce message overhearing using a four-way request to send (RTS) – clear to send (CTS) – data – acknowledgement (ACK) handshake to reserve the medium before sending data. Both the RTS and CTS messages contain a duration field which advertises to all surrounding nodes the length of the transmission exchange. Nodes set their network allocation vector (NAV) countdown timers for the duration of the exchange. Message passing provides a means for nodes to schedule a NAV sleep period after an overheard RTS-CTS handshake sequence by extracting the message duration field and scheduling a NAV table interrupt Sing. S, and C. Raghavendra (1998). To reduce the probability of costly retransmissions and added latency, message passing also uses RTS-CTS exchanges to gain medium access and then transmits a burst of fragments of the larger message. As shown in Figure. (4)The receiver responds with an acknowledgement (ACK) message after each successful fragment transmission.

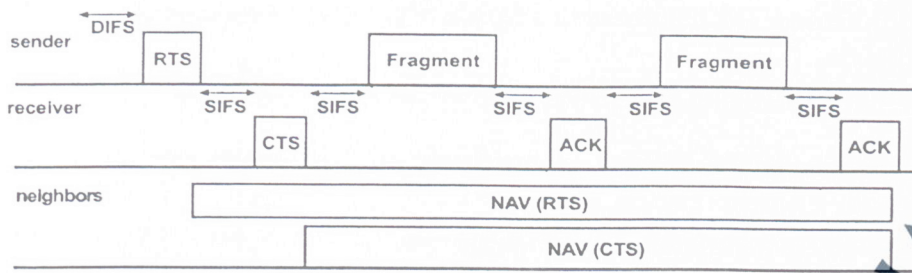


Figure 4. Message passing timing and signalling Ye et al.,(2002)

2.3 WSN Sensor MAC Protocols

Sensor MAC (SMAC) is a WSN MAC protocol which represents the baseline energy-efficient protocol designed to extend WSN network lifetime Ye, W. J. Heidemann, and D. Estrin,(2002) . SMAC divides a time frame into listen and sleep periods. The listen period is further divided into a synchronization period and a data transfer period. The synchronization period allows nodes to periodically announce their sleep schedules to correct network time drift and synchronize their sleep times to form virtual clusters of nodes with the same active listen and sleep periods. By creating a small active duty cycle, node lifetimes can be significantly extended with bounded throughput and latency tradeoffs. Sensors that border two synchronized clusters have the option of choosing one or both sleep schedules.



Figure 5 .SMAC static and T-MAC dynamic duty cycles Van Dam and Langendoen, (2003)

The bi-directional traffic in Figure(5). represented by arrows illustrates how creating a slotted starting time for all network traffic and concentrating the traffic into a smaller active time frame reduces idle listening, trading off latency and throughput. To minimize collisions, nodes use the IEEE 802.11 standard exponential contention backoff for all channel access attempts. Furthermore, SMAC also reduces energy consumption using the message passing techniques employed for overhearing avoidance.

2.3.1 Timeout MAC

Timeout MAC (TMAC) is a WSN MAC protocol that decreases idle listening in WSN networks by establishing a dynamic sleep cycle [Van Dam, P and K. Langendoan (2003)]. TMAC nodes vary their active message exchange period depending on current traffic conditions.

Unlike the SMAC static duty cycle, the TMAC dynamic duty cycle uses adaptive listening to attain significant energy savings and accommodate various network traffic loads experienced during a WSN's lifetime. TMAC nodes also form virtual clusters and automatically determine the initiation of a cluster sleep cycle based upon an adaptive timeout (TA) mechanism. To provide for multi-hop network communication, the TA period represents the worst case delay a CTS response packet could undergo before being transmitted. Equation (1) highlights the parameters used to calculate the TA period:

$$TA = 1.5 * (t_{SIFS} + t_{CW_{max}} + t_{RTS}) \quad (1)$$

where t_{SIFS} is the duration of a short in terframe spacing, $t_{CW\max}$ is the duration of the longest contention window backoff, and t_{RTS} is the duration of a RTS packet. Simulations indicated a need to scale this TA period by 50% for effective message exchange. Figure 5 illustrates how TMAC effectively condenses the same amount of traffic as SMAC into a smaller dynamic time window to save energy by reducing idle listening at the expense of increased message delay.

2.4 Radio Power Management

2.4.1 Existing Power Management Standards in Wireless Sensor Networks.

The 802.15.4 (IEEE802.15.4) wireless networking standard provides low data rate, low power communication that is ideal for wireless sensor networking applications. It too is based on a synchronous sleep scheduling policy that periodically wakes nodes up and puts them to sleep in order to exchange data. The difference between this standard and the others is in the frequency with which nodes wake up, and the data rate (and correspondingly the required transmission power) with which they transmit data. A low power protocol stack called (Zigbee) has been developed on top of the 802.15.4

MAC layer in order to provide low power solutions for WSNs. Many products for WSNs are being developed in industry with "Zigbee" compatibility as a very strong marketing point.

2.4.2 Current Research Efforts

In addition to the standards that have been developed for low power communication in wireless networks, on-going research continues to provide innovative solutions to this

problem. This section discusses some of the more recent advances and provides references to some of the older ones. Since it is impossible to list every single power management protocol that has ever been developed for wireless networking, only the most representative ones have been provided here.

2.4.3 Power Aware Routing

Backbone based protocols such as ASCENT (Cerpa, A & D. Estrin) and SPAN (Chen B, et al.,2002), utilize local rules to assess a node's connectivity with its neighbors and decide whether the node should stay active to join a communication backbone. These protocols focus on maintaining network connectivity, and are best suited for ad-hoc multihop networks running at high data rates.

In a wireless sensor network setting, nodes are not just concerned with communicating with one another, but also in maintaining proper sensing coverage. A number of hybrid based protocols for wireless sensor networks that achieve this goal have been explored most recently in PEAS (Ye, F et al.,2003).

2.4.4 Sleep Scheduling

A number of different sleep scheduling protocols exist, each with their own set of advantages and disadvantages for different types of wireless networking systems/applications. While both 802.11 PSM [Ieee802.11-PSM] and S-MAC (Ye, W et al.,2002) are synchronous sleep scheduling policies, they are targeted towards two very distinct wireless networking domains. 802.11 PSM targets high data rate wireless devices existing in an infrastructure based WLAN, while S-MAC targets very low data rate wireless sensing devices existing in a wireless sensor network. As stated before, however, even with these types of policies available, users tend to prefer

higher throughput to the power savings they can achieve. One solution known as PAMAS (Power Aware Multi-Access Signaling) has proven to be very effective in reducing the power consumed in both types of networks (Singh, S et al, .1998). Using PAMAS, nodes are able to detect when a packet on the channel is destined for someone else and put themselves to sleep. PAMA Scan is combined with some of the other sleep scheduling protocols discussed below to produce even more power savings.

An asynchronous sleep scheduling protocol known as Low Power Listening (LPL) (Polastre, J et al,.2005) is quickly becoming the de facto standard for sleep scheduling policies in the world of wireless sensor networks. LPL operates just as any other asynchronous sleep scheduling protocol with one key difference. When LPL turns the radio on to check the channel for incoming packets, it does so very quickly (and reliably) so as to go back to sleep as quickly as possible. The time between each of these checks is known as a check interval. LPL only achieves significant power savings if many check intervals are allowed to pass before a packet is actually detected on the channel. This makes LPL ideal for the low data rate environment pertinent in wireless sensor networks.

While the protocols described above only scratch the surface on the number of sleep scheduling protocols that have been developed to date, they do provide a good reference to the different domains in which different types of sleep scheduling protocols are most applicable.

2.4.5 Energy Harvesting

Traditionally, energy has been harvested through the use of solar panels attached to the periphery of a wireless device. These solar panels are made up of photovoltaic cells that convert sunlight directly into electrical current (Brown Chappell, 2006). The primary disadvantage of solar panels, however, is that they are large and that they require sunlight in order to work. In most wireless networking situations (but not all), it is not practical to be limited by such constraints. Laptops should not have bulky solar panels attached to them and only be operational outdoors, while nodes deployed for a wireless sensor network to take wind measurements in the Sahara desert may welcome such a technology.

Most recently, advances have been made with a technology involving the use of piezoelectric materials. Piezoelectricity is the ability to create an electric current by suppressing certain types of crystal to mechanical stress. The primary advantages that piezoelectric materials have over solar panels is that they are small, do not require access to direct sunlight, and they operate with about a 70% mechanical to electrical transduction efficiency. Solar panels achieve only about 16-18% efficiency (Brown.Chappell, 2006).

While the science behind both solar energy harvesting and piezoelectric materials has been well understood for quite some time, their potential in the wireless networking domain are just now being realized

2.5. Wireless Sensor Networking: (Power Management Techniques)

2.5.1 Introduction

This section discusses the various power management techniques used by these standards for reducing the power consumed wireless networks. Many of the techniques explained are used in common practice to reduce the power of devices in both WLANs and WPANs. These techniques exist from the application layer all the way down to the physical layer of a traditional networking protocol stack. Techniques specific to a particular type of network are annotated as appropriate.

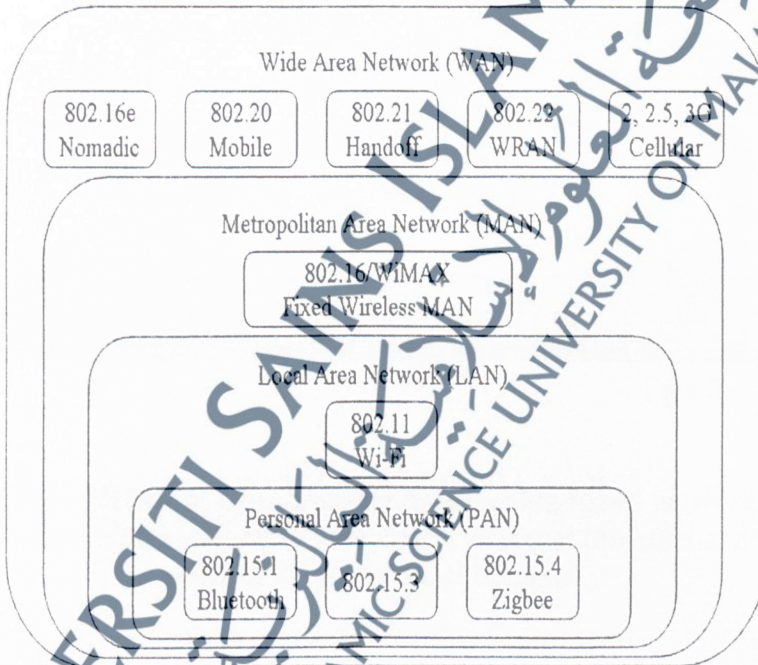


Figure 6: Wireless Standards

2.5.2. Application Layer

At the application layer a number of different techniques can be used to reduce the power consumed by a wireless device. A technique known as load partitioning allows an application to have all of its power intensive computation performed at its base

station rather than locally (Jones.C. E et al ,.2001). The wireless device simply sends the request for the computation to be performed, and then waits for the result. Another technique uses proxies in order to inform an application to changes in battery power. Applications use this information to limit their functionality and only provide their most essential features. This technique

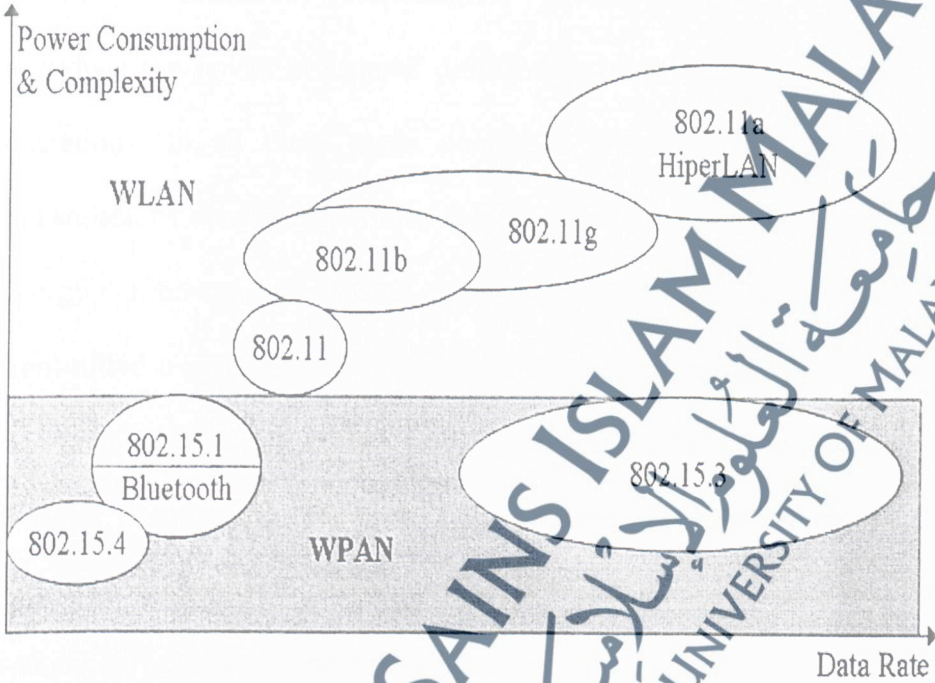


Figure 7: Power Consumption in IEEE 802 based networks might be used to suppress certain "unnecessary" visual effects that accompany a process (Jones. C.E et al ,.2001).



Figure 8: Backbone based routing

While these techniques may be adapted to work with any application that wishes to support them, a number of techniques also exist for specific classes of applications. Some applications are so common that it is worth exploring techniques that specifically deal with reducing the power consumed while running them. Two of the most common such applications include database operations and video processing (Jones. C. E et al.,2001). For database systems, techniques are explored that are able to reduce the power consumed during data retrieval, indexing, as well as querying operations. In all three cases, energy is conserved by reducing the number of transmissions needed to perform these operations. For video processing applications, energy can be conserved using compression techniques to reduce the number of bits transmitted over the wireless medium. Since performing the compression itself may consume a lot of power, however, other techniques that allow the video quality to become slightly degraded have been explored in order to reduce the power even further. Please refer to (Negri .L et al., 2004) for a more complete list of application specific power management schemes.

2.5.3. Transport Layer

The various techniques used to conserve energy at the transport layer all try to reduce the number of retransmissions necessary due to packet losses from a faulty wireless link (Jones. C. E et al.,2001). In a traditional (wired) network, packet losses are used to signify congestion and require back off mechanisms to account for this. In a wireless network, however, losses can occur sporadically and should not immediately be interpreted as the onset of congestion. The TCP-Probing (Tsaoussidis .V& H. Badr,2000) and Wave and Wait Protocols (Zhang. C& V.Tsaoussidis,2001) have been developed with this knowledge in mind. They are meant as replacements for

traditional TCP, and are able to guarantee end-to-end data delivery with high throughput and low power consumption.

2.5.4 Network Layer

Power management techniques existing at the network layer are concerned with performing power efficient routing through a multi-hop network (Jones.C. E et al 2001) & (Manoj. B. S & Siva Ram Murthy,.2004)&(Karl.Holger,.2003). They are typically backbone based, topology control based, or a hybrid of them both. In a backbone based protocol (sometimes also referred to as Charge Based Clustering), some nodes are chosen to remain active at all times (backbone nodes), while others are allowed to sleep periodically. The backbone nodes are used to establish a path between all source and destination nodes in the network. Any node in the network must therefore be within one hop of at least one backbone node, including backbone nodes themselves.

Energy savings are achieved by allowing non-backbone nodes to sleep periodically, as well as by periodically changing which nodes in fact make up the backbone. Figure 8: Backbone based routing.

Figure 8 shows how packets would be routed from node 3 to node 4 and from node 1 to node 2 using the backbone that has been established. Black nodes signify backbone nodes, while numbered nodes signify non-backbone nodes. Solid lines indicate paths along which a packet may travel, while dashed ones show paths that will not be followed. Given this backbone structure, packets traveling from node 3 to node 4 will have to travel through 4 different backbone nodes before reaching their

destination. If node 5 had been chosen as a backbone node as well, packets would only have had to traverse through 2.

Topology based routing protocols achieve energy savings in a different way. Their goal is to reduce the transmission power of all nodes in a network such that the network remains connected, but all nodes operate with the lowest transmission power possible. In a homogeneous network, this means that the transmission powers of all nodes are adjusted so that they are just within range of their nearest one-hop neighbor. In heterogeneous networks (i.e. networks with nodes of different type, power limitations, etc.) the transmission powers may be adjusted according to the needs of that network. A summary of the different types of topology based protocols that exist can be seen in Figure 9. As seen in the figure, certain location based topology control protocols attempt to use the topology of the network to provide the most energy efficient communication path possible. These protocols produce a sort of "Localized Power-Aware Routing" mechanism for the network. In some cases, providing this path means taking a larger number of hops through the network than would otherwise be taken when transmitting directly from one node to another. While this may seem counterintuitive at first, it makes sense if the amount of energy expended in transmitting to a node very far away is significantly greater than the energy expended when transmitting between a large numbers of nodes that are within closer range of one another. The rationale behind the other topology based protocols found in Figure. 9 can be found in (Bao. Lichun, & J.J.Garcia-Luna-Aceves , .2003).

Transmission power control schemes are combined with backbone based ones to produce a hybrid of them both. Using hybrid based protocols, the benefits of both backbone based and topology based routing protocols can be achieved simultaneously.

Section 5.1 explores a number of different power efficient routing protocols that use the ideas presented in this section.

2.5.5. Data Link Layer

The two most common techniques used to conserve energy at the link layer involve reducing the transmission overhead during the Automatic Repeat Request (ARQ) and Forward Error Correction (FEC) schemes. Both of these schemes are used to reduce the number of packet errors at a receiving node. By enabling ARQ, a router is able to automatically request the retransmission of a packet directly from its source without first requiring the receiver node to detect that a packet error has occurred.

Results have shown that sometimes it is more energy efficient to transmit at a lower transmission power and have to send multiple ARQs than to send at a high transmission power and achieve better throughput. Integrating the use of FEC codes to reduce the number of retransmissions necessary at the lower transmission power can result in even more energy savings. Power management techniques exist that exploit these observations (Jones.C.E et al, .2001).

Other power management techniques existing at the link layer are based on some sort of packet scheduling protocol (Alghamdi. M.I et al, .2005). By scheduling multiple packet transmission to occur back to back (i.e. in a burst), it may be possible to reduce the overhead associated with sending each packet individually. Preamble bytes only need to be sent for the first packet in order to announce its presence on the radio channel, and all subsequent packets essentially "piggyback" this announcement. Packet scheduling algorithms may also reduce the number of retransmissions necessary if a packet is only scheduled to be sent during a time when its destination is

known to be able to receive packets. By reducing the number of retransmissions necessary, the overall power consumption is consequently reduced as well.

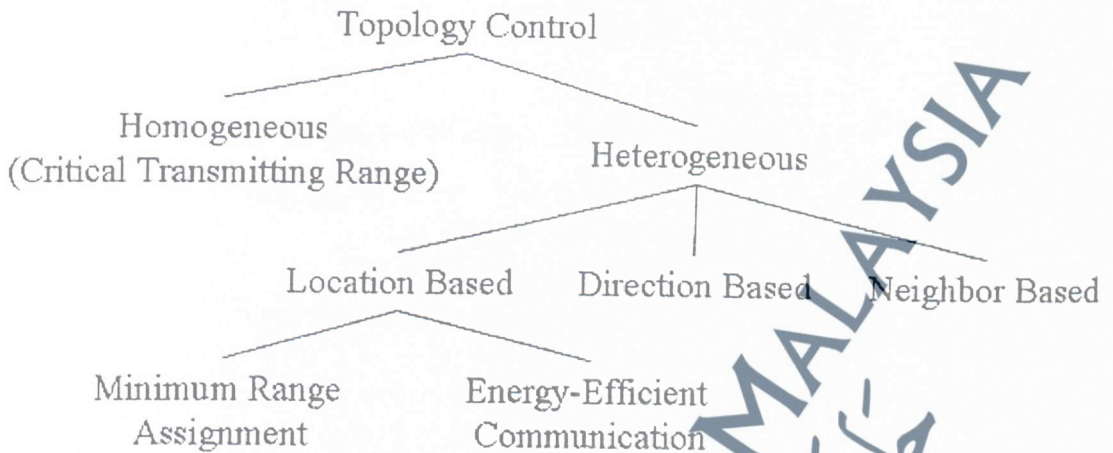


Figure 9: Topology based routing protocols

2.5.6 MAC Layer

Power saving techniques existing at the MAC layer consist primarily of sleep scheduling protocols. The basic principle behind all sleep scheduling protocols is that lots of power is wasted listening on the radio channel while there is nothing there to receive. Sleep schedulers are used to duty cycle a radio between it's on and off power states in order to reduce the effects of this idle listening. They are used to wake up a radio whenever it expects to transmit or receive packets and sleep otherwise. Other power saving techniques at this layer include battery aware MAC protocols (BAMAC) (Jayashree. S et al.,2004) in which the decision of who should send next is based on the battery level of all surrounding nodes in the network.

Battery level information is piggy-backed on each packet that is transmitted, and individual nodes base their decisions for sending on this information.

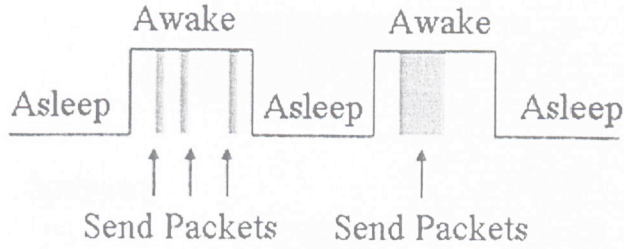
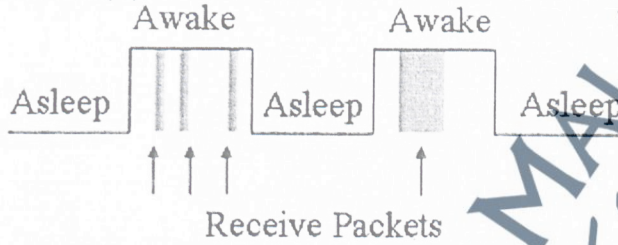
Transmitter:Receiver:

Figure :10 Synchronous sleep scheduler

Sleep scheduling protocols can be broken up into two categories: synchronous and asynchronous (Zheng, R et al, .2003) & (Dam, T, W & K, Langendoen, 2003). Synchronous sleep scheduling policies rely on clock synchronization between nodes all nodes in a network. As seen in Figure. 10., senders and receivers are aware of when each other should be on and only send to one another during those time periods. They go to sleep otherwise.

Asynchronous sleep scheduling, on the other hand, does not rely on any clock synchronization between nodes whatsoever. Nodes can send and receive packets whenever they please, according to the MAC protocol in use.

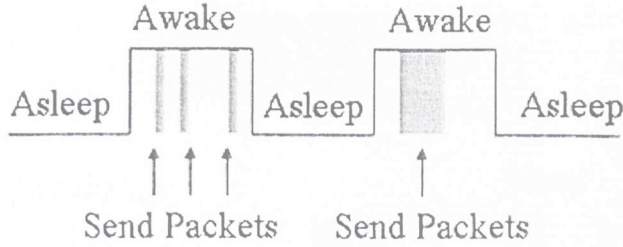
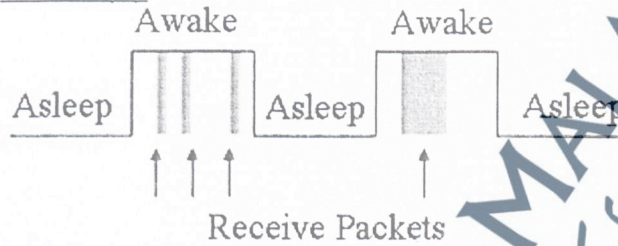
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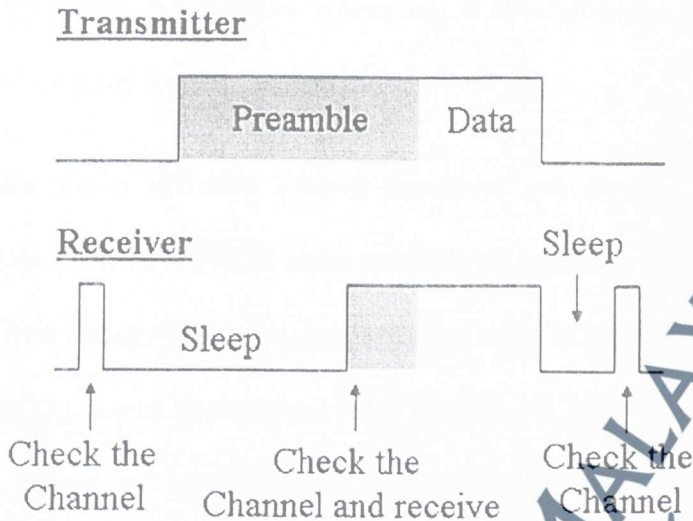


Figure 11: Asynchronous sleep scheduler

Figure 11 shows how two nodes running asynchronous sleep schedulers are able to communicate.

2.5.7. Asynchronous sleep scheduler

Nodes wake up and go to sleep periodically in the same way they do for synchronous sleep scheduling. Since there is no time synchronization, however, there must be a way to ensure that receiving nodes are awake to hear the transmissions coming in from other nodes. Normally preamble bytes are sent by a packet in order to synchronize the starting point of the incoming data stream between the transmitter and receiver. With asynchronous sleep scheduling, a significant number of extra preamble bytes are sent per packet in order to guarantee that a receiver has the chance to synchronize to it at some point. In the worst case, a packet will begin transmitting just as its receiver goes to sleep, and preamble bytes will have to be sent for a time equal to the receiver's sleep interval (plus a little more to allow for proper synchronization

once it wakes up). Once the receiver wakes up, it synchronizes to these preamble bytes and remains on until it receives the packet.

Unlike the power efficient routing protocols introduced in section 3.3, it doesn't make sense to have a hybrid sleep scheduling protocol based on each of the two techniques. The energy savings achieved using each of them varies from system to system and application to application. One technique is not "better" than the other in this sense, so efforts are being made to define exactly when each type should be used. Section 5.2 explores this concept further.

2.5.8. Physical Layer

At the physical layer, techniques can be used to not only preserve energy, but also generate it. Proper hardware design techniques allow one to decrease the level of parasitic leak currents in an electronic device to almost nothing (Jacome, Francky and Cattoor, 2003). These smaller leakage currents ultimately result in longer lifetimes for these devices, as less energy is wasted while idle. Variable clock CPUs, CPU voltage scaling, flash memory, and disk spin down techniques can also be used to further reduce the power consumed at the physical layer (Jones. C. E et al.,2001) &(Manoj. B. S &C. Siva Ram Murthy,.2004). A technique known as Remote Access Switch (RAS) can be used to wake up a receiver only when it has data destined for it. A low power radio circuit is run to detect a certain type of activity on the channel. Only when this activity is detected does the circuit wake up the rest of the system for reception of a packet. A transmitter has to know what type of activity needs to be sent on the channel to wake up each of its receivers. (Manoj. B. S & C. Siva Ram Murthy,.2004)

Energy harvesting techniques allow a device to actually gather energy from its surrounding environment. Ambient energy is all around in the form of vibration, strain, inertial forces, heat, light, wind, magnetic forces, etc (Brown.Chappell,.2006). Energy harvesting techniques allow one to harness this energy and either convert it directly into usable electric current or store it for later use within an electrical. In section 5.3 the latest technological advances in both low power design and energy harvesting techniques will be introduced.

2.5.9. Existing Standards

In the previous section, various techniques were explored that enable energy to be conserved at various layers within the wireless networking protocol stack. Some techniques were looked at in greater detail than others, and some techniques existing at the overall system level were not discussed at all. These power management schemes involve controlling the power state for peripheral devices such as the display or hard disk on a laptop computer. Others include cycling through the use of multiple batteries on a device in order to increase the overall lifetime of each individual one. Since these techniques do not explicitly exist at any single layer within the wireless networking protocol stack itself, they have been left out of this discussion. For more information on these and other power management techniques not discussed in the previous section, please refer to chapter eleven of (Manoj. B. S & C. Siva Ram Murthy, .2004) and its corresponding list of references.

2.5.10. Wireless LANs

The IEEE 802.11 standard specifies how communication is achieved for wireless nodes existing in a Wireless Local Area Network (WLAN). Part of this standard is

dedicated to describing a feature known as Power Save Mode (PSM) that is available for nodes existing in an infrastructure based 802.11 WLAN (IEEE802.11-PSM). PSM is based on a synchronous sleep scheduling policy, in which wireless nodes (stations) are able to alternate between an active mode and a sleep mode. As a wireless station using PSM first joins an infrastructure based WLAN, it must notify its access point that it has PSM enabled.

The access point then synchronizes with the PSM station allowing it to begin running its synchronous sleep schedule. When packets arrive for each of these PSM stations, the access point buffers them until their active period comes around again. At the beginning of each active period, a beacon message is sent from the access point to each wireless station in order to notify them of these buffered packets. PSM stations then request these packets and they are forwarded from the access point. Once all buffered frames have been received, a PSM station resumes with its sleep schedule wherever it left off. Whenever a PSM station has data to send, it simply wakes up, sends its packet, and then resumes its sleep schedule protocol as appropriate.

Although this feature of 802.11 networks is readily available on all devices implementing the full 802.11 specification, it is not very widely used. Many studies have been done to investigate the effects of using PSM and other power saving techniques for WLANs (Simunic.T.,2005)&(Bononi. L et al.,2001) & (Molta D.,2005) & (Gruteser. M et al, .2001) & (Anastasi. G et al, 2004) & (Chen. H & Cheng-W. H ,2004).

They all conclude that the throughput achieved with these techniques is significantly less than with them disabled. While PSM may significantly reduce the

energy consumed by a wireless station, many users prefer to sacrifice these power savings for an increase in performance.

2.5.11. Wireless PANs

The 802.15.1 standard [Bluetooth] provides provisions for power management as well. Wireless nodes in a Bluetooth network are organized into groups known as piconets, with one node dedicated as the master node and all others as slave nodes. Up to seven active nodes can exist in a piconet at any given time, with up to 256 potential members (249 inactive). All nodes operate using a synchronous sleep scheduling policy in order to exchange data. A beacon messaging system similar to the one described in Section 4.1 for 802.11 based networks is used to exchange messages between slave nodes and their master. All nodes are able to communicate with all other nodes within the Piconet, but messages between slaves must be sent exclusively through the master node.

Bluetooth defines eight different operational states, 3 of which are dedicated to low power operations. These three low power states are known as Sniff, Hold, and Park. While in the Sniff state, an active Bluetooth device simply lowers its duty cycle and listens to the piconet at a reduced rate. When switching to the Hold state, a device will shut down all communication capabilities it has with a piconet, but remain "active" in the sense that it does not give up its access to one of the seven active slots available for devices within the piconet. Devices in the Park state disable all communication with the piconet just as in the Hold state, except that they also relinquish their active node status.

2.5.12. Existing Power Management Standards in Wireless Sensor Networks.

The 802.15.4 (IEEE802.15.4) wireless networking standard provides low data rate, low power communication that is ideal for wireless sensor networking applications. It too is based on a synchronous sleep scheduling policy that periodically wakes nodes up and puts them to sleep in order to exchange data. The difference between this standard and the others is in the frequency with which nodes wake up, and the data rate (and correspondingly the required transmission power) with which they transmit data. A low power protocol stack called (Zigbee) has been developed on top of the 802.15.4

MAC layer in order to provide low power solutions for WSNs. As will be seen in section 6, many products for WSNs are being developed in industry with "Zigbee" compatibility as a very strong marketing point.

2.5.13. Current Research Efforts

In addition to the standards that have been developed for low power communication in wireless networks, ongoing research continues to provide innovative solutions to this problem. This section discusses some of the more recent advances and provides references to some of the older ones. Since it is impossible to list every single power management protocol that has ever been developed for wireless networking, only the most representative ones have been provided here.

2.5.14. Power Aware Routing

Backbone based protocols such as ASCENT (Cerpa, A& D.Estin) and SPAN (Chen .B et al, .2002), utilize local rules to assess a node's connectivity with its neighbors

and decide whether the node should stay active to join a communication backbone. These protocols focus on maintaining network connectivity, and are best suited for ad-hoc multihop networks running at high data rates.

In a wireless sensor network setting, nodes are not just concerned with communicating with one another, but also in maintaining proper sensing coverage. A number of hybrid based protocols for wireless sensor networks that achieve this goal have been explored most recently in PEAS (Ye.F.et al, .2003).

2.5.15. Sleep Scheduling

A number of different sleep scheduling protocols exist, each with their own set of advantages and disadvantages for different types of wireless networking systems/applications. While both 802.11 PSM (IEEE802.11-PSM) and S-MAC (Ye. Wet al .,2002) are synchronous sleep scheduling policies, they are targeted towards two very distinct wireless networking domains. 802.11 PSM targets high data rate wireless devices existing in an infrastructure based WLAN, while S-MAC targets very low data rate wireless sensing devices existing in a wireless sensor network. As stated before, however, even with these types of policies available, users tend to prefer higher throughput to the power savings they can achieve. One solution known as PAMAS (Power Aware Multi-Access Signaling) has proven to be very effective in reducing the power consumed in both types of networks (Singh. S et al .,1998). Using PAMAS, nodes are able to detect when a packet on the channel is destined for someone else and put themselves to sleep. PAMAS can be combined with some of the other sleep scheduling protocols discussed below to produce even more power savings.

An asynchronous sleep scheduling protocol known as Low Power Listening (LPL) (Polastre.J et al, .2005) is quickly becoming the de facto standard for sleep scheduling policies in the world of wireless sensor networks. LPL operates just as any other asynchronous sleep scheduling protocol with one key difference. When LPL turns the radio on to check the channel for incoming packets, it does so very quickly (and reliably) so as to go back to sleep as quickly as possible. The time between each of these checks is known as a check interval. LPL only achieves significant power savings if many check intervals are allowed to pass before a packet is actually detected on the channel. This makes LPL ideal for the low data rate environment pertinent in wireless sensor networks.

While the protocols described above only scratch the surface on the number of sleep scheduling protocols that have been developed to date, they do provide a good reference to the different domains in which different types of sleep scheduling protocols are most applicable.

2.5.16. Energy Harvesting

Traditionally, energy has been harvested through the use of solar panels attached to the periphery of a wireless device. These solar panels are made up of photovoltaic cells that convert sunlight directly into electrical current (Brown.C.,2006). The primary disadvantage of solar panels, however, is that they are large and that they require sunlight in order to work. In most wireless networking situations (but not all), it is not practical to be limited by such constraints. Laptops should not have bulky solar panels attached to them and only be operational outdoors, while nodes deployed for a wireless sensor network to take wind measurements in the Sahara desert may welcome such a technology.

Most recently, advances have been made with a technology involving the use of piezoelectric materials. Piezoelectricity is the ability to create an electric current by suppressing certain types of crystal to mechanical stress. The primary advantages that piezoelectric materials have over solar panels is that they are small, do not require access to direct sunlight, and they operate with about a 70% mechanical to electrical transduction efficiency. Solar panels achieve only about 16-18% efficiency (Brown.C.,2006).While the science behind both solar energy harvesting and piezoelectric materials has been well understood for quite some time, their potential in the wireless networking domain are just now being realized. Section 6 discusses some of these applications and what products are being manufactured to support them.