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Effective Power Consumption in MAC Protocols for Wireless Sensor Networks

Master's Thesis in Computer System Engineering

submitted by

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Affidavit

Herewith I, Angelika Augustin, born on the 14th of April 1983 in Klagenfurt, Austria, declare that I have written the present master's thesis fully on my own and that I have not used any other sources apart from those given.

Halmstad, January 2006

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Angelika Augustin

Acknowledgements

The journey is the reward
title of a book
written by Steve Jobs

I would like to thank my supervisor Urban Bilstrup for his support with this master's thesis and Changsu Suh for his help with the practical part. Furthermore, I would like to thank my parents for their mental and sympathetic support and help not only during my studying period.

Preface

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1st Keyword:	Wireless Sensor Network
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Abstract

Wireless sensor networks offer easy implementation, flexibility and mobility of hand held devices. Sensors consist of an internal power source, which is the great limitation for the life time and the usage of sensor networks. To increase the life time, sensors should stay in energy saving sleep mode as long as possible, because in sleep mode the radio is either shut down or working with less energy. Better energy handling is implemented in different power saving mechanism of common Medium Access Control protocols, which are evaluated and analyzed and further extensions and ideas to improve the energy efficiency are presented. Slotted PSM is simulated with the NS2 and compared to the WLAN 802.11 PSM technology and the results show that energy efficiency and power consumption are much better implemented and life time increases with the use of Slotted PSM.

Contents

List of Abbreviations

ACK	Acknowledgement
AP	Access Point
ATIM	Announcement Traffic Indication Map
BEB	Binary Exponential Backoff
BT	Bluetooth
CDMA	Code Division Multiple Access
CDS	Connected Dominating Set
CIT	Channel Idle Time
CITT	Channel Idle Time Threshold
CPU	Central Processing Unit
CTS	Clear - To - Send
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
DCF	Distributed Coordination Function
DIFS	Distributed Coordination Function Interframe Space
DTIM	Delivery Traffic Indication Map
EE-MAC	Energy-Efficient MAC Protocol
EIFS	Extended Interframe Space
FDMA	Frequency Division Multiple Access
FFD	Full Function Device
FHS	Frequency Hop Synchronization
GTS	Guaranteed Time Slot
HCI	Human Control Interface
IEEE	Institute of Electrical and Electronics Engineering
IP	Internet Protocol
IPS	Interpiconet Scheduling
M	Master of a Bluetooth Network
MAC	Medium Access Control
NAV	Network Allocation Vector
NS	Network Simulator
OSI	Open System Interconnection
PAMAS	Power Aware Multiple Access Protocol
PAN	Personal Area Network
PCF	Point Coordination Function
PIFS	Point Coordination Function Interframe Space
PSM	Power Saving Mechanism
QoS	Quality of Service
RFD	Reduced Function Device
RFID	Radio Frequency Identification
RP	Rendezvous Point
RTS	Request - To - Send
S	Slave of a Bluetooth Network
SEC	Seconds
SIFS	Short Interframe Space
SIR	Signal - To - Interference Ratio
TCP	Transmission Control Protocol

TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TIM	Traffic Indication Map
TSF	Timing Synchronization Function
WiseMAC	Wireless Sensor MAC Protocol
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network
WWW	World Wide Web

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1 Introduction

Interconnection between wireless and hand held devices becomes more important every day. In every surrounding it is nearly necessary to be connected to the Internet or to another device for data exchange to make life easier, more flexible and more efficient. In the case of a company meeting, each employee could reach his/her data all the time or in an emergency case or disaster connections between devices can be used efficiently to read out personal information or assurance data. Cable infrastructures are not useful in such cases when everyone has to be spontaneous and movable all the time. Research focuses more and more commonly on wireless connections, which can be used every time and everywhere, with or without predefined infrastructure.

Interconnection is necessary not only for users, but also for goods and products. Physical laws, specifications and limitations make it more and more important to use higher technology to protect and ensure correct conditions of goods and products, such as temperature, vibration, sound or pressure. Such a high technology is the implementation of a wireless sensor network which can be used to monitor the conditions of goods and products at different locations. A self-organising sensor network is used to collect data, which are then aggregated and analyzed by an external computer.

The wireless sensor network is made of sensors, which are small, low-cost devices, that can be produced in large numbers. A sensor typically consists of a radio transceiver, a small micro controller and an energy source such as a battery, which is the most critical part of such sensors.

The exact functionality of wireless sensor networks depends on the coverage range, external circumstances and the compatibility among different technologies and equipment. Nodes in such networks communicate via radio and the radio spectrum has to be shared among all nodes. Therefore different medium access methods and techniques were developed to offer usability and fairness between all devices. The goal of these protocols was mainly to maximize throughput and minimize transmission delay[3], but the new aspect in developing protocols is to reach a longer life time for a network, which is dependent on power sources. As the main advantage of a sensor network is flexibility, it should be possible that no external power supply has to be used. Single-hop networks can be built, which are controlled by a base station, that offers an infinite life time because it is connected to an external power supply. Nodes in a single-hop network are typically connected in a star topology, which offers the connected devices only less possibility of movements and flexibility. Implementations of multi-hop or ad hoc networks, which consist of peer-to-peer connected devices were found to be more useful in cases where the highest priorities are movability and flexibility. These devices, which are also called sensors, are battery based. Therefore, low power consumption has the highest priority to provide longer life time to

the sensor networks, because the battery life time is not expected to increase significantly in the next coming years[3].
Common protocols for short range wireless communication systems are Bluetooth, ZigBee and Wireless Local Area Network (WLAN), which can offer transmission distances of about 10m up to 100m. These technologies were introduced to offer connectivity, correct and successful transmissions among the devices and take care of synchronization, illustrated in chapter 3. All these common standards lack of effective power consumption for wireless sensor networks in the sense of increasing sensor's life time significantly, but some suggestions of better power consumption handling are presented in chapter 4. A simulation of two protocols and their power saving mechanism is illustrated in chapter 5.

1.1 Use Cases

1.1.1 The Poket Doktor System

The Poket Doktor System, which was introduced in 2002 by Bringham Young University, describes a Bluetooth enabled smart card. The idea is that personal information, such as insurance information, medical history, allergies and current medication are stored on a smart card and are reachable as fast as possible in medical emergency situations. Since a smart card is a small device, it can be placed in each personal pocket and read out by a doctor or medical personal if it is necessary [4].
The Poket Doktor System is a so called *Rendez-Blue* technology, which is a combination of Bluetooth and Radio Frequency Identification (RFID) functions. The technology offers a life time of about 20000 hours, while the only use of Bluetooth in idle mode will expire all the energy resources in about 1.5 hours.

- Bluetooth
  Bluetooth is a radio frequency standard, which uses the official 2.4 GHz frequency ISM Band. If a Bluetooth device is powered on, it will look for other Bluetooth devices via broadcast within its coverage range. If it receives an answer, a small network, called personal area network (PAN) or piconet will be built. A piconet typically consists of one master and up to seven active slaves. To increase the ability of more than seven connected devices within a network, scatternets can be built, which are a set of connected piconets and improve the great limitation of network size in Bluetooth. A disadvantage of Bluetooth is the inefficient power management and the long discovery time, which is normally about 10 seconds. This long discovery time is needed in Bluetooth to find all other devices in the coverage

range, exchange parameters and build the connections among each other, determine master and slave roles and synchronize within the network. In chapter 3.1, this technology is explained in more detail.

- RFID
  RFID technology is a cheap, low bandwidth and low power management technology. A typical RFID device consists of an antenna, a transceiver and a transponder and is called the RFID tag. A small amount of data can be sent between an RFID host and a mobile tag, mostly within a range of up to 30m. RFID tags are classified into active and passive devices. The active RFID tags, which consist of an internal power source, offer write and read possibilities and can store about 1MB of data. Passive RFID tags, which do not need an internal battery or energy source, provide a virtually unlimited life time, because they obtain the needed operating power from the received radio waves.[5]

- Rendez-Blue
  Rendez-Blue, which works with node rendezvous technique, offers the possibility to place a high power radio into a device, that is in low power state. Therefore, the low power RFID tag is used to awake the high power Bluetooth radio, see figure 1.1. The whole scanning and inquiry state of Bluetooth can be neglected, because RFID is used to transmit all Bluetooth specified parameters [5].

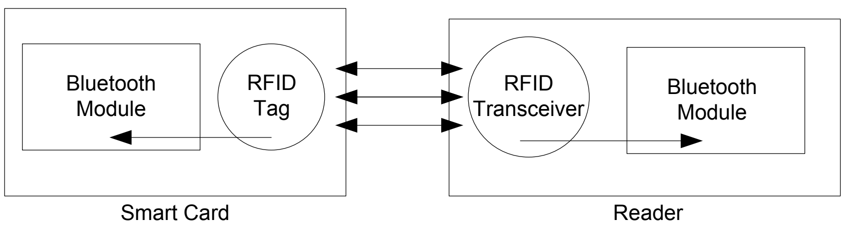

Figure 1.1: The Poket Doktor System

1.1.2 Industrial Automation

Sensors are used to control industrial machinery, processes and to ensure correct work procedures. When technical devices are used, states of machines can change faster and more efficiently than with human controlling. The most common automation can be seen in industrial robotics, which increase productivity due to faster and effective assignments but decrease labor opportunities for human beings. Therefore, industrial automation is in a critical state nowadays, although the advantages surpass the disadvantages, which are higher initial, repair and controlling costs of the sensors or robotics.

1.2 Project Definition and Goal

Due to the lack of effective power consumption in protocols, the main goal of the project is to find an efficient way to save energy in sensor networks. One of the best possibilities to attain that goal is to turn the sensors into energy saving standby or sleep mode. These sensors should be awaken by an internal signal in the most energy saving way only when they are needed, which will achieve a lot of power savings, energy efficiency and great power consumption. Moreover each sensor should be collected individually by a specific address. As each technology is based on the Open System Interconnection (OSI) reference model and its seven different layers, this Master's thesis will mainly focus on the Medium Access Control (MAC) layer, which is a sublayer of the second layer of the OSI model, that is called the data link layer. The project will evaluate and analyze the common MAC protocols according to their implementation of energy consumption based on different network topologies.

1.3 Problem Statement - Power Consumption

Power consumption is defined as the amount of energy per second, which must be supplied to an electrical device to maintain any operation or function. Each sensor in a wireless sensor network consists of different energy consuming sources, like the Central Processing Unit (CPU), the micro controller, the transmitter and the receiver, which also have different power consumption. Therefore, it must be ensured that each part of the device uses the provided energy efficiently and do not waste it to increase the sensor's, and consequently the network's life time. Each sensor consists of an internal power supply, such as a battery, which offers a limited level of energy and, therefore, a limited life time.
Transmission needs the most amount of energy within a network. The energy, required to send a packet depends on the distance between the source and destination. If the transmission is not successful, the source will send the packet again, with a higher energy consumption as a result. Therefore, it is necessary to avoid retransmissions as much as possible. One possible solution will be the use of a fixed specification of energy amount, which is used for transmission between the source and destination. This has the disadvantage that the energy level can be too high when the distance is shorter or the level can be too low, if the distance is too large for the specified energy. Another solution is to

use flexible exchange of energy levels between source and destination. This information is transmitted either in individual packets, which will increase the amount of packet exchanges in the network or the information has to be sent as an additional part of a packet, which will increase the length of packets.
Energy can be used more efficiently in the receiver, if the transmission will start as soon as possible and source and destination will know the exact time of transmission. The receiver has not to wait for the data and turn into energy-efficient sleep mode earlier. With the lack of the exact timing, receivers have to wait and listen for data, which will waste a lot of energy due to idle listening.

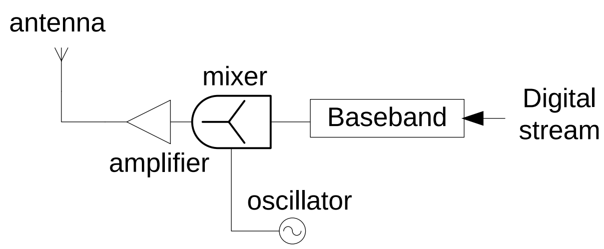

Figure 1.2: Simple Transmitter

A transmitter, shown in figure 1.2 consists of different power consuming parts. A bit stream is sent into the transmitter and converted into baseband frequency with different transformation technologies.
The baseband frequency is mixed with the carrier frequency, which is provided by the oscillator, in the mixer and forwarded to the power amplifier, which increases the amplitude of the signal. Finally the antenna transmits the signal over the air to the destination.
The oscillator needs a constant amount of energy to provide the carrier frequency. The energy consumed in the oscillator can not be decreased, the only power saving that can be done is achieved by shutting down the oscillator. The baseband conversion depends on the received data stream, the data bursts and their size, as well as on the load. The power amplifier consumes different amounts of energy dependent on the distance between the transmitter and the receiver within the network. Enough energy to ensure the right transmission range must be provided, so the energy consumption can only be limited when the distances are decreasing. The implementation of energy efficiency in a transmitter is very hard, because of the different parts of the transmitter, which depend on each other. Generally, the transmitter energy can only be decreased by minimizing its awake time, the awake time of the oscillator and/or the amplifier, i.e. less transmission time.

The sources of power consumption can be classified into computation and communication related perspectives [6]. The communication related sources are the transmitting and the receiving nodes. In general, the radio in each device has three different modes, namely transmit - receive - sleep. Each mode consumes a different amount of energy and the switch between the different states also consumes different amounts of energy, which depend on the protocols and the technology implemented.
The different energy consuming states are shown in table 1.1.

different energy consuming modes in sensors
Transmit Mode
Receive Mode
sleep mode
Switch from sleep to transmit mode
Switch from sleep to receive mode
Switch from transmit to receive mode

Table 1.1: Definition of Modes

In most common wireless technologies, the most amount of energy is consumed by the transmitter. Therefore, one of the highest priorities is the optimized design of a transmitter in a wireless sensor network [6]. The computation aspects involve the power required by the CPU, the memory and the micro controller, which are responsible for the correct employment of the protocols. The computation parts should be implemented carefully. In protocol design, a trade-off between communication and computation must be considered, because very often, the computation energy will increase with lower communication costs and vice-versa.

As an example, the power consumption in Bluetooth is about 1-100mW. The master consumes the most amount of energy, because it is awake all the time and administrates the piconet. When all connections between the master and the slaves in a network are built, Bluetooth offers each slave the possibility to join an energy-efficient mode. An example of energy consumption in the different Bluetooth modes is shown in table 1.2. The functions of each device and the Bluetooth protocol are explained in chapter 3.1.

Modes	Average Energy Consumption
Hold Mode	61mW
Hold Mode Entry	68mW
Hold Mode Exit	216mW
Park Mode	61mW
Park Mode Entry	77mW
Park Mode Exit	126mW
Sniff Mode	61mW
Sniff Mode Entry	78mW
Sniff Mode Exit	194mW

Table 1.2: Energy Consumption in different Bluetooth Modes[1]

Different common applications were tested and analyzed in [1]. It shows the different power consumption levels used in WLAN and Bluetooth to handle E-Mail, Telnet, World Wide Web (WWW), the transmission of an MP3 audio file and an MPEG4 video stream. The graphs in figure 1.3 and figure 1.4 show the energy consumption of Bluetooth and WLAN with and without enabled sleep mode.

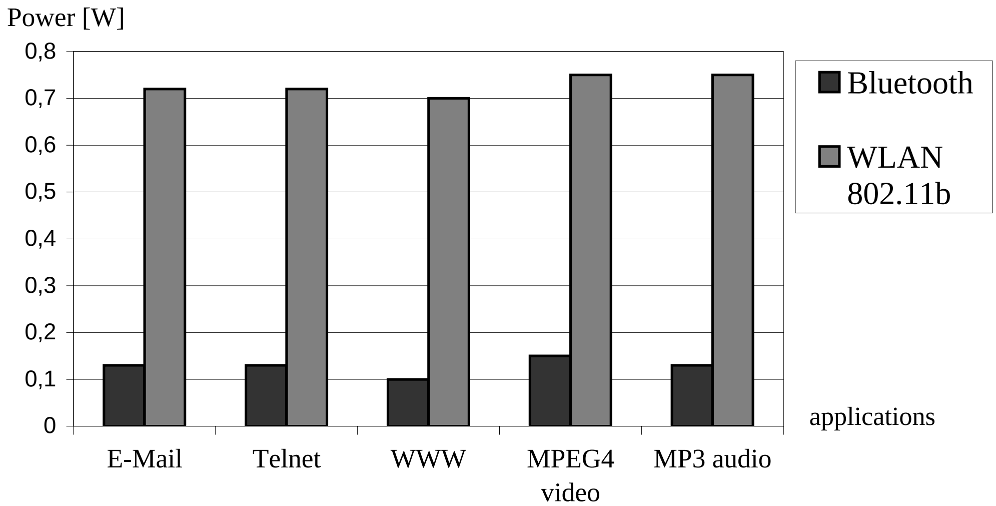

Figure 1.3: WLAN - Bluetooth Comparison I without energy-efficient sleep mode[1]

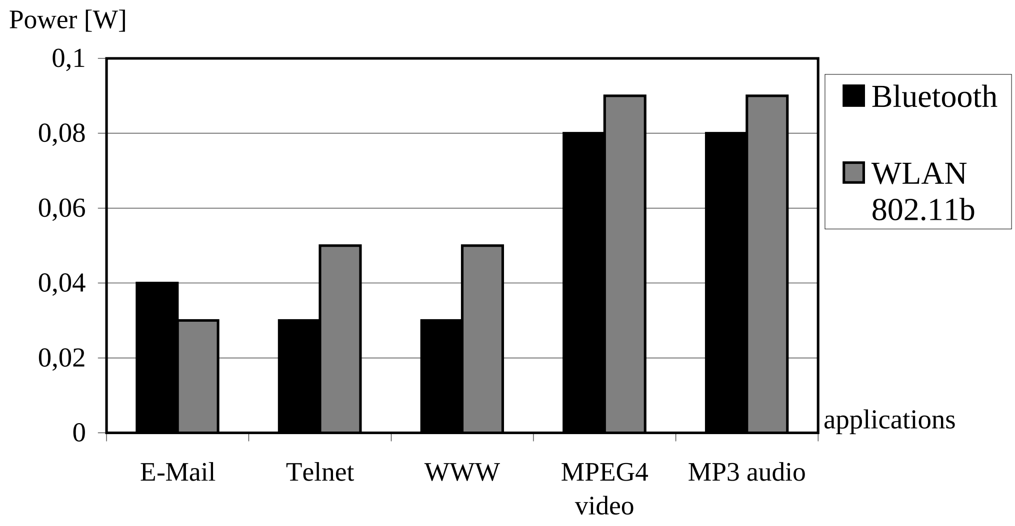

Figure 1.4: WLAN - Bluetooth Comparison II with energy-efficient sleep mode[1]

ZigBee, introduced in chapter 3.3, is a low power short range wireless communication standard, which offers the implementation of three different devices, that have different priorities and functions. Table 1.3 shows the consumed energy required by each device in the different modes. In the transmit mode, a device transmits data, while in the receive mode, a device listens and waits for data and during the sleep mode, a device is not awake and do not follow the traffic within the network.

	Reduced Function Device	Full Function Device	PAN Coordinator
Idle	9µW	10.5µW	10.5µA
Receive	117mW	124.5mW	144mW
Transmit	102mW	109.5mW	129mW

Table 1.3: Energy Consumption in ZigBee[2]

As ZigBee is a typical ad hoc network protocol, it is very useful in a lot of different applications. Table 1.4 shows three examples of applications, where sensors use a 3V coin cell battery, and their life time according to their transmission rate:

Application	Transmission Rate	Life Time
Light Switch	6ops/day	10 years
Water Level Sensor	1op/hour	1-2 years
Patient Heart Monitor	1op/5ms	1 day

Table 1.4: Applications and their life time[2]

ZigBee provides usability in single-hop networks [7] and is compared to WiseMAC, explained in chapter 4.3. WiseMAC requires 7µW in the receiving sensor node (with additional preamble sampling) compared to ZigBee, which consumes 13µW. The reception of packets was periodically handled every half second and ZigBee consumed about 85% more energy than WiseMAC.

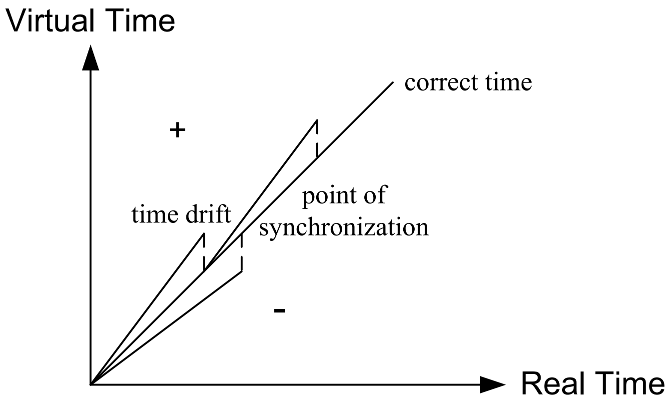

Figure 1.5: Time Drifts in Wireless Sensor Networks

Due to the sleep mode, the internal clock time in each device will drift apart from the Real Time and has to be synchronized again, explained in figure 1.5. Real Time is the actual clock time and the Virtual Time is the time running in the local clocks of each device. The clocks providing the Virtual Time try ineffectively to imitate the Real Time. The drift for a clock can be either positive or negative, which means the local clocks run either too fast or too slow. In single-hop networks, the synchronization is handled by base stations, which periodically transmit beacons, that correct the local clock. Each node is aware of beacons and synchronizes its clocks with the new received clock time. In ad hoc networks, beacons can also be used, but this causes a lot of problems. If each node transmits beacons, the network will be overloaded, collisions occur and energy will be wasted. If just one node handles the beacons, the network topology will be like a single-hop network and all nodes have to be connected to this device. The flexibility and mobility of all the nodes in an ad hoc network make the synchronization in protocols more complicated. Typically, each node in an ad hoc network assumes the Real Time due to information received from its neighbors and its own clock. The correctness of the clock can be given, because the time in each device depends on its neighbors time, that also depends on their neighbors time and so on. All nodes converge into a common opinion of time if the correct clock synchronization algorithm is applied.

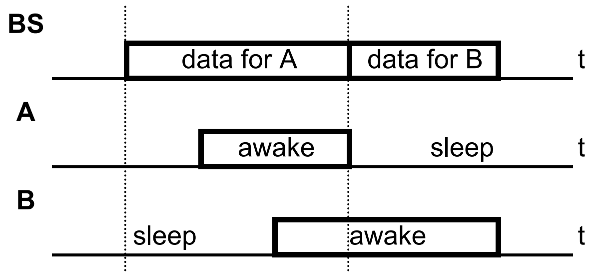

Figure 1.6: Single-hop Network without Synchronization

Let us assume that within a single-hop network synchronization is not handled at all as shown in figure 1.6. Nodes will turn into the sleep mode and wake up after a defined period. The base station will know the length of the sleeping period and send out data at the wake up time of the node or listen, if the node has to transmit data. Due to the drift, the base station has to wait for the node to wake up, which will increase the idle listening time for the base station and waste bandwidth. From the power consumption perspective, this is not really a problem because the base station is connected to an external power supply, which provides infinite life time. Energy waste will occur, if a node wakes up earlier than its specified time interval. Thus the node has to stay awake to receive data from the base station, which will consume energy, due to idle listening. The node's life time will decrease and therefore the whole network's life time decreases. To ensure the correct timing and decrease the energy waste, all the nodes wake up earlier than their specified sleep period has ended.

The most power efficiency is reached, if all the nodes in an ad hoc network know all about each other to build an efficient schedule, which handles transmissions among all nodes. Therefore, all the nodes have to exchange information within the whole network. A node will need a very large storage to handle all the information and the control data have to be exchanged very often to keep the schedules up-to-date. This involves an overload in the network traffic due to the high amount of control data, which have to be exchanged and that makes the idea unsolvable because the sensors typically have relatively low storage and communication capacity.

Nodes are transmitting different network relevant control data among each other. If they exchange these control data with all nodes, the network traffic will be very large. In addition to the overload there will be too less capacity in the middle of the network. Capacity bottlenecks will decrease the whole network traffic and aperture of important data. As solution, the information is not exchanged between all nodes. It is handled locally in each device and exchanged just between adjacent sensors to acquire time and transmission schedules.

2 Theoretical Background

2.1 OSI Model

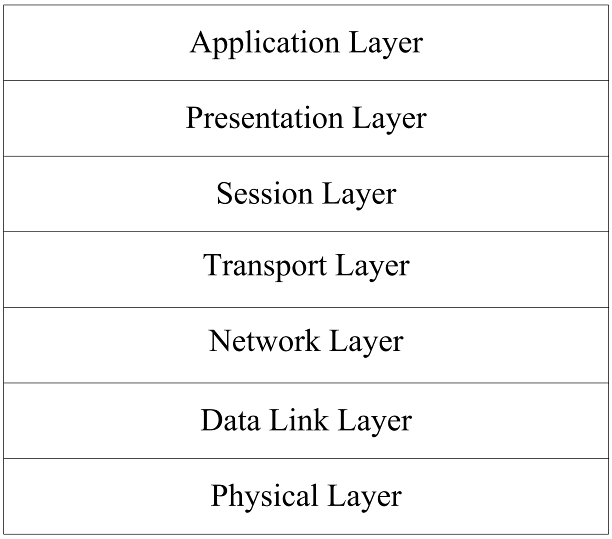

Figure 2.1: OSI Model

The OSI model consists of seven layers, which describe the interconnection of network communication, see figure 2.1. Transmission between two users starts in the application layer, and the process continues executing one layer after another until the bottom is reached. Data flow via a link between the physical layers of both users either in a wired or wireless environment and executes the layers until the top is reached again.

Each layer proposes different functions, which should be handled by a protocol, that depends on the lower layer and forwards new achievements to the upper layer. To design new protocols and technologies, the model should be focused on to develop successful functionality, compatibility and interconnection. In general, the functions implemented in the hardware consist of the specifications in the lower layers, while the layers on the top are represented in the software.

Each layer provides different requirements to the protocols [8]:
The *Physical Layer*, which defines the pretensions to ensure a link between devices, specifies cable or wireless requirements, interfaces and physical conditions.
The *Data Link Layer* encodes and decodes the received bits from the physical layer into frames and ensures reliable point-to-point and point-to-multipoint connections. Destinations are addressed by their hardware address, called MAC address.

The layer is divided into two sublayers:

- MAC Layer
  It controls and handles how to gain data in a network. Each data frame is increased by the source and destination MAC address and a checksum variable to control errors in the frame.

- Logical Link Layer
  Frame synchronization, flow control and error checking of the bit stream are handled by this sublayer.

The *Network Layer* is responsible of the successful arrival of the information at the destination. Routing through the network and algorithms for logical link and path control are offered by the correct addressing of devices. The frames are put into packets, addressed with a network address, usually the Internet Protocol (IP) address and are finally forwarded.
Data should be transparent between users, which is provided by the *Transport Layer*. The most common protocol is the Transmission Control Protocol (TCP), which implements connection-oriented transports. The layer checks unreachable destinations and changes routes to ensure correct end-to-end reachability.
The *Session Layer* is the interconnection point between hardware and software or among applications. It provides compatibility, sets up and restarts sessions, manages time synchronization, user preferences and name recognition.
The *Presentation Layer*, which is not implemented in all technologies, translates all data into a language, that is understandable by all layers of the OSI model.
The application and all its functionalities are specified in the *Application Layer*, such as user authentication and privacy limitations. Common applications of this layer are the File Transfer Protocol (FTP) or Telnet.

2.2 MAC Protocol

The implementation of the MAC protocol is based on the MAC layer, one of the sublayers of the second layer in the OSI model, whose functionalities are introduced in chapter 2.1. Generally, the chief sources of energy consumption in a mobile device are the CPU, the transmitter and the receiver. The radio, which is used to transmit data and control parameters, has three different modes; namely transmit, receive and standby or sleep, which also need different amounts of power and energy. Radio in the standby or sleep mode consumes the least amount of energy of all different states. The highest optimization priority of research in wireless sensor networks is to achieve a very low power consumption of about µW [9], which can be reached by longer sleeping times and effective power handling in transmit and receive mode.

There are principles that may be observed to conserve energy at the MAC layer [10]:

- Collision avoidance
  Collisions during transmission should be avoided as far as possible, because they result in retransmissions, requiring unnecessary energy consumptions. Since link error control, which provides successful end-to-end transmission, is implemented in the higher layers of the OSI model, it is obvious that collisions cannot be completely eliminated.

- Idle listening
  Idle listening means that the radio of a device is powered on all the time. Nodes cannot turn into energy-efficient sleep mode, because they are always aware of transmissions. The idle listening should be avoided, because it consumes a lot of energy. Unfortunately, the energy is often wasted, due to the fact that nodes receive packets, which are not even destined for them. This problem can be solved with the use of specified sleeping schedules.

- Switching between different modes
  Although the sleep mode is energy saving, it should be used in only profitable situations. Switching between modes also needs energy, and if the switching occurs too often, more energy will be consumed than conserved. The length of the sleeping period is very important, but it must be decided as a trade off between the idle listening of the transmitting node and the idle listening of the destination node.

- Sleep mode
  In a single-hop network, where a base station controls the network traffic, handles connection and packet requests and buffers packets, the nodes can turn into energy saving sleep mode. They are only awake when packets are available for them. To awake and inform a sleeping node about buffered packets, the base station periodically sends beacons with general and detailed information and also uses them to synchronize nodes within a network.

- Bandwidth reservations
  If bandwidth reservations are used in a network, it will be more efficient to reserve more time slots or frequency bands with a single reservation packet. If a node has to send two data packets to the same node, it should have the possibility to reserve more time slots, depending on the size of the transmitting data packets. For reservation, it would be more effective to send out one packet, which contains the information, about the amount of time slots the node will need for successful transmission. A mobile would have larger chunks of bandwidth, which would reduce reservation overhead and implement better bandwidth handling.

- Schedules
  In multi-hop networks, where each node computes a schedule independently to handle transmission and reception, heuristic schedule algorithms have to be used. The storage in each device has to be large and all nodes have to be aware of topology or network situation changes to adapt their schedules in order to be up-to-date. Therefore, a general schedule algorithm, which is implemented in a base station is more energy efficient for the network, but of course not useful in ad hoc networks.

2.3 Internal Signals

Generally, a signal, which uses a certain amount of bandwith, is the transportation medium of data between different devices. There is no standard classification for signals, but mainly they can be categorized into internal and external signals.
Focusing on wireless sensor networks, it can be said that internal signals are used to handle traffic between the hardware and applications within a sensor. Therefore, external signals are used among sensors to transmit data and information within a network.
This Master's Thesis uses another definition, which classifies the signals according to their implemented functionalities, see table 2.1.

Internal Signals	External Signals
protocol-based schedules time synchronization	not protocol-based no schedules no synchronization
ZigBee WLAN Bluetooth	passive RFID

Table 2.1: Definition of Signals

Internal Signals are protocol-based, which means they can be referenced to the OSI model. The implemented technology is based on the seven different layers and offers suitability for different kinds of network implementations. Typical internal signals offer schedules and a correct time plan for all the nodes within the network. Schedules can be implemented in either each node or in the base station of a network. Due to the problem of time drifts, different technologies handle time synchronization and offer correct timing. Examples of technologies that use internal signals for waking up nodes from sleep mode are ZigBee, Bluetooth and the WLAN technology. Unlike internal signals, external ones do not offer controlled structures.

2.4 Wireless Sensor Network

A Wireless Sensor Network (WSN) is self-organizing and consists of autonomous devices, generally sensors. These monitor different conditions of goods or the environment. The connections between the devices are based on a wireless medium. Sensors are usually small and cheap devices. Due to their low costs and their possibilities of use, they become more and more attractive in today's technology. They consist of one or more radio systems, transmitters and receivers, a small storage and an internal power source. Sensors are typically used to monitor conditions and store them for a short time to forward the data later to an external station.

The typical factors for characterizing and implementing a WSN are costs, range, data rate and life time. There are many parameters to tune for achieving an optimal working sensor network. One of the important parameters is the correct choice of the operating frequency and the handling of the radio frequency channel in an efficient way. To avoid frequency overlapping with other wireless standards, the used frequency must comply with government regulations and wireless standards. Channels can be disturbed by interference and bad propagation conditions, limiting the network's performance. The correctness of the received data at a node depends on the received power levels.

2.4.1 Single-hop Network

In single-hop networks data is transmitted only between a base station and one node. Nodes cannot transmit data between each other, they have to send data to the base station, which forwards the information to the destination. A base station is managing the traffic within a network and coordinates connections, schedules, time synchronization and frequency use. Typical single-hop networks are the infrastructure network, used in WLAN or piconets introduced in Bluetooth.

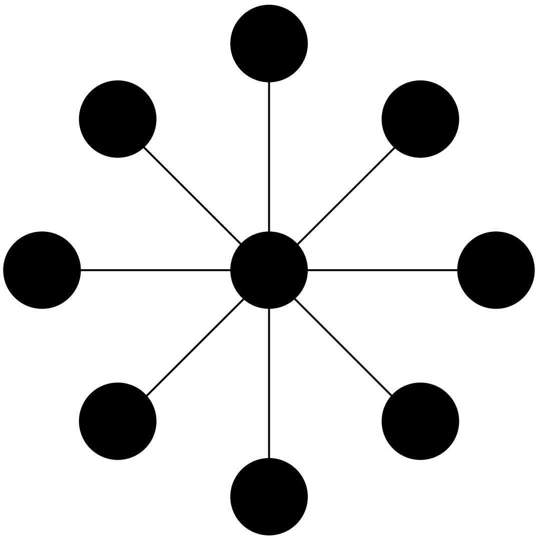

Figure 2.2: Star Topology

The base station is fixed in its position, due to its use of an external power supply. Therefore, it offers infinite life time. The other nodes in the network are movable and consist of internal power sources, like batteries. The connections are built in a star topology, see figure 2.2 and the ranking of the transmission of the nodes is specified by each standard or technology.

The advantages of a star topology are that it is implemented fast and easily. The main disadvantages are that the number of nodes within such networks is limited and if the base station does not work properly, the whole network is affected. So the whole network performance generally depends on the base station's characteristics.

2.4.2 Ad hoc Network

An ad hoc network consists of autonomous nodes, which handle traffic, connections, synchronization and transmissions on their own. Unlike the single-hop networks, the ad hoc network does not have a base station. All nodes can be either static or mobile and very large distributed networks can be built.

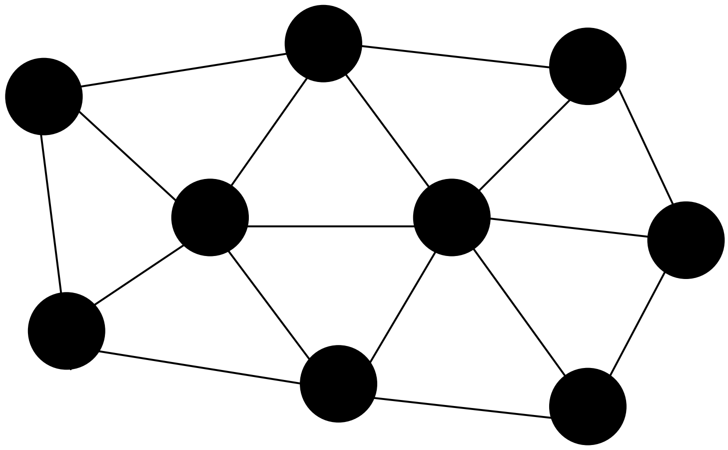

Figure 2.3: Peer-to-Peer Topology

A device will be connected to more than one device, building a peer-to-peer topology, figure 2.3. Due to the mobility of all nodes, links can break very often and each device must have the ability to build new efficient links very fast. The implementation of a protocol must consider the flexibility of each node, which is the main advantage of ad hoc networks.
Flexibility makes the synchronization matter very hard, because there is no standard clock and time, which can be broadcast. To offer successful transmissions, most ad hoc protocols use schedules, which are managed by each device individually. The devices exchange their transmission schedules with their neighbors and update their schedule when they receive new information.
Great advantages of an ad hoc network are the mobility and flexibility of each node, due to the easy implementation of connections. One of the disadvantages, which is one of the main research topics, is the problem of power consumption and the limited energy level provided by the internal power sources of sensors. The idea is to extend the sensor's life time and therefore the whole network's life time.

2.5 Channel Assignment

A wireless channel defines the medium over which the data is transmitted. As a network consists of a lot of devices, they have to share the transmission channel. The parting of the channel is a great problem, which is solved by three different technologies:

- Time Division Multiple Access (TDMA)
- Frequency Division Multiple Access (FDMA)
- Code Division Multiple Access (CDMA)

In TDMA, the frames are divided into time slots and each node is allocated to one or more time slots, while in FDMA each node is allocated to a particular frequency. In CDMA, each data frame is encoded with a code associated with the channel. The technologies can be used individually or as a combination and they all limit the number of the devices, which can share the same channel simultaneously. Thus the reuse of the channel with the same time slot, frequency or code, is very important to offer a high amount of devices within a network.

A medium access method and spatial reuse are defined by different implementation constraints[11]:

- Adjacent devices
  The devices, which are neighbors, are not allowed to use the same time window, frequency or code.
- Same neighbor
  If two devices have one common neighbor, which is connected to both devices, they have to use different time window, frequencies or codes.
- Broadcast
  During a broadcast transmission, all the neighbors and nodes, adjacent to the neighbors, have to avoid the use of the same time window, frequency or code to prevent collisions.
- Links to same device
  To handle successful transmissions, two or more links to the same node should have different time window, frequencies or codes. If the links are in use at the same time, the destination could not handle the data.

- Co-Interference
  The distance between links, which are using the same time window, frequency or code either to offer half-duplex or full-duplex communication, must be large enough to avoid interference.

- Directional antenna
  By using directional antennas in each sensor, the same conditions can be used, which would limit the amount of constraints very much.

- Handshake
  Handshake communication involves the need for bandwidth and channel reservation by sending requests to the destination and waiting for the respond until transmission can start. This increases the awareness of constraints, because more packets are used and the percentage of collisions rises.

A general algorithm, which solves all constraints in wireless ad hoc networks is given in [11]. It defines the allocation of channels and their reuse. The algorithm, which tries to use as few channels as possible, can solve up to 144 potential assignment problems by using the defined eleven atomic constraints and the following constraint set. A graph coloring problem [12] is used to show the problem statement in a better way. Therefore, vertices, which are ordered in different ways and have different amounts of neighbors, should be colored without the use of the same color in adjacent vertices.
The algorithm consists of two phases: labeling and coloring phase.
In the labeling phase, the nodes are numbered and in the coloring phase, they are assigned with three different possible heuristics:

- random
  The vertices are labeled and colored in random order.

- Minimum Neighbor First (MNF)
  The vertex with the minimum amount of neighbors is labeled at first, while coloring starts with the highest labeled vertex.

- Progressive Minimum Neighbor First (PMNF)
  The nodes are labeled in the same way as in MNF and during the coloring phase a vertex is chosen but ignored and all the other nodes are colored at first. So the nodes' colors change all the time.

3 Internal Signals

3.1 Bluetooth

The 802.15.1 standard, which describes the Bluetooth technology, uses the unlicensed ISM Band from 2.400GHz to 2.480GHz and a fast frequency hopping scheme to ensure the usage of the whole ISM Band. The band is split up into 79 separated channels, which have 1MHz allocated for each channel. The Bluetooth standard can reach a transmission rate up to 3Mbps.[13]
Bluetooth is used to build wireless connections between devices to form a Wireless Personal Area Network (WPAN) named piconet. The devices, which can either be mobile or static, are mostly mobile phones, hand helds or notebooks. It is built in ad hoc manner, which means a connection is established whenever two devices or applications come into range and want to exchange data. Each device can be identified by a unique specific address, the Bluetooth device address, namely BD_ADDR.

3.1.1 General Technology

The Bluetooth technology supports synchronous and asynchronous communication channels, where the synchronous communication channels are used for voice communications and the asynchronous communication channels are used for data communications.
The typical characteristic of a piconet is the master/slave relationship. The master, which is the control point of the network starts transmissions, controls traffic by a polling scheme and establishes synchronization. Within a piconet each connection is generated in either point-to-point or point-to-multipoint manner between the master and the other devices, called slaves. The point-to-point transmission, that is placed between the master and one slave uses synchronous channels, which are reserved by the master at regular intervals. Asynchronous channels are used for broadcast transmissions, which do not need reserved slots.[14]

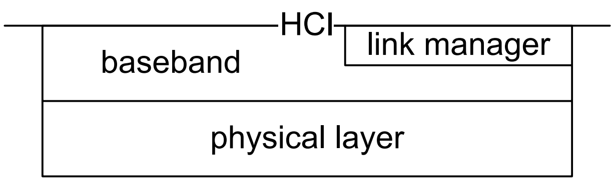

Figure 3.1: Physical and Data Link Layer of the Bluetooth Protocol Stack

The baseband protocol can be seen as the MAC layer, see figure 3.1, which is implemented in the logical link controller. The *Time-Division Duplex (TDD)* scheme, which is used to ensure full-duplex and collision-free characteristic of Bluetooth, divides the wireless channel in slots, each 625 µs long. The data packets are exchanged at different frequencies according to the frequency hopping technology. The size of the packets is usually one slot, but it can be increased up to 5 slots. The slots are numbered to define transmission and reception slots for master and slaves. Even numbered slots are reserved for the master transmission/slave reception and odd numbered slots are used for slave transmission/master reception.[15]

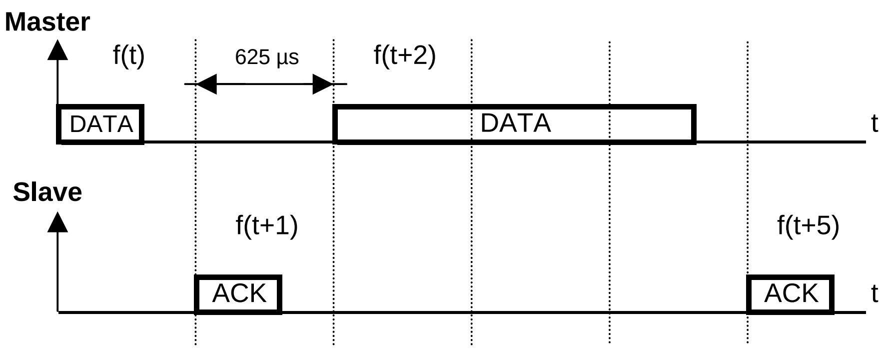

Figure 3.2: Time Division Duplex Scheme

As seen in figure 3.2, the master is sending a packet to a slave at the beginning of the time slot, using a defined frequency f(t). In the next slot, after 625 µs, the transmission of the slave can start at frequency f(t+1), which sends an acknowledgement package (ACK) to the master, to inform it about the correct reception of the packet. If packets are longer than one slot, the master may use several time slots without changing the frequency. For example, the packet, which is 3 slots long, is sent with frequency f(t+2) and the ACK is sent back with frequency f(t+5). This ensures the independence of the packet length and the used frequency.

A great disadvantage of Bluetooth is, that it is developed without any polling scheme standard, which effects the Quality of Service (QoS) in the network. The implementation of the polling scheme differs from vendors and applications. The ranking of the transmissions between the master and the slave in a piconet can be random or other different techniques can be used, like Longest or Shortest Queue or even the Round-Robin algorithm. Due to the different algorithms, the performance of the network differs, which makes energy efficiency and effective power consumption optimization very hard.

3.1.2 The Bluetooth Clock

Each Bluetooth device has its own internal clock, which is needed for correct transmission and reception time. During the life time of piconets, the internal clocks drift apart and have to be synchronized for each transmission.
The phase in the frequency sequence is determined by the master's clock, which is a free always running native clock, that has nothing in common with the daily time. It is never adjusted or stopped. The synchronization process uses offsets, which consist of the correct clock time. The synchronization happens by comparing the exact and estimated receiving time of the packets and afterwards the correct clock time is set.

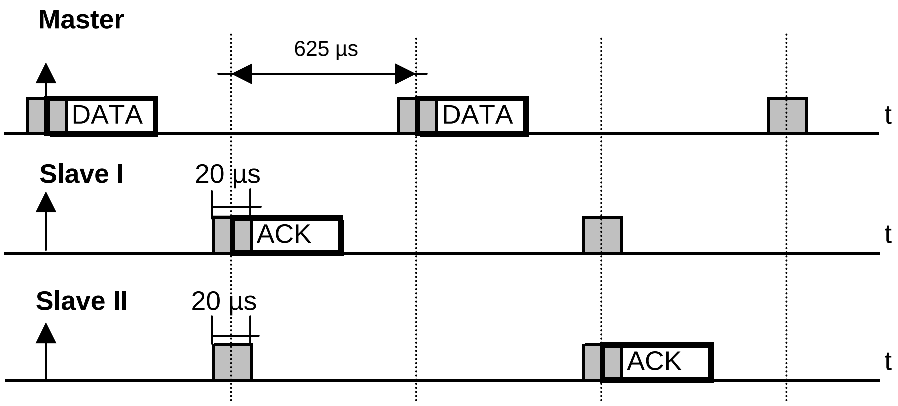

Figure 3.3: Uncertainty Window

The master sends out data packets in an interval of 1250 µs, which is defined by TDD. So each slave has to listen for packets at the same interval with a shift of 625 µs. Due to the drift of the clocks in the devices, each slave starts to listen around 10 µs earlier, to ensure correct reception time. This time period is called uncertainty window, explained in figure 3.3, which can be changed by the slave's behavior. If a slave has not received packets for many slots, it will increase the length of the uncertainty window.[15]

3.1.3 Power Consumption

Generally, the power consumption is dependent on the range, which can be up to 10m or up to 100 m, depending on the implemented Bluetooth class. The longer the range is, more energy is consumed and needed for transmission.

The main steps in building a piconet are two important states of devices, the inquiry and paging state. During these states, the master looks for slaves, which are in range, and builds up the connections to them. As these states are very power consuming for master and slaves, the slaves can turn into different energy-efficient sleeping modes:

- hold mode
- park mode
- sniff mode

Generally, internal signals and/or commands are used by the link controller to coordinate the switch between the different modes. During the inquiry state, a device listens for packets, which are addressed to it. If there are no packets forwarded to it, the receiver turns into sleep mode. It awakes periodically to listen for packets in each receiving cycle. If a transmission takes place, the receiver will stay awake until the end of transmission.
To save energy during the energy-efficient life time of a Bluetooth device, the device can turn into hold mode. They do not transmit or receive in this mode. Master and slave define the time, how long a slave can stay in hold mode. After the defined time the slave will awake and has to double its uncertainty window to be aware of the master's transmission and synchronize its clock. This mode is not really energy-efficient, because the drift between the clocks is very high. If the defined time between master and slave is too long, the whole inquiry and paging states have to take place again to synchronize the device's clock and establish the connection again. The hold mode is more or less a typical shut down of a device.[16]
The difference between the hold, park and sniff modes, is that the devices in the hold mode really sleep. In the park mode, the devices periodically awake and do not only listen for packets but also synchronize their clocks periodically. Therefore, they also use the double sized uncertainty window so that they do not lose the connection to the network. In the sniff mode, the devices listen to the network traffic on reduced rate and reduced duty cycle.[17]

During the paging state, the binding of a slave to the master takes place. Therefore, the master sends out its device access code, in the so-called ID packet, using a lot of different frequencies to look for other devices. The code is sent twice in one slot at different frequencies by the master while the slave listens at one frequency for 20ms. If the slave did not receive the ID packet, it switches to the next frequency and listens at this frequency for 20ms. The master and slave are binded to each other when the same frequency is found.

After successful searching, the receiver also answers with an ID packet, followed by the master's frequency hopping synchronization (FHS) packet. This packet involves time and frequency synchronization and is sent at the frequency, that was detected by the receiver and was used to respond to the master's ID packet.[15]

In a Bluetooth network, the master consumes the most energy. The time how long a master is awake depends on different applications, but mainly a master starts transmission and polling requests, which consume a lot of power. The basic idea to save power is the role switch of master and slave, which will decrease the power consumption in the old master and increases the life time of a piconet. During a master/slave switch not only the roles of two devices are exchanged but also a new piconet topology, described in chapter 3.1.5 is formed.
The power consumption during transmissions can be seen as a function of the distance, see table 3.1, which depends on the different Bluetooth classes [18]:

Class	Distance [m]	Output Power [mW]
1	100	100
2	10	2.5
3	1	1

Table 3.1: Output Power at Different Distances

3.1.4 Piconet - The single-hop network

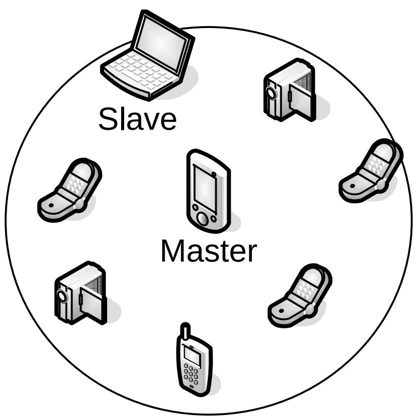

Figure 3.4: Piconet

Two or more Bluetooth devices, which use the same channel hopping pattern for transmission form a piconet, see figure 3.4. The maximum size of a piconet is 8 devices, where one device is the master and the others are slaves. Each piconet uses its unique hopping sequence and phase in the sequence, which is determined by the Bluetooth device address of the master and its clock.

Bluetooth is a typical single-hop network protocol, because of its master/slave relationship and the consequential dependencies. Considering the power consumption perspective, it is not useful in wireless sensor networks, which should have a long life time. As Bluetooth devices need energy sources, like batteries, they should use an energy saving technology. Although there are hold, park and sniff modes, which the devices can turn into, most of the energy is wasted in such systems. Inquiry and paging processes take up to 10 seconds time, in which a lot of energy is consumed.

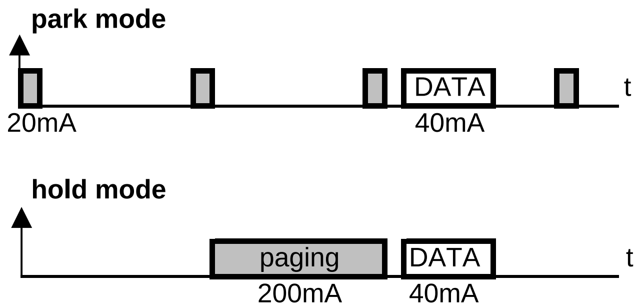

Figure 3.5: Hold and Park Mode

Nodes, which are in park mode, periodically listen for the master to synchronize their clocks and receive packets. Such a short period is assumed to consume about 20mA. When a packet is addressed to the parking node, it stays awake and receives the packet. While nodes in park mode are still synchronized with the network, nodes in hold mode do not synchronize their clocks. After the defined sleeping time, the slaves wake up and join the network. In figure 3.5, the sleeping time was too long and the clocks have drift apart too much. So the node has to do the paging process again to build a connection with the master to receive packets. This process, which needs time of up to 10 seconds, has high current consumption, about 200mA. Consequently the hold mode is a critical state that is not really energy-efficient for nodes in a network. Therefore, park and sniff modes are more or less the energy-efficient modes for a Bluetooth network, although in general, Bluetooth is not really energy-efficient at all due to its power consuming inquiry and paging state and the dependency of the different energy-efficient modes to data rates.

3.1.5 Scatternet - The multi-hop network

Up to 10 piconets can be connected together to build a scatternet, which is a multi-hop network. In a scatternet, one device can be a slave in more than one piconet, but it can only be master in one of them. A scatternet with a device, which is master and slave in two different piconets, is a very complex structure according to scheduling.
Theoretically, an ad hoc network can be built without the master/slave technology, and Bluetooth can be used as transmission technology. Therefore, the role of the master is not predefined, and each device can switch at any time to master or slave state. So if a device wants to send data, it will become a master and transmit the data packet to the destination slave and then the master can switch back to be a slave again and another device will become the master.
A master/slave switch, also called TDD switch, results in a new piconet, because the role of the devices have changed, and new connections have to be built with the new time and frequency definitions, that are given by each new master but with the connection parameters of the old existing piconet.[19]

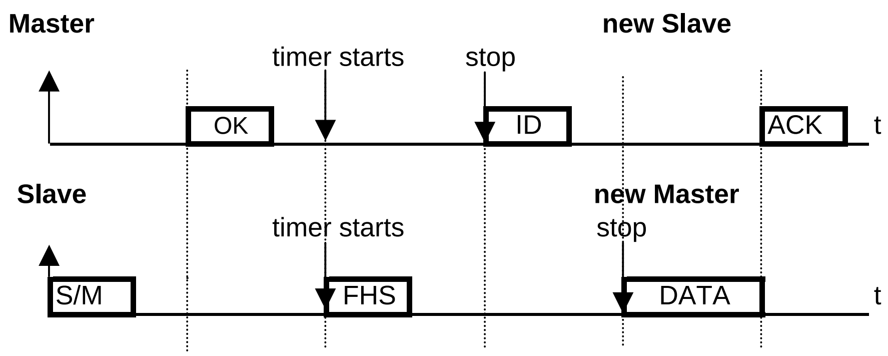

Figure 3.6: Master/Slave Switch

In figure 3.6, the slave, which wants to become a new master, asks the existing master to make a switch. If it receives a positive answer, that the switch is possible, both devices will start a special timer to exchange their parameters and define their new roles. The new master sends out an FHS packet, which includes time and frequency information. When the new slave receives the packet, it stops its timer and responds with an ID packet. The timer in the master is stopped as soon as the ID packet is received. Thus these two devices are synchronized and a new piconet can be built.[15]

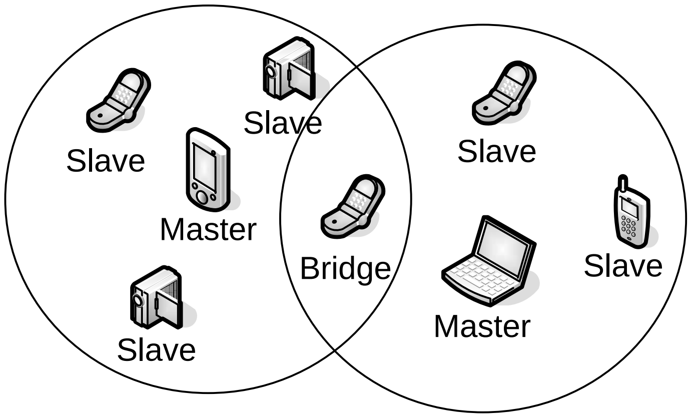

Figure 3.7: Scatternet with Bridge

The scatternet, shown in figure 3.7 consists of two piconets, which have one device in common. The device, called bridge is a slave in each piconet and works as an interconnection point. It forwards the traffic between the two piconets. The bridge, which can only be active in one of the piconets, has to be inactive in the other one at the same time. The scheduling of the active time of the bridge in each piconet is defined by Interpiconet Scheduling (IPS). During the inactivity, the node turns into hold or sniff mode to save energy, but it does not lose the network connection.[20] The main purpose of IPS is to reduce the delay of the switching time and to provide the efficient data transmission between the different piconets. When the bridge switches between the networks, a delay of one or two slots is produced.
One of the most useful algorithms to do the IPS is the Rendezvous Point IPS Algorithm. It provides a fixed time slot, when master and bridge meet to exchange data. The Rendezvous Point (RP) can occur in a periodic manner or spread out in a pseudo-random choice, which has to be known by both nodes. Such a strict scheduling privileges data transmission in the scatternet than transmissions within the individual piconets.

According to the scheduled RP, different categories can be given [21]:

- Honoring-Periodic Static-Window:
  Master and bridge have set a fixed time slot to meet and exchange the same amount of data in each period. The distance between the time slots is called superframe and has the greatest priority in the scatternet.

- Honoring-Periodic Dynamic-Window:
  The time slot is also defined for each period but has a different size in all durations. The exchange of different amount of data is given, but the occurrence of the RP is not periodic, according to the different size of the predefined time slots.

- Honoring-Random Static-Window:
  A random schedule is proposed between the master and the bridge, which arranges the time slot to exchange data between the piconets. The size of the RP is determined static.

- Master-Honoring Dynamic-Window:
  The time slot is defined in the scatternet, but the bridge has the ability to skip the meeting to offer higher priority to any other data exchange.

According to the different schedule algorithms and possibilities to implement them, a scatternet can never be ad hoc. Due to a small change in topology or data size, reallocations have to be handled between the bridge, master and also the other slaves in a scatternet, which do not offer flexibility, which is one of the main purposes of ad hoc networks.

3.2 Wireless Local Area Network

WLANs, defined in the IEEE 802.11 standard, have the ability to build single-hop and multi-hop networks. The most used and best implemented is the single-hop network, named infrastructure network, which is controlled by an Access Point (AP). An AP, which is the transmission point in a wireless network, controls traffic and provides an interface for connecting to wired networks. The WLAN standard shares the 2.4GHz ISM Band and reaches speed up to 11Mbps in 802.11b and 54Mbps in 802.11g, except of 802.11a, which uses the 5GHz ISM Band to reach speed up to 54Mbps[13]. The aim of the new standard 802.11n is to achieve 100Mbps[22]. For all different standards, the AP ensures the correct conditions and usage of frequency through *Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA)* technology.
Contention and contention-free priorities are supported and implemented in the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF), which are the most important functions of CSMA/CA, that can work alone and in coexistence. DCF provides contention priority and can be used in all different kinds of wireless networks. PCF, which can only be used in infrastructure networks, supports contention-free precedence.

3.2.1 General technology

In general, each node, which wants to send out a data packet, senses the medium. The medium, which is either free or occupied, is used to transfer the data packets. If the medium is free, the node will transmit the data and if the medium is busy, the node will defer transmission. Each node, which receives a packet, responds with an ACK to inform the source node of correct transmission. If the source node does not receive an ACK, the transmission is selected as unsuccessful and the data will be retransmitted at a later time.[23]

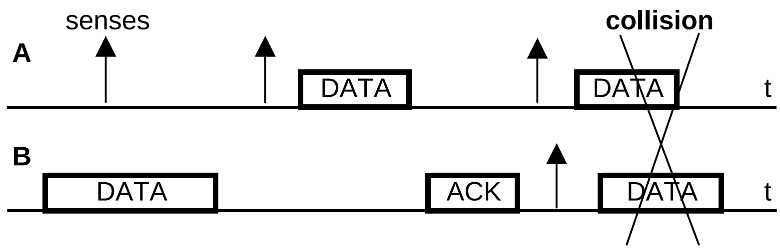

Figure 3.8: General CSMA Technology

In figure 3.8, node A wants to start transmission and senses the medium. A busy channel is recognized and therefore transmission does not start. At the next sense of the medium, the channel is free and node A transmits a data packet, which is acknowledged by the destination node B. If these two nodes sense the medium at nearly the same time, collisions can occur due to the minimum delay between sensing and transmission.
To avoid collisions, different waiting intervals are implemented in CSMA/CA. After sensing the medium, the source node listens for a specified time until it is allowed to transmit data. The time intervals, which are specified by the physical layer, define the listening time between different packets in a WLAN [24]:

- SIFS–short interframe space
  A SIFS, which is the shortest waiting interval, is used between the different packets during transmission.

- DIFS–distributed (coordination function) interframe space
  DCF uses DIFSs, which define the waiting time until a node can start its transmission.

- PIFS–point (coordination function) interframe space
  PCF uses PIFSs, which define the waiting time until a node can start its transmission.

- EIFS–extended interframe space
  EIFS is used after data packets, which were not understandable by a destination node. The longer waiting time avoids collisions.

If all nodes are in coverage range, the interframe spaces will avoid collisions. As nodes in a wireless network are static or mobile, the hidden terminal problem occur. This problem is caused by the fact that all the nodes can not hear each other although they are all connected to the same AP or the same neighbor.

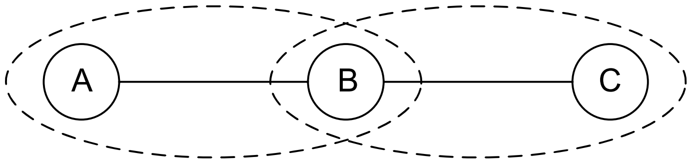

Figure 3.9: Hidden Terminal Problem

The hidden terminal problem is explained in figure 3.9. The nodes A,B and C build a WLAN, where A and C are connected to their common neighbor B. If nodes A and C will not be aware of each other, they do not know the presence of each other. If they start a transmission to node B at the same time, collisions will occur at this node.
To overcome the hidden terminal problem, the virtual carrier sense mechanism was implemented, shown in figure 3.10. The mechanism uses request-to-send (RTS) and clear-to-send (CTS) frames, which inform the nodes in the network about transmission, the length of the following data packets and the needed time for reserving the medium. The source node transmits the RTS packet to the destination. If the destination is available, it will respond with a CTS packet, and the transmission can start. The hidden terminal problem is avoided due to the fact that a node, which can not hear the source node and the RTS packet, will hear the destination node and the CTS packet instead. All nodes, which recognize either an RTS or a CTS, will use all received information and set a network allocation vector (NAV). So all nodes know that the medium is occupied for a defined time and nodes can avoid to interrupt the transmission.[24]

In addition to the NAV, an exponential backoff algorithm is used to increase the collision avoidance. Therefore, each node has to wait for a specified amount of time slots, which is defined by random, until it will start the next transmission. The slots are combined in a contention window. The backoff algorithm is used after each successful transmission, each retransmission, before the first transmission and if the medium is occupied.[23] The only exception is, when the medium is detected as free.

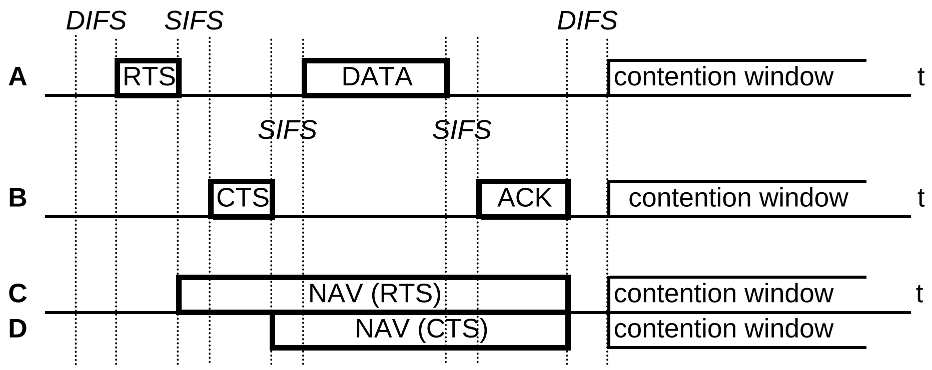

Figure 3.10: General CSMA/CA Technology

PCF is used to transmit data with higher priority like time-critical traffic; therefore, the AP can transmit a polling request, which will inform all nodes about the important traffic. The medium is reserved for this transmission as soon as possible. PCF uses PIFS instead of DIFS before transmission starts, which are shorter and the medium can be reserved more quickly. It must be ensured, that there is enough time among PCF demands on the medium, that normal traffic, which is exchanged by DCF, can still be used.[25]

3.2.2 Synchronization

All nodes in a WLAN consist of an internal clock. During the synchronization process all clocks in the network are adjusted to the same time. This procedure is done by using the Timing Synchronization Function (TSF), which is independent for each kind of WLAN. In an infrastructure network, the AP performs the TSF. Thus, it transmits periodically beacons, which contain a copy of the AP's clock time. If the beacon can not be sent, as the medium is busy, the beacon is sent as soon as possible, when the medium is free again. When a node receives a beacon, it adjusts its internal timer to the transmitted AP clock time.[23]

The difference between the infrastructure and ad hoc networks, is that in an ad hoc network each node sends out a beacon periodically, which contains its own internal timer. Each node compares the received timer to its own and only changes it if the transmitted one is later than its own. Due to the recurrent transmission of beacons, each node knows when a beacon should be received and the clock has to be admitted.[24] To ensure the correct time of beacon reception, the nodes begin to listen before the specified beacon interval.

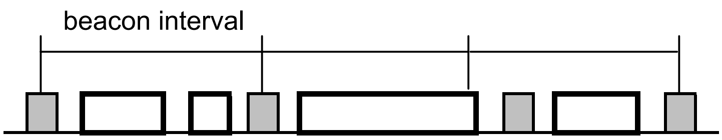

Figure 3.11: Synchronization with Beacons

Figure 3.11 shows the usage of the medium in a WLAN. If the medium is free, beacons will periodically occur. If the medium is busy, the beacons will be sent as soon as possible after transmissions have ended.

3.2.3 Power Consumption

In a WLAN, nodes can switch from the awake mode into power-safe mode to conserve energy. Due to the backoff algorithm technology, the nodes are listening for traffic all the time in the awake mode. To save energy nodes can turn into the power-safe mode. If a node turns into power-safe mode for a longer time, it has to exchange the whole configuration parameters when it wakes up, which is nearly the same as when it becomes a new member of the network. In general, all nodes have to be aware of synchronization packets and wake up periodically to receive them.

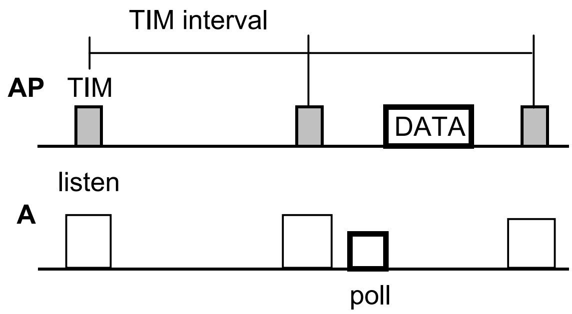

Figure 3.12: Power-safe Mode

In an infrastructure network, APs, which are informed about the modes of the nodes, handle a traffic indication map (TIM), that stores the current state of each node and information about packets. If a node is in the power-safe mode, no packets will be forwarded to it. The AP buffers all the packets and informs the node periodically about the buffered packets by sending a beacon, which also includes the TIM. Thus a beacon consists of synchronization information and information about buffered packets. Nodes periodically listen for beacons to synchronize their clocks and to be informed about currently available packets. To receive the stored packets, they have to send a polling request to the AP to inform it that they want to change mode and receive the packet, see figure 3.12. Then the nodes turn into awake mode and wait for the packets or an ACK, which informs them, that transmission can not be started yet. If transmission does not occur, the AP will set a new transmission time and send this information within the ACK. After a successful transmission, the nodes turn back into power-safe mode.[24]

A special version of the TIM is the delivery TIM (DTIM), which initiates buffered multicast and broadcast packets. All nodes have to change their mode and will receive the multicast or broadcast packets immediately after the next beacon. The DTIM interval is typically longer than the TIM interval.

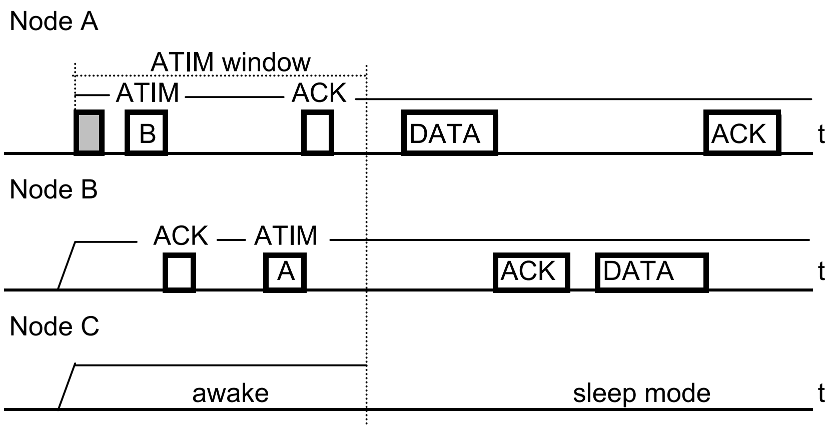

Figure 3.13: Power Consumption in Ad hoc Networks

In an ad hoc network, see figure 3.13, the nodes also turn into power-safe mode. The correct clock time is provided due to beacon transmissions. Each node can send out a beacon, which consists of its internal clock time. Due to the lack of schedules in ad hoc networks and the random beacon transmissions, a lot of collisions occur.
The same technology is used in both infrastructure and ad hoc networks, with the only difference that instead of TIM or DTIM, Announcement TIM (ATIM) messages are sent in ad hoc networks, which consist of the buffered packet information. The nodes wake up at defined time intervals and listen for beacons or send out a beacon. After the beacon reception, a time period called ATIM window starts. During this time, the nodes exchange ATIM packets. With the use of ATIM packets, the nodes declare the destination and inform it, that data has to be transmitted. If a node receives an ATIM packet, it will transmit an ACK and will stay awake to receive the data packet. As a lot of nodes want to start transmission, the awake time of the nodes can be very long. They can turn into sleep mode, if no packets are addressed to it, after successful transmission or if

no transmission has occurred after a predefined time although packets were addressed to it.[26]

In general, nodes, which are waiting to start transmission, are working in the contention window. They listen for each time slot to check if the medium is free or busy. The whole scanning process consumes a lot of energy, because nodes have to be awake all the time. They receive packets, which are not destined for them. If the medium is free, transmission has to start with the RTS packet. Additional packets have to be exchanged until the start of real data exchange, which also consumes a lot of power, due to sending and receiving of all those packets and also setting the NAV window. If collisions occur, the retransmissions will also consume a lot of energy.

3.2.4 Infrastructure Networks

Although the RTS/CTS technology is specified for the infrastructure networks, there is no need to use it. An infrastructure network is controlled by an AP, which handles all schedule requests. When a node wants to transmit data, it sends a polling request to the AP, that will offer a specified time slot for the node, when it can transmit. The source node will transmit the packet to the AP, which will forward the data packet to the destination. The virtual carrier sense technology is used in such networks to ensure that no other node will interrupt transmissions with sending a polling request; therefore, it will set the NAV. After the NAV has ended, it will turn into the contention window to listen for a free channel.
The whole infrastructure network uses the same frequency channel for negotiation, which is offered by the AP. The AP does not specify the frequency channel on its own, the configuration has to be done by hand at the beginning of the network implementation.

Due to the manual configuration of the frequency channel, the reuse of frequency is the most critical part of the procedure. If there are infrastructure networks next to each other using different frequency channels, the networks will work properly.

Each infrastructure network builds a ring-formed area, called dead zone, see figure 3.14, where transmission can not take place anymore due to the weak signal and the low signal-to-interference ratio (SIR). The longer the transmission distance is, the weaker the signal will be. In the dead zone the signal is very weak and when the adjacent infrastructure networks try to reuse the same frequency channel, the interference is too high and a node can not receive any packets.

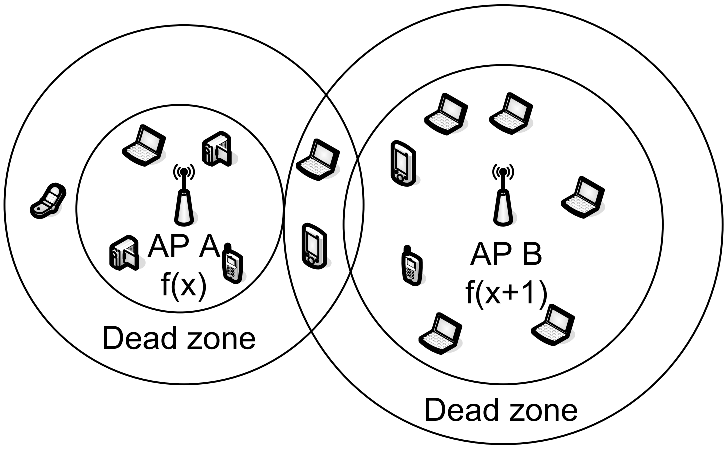

Figure 3.14: Infrastructure Networks and the Dead Zone

3.2.5 Ad hoc Networks

There are a lot of problems concerning the use of CSMA/CA in ad hoc networks. The SIR is one of the main problems, which make the reuse of a frequency channel very hard.

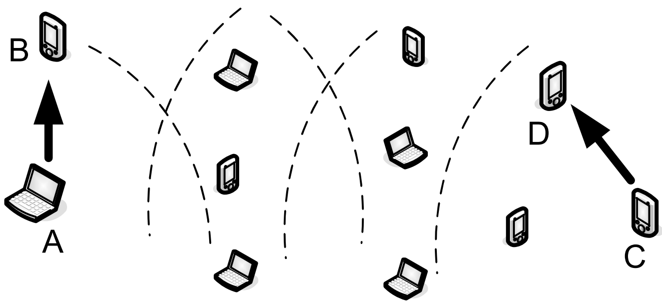

Figure 3.15: Interference in Ad hoc Networks

As shown in figure 3.15, node A wants to transmit a packet to node B at the same time as node C wants to transmit a packet to node D, both using the same frequency channel. The WLAN devices are very sensible and will not start transmission, if they check another signal on the medium to avoid collisions. The distance between the two transmitting nodes is very far, but still a signal can be measured in each device and transmission will not start. On the one hand, the sensibility of WLAN devices avoids collisions, but on the other hand, it consumes a lot of power. If the transmission does not start because another signal is measured on the channel, the nodes turn into contention window and listen for a free medium to start the data exchange at a later time. Listening and waiting consume a lot of power and make the use of WLAN not energy-efficient.

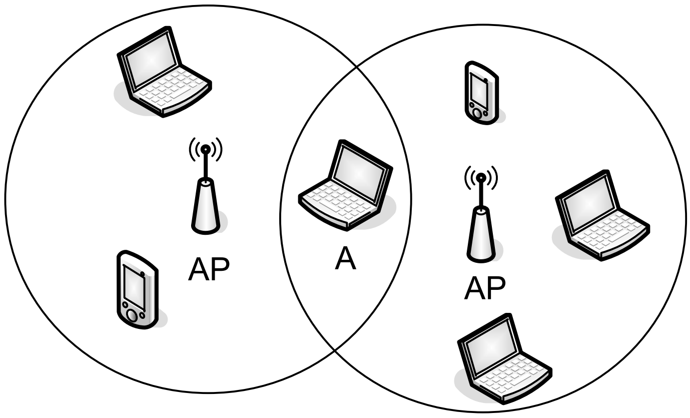

Figure 3.16: Cluster of Infrastructure Networks

An ad hoc network can also be built as a cluster of different infrastructure networks, shown in figure 3.16, which use different frequency channels to overcome the problem of the frequency reuse. A WLAN device can be a member in more than one network. To handle transmission and reception for this node, a schedule algorithm, which settles the time, has to be deployed. There is no standard algorithm implemented, which can offer the ability to build WLAN ad hoc networks in such a topology.

3.3 ZigBee

The IEEE 802.15.4 standard describes the ZigBee technology and supports single-hop and multi-hop networks. Single-hop networks use a star network topology and multi-hop networks are connected peer-to-peer. CSMA/CA is used to implement the channel access in the ISM Band like in 802.11. There are 16 channels used in the 2.45GHz band, 10 channels in 915MHz band and one channel in the 868MHz band.[27]
ZigBee is designed to use low power radios, cheaper hardware and less software requirements and applications for building a WPAN within a range between 10m and 75m.

3.3.1 General Technology

Generally, a ZigBee WPAN has no limited number of devices connected within the network. There are two different device classes, namely Full Function Devices (FFD) and Reduced Function Devices (RFD): An FFD can work in three different modes, as a PAN coordinator, a coordinator, which is the substitute of the PAN coordinator or as a device.[27]

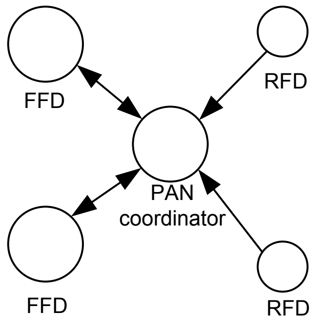

Figure 3.17: Star Topology in ZigBee

A typical ZigBee star network consists of FFDs and RFDs. Transmission can only take place between FFDs or an FFD and an RFD, but never between RFDs. RFDs, which are very low power consuming devices, like light switches, carry out transmission only very rare during network life. The devices can be connected either in star topology, figure 3.17 or peer-to-peer topology, shown in figure 3.18.

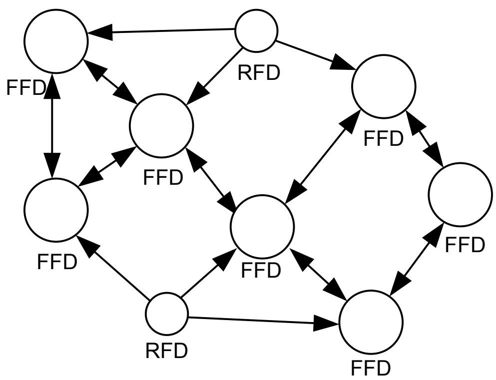

Figure 3.18: Peer-to-Peer Topology in ZigBee

The general technology of ZigBee is based on the CSMA/CA technology, but ZigBee implements three functionalities of CSMA/CA in a different way. Compared to WLAN, where each node has to respond with the ACK after receiving a packet, ZigBee uses ACKs as an optional feature. Nodes can never be sure that their transmission was successful, when they do not receive an ACK after forwarding a packet. Due to the optionality of sending ACKs, energy and bandwidth is not wasted in such a high order as in WLANs.
The second different function provides different possibilities to handle synchronization. Thus beacons, which are also used in CSMA/CA, or polling requests can be handled, depending on the network configuration.

The third and main feature is the division of a channel into time slots for a different usage, called superframe structure. CSMA/CA uses the exponential backoff algorithm, which offers a kind of competition between the devices in a network. Due to the channel division into time slots in ZigBee, which are allocated to the devices, each device has a guaranteed time slot, that it can use for transmission without collisions. The PAN coordinator administrates the network and arranges the time slots for each node.[28]

3.3.2 Synchronization

ZigBee supports two different types of synchronization depending on the implementation of the network, which can be beacon-enabled or nonbeacon-enabled.
In a beacon-enabled network, the PAN coordinator generates beacons, which consist of synchronization information that is broadcast periodically at an interval between 0.015 and 252 seconds.[29] As each device periodically listens for beacons, the synchronization parameters are decoded and each device adjusts its internal clock. All the devices are synchronized to the PAN coordinator's clock.
The second possibility offers the implementation of a nonbeacon-enabled WPAN. If a device wants to keep synchronization to the PAN coordinator, it will send a polling request. After the reception of the polling request, the PAN coordinator transmits an ACK, which contains its internal clock time.[27]

3.3.3 Power Consumption

The main focus of the ZigBee standard is the effective usage of power consumption. Most of the time, all the devices, which are not the PAN coordinator, are in deep sleep mode and they only wake up for some seconds to confirm their presence in the network. Sometimes also the PAN coordinator turns into sleep mode to save energy. When a device wakes up according to its schedule, which was defined by the PAN coordinator, it registers with the coordinator, that has buffered packets for the node during its sleep period. If there are no packets available, the device will turn back to sleep mode.
All devices have to be aware of the correct schedule timing. If a device sleeps for a longer interval, it has to wake up earlier to ensure the reception of the beacons to be synchronized with the network. The longer the sleeping time, less power is needed in the network. A device is not allowed to sleep longer than 252 seconds, which is the longest beacon interval to stay present in the network.[29]

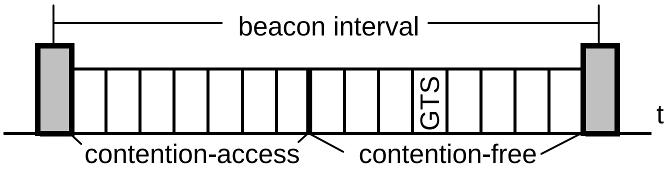

Figure 3.19: Superframe Structure

To save energy, the superframe, which is the space between two beacons, is divided into contention-access and contention-free periods. As described in figure 3.19, the whole superframe is divided into 16 slots and the slots, which are in the contention-free period are called guaranteed time slots (GTS). If a device wants to use a GTS, it has to send a request to the PAN coordinator. Through first-come first-serve policy, the GTSs are shared among the devices. One device can use one GTS for transmission, but must ensure to finish transmission until the next GTS starts. Time slots in the contention-access period secure the ability for new devices to join the already existing WPAN.[27]
The ZigBee sleep mode was specially designed for battery-powered WSNs. Depending on different applications, nodes can sleep up to 99% of their network life, which resultes in a very low duty cycle and a very low average power consumption.

3.3.4 Single-hop Networks

Single-hop networks can be either beacon-enabled or nonbeacon-enabled.

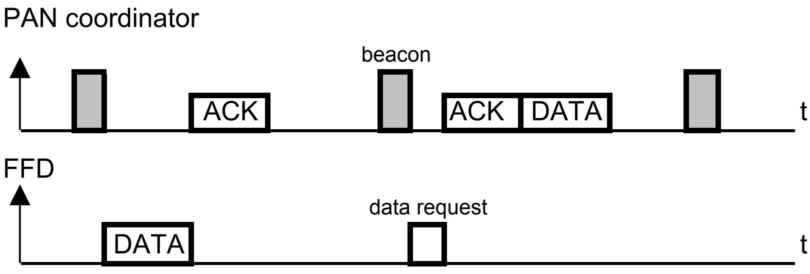

Figure 3.20: Transmission in Beacon-enabled Networks

Figure 3.20 shows the transmission between the PAN coordinator and a network device, assumed to be an FFD. As network devices are sleeping most of the time, they use beacons to obtain information about packets and synchronization. After the first beacon is received, the FFD starts transmission without knowing the state of the medium. The coordinator receives the packet and responds with an ACK, which is optional in ZigBee. If the beacon informs the sleeping device that data packets are buffered for it, the device will send a polling request to acknowledge the coordinator about the wish to receive the data. The FFD will wait for the data packet and turn back into sleep mode again after a successful reception. To save energy, it does not send an ACK and turns into sleep mode as soon as possible.

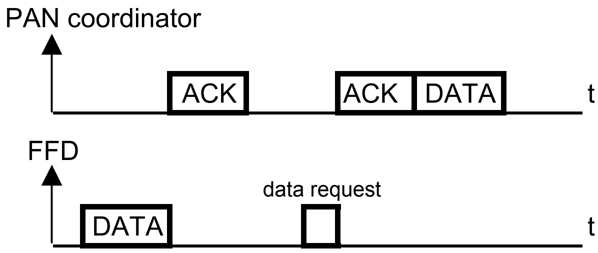

Figure 3.21: Transmission in Nonbeacon-enabled Networks

In a nonbeacon-enabled network, an FFD just transmits data without knowledge about the state of the medium and there is no defined schedule for transmissions, see figure 3.21. If the PAN coordinator receives the packet, it will respond with an ACK, which is optional. When an FFD is in the sleep mode, the coordinator buffers all the packets for this node. When the node wakes up and wants to receive buffered packets, it has to send a polling request. The coordinator transmits an ACK, which informs about the availability of data. If there is stored data, it will be sent directly after the ACK. The whole network is not synchronized at all.

3.3.5 Ad hoc Networks

In a peer-to-peer network, each node is autonomous and the network is typically a non beacon-enabled network. If a node wants to transmit data, it will start the transmission without synchronization. Therefore, the transmission does not have to be successful, because the nodes are just sending their information and do not sense the medium before transmission to check if it is free or occupied.[29]
Due to the optionality of ACK, the nodes will not know about collisions and data can be lost. There is also no definition against the hidden terminal problem, because RTS and CTS packets are not used. ZigBee does not provide any collision avoidance in ad hoc networks.

4 Energy-efficient MAC Protocols

4.1 Improvements of CSMA/CA

According to the CSMA/CA technology and its implementation of the Power Saving Mechanism (PSM), chapter 3.2.3, research has been carried out to increase the energy-efficiency in ad hoc WLANs.

4.1.1 Slotted PSM

In an ad hoc WLAN, beacons are sent out periodically to keep synchronization. After each beacon, nodes can send ATIM packets to inform other nodes in the network about buffered packets and necessary transmissions. In CSMA/CA each node has to stay awake during the beacon interval and the ATIM window. During the ATIM window, the source declares the destination and informs it about transmissions. Source and destination stay awake after the ATIM window to be aware of transmission, while nodes, which are not part of any transmissions can turn into sleep mode immediately. With Slotted PSM the channel is divided into a number of equal length time slots, which can be used by all nodes. The advantage of Slotted PSM is that it uses ATIM packets to order time slots, which they want to use for transmission. The slots are numbered and a node addresses the destination during the ATIM window and informs it about the specified slots, it wants to use. The receiver responds with an ACK to ensure that transmission between those two nodes can occur. The time slot reservation can be done in two different ways [30]:

- sender-based
- receiver-based

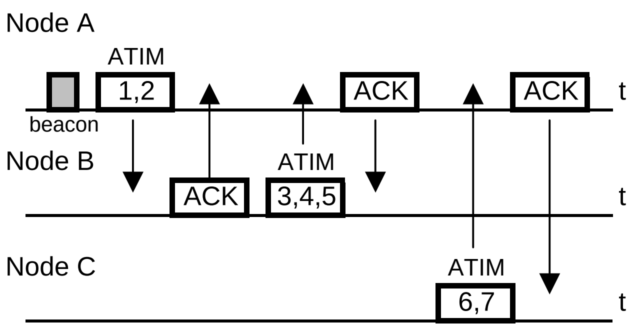

Figure 4.1: Sender-Based Time Slot Reservation

In the sender-based method, shown in figure 4.1, the source node offers a number of time slots it wants to use for transmission. If the slots are free, the destination will respond with an ACK. If the destination has information from other nodes, that they want to use the same time slots, it will send out an ATIM-RE packet. This packet informs the source, that its offered time slots can not be used. Additionally, the ATIM-RE packet consists of a list of other free time slots, which should be used instead. If a sender receives an ATIM-RE, it will choose slots, which the destination has offered, and send a new ATIM packet with the new number of slots.

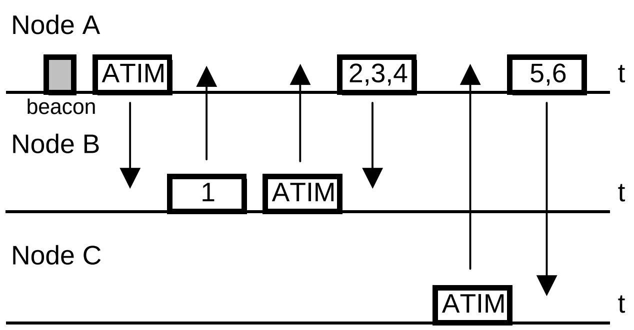

Figure 4.2: Receiver-Based Time Slot Reservation

The figure 4.2 shows the receiver-based method. The sender sends out a list of slots in its ATIM packet, which it can use for transmission. The receiver chooses the number of slots and responds with these information implemented in the ACK. The disadvantage of this method is that other nodes, which are only in range with the sender, will not know about the chosen time slots. To avoid collisions, the sender has to forward the ACK to all the other nodes in its range, which will cause more overhead than the other possibility.

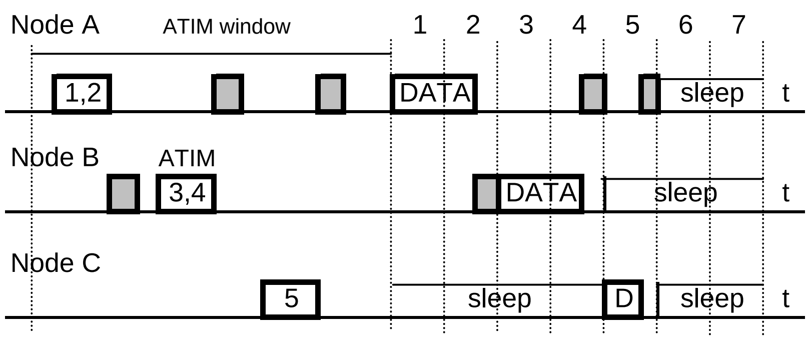

Figure 4.3: Sender-Based Reserved Transmissions with Slotted PSM

All nodes handle an internal schedule and a list of the time slots. The schedule offers information about available and occupied time slots and transmission arrangements. After the reservation period, the ATIM window, the transmission will only occur in the reserved time slots. Nodes are just awake when they are a part of a transmission and turn into sleep mode during the remaining time, see figure 4.3. This ability saves more energy than CSMA/CA due to the fact that the nodes do not have to stay awake all the time. Due to the channel and the transmission date, the nodes know when they have to transmit and receive data. Unlike in WLAN, RTS/CTS packets are just used during the ATIM window and are not needed for data transmissions. After each new beacon, the reservations are lost, and the transmission timing has to be renewed.[30]

According to the problem caused by the new nodes, which send out packets when they join the network, each sender waits for a DIFS period until it starts its transmission to avoid packet collision. The DIFS can cause the transmission not to be finished in the reserved time slots. Therefore, a specified number of slots is reserved and can be used by all nodes to finish their transmission. These slots can not be reserved during the ATIM window and they occur after all reserved slots but before the next beacon. If a node has not finished its transmission, it can use these slots. To start transmission within these time slots, the CSMA/CA technology is used to handle transmissions and avoid collisions. Another critical factor is the size of the time slots. If the length of the time slot is too long, a lot of time is wasted in the network. If the length of the slot is too small, the transmission will need more slots, and a lot of energy is wasted due to retransmissions and the use of the CSMA/CA technology to finish the data exchange.

4.1.2 Improved PSM

In CSMA/CA, the ATIM window is used to exchange pending data information among the nodes in an ad hoc network. The ATIM window has a fixed length, which causes the problem that the window can be too long or too short. If the ATIM window is too long, a lot of energy, bandwidth and time will be wasted and if it is too short, the nodes can not exchange all information, which they have to send. With improved PSM (IPSM), all nodes can select the size of the ATIM window individually, which offers the most efficient way of data exchange. If all nodes have sent their pending data information, the transmissions can start immediately and the nodes do not have to wait for a specified time.[31]

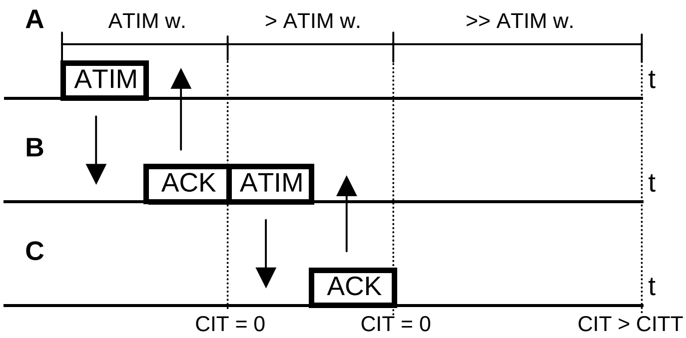

Figure 4.4: Flexible ATIM Window Size

The minimum length of the ATIM window is specified between all the nodes in the network before the first transmission and all nodes maintain a special variable, the Channel Idle Time (CIT), which changes according to the network conditions. Nodes count the current channel idle time during the ATIM window and reset the CIT to 0, always if an ATIM packet occurred, see figure 4.4. At the end of the window, the CIT is compared to a predefined Channel Idle Time Threshold (CITT). If the CIT is less or equal to the threshold, the size of the ATIM window increases, and the nodes listen for further ATIM packets. If the CIT is greater than the threshold, the transmissions will start immediately.[31]
The following variables are specified in IPSM:

- ATIM minimum size
- ATIM maximum size
- ATIM increased size
- CIT
- CITT

The second advantage compared to CSMA/CA is that each node can turn into sleep mode before the beacon interval has ended; thus it does not have to stay awake all the time. As all the nodes know the beacon interval, they know how much time is left until the next beacon occurs and can decide if they turn into the sleep mode or not. As the change of the sleep and awake-modes also consumes power, each node will decide according to the remaining time, if it is really energy-saving to turn into sleep mode or if it is more energy-efficient to stay awake. If the remaining time is too short, the node will stay awake and wait for the next beacon.[31]

4.2 Power Aware Multiple Access Protocol

The Power Aware Multiple Access Protocol (PAMAS), which was specially designed for ad hoc networks, uses two different channels, the control and the data channel, and therefore devices need two different radio systems. The data channel is only used for the transmission of data packets. Due to listening to the control channel, the nodes determine when transmissions take place, for how long they occur, when they can turn into the sleep mode and when they have to wake up again.[31]
In general, each node, which wants to start a transmission addresses the destination and sends out an RTS over the control channel. The destination responds with a CTS, and the data exchange follows using the data channel. To ensure the correct transmission and to avoid collisions, the destination sends a busy tone over the control channel, which can be received by every network member. All the nodes, which listen to the control channel, determine that the data channel is busy and they turn into power saving sleep mode, when both channels are shut down. Information about how long a negotiation will take is also transmitted over the control channel as part of the CTS, thus each node will know when to wake up again.[6]

Nodes, which use the PAMAS protocol, can stay in 6 different states:

- Idle
- Await CTS
- Transmit Packet
- Await Packet
- Receive Packet
- Binary Exponential Backoff (BEB)

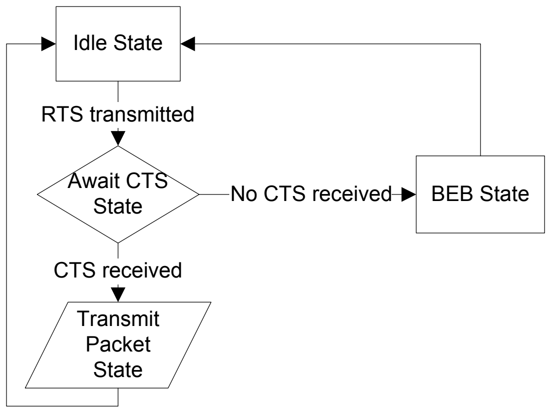

Figure 4.5: Different States of a transmitting Node

All the nodes, which do not have to transmit or receive a packet, stay in the Idle mode. If a node wants to transmit data, see figure 4.5, it sends out an RTS and joins the Await CTS mode. After a defined time out, the sender turns into BEB mode, when there is no CTS received. If it receives a CTS, the sender will turn into Transmit Packet state and sends the data packet.

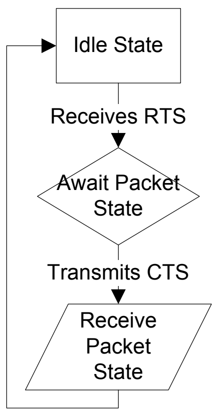

Figure 4.6: Different States of a receiving Node

The different states for a destination are shown in figure 4.6. After transmitting the CTS, the receiver will turn into Receive Packet state and listen on the data channel for the packet. If it receives a packet, it will send out a busy tone on the control channel to inform the other nodes in the network about the transmission.[3]

PAMAS is based on CSMA/CA with the exception that no NAV is used. Instead of the NAV, nodes will turn into sleep mode, if their transmission cannot take place due to a busy medium. To avoid collisions, the nodes sense the data channel for current negotiations and listen to the control channel to notice RTS, CTS packets or the busy tone.
One of the advantages of PAMAS is that a node can receive a packet and listen to the control channel at the same time. Therefore, it will observe if another member of the network tries to start transmission by sending an RTS. To stop the node's behavior the receiver will transmit a busy tone immediately to avoid collisions.

The efficient power consumption is implemented in PAMAS in a way that each node can turn into sleep mode individually. The main idea is that all the nodes are saving energy in the sleep mode, which they join when transmissions, that are not involving their presence, take place. Thus, all the nodes, which are not part of the current transmission will turn into the sleep mode and it does not matter if they have to transmit packets or not. When a node wakes up, it will listen to the data channel to be aware of the network's and medium's situation. If there are negotiations, it will turn back into the energy saving mode and wake up later again.[3]
If a node wants to transmit a packet to a sleeping node, it will send out an RTS, but not receive a respond, so it will turn into the BEB mode and try it again later. Problems could occur due to the transmissions, which have started during a sleeping period of a node. If a node wakes up and there are transmissions on the channel, it will not know who is transmitting and how long the transmission will take place. Therefore, PAMAS has implemented an intelligent binary search algorithm by using a *probe protocol*, explained in figure 4.7, which exchanges special packets on the signal channel to obtain knowledge of the current transmission length.[3]

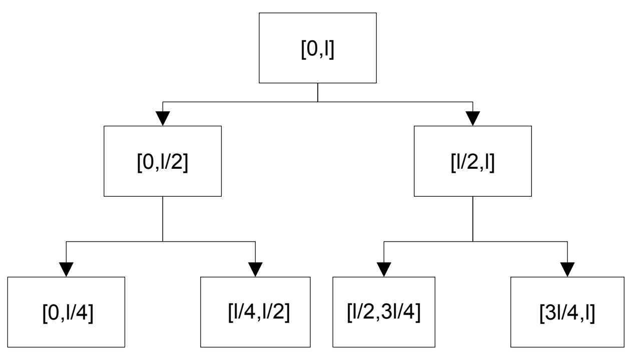

Figure 4.7: Binary Search Algorithm

Assume that node A woke up and has no knowledge about the network situation. It will send out a t_probe packet, which contains a variable, that defines the maximum packet length l. All the nodes, which complete their transmissions between [l/2,l], answer with a t_probe_response packet, that contains the time when the transmission will end exactly. Node A will turn into the sleep mode until the other transmission ends. If there will be no response, node A transmits a probe for the interval [3l/4,l] and waits for responds. If there is no answer, it will probe the interval [l/2,3l/4] and so forth.[3] In general, different time intervals are probed and transmitting nodes answer to inform the other nodes about the length of their transmissions. The implementation of the probe protocol increases collision emersion but with the knowledge about transmission length, the nodes can turn into sleep mode again, which will decrease power consumption.
The complexity of the probe protocol can be limited and decreased, if a node will not shut down the data and the control channels, when it turns into sleep mode. During sleeping, it could listen to the control channel and would be aware of the whole network conditions.

4.3 Wireless Sensor - MAC

The Wireless Sensor MAC (WiseMAC) protocol was specially designed for the WiseNET™ network. The WiseNET™project was introduced by the Microelectronics Division to build a power efficient ad hoc network with low power devices, that reaches a life time for about 5 years.[32]
WiseMAC, which provides energy efficiency, uses *preamble sampling* techniques and exchange of sampling schedules among the devices. Effective power consumption is gained due to decreasing the overhearing in such networks.

The general technology of WiseMAC is shown in figure 4.8. At regular time intervals, the nodes listen to the data channel for a short time. The time, when they sample the medium is independent but constant for each node. So each node has its own sampling schedule, which it stores but also sends out to its neighbors. Each node, which receives a sampling schedule from a neighbor, updates its own with this information. Therefore, all network nodes know when the other nodes are awake and sample the medium or when they are in sleep mode.[33]

When one node has to transmit data to another node within the network, the source checks its sampling schedule to know when the destination is awake to receive the packet. The sampling schedule and the knowledge about other nodes avoid the long period of idle listening. If the source wants to start transmission, it will listen to the data channel and if it is busy, the node will go back to sleep mode and try transmission at the next sampling time. If the channel is free, the source node will wait until the destination wakes up and then it sends out the data packets with a preamble in front of each packet. The preamble ensures, that the destination stays awake and receives the forwarded data. Due to the knowledge of each nodes' schedule, the preamble size can be very small, which reduces energy waste, that appears because of the sending of longer packets.[33]

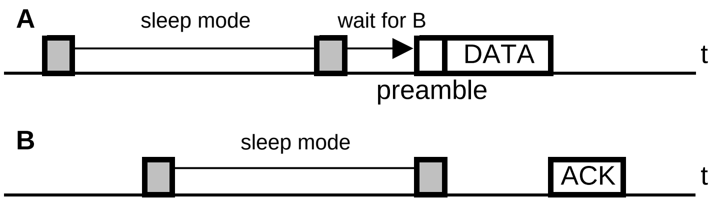

Figure 4.8: WiseMAC Protocol

WiseMAC does not use synchronization, although the internal clocks in each device drift apart because of the long and numerous sleeping of each node. To keep successful transmissions, the preambles, which are also used as a reservation of the medium, are sent before the data packet and ensure that nodes really wake up. If two nodes wanted to transmit at the same time, collisions would occur and in addition to mitigate those collisions, WiseMAC also uses non-persistent carrier sensing with a backoff time like WLAN. This increases the power consumption of each node due to the waiting in the backoff time until the destination node wakes up.
The WiseMAC protocol can also be used for infrastructure networks. The access point sends out the preambles and data packets.[7]

4.4 Energy-efficient MAC

The energy-efficient MAC protocol (EE-MAC) is based on CSMA/CA and to offer usability in ad hoc networks, a connected dominating set (CDS) is built. The set consists of masters, which are always awake and fully-powered, and slaves, that can turn into sleep mode. When slaves do not carry any data, they turn into the energy saving sleep mode and wake up periodically to be aware of the transmitted beacons. The network consists of more than one master, which sends out beacons at specified time intervals and informs the slaves about the available data. If a slave is in sleep mode, the master buffers all the packets for this node.

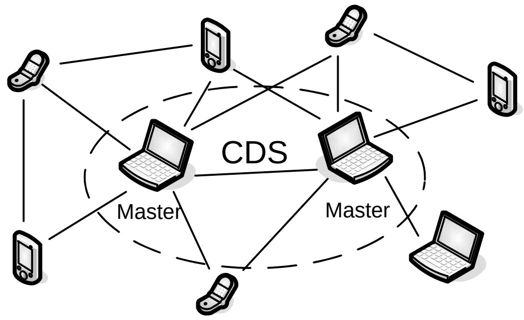

Figure 4.9: Connected Dominating Set

The CDS, figure 4.9, consists of master nodes, which offer the backbone of the networks. It must be ensured that each slave has at least one master in its range, so that it can be a member of the network and receive data packets. The masters are chosen due to their local energy resources and external information like their neighbors' battery load. The information is checked periodically, which guarantees the fairness among all nodes. All masters are calculating the average energy level of all their neighbors and compare it to their own energy level. If the average energy load of the neighbors is more than its own load, the master will switch its state and become a slave. Then another slave, one with higher or at least the highest battery power level will become the new master.[34] This advantage increases the network's lifetime because the energy reserves of all the nodes are used. The disadvantage of the protocol is the fast switch between master and slave. If a master observes that its energy level is lower than its neighbor's average battery load, it switches its state, although there is no other master in range; thus slaves will lose their network availability.

EE-MAC consists of three key features [34], which make the energy use in the network more efficient than in general CSMA technology.

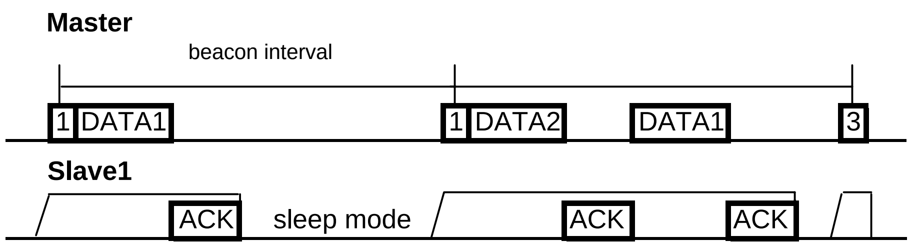

Figure 4.10: Energy Efficiency in EE-MAC I

If a master transmits data to a slave, the data packet will also contain information about

the pending data packets, see figure 4.10. So each node will know how many packets it has to receive and can stay awake just for this time and turn into sleep mode earlier than in general CSMA/CA.
Data transmission from master to slaves are prioritized to master to master transmissions. So slaves can turn into sleep mode earlier, as masters are always awake and can receive data all the time.

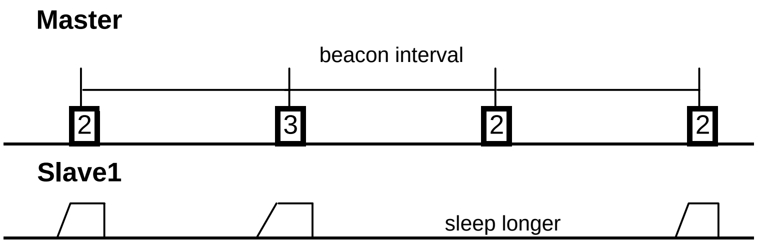

Figure 4.11: Energy Efficiency in EE-MAC II

If a slave has noticed that for more than two consecutive beacon intervals no data was addressed to it, shown in figure 4.11, it will have the possibility to turn into sleep mode for more than one beacon interval. A master will buffer data packets for a sleeping node for two intervals until it will delete the data packets. Due to the increasing sleep time with EE-MAC, the energy consumption decreases.

5 Simulation

In this chapter a simulation and power consumption comparison between Slotted PSM and the original 802.11 PSM protocol is performed. Slotted PSM does not support RTS and CTS packets to announce transmissions, it uses the exchange of transmission parameters in the ATIM window period. With sender-based Slotted PSM, the destination, the length of the transmission and the exact time, when transmission will take place are allocated. Less packets are needed than in the original 802.11 MAC protocol and idle listening is decreased, because nodes know how long they can stay in the sleep mode and when to wake up to keep track of transmissions.

5.1 Simulation Environment

The simulation was done with the official network simulator NS version 2.27[35]. It is programmed in C++ and TcL scripts are used as an interface to the program. NS2 offers MAC 802.11 compatibility and power consumption measurements for wired and wireless networks.
The NS2 was installed and compiled on an Intel P4 1.6GHz computer, 512MB RAM. The operating system is the Hancom Linux release 3.0 distribution and access was granted via FTP and Telnet.

The considered ad hoc network consists of 20 nodes, which are divided in 10 transmitting and receiving nodes and 10 sleeping nodes. The 10 sleeping nodes were choosen to show the longest sleeping time a node can achieve within the ad hoc network. The 10 transmitting and receiving nodes are divided in 5 sending and 5 receiving nodes. The data was generated by the 5 transmitting nodes while the beacons were generated and transmitted randomly by all nodes, which means that the data packet was just received by 5 nodes while the beacons were received by all nodes to keep the network synchronization.

The construction of the ad hoc network was a mesh network with equal distances among all nodes. The total simulation time is 50 seconds and the beacons, used for synchronization among the nodes, were transmitted every 200ms, which is a short interval. The shorter interval has the advantage of better network synchronization. The size of the beacon packet was 612bit and took 306µs. After the beacon, the ATIM window was announced to be 20ms long and nodes exchange transmission information during the ATIM window. The ATIM window was chosen as 10% of the beacon interval to offer the opportunity for all nodes to turn into sleep mode for a longer time. The length of the data packets is considered as 512Bytes. As the 802.11 standard offers data packet length between 29Bytes and 2346Bytes, 512Bytes were chosen to achieve successful data transmission for Slotted

PSM with the use of more than one time slot. The size of one time slot was 1ms and the channel was divided into 180 time slots. The transfer rate was 2Mbps.

Power consumption was measured according to different message intervals between 50ms and 2 seconds, which define how often transmissions occur. All nodes are aware of beacons and the following ATIM window. Due to the exchanged information during the ATIM window, nodes can join three different modes afterwards; transmit, receive or sleep mode.

The different power consumption levels, see table 5.1, were assumed [35]:

	Transmit Mode	Receive Mode	Sleep Mode
Power Consumption [W]	1.400	1.020	0.070

Table 5.1: Definition of Power Consumption Levels

5.2 Simulation Results

The sleeping time of the nodes, which are neither transmitting nor receiving is the same in 802.11 PSM and Slotted PSM. These nodes are awake during the beacons and the ATIM window and turn into sleep mode immediately after that. This results in a sleeping time of 44.820 seconds for each node. The sleeping time differs for all the other nodes in 802.11 PSM and Slotted PSM according to the message intervals. Therefore, the sleeping times were calculated as an average between all nodes to get a result for the sleeping time of all nodes within the simulated network, see table 5.2.

More energy is saved within the network when the nodes more often and longer stay in sleep mode. It can be seen that the advantage of Slotted PSM is the better energy handling when the message intervals are very short and transmissions occur more often. This is, due to their knowledge about the exact transmission length and time.

Message Interval [sec]	802.11 PSM [sec]	Slotted PSM [sec]
0.050	28.620	38.220
0.100	28.620	33.420
0.200	28.620	31.020
0.300	33.858	35.454
0.400	36.396	37.596
0.500	38.061	39.021
0.600	38.997	39.789
0.700	39.969	40.653
0.800	40.554	41.154
0.900	40.995	41.523
1.000	41.454	41.934
1.100	41.661	42.093
1.200	42.003	42.399
1.300	42.183	42.543
1.400	42.336	42.672
1.500	42.543	42.855
1.600	42.678	42.978
1.700	42.777	43.053
1.800	43.047	43.311
1.900	43.092	43.344
2.000	43.092	43.332

Table 5.2: Average Sleeping Time per Node

The duty cycle shows the time, given in %, how long one node or all nodes are sleeping compared to the whole simulation time, which is 100%. If the sleeping time of the nodes is 100%, they would be in sleep mode all the time and there would be no network traffic at all. The higher the duty cycle is for a node, the more it is sleeping and therefore saving energy.

$$duty\_cycle/node[\%] = \frac{active/sleep\_time}{simulation\_time \times no\_of\_nodes} \tag{5.1}$$

$$duty\_cycle/total\_network[\%] = \frac{active/sleep\_time}{simulation\_time} \tag{5.2}$$

As seen in figure 5.1, nodes using the Slotted PSM protocol are sleeping nearly 80% at a message interval of about 50ms, compared to 802.11 PSM, when nodes are only sleeping 60% of the simulation time. With the increase of the message interval, the sleeping times become nearly equal, because transmissions do not occur so often anymore and Slotted PSM uses energy more efficiently just during transmission periods. The sleeping time hits its peak at 89.64%, which can not be increased anymore because beacons, the ATIM window and other control informations do not allow the nodes to turn into sleep mode during these transmissions and periods. Nodes have to be aware of these packets to know the network situation.

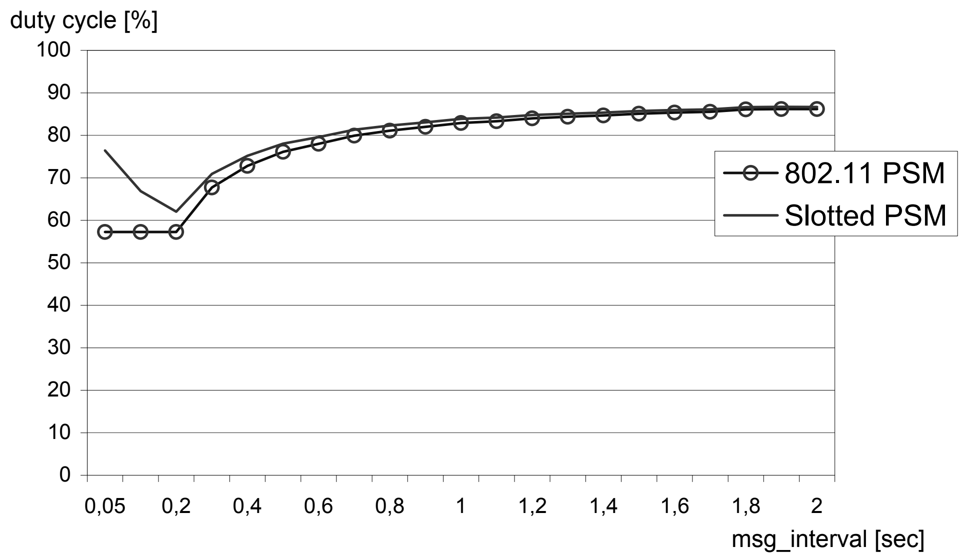

Figure 5.1: Sleep Time Duty Cycles per Node

The remaining time is divided in transmissions and receptions of data and information packets. Information packets are the ATIMs, ACKs, RTS and CTS packets, that inform the nodes about transmissions and their length, reserve channels or bind source and destination to each other. Depending on the different protocols the reception and transmission times can vary.

Generally, the transmission and reception times are nearly equal in 802.11 PSM and Slotted PSM, see table 5.3 and table 5.4.

Message Interval [sec]	802.11 PSM [sec]	Slotted PSM [sec]
0.050	6.804	5.999
0.100	6.806	6.011
0.200	6.806	5.987
0.300	4.662	4.061
0.400	3.581	3.087
0.500	2.893	2.498
0.600	2.512	2.158
0.700	2.119	1.827
0.800	2.307	2.044
0.900	2.290	2.055
1.000	1.515	1.323
1.100	1.432	1.241
1.200	1.291	1.141
1.300	1.217	1.060
1.400	1.154	1.001
1.500	1.076	0.940
1.600	1.011	0.880
1.700	0.977	0.854
1.800	0.942	0.825
1.900	0.858	0.756
2.000	0.846	0.735

Table 5.3: Transmission Time per Total Network

802.11 PSM uses more time for transmissions and the transmission duty cycle is higher, see figure 5.2, because more packets are needed than in Slotted PSM. In Slotted PSM, data exchange can start immediately in the agreed time slot while in 802.11 PSM, nodes have to exchange RTS and CTS packets to reserve the channel. Therefore, nodes are longer awake in 802.11 PSM to exchange all required packets than in Slotted PSM. During the ATIM window a lot of collisions occur because of the competition among all nodes.
At a message interval of about 50ms the transmission duty cycle of 802.11 PSM is 2% higher than in Slotted PSM. As shorter the message intervals, as lower both duty cycles. Also the difference between the duty cycles decreases until it becomes nearly equal at 2% transmission duty cycle for 802.11 PSM and Slotted PSM. The duty cycle will stay equal with the longer message intervals. As longer the message intervals, as more the nodes are in sleep mode and as less they are transmitting data. The exchange of information packets is necessary and can not be avoided, which is the main reason for the nearly equal duty cycles in both protocols.

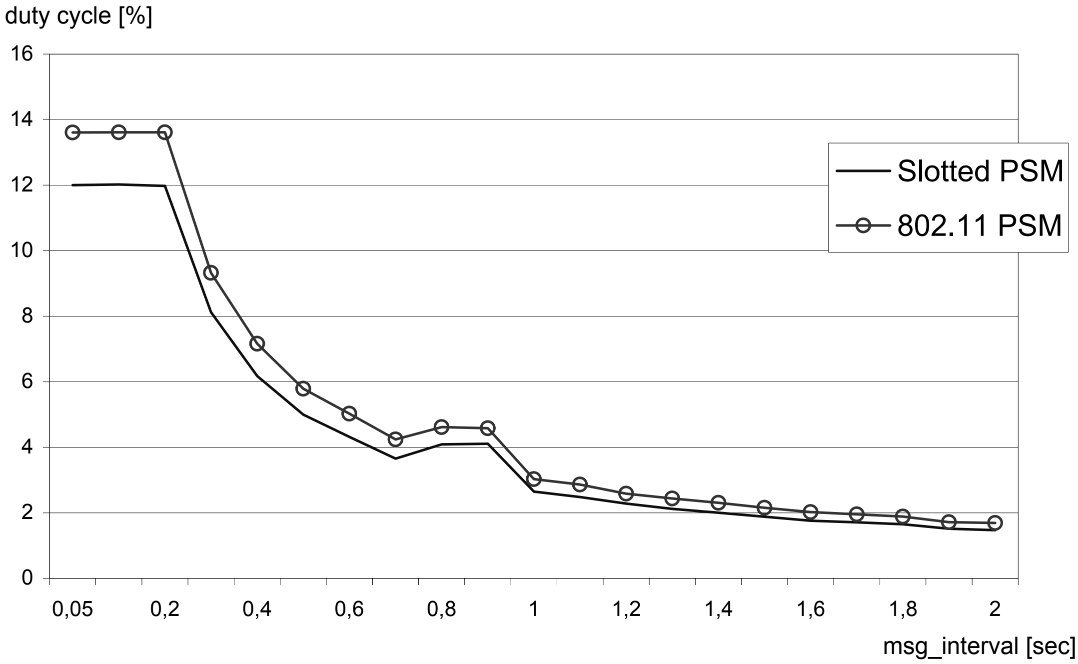

Figure 5.2: Transmission Time Duty Cycles per Total Network

As the transmission time is higher than in Slotted PSM, the reception time is also higher. With the 802.11 technology more packets are transmitted and received. All received packets have to be acknowledged with an ACK. The transmissions are not handled at a specified time, so destination nodes have to be aware of data transmissions all the time, which results in idle listening on the channel. Idle listening is avoided in Slotted PSM.

The calculated reception duty cycle can be seen in figure 5.3 and at shorter message intervals Slotted PSM offers a reception duty cycle of about 10%. 802.11 PSM devices are in the receiving state 31% of the network time at the same message intervals. This results in a difference of 21% but the difference decreases to 7% with the increase of the message interval to 200ms. At the message interval of 200ms, beacons and data transmissions occur at the same time, which increases the collision occurence of packets in Slotted PSM. The nodes could not handle the equal periods of beacons and data packets, which increased the receiving time significantly while the transmission duty cycle, figure 5.2 stayed constant. In general, the duty cycle of 802.11 PSM is higher than in Slotted PSM for all different message intervals and the duty cycles reach its lowest level at 12.3% for 802.11 PSM, while the duty cycle of Slotted PSM is 11.5% at a message interval of 2 seconds.

Message Interval [sec]	802.11 PSM [sec]	Slotted PSM [sec]
0.050	15.381	4.976
0.100	15.369	9.774
0.200	15.393	12.174
0.300	12.081	9.884
0.400	10.517	8.823
0.500	9.441	8.086
0.600	8.845	7.699
0.700	8.204	7.228
0.800	7.402	6.539
0.900	6.950	6.187
1.000	7.223	6.551
1.100	7.098	6.475
1.200	6.856	6.310
1.300	6.757	6.240
1.400	6.663	6.174
1.500	6.517	6.069
1.600	6.442	6.011
1.700	6.369	5.970
1.800	6.128	5.747
1.900	6.152	5.798
2.000	6.172	5.822

Table 5.4: Reception Time per Total Network

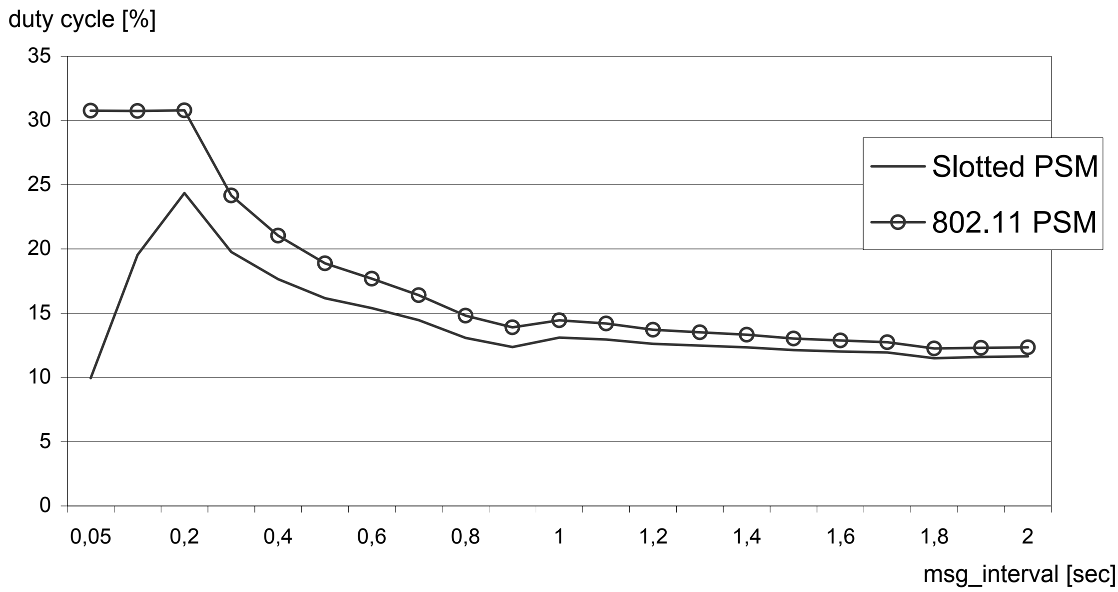

Figure 5.3: Reception Time Duty Cycles per Total Network

Due to longer transmission and reception time in 802.11 PSM, the power consumption during data exchange is higher than in Slotted PSM. The average power consumption per node per second can be calculated:

$$Power\_Consumption_{TX}[W] = \frac{tx\_time \times 1.400}{simulation\_time \times no\_of\_nodes} \quad (5.3)$$

$$Power\_Consumption_{RX}[W] = \frac{rx\_time \times 1.020}{simulation\_time \times no\_of\_nodes} \quad (5.4)$$

$$Power\_Consumption_{SM}[W] = \frac{sl\_time \times 0.070}{simulation\_time \times no\_of\_nodes} \quad (5.5)$$

As seen in figure 5.4, the nodes using 802.11 PSM consume about 1mW more power than Slotted PSM at shorter message intervals. Due to the increase of the message intervals, transmissions become less and the energy consumption decreases in both protocols. Slotted PSM uses 500µW less power at an interval of 2 seconds than 802.11 PSM.
When data transmissions occur at an interval of about 800ms, the energy consumption rises. The simulation results show, that at this message interval more collisions occur during the beacon transmission and the ATIM window and due to the retransmissions more energy is consumed.

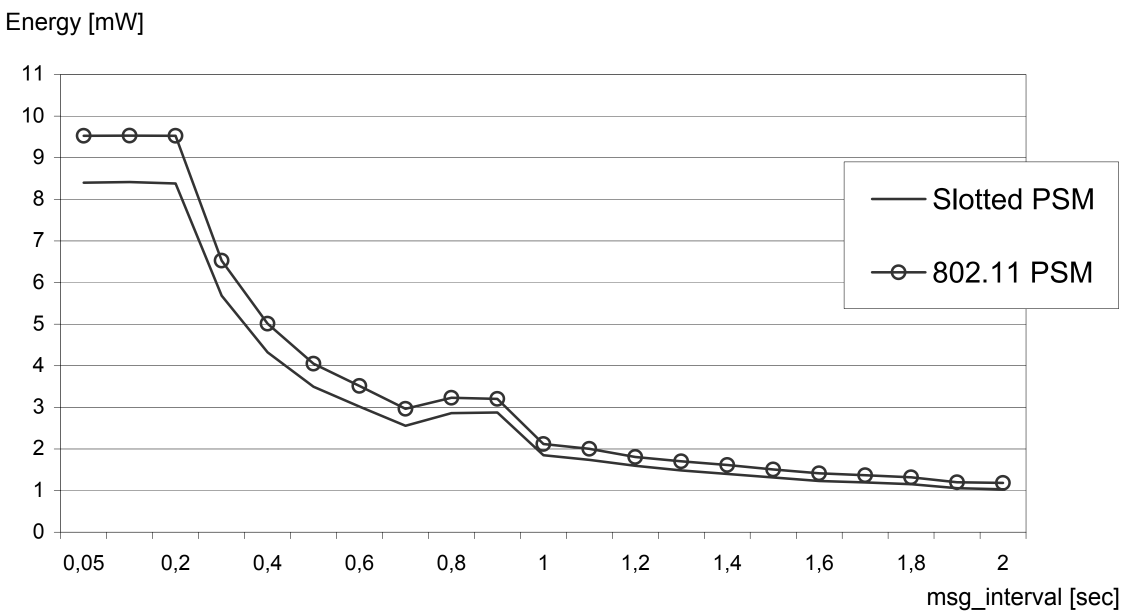

Figure 5.4: Transmission Power Consumption per Node

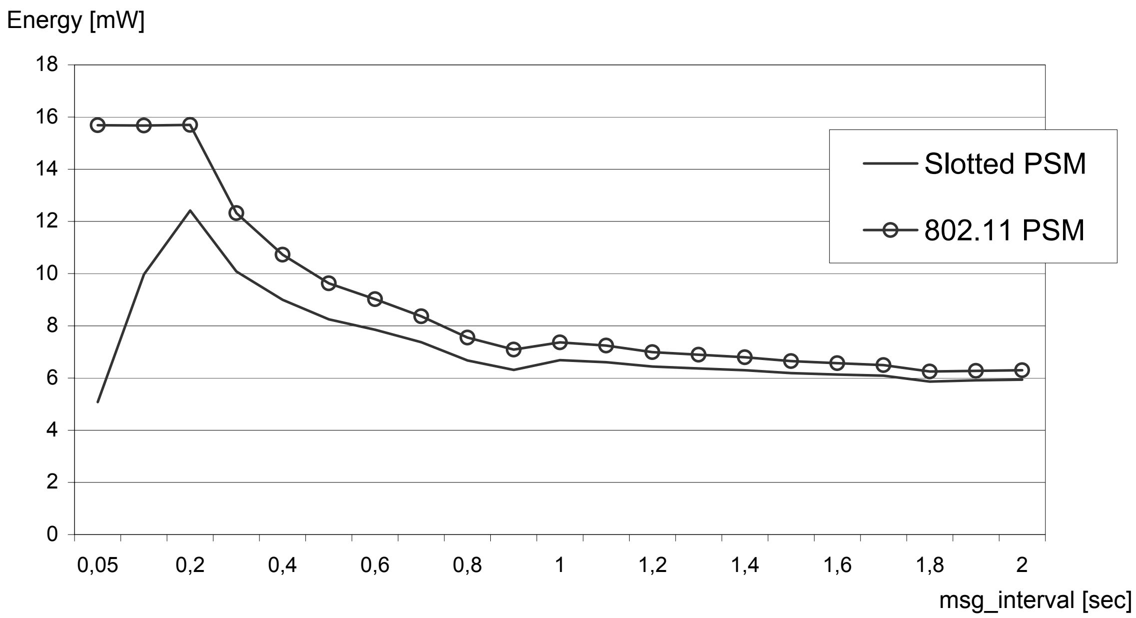

Figure 5.5: Reception Power Consumption per Node

Slotted PSM and 802.11 PSM are MAC protocols, which consume more energy during receptions than transmissions. The great advantage of Slotted PSM is that the nodes receive less time and therefore consume less energy, figure 5.5 than in 802.11 PSM. At a message interval of 50ms, nodes using Slotted PSM consume 5mW and nodes using 802.11 PSM consume nearly 16mW, which gives a difference of 11mW. When the message intervals become longer, the energy consumption in the receiving state of Slotted PSM increases and hits its peak at 12.4mW at a message interval of 200ms, when transmissions and beacons occur at the same time. 802.11 PSM decreases constantly from nearly 16mW to 6.2mW.

The overall power consumption is shown in figure 5.6 and involves the consumed energy during transmissions, receptions and sleep mode. The power consumption in 802.11 PSM is constant at 27mW at shorter message intervals, while Slotted PSM consumes 16mW at an interval of about 50ms. The power consumption of Slotted PSM increases and the maximum power consumption is gained at 23mW at a message interval of 200ms.
For the remaining message intervals, the consumed energy decreases constantly for both protocols. At a message interval of 2 seconds the energy consumption is 10mW for Slotted PSM and 10.4mW in 802.11 PSM. Due to information packets, necessary synchronization packets and transmission arrangements, which have to be exchanged periodically, the energy level can not be minimized anymore.

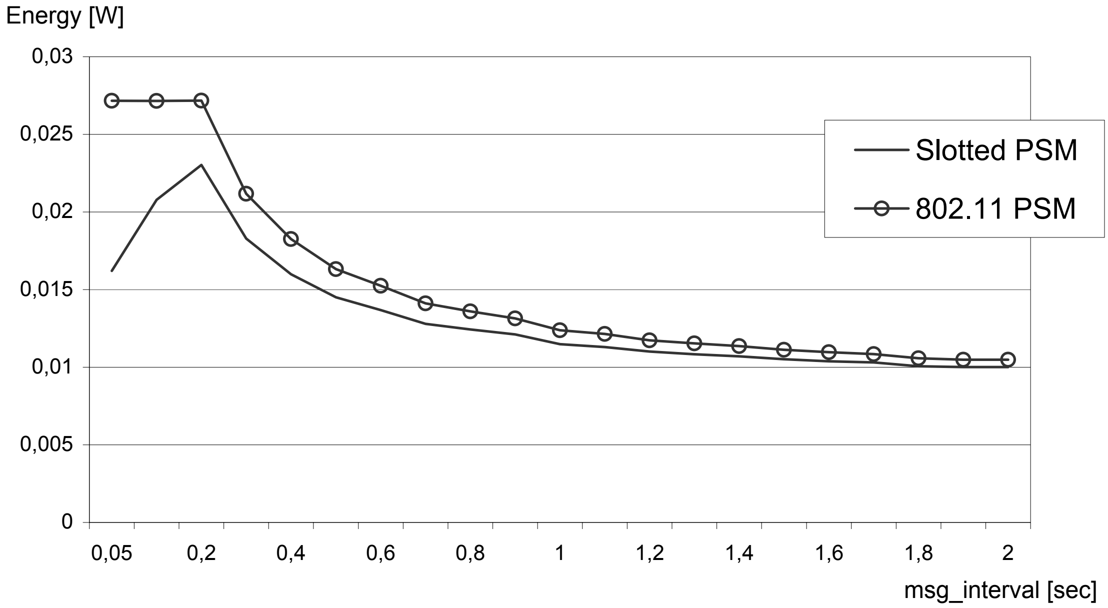

Figure 5.6: Overall Power Consumption per Node

Concluding, Slotted PSM achieves better energy handling than 802.11 PSM, due to channel reservation at specified time slots. Idle listening and the competition, which are necessary in 802.11 PSM, is avoided. Slotted PSM does not exchange RTS and CTS packets, that also saves a lot of energy and bandwidth. The simulation results showed that Slotted PSM and its energy efficiency are more effective at shorter message intervals and when transmissions take place more often.

6 Conclusion

All the evaluated and analyzed MAC protocols offer energy saving, sleep or standby modes to offer greater energy efficiency for wireless sensor networks. The highest amount of energy is required during transmissions, where nodes and devices have either to transmit or receive data packets. Before and after transmissions, nodes can turn into the energy-efficient sleep mode, which involves the problem of synchronization within the network. Due to the sleeping periods the clock in each node drifts apart from the general time either in the base station or in the other nodes. The synchronization problem is solved in all common protocols like Bluetooth, WLAN and ZigBee, by the periodical transmission of beacons, which contain the actual time. All nodes are aware of the beacons and adapt their internal clocks with the received time.
The amount of energy, which has to be used for transmission depends on the distance between source and destination. If a transmission was not successful, the source will retransmit the data but with a higher energy consumption as result. Due to that, the power consumption increases with the amount of retransmissions, which should be avoided as much as possible. As the switch between different modes also consumes energy, there must be a trade off between the switch or the persistence in the mode. Nodes should decide if it is really more energy-efficient to switch or to stay individually.
The greatest disadvantage of Bluetooth and WLAN is the long time the devices are awake for idle listening on the channel. The nodes are waiting to receive data packets. Idle listening consumes a high amount of energy per device, which also limits the overall life time of the network.

Protocols, which offer improved functionality and more energy efficiency than CSMA/CA, used in WLAN or Bluetooth were analyzed:
Slotted PSM, an improvement of CSMA/CA offers the exchange of the length of the data packet and a fixed time when transmission will start between source and destination. After the beacon, the source announces how many time slots it will need for transmission and it addresses the destination. Each node knows when to receive, transmit or to sleep and for how long.
The *EE-MAC* protocol uses the arrangement of masters and slaves in a wireless network. Masters build the backbone of the network, and slaves can turn into sleep mode, while masters are awake all the time. The slaves exchange their power levels periodically with the master, which calculates the average power level of all slaves it is connected to. If the average energy level is higher than its own, the master will become slave and another slave will become master. This offers fairness and nearly equal power levels in all different nodes within the network.
Improved PSM, another alteration of CSMA/CA offers the changeable length of the ATIM

window. During the ATIM window nodes exchange the information that they have to transmit data. In CSMA/CA the ATIM window is specified and all nodes have to be awake during this fixed time interval. Improved PSM decreases the energy consumption during the ATIM window due to the individual decision of the window's length by each node. If no transmission announcements occur anymore, the ATIM window will stop and data exchange will start immediately.
Different channels for the exchange of control and data packets are used in *PAMAS*. Two different radio systems have to be used to listen on the two different channels. Nodes have to be aware of the traffic on both channels until they can start their own transmissions. As the different radio systems need different amounts of energy at least, one system can sleep most of the time, which reduces the power consumption of a node.
Nodes, using the *WiseMAC* protocol, follow a strict schedule, which offers them a fixed period of time, that they are allowed to stay in sleep mode. The schedule is exchanged with all nodes of the network and each node handles the schedule. Therefore, all nodes know when other nodes are transmitting or sleeping and when they are awake to receive data packets.

6.1 Results

An ad hoc network, which consists of 20 nodes, was simulated and Slotted PSM was analyzed and compared to 802.11 PSM, the implemented power saving mechanism of WLAN. The results showed that the power consumption in Slotted PSM was less than in 802.11 PSM. The difference was high, when the interval between the data transmissions was very low. The nodes, that were using Slotted PSM stayed in sleep mode for 20% more of the time at a message interval of 50ms than the nodes using 802.11 PSM. RTS and CTS are not used in Slotted PSM. Therefore, the nodes' duty cycle for transmitting was 2% less and for receiving more than 20% less than in 802.11 PSM. This results in less power consumption for Slotted PSM than for 802.11 PSM.

The calculated overall power consumption for the 50 seconds long simulated wireless sensor network was about 27mW in 802.11 PSM and 16mW in Slotted PSM. When the message intervals increased, the power consumption during data exchange became nearly equal for both protocols. Slotted PSM used less power than 802.11 PSM in all different modes; transmit, receive and sleep mode. The difference between both protocols and their power consumption decreased from 11mW to 500µW with an increase of the message interval from 50ms to 2 seconds. Generally, Slotted PSM has higher power efficiency and longer life time than 802.11 PSM and saves more energy if transmissions occur at a high rate.

It is very useful in a network, where the amount of data traffic is very high.

6.2 Future Work

Retransmissions and idle listening consume a great amount of energy within a wireless network and limit the life time of each device and thus the whole network.
There are different methods to avoid retransmissions and idle listening:

- Exchange of data packet length
- Specify a time for data exchange
- Define transmission time for each node

One method is the exchange of the length of the following data packet between source and destination either as information in an own packet or as a part of the data packet. The involved nodes will then know how long the transmission will take and they can therefore turn into sleep mode earlier.
If the channel is divided into time slots, the nodes will know when each time slot starts and ends. Thus, nodes can reserve one or more time slots for their transmission. Idle listening and the waiting time for each node until the transmission occur and data has to be received, will be avoided. Another advantage is that there will be no collisions and retransmissions during data exchange.
The third method is a specified schedule for each node, when it can start its transmission and when it has to be awake to receive data. The disadvantage is that data packets have different sizes and if nodes need more time, than they have in their hands or need less time for their transmission, energy and/or bandwidth will be wasted.
The usage and necessity of the implementation of wireless ad hoc networks will rise in the next years and it is very important to increase their life time and efficiency in power consumption.

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