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A Preliminary Study of Wireless Body Area Networks

Katrin Bilstrup

School of Information Science, Computer and Electrical Engineering,
Halmstad University, Box 823, SE-30118 Halmstad, Sweden

ABSTRACT

The purpose of this preliminary study is to introduce wireless body area networks (WBAN) to the reader but also to give an understanding of what possibilities and challenges there are when using short range wireless communication in this domain. Up to date, there is no standard specifically intended for low-power WBANs thus a developer is referred to use proprietary solutions which could be demanding to compare and choose. This study tries to provide the reader with the knowledge about important parameters in low-power sensor networks. Energy consumption is the really weak part of a wireless sensor network since the transceiver and other hardware equipment still drain batteries. For example the startup time for a transceiver that has been in power-down mode could consume as much as three times the energy as compared when sending the actual bits that invoked the transceiver in first place. The actual application must be the one driving the requirements on the communication. However, the application must be designed with for example the startup time in mind. A sensor network is a true cross-layer design problem where many different areas must meet such as hardware designers, application developers and communication people.

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1 Introduction

Wireless networking is an exciting area and it has completely invaded our homes and environment during the last decade due to cheap equipment and easily implementable standards. In 1965 the co-founder of Intel Gordon Moore said that the number of transistors that could be fit onto an integrated circuit would double every second year. This has later on been called the Moore's law and since this statement there has been a doubling every two years leading to today's possible miniaturization of hardware. Sensor networks with small energy-efficient nodes have become reality and a whole new world of applications has emerged. In 1998 the Smart Dust project started at Berkeley in California and run for three years. The goal of the project was to create autonomous sensing communication nodes as big as a cubic millimetre [27] to be used in a massively distributed sensor network. The application areas for this project were diverse ranging from weather/seismological monitoring on Mars to smart office spaces. Because this project was the first of its kind it is widely known and several other big projects have theirs origin here.

Wireless body area networks (WBAN) was first presented by T. G. Zimmerman in an article from 1996 [28] but he gave these body networks the name wireless personal are network (WPAN) from the beginning. Later on PAN was redefined to be, e.g., cable replacement for up to 10 meters (e.g., Bluetooth) and the name WBAN evolved instead. WBAN is still in its infancy and there is a lot of research going on. A WBAN will be a network containing sensor nodes monitoring , e.g., vital signs of the human body and a more intelligent node capable of handle more advanced signal processing etc., which all sensors report theirs data to. The sensor nodes could be on the body (wearable) as well as implant (inside the body). Healthcare will be the really dominating application area for WBANs and as soon as a really technology breakthrough is done within WBAN there will be no end of the numerous of applications that will reach us through the healthcare domain. One big issue that has to be solved is the battery life time, which must be attacked from two ways; better battery technologies and more energy-efficient hardware design. The first application domain of WBAN within healthcare will probably be monitoring patients suffering from chronic diseases such as diabetes in order to have a more precise treatment in terms of medication.

This preliminary study will try to shed some light over general questions that arise in all kinds of application domains when using low-power sensor networks where the nodes communicate wirelessly. Up to date there is no standard specifically intended for WBANs. IEEE chartered a new subworking group within 802.15 to bring a WBAN standard forward in November 2007. The closest standard that can be used today for WBANs is the IEEE 802.15.4 providing a medium access layer and physical layers which could be used for building an application on top. However, there exists a plethora of transceivers, sensors and microcontrollers that can be used for sensor networks. These are though proprietary solutions for unlicensed frequency bands and they are hard to compare since they are exactly proprietary. Some solutions from manufacturers provide complete sensor nodes with a whole protocol stack while others have only chip sets for sale. A standard is not always the most efficient technical solution but it is a good starting point in order to achieve interoperability between different product vendors and application architects have more than one manufacturer to choose from.

In Chapter 2 general communication theory is detailed that is needed to understand the rest of this study. Chapter 3 gives an overview of different wireless standards and why these do not meet the requirements of a WBAN and in Chapter 4 more specific questions concerning sensor networks are examined. The study is ended with a conclusion.

2 Wireless networking

In wireless networks communication takes place without a wire and it could be done through, e.g., radio (electromagnetic wave propagation), or infrared (IR). Wireless networks provide mobility which is one of its major advantages and wireless networks can be classified according to its geographical coverage [1], see Table 1. WWAN stands for wireless wide area network and it spans the largest geographical region, e.g. satellite communication, mobile telephone systems. Metropolitan area networks usually span a city and an example of these is the cable TV network and the upcoming wireless broadband standard IEEE 802.16. Networking in a local area has been given the term LAN and here the dominant technologies are found within IEEE's LAN family containing Ethernet in the wired case as well as IEEE 802.11 in the wireless ditto (WLAN). WPAN stands for wireless personal area networks and here both commercial as well as IEEE standards are found, e.g., Bluetooth and IEEE 802.15.4. A body area network has the smallest coverage area only surrounding the body of a human. Here no standards are available for the moment. However, in November 2007 IEEE appointed a new task group, numbered to 6, within the 802.15 [2] to work out a new standard for WBANs.

Table 1. Classification of wireless networks according to their coverage.

Network	Coverage	Data rate	Applications	Technologies
WWAN	> 10 km	< 10 Mbps	Mobile Internet, telephony	Satellite, GSM, UMTS
WMAN	< 10 km	< 100 Mbps	Broadband	IEEE 802.16
WLAN	< 1 km	< 100 Mbps	Hot spots, Ethernet replacement	IEEE 802.11
WPAN	< 10 m	< 10 Mbps	Data transfer	Bluetooth, IEEE 802.15.4
WBAN	< 2-5 m	< 1 Mbps	Health monitoring	Proprietary

The borders between the different listed networks in Table 1 are not as clear as the table makes it look. The mobile telephone system could also belong to the group of WMANs when the cell sizes become really small. Networks with smaller coverage area connect to networks with larger networks, e.g., WLAN connects to WMAN. WBANs could be connected to any of the mentioned networking techniques in the table. There are two different types of network topologies within wireless communication; peer-to-peer and communication through infrastructure. Peer-to-peer communication is used in ad hoc networks whereas infrastructure based networks contain an access point (AP) or base station (BS) which forward the traffic to the intended recipient. In infrastructure based networks all communication must go through the AP/BS even though the sender and receiver are in radio range of each other, i.e., the AP/BS is in charge of the network. In Figure 1 (a) an ad hoc network is shown where all nodes can send data traffic to all other nodes within radio range and in Figure 1(b) the infrastructure mode is depicted. Today, for example all mobile telephone systems work in infrastructure mode and the same goes for the WLAN standard 802.11. However, the latter has support for ad hoc mode as well, which could be used for example during a meeting when meeting participants want to exchange documents.

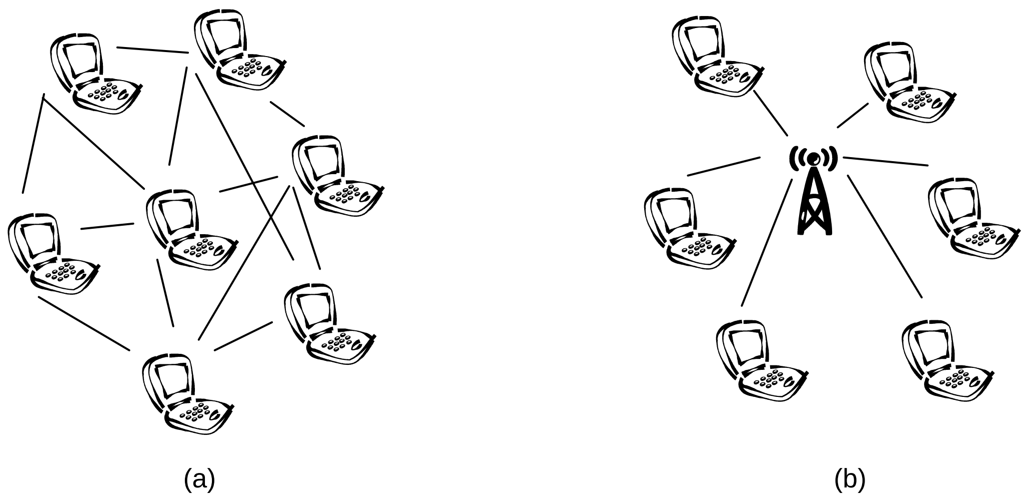

Figure 1. Two different network topologies are depicted: (a) ad hoc mode and (b) infrastructure mode.

A WBAN could connect to other network types through a gateway[1]. In Figure 2 (a) a WBAN is depicted on a human body and through a personal digital assistant (PDA), acting as a gateway, the WBAN could communicate for example with an AP of a WLAN. But the WBAN could also be connected to a mobile phone, which is a direct link to a WWAN as in Figure 2 (b).

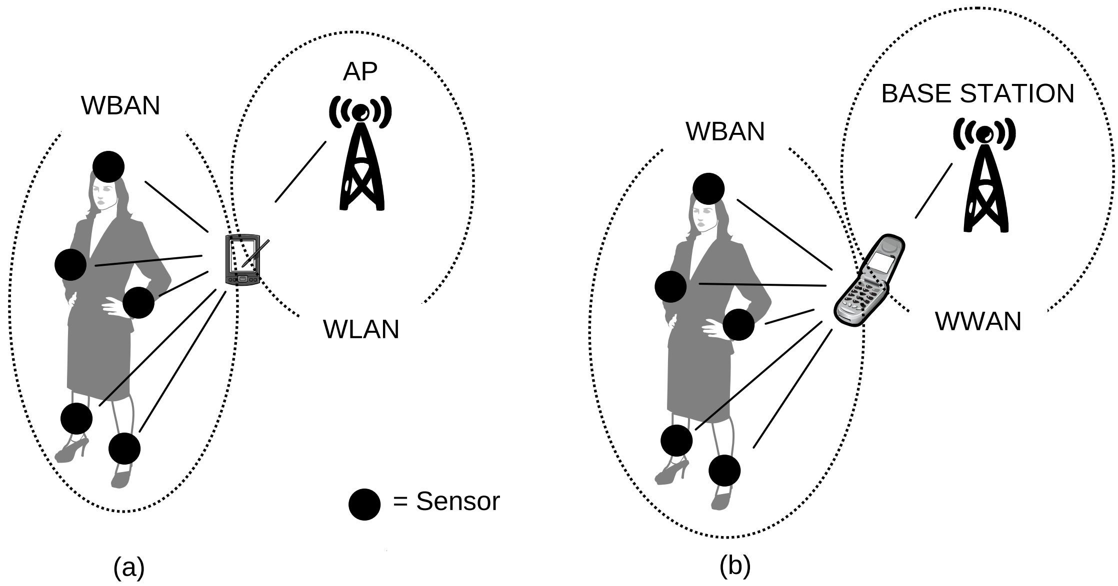

Figure 2. Two different gateways' for a WBAN: (a) WBAN connected to WLAN, (b) WBAN connected to WWAN.

[1] A gateway is a device that converts between two different network techniques.

2.1 Communication protocols

All nodes constituting a network must obey to a set of rules in order to communicate with each other. These rules are gathered in protocols and protocols belong to a layer of a protocol stack. There is a universally prevailing reference protocol stack called the open system interconnection (OSI) model, Figure 3(a), developed by ISO[2]. This model consists of seven layers stacked on top of each other: application, presentation, session, transport, network, data link and physical. The application layer is at the top closest to the user interface and the actual application running on a host whereas the physical layer is at the bottom of the stack closest to the communication channel involving the actual hardware. Every layer deals with its specific part of the communication task and each layer provide services to the layer above. On the Internet the TCP/IP protocol stack, Figure 3(b) is used and it consists of five layers, where the top three layers of the OSI model: application, presentation and session have been merged into one application layer. The layered approach is adopted to break down the complex task of building a communication system, in a divide-and-conquer fashion. Each layer can thus be optimized individually. A layer can also contain more than one protocol, e.g., the TCP/IP stack where at least two protocols resides in the transport layer: user datagram protocol (UDP) and transmission control protocol (TCP).

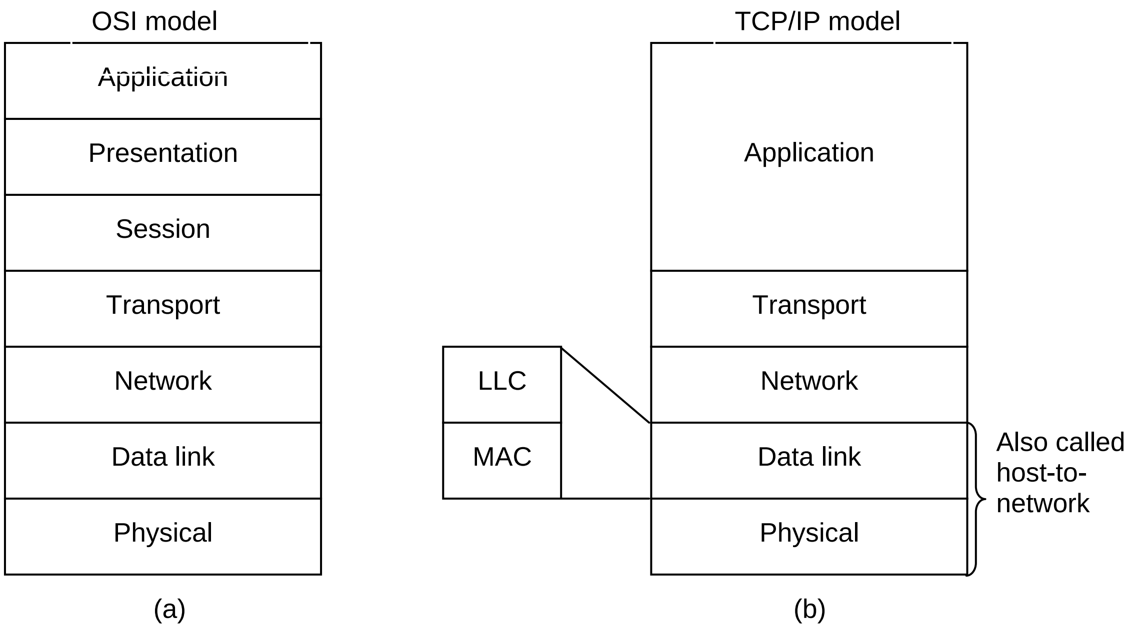

Figure 3. Two different protocol stacks: (a) OSI stack a reference model from ISO, (b) TCP/IP model used on the Internet.

All communication systems have a predefined protocol stack and all nodes that participate in the network implements this. The protocols reside within the software on a node and they are an integral part of a communicating node's operating system. In the TCP/IP protocol stack used on the Internet there is usually more than one protocol in each layer. The protocols belonging to the network, transport and application layer are all developed by the Internet Engineering Task Force (IETF) [4]. This is an organization which is responsible for questions concerning the Internet and the members of IETF are many and diverse. All protocols developed for the Internet and approved by IETF will be given a RFC number, where RFC stands for

[2] International Organization of Standardization

request for comment. All RFCs, i.e., protocol specifications, are free of charge and found on IETF's homepage. For the data link and physical layer there is a couple of RFCs but here we also find for example IEEE[3] standards, which specifies over both layers. In Table 2 different protocols in the different layers are shown. However, this is only a subset of what can be found in these layers on the Internet.

Table 2. Example protocols find on the Internet belonging to the TCP/IP stack.

Layer	Protocol	RFC	Application
Application	Hypertext transfer protocol (HTTP)	1945	Web browsing
	File transfer protocol (FTP)	0959	File downloading
	Simple mail transfer protocol (SMTP)	0821	Email
Transport	Transmission control protocol (TCP)	0761	Reliable transmission
	User datagram protocol (UDP)	0768	Unreliable transmission
Network	Internet protocol (IP)	0791	End-to-end addressing
Data link	IEEE 802.3 Ethernet	-	Networking in a local area
	IEEE 802.11 Wireless LAN	-	Networking in a local area
Physical	IEEE 802.3 Ethernet	-	Networking in a local area
	IEEE 802.11 Wireless LAN	-	Networking in a local area

A standard is a way of guiding the design of a protocol such that all protocols following the standard will be compatible. A standard can specify a whole protocol stack or just a protocol. IETF standardizes different protocols within each layer mainly to the upper layers and IEEE is well-know for its LAN and MAN techniques comprising the lower layers of the stack. Standards are developed both by organizations (national and worldwide) and by company alliances. Bluetooth [5] is an example of a wireless communication standard developed by a special interest group (SIG) of companies and it defines a total protocol suite, whereas the WLAN standard developed by the IEEE is defining only the physical layer and a part of the data link layer.

When communication takes place the protocol stack is traversed from the top, which is the application layer, down to the bottom when sending and vice versa when receiving. All protocols that are used in the communication process will add information to the original data, i.e., the payload (original application data) of the packet is encapsulated. In Figure 4 a packet encapsulation is depicted originating from a web browser request. When there is a protocol stack present all layers must be traversed and must encapsulate the original application data. A general purpose communication system such as the Internet supports a diverse set of applications ranging from IP telephony to file downloading. Due to this the protocol stack is also more complex supporting more protocols and the data that is sent will therefore contain more overhead, i.e., data information belonging to the protocols. On the Internet the data packets sent contain a lot of overhead due to the number of different applications. On the other hand, for example application specific networks such as industrial networks controlling a process usually have small protocol stacks to keep the amount of sent data low and also to keep the delay

[3] Institute of Electrical and Electronics Engineers

on a moderate level. There are of course other important factors when you want to keep the complexity of a protocol stack low and this could be for example if a node is battery powered then a complex stack implies a lot of computation draining batteries.

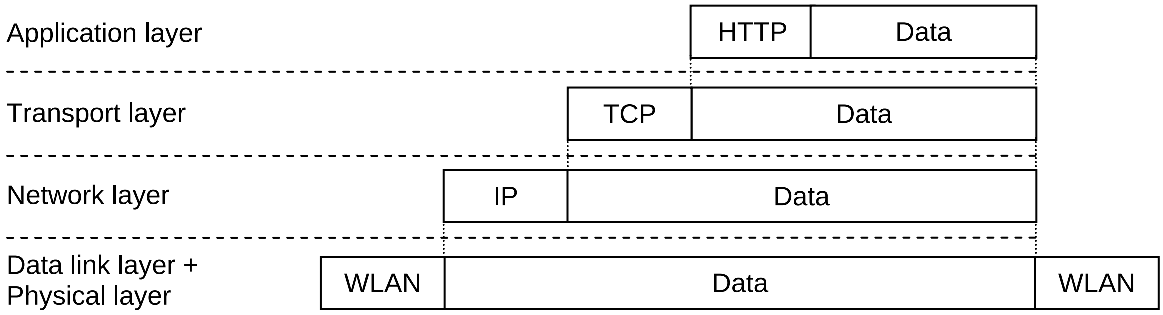

Figure 4. Packet encapsulation after a web browsing request; HTTP→TCP→IP→WLAN.

3 Wireless communication standards

There exists a diverse set of wireless communication standards and some of these are designed for carrying voice, e.g., GSM and 3G, whereas some was from the beginning designed for carrying data traffic. Standards can be categorized as telecommunication or data communication standards, the former contains delay sensitive applications whereas the latter is more intended for high reliability applications (i.e., you want all bits in an email to be received correctly but it does not matter if the email is arriving one second later due to this). There is no standard that is intended especially for wireless body area networks (WBAN). However, wireless personal area networks (WPAN) standards such as Bluetooth and IEEE 802.15.4 are seen in WBAN applications even though these have a longer transmission range. In this chapter WBAN and wireless local area network (WLAN) standards will be glanced through even though they might not be the option in a WBAN but it is good to have the understanding of why these are not suitable for low-power applications.

3.1 IEEE 802.11

The IEEE 802 LAN standards, Figure 5, which includes IEEE 802.11 and the wired IEEE 802.3 among others, use the same bridging protocol, IEEE 802.1, and the same logical link control (LLC) in the logical link sublayer, IEEE 802.2. This separation between logical link and medium access control (MAC)/physical (PHY) layer makes it possible to overcome the differences in medium and network topology between the different LAN standards. This construction simply hides the differences between the various network types (wired and wireless).

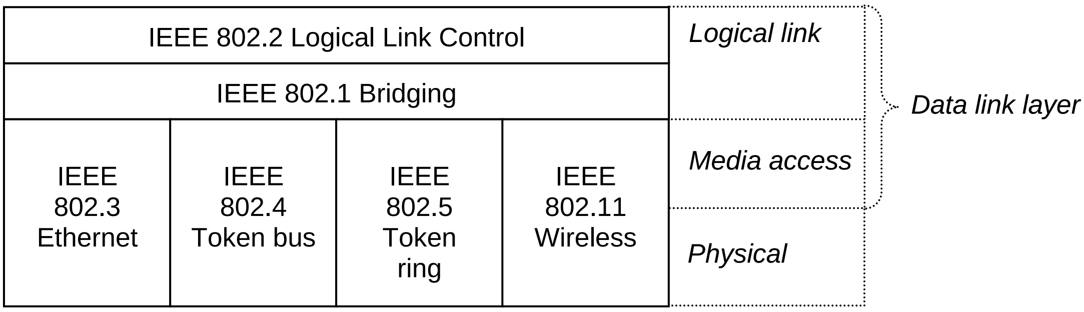

Figure 5. An overview of the IEEE 802 LAN Family.

The IEEE 802.11 [6] was first released in 1997 but has since then been extended a couple of times with both amendments[4] and supplements[5]. There are six different physical layers to 802.11, Figure 6; frequency hopping spread spectrum (FHSS), direct sequence spread spectrum (DSSS), infrared (IR), orthogonal frequency division multiplexing (OFDM), DSSS/high rate (DSSS/HR) and OFDM/DSSS/complementary code keying (CCK)/packet binary convolutional coding (PBCC). In Figure 6 the different data rates, modulation types and the operating frequency are depicted. The FHSS, DSSS, and IR physical layers were released together with the base standard in 1997 whereas the other three are extensions to the base standard.

[4] An amendment is a correction/improvement of an already existing work.
[5] A supplement is an addition to an already existing work.

Medium access control (MAC)						
FHSS 2.4 GHz 1-2 Mbps	DSSS 2.4 GHz 1-2 Mbps	IR 1-2 Mbps	OFDM 5 GHz 6-54 Mbps (802.11a)	DSSS/HR 2.4 GHz 1-11 Mbps (802.11b)	DSSS/ CCK/OFDM/ PBCC 2.4 GHz 1-54 Mbps (802.11g)	Physical layers

Figure 6. An overview of the IEEE 802.11 standard

In Table 3 the alphabet soup (a, b, g, e, n, etc) of IEEE 802.11 is summarized.

Table 3. Alphabet soup of IEEE 802.11.

Standard	A=approved U=Unapproved W=Withdrawn	Description
802.11	A	The original base standard containing three physical layers.
802.11**a**	A	Physical layer supplement using the 5 GHz frequency band.
802.11**b**	A	Physical layer supplement using the 2.45 GHz frequency band.
802.11**c**	A	Concerning bridge operations and it is included in the IEEE 802.1D.
802.11**d**	A	Concerning roaming extensions (country-to-country).
802.11**e**	A	QoS enhancement to the MAC layer.
802.11**F**	W	This was a stand-alone document about inter-access point protocol.
802.11**g**	A	Physical layer supplement using the 2.45 GHz frequency band.
802.11**h**	A	Spectrum management of the 5 GHz band of Europe.
802.11**i**	A	Enhanced security.
802.11**j**	A	4.9-5.0 GHz operation in Japan.
802.11**k**	U	Radio resource measurements.
802.11**m**		Maintenance of the standard.
802.11**n**	U	Higher throughput. 2.4 GHz or 5 GHz. Will use multiple antennas for receiving and transmitting data (MIMO).
802.11**p**	U	Extension to the 802.11 both at PHY and MAC level to support high mobility in vehicular networks.
802.11**r**	U	Fast roaming.
802.11**s**	U	WLAN mesh networking.
802.11**T**	U	Stand-alone document about testing WLAN equipment.
802.11**u**	U	Specifying inter-networking with other type of networks, e.g., UMTS.
802.11**v**	U	Network management.
802.11**w**	U	Extension to 802.11i, enhancing the security even further.
802.11**y**	U	3.65-3.7 GHz operation in the US.

Wireless fidelity (WiFi) alliance is an organisation [7] working for certifying IEEE 802.11 products coming from different vendors so they conform to the standard and therefore can interoperate in wireless local area networks.

The 802.11 standard contains two basic network topologies [6]; the infrastructure basic service set (BSS) and the independent basic service set (IBSS). An IBSS is a set of stations that communicate directly with each other without an access point (AP); this is also called ad hoc or peer-to-peer network, see Figure 1(a). If there is an AP present, the network is referred to as an infrastructure BSS and in Figure 1(b) this network topology is depicted. If one node wants to communicate with another node in a cell containing an AP, then the traffic first goes to the AP and the AP distributes it to the intended node even though the two nodes are in radio range of each other.

There are two different modes of gaining access to the wireless medium in 802.11; the contention mode, known as the distributed coordination function (DCF) and the contention-free mode with the point coordination function (PCF). The PCF is called the priority-based access and can only be used when the network contains an AP which holds a traffic and access controller, called a point coordinator (PC). In this mode all stations must obey the PC residing in the AP and all nodes must receive permission from the AP to transfer frames. This procedure begins with a node requesting the AP to be put on the polling list, and thereafter the AP will regularly poll the node. This contention-free mode is optional in the standard. The DCF is mandatory and will coexist with the PCF. When both modes are present the AP will alternate between these two modes.

The DCF is based on the carrier sense multiple access with collision avoidance (CSMA/CA) protocol and all nodes must compete for access to the channel (best effort system). When a node wants to send a packet, it starts by listening to the channel referred to as the physical carrier sense part of the protocol. If the channel is free for a certain time, known as the distributed interframe spacing (DIFS) time, the station will start sending immediately. The 802.11 standard specifies also a virtual carrier sense mechanism. This is known as the network allocation vector (NAV) and is a value that indicates the amount of time before the channel will become available again. Every packet sent in the network contains information about the duration (i.e., the NAV time) of its transmission. Every node must update their NAV according to the traffic in the network. The NAV thus indicates whether the medium is busy even when the channel does not appear to be busy as sensed by the physical carrier sense. These two carrier sense mechanisms make the collision avoidance part in the protocol. If a node senses that the medium is busy, either virtually or physically, the station must randomize a backoff time before a transmission can be initiated anew. As long as the channel is free the node decrements the backoff time and when it reaches zero the node starts sending right away. This backoff procedure is used to prevent collisions among nodes, and hence the highest probability of collisions is right after a busy channel – especially during high utilisation periods. The probability of collisions will, however, decrease if the nodes have different backoff times.

3.2 IEEE 802.15

The IEEE 802.15 [8] is a working group focusing on WPAN. It has seven different approved standards within the group and it has ten different ongoing standards' discussions which are in different phases of the standardization process. The 802.15.1 is an IEEE standard of the lower transport layers of the Bluetooth stack version 1.1 and it contains a MAC and a PHY layer specification. Today, Bluetooth has reached version 2.1 [5] and the task group of 802.15.1

does not intend to follow up with new specifications when new versions of Bluetooth arrives. Task group 2 has delivered a recommended practice, i.e., 802.15.2, for coexistence of WPAN devices with other radio equipment in unlicensed frequency bands. Task group 3 of 802.15 presented a standard in 2003 and it is intended for high-rate WPAN with application areas such as multimedia and digital imaging. High-rate in this context is transfer rates of 11, 22, 33, 44 and 55 Mbps. Task group 3 has two subworking groups called 802.15.3*a* and 802.15.3*b*, where the former was supposed to present a new PHY based on ultra-wide band (UWB) radio technique and the latter came up with an amendment to the MAC sublayer in 2005. In subgroup 3*a* two different proposals of UWB techniques was discussed as a new PHY layer but there was also two different industry alliances behind these which could not come to a consensus. Therefore, IEEE decided to postpone further meetings in this subgroup and there is no UWB PHY standard yet to high-rate WPAN. Task group 4 of 802.15 has developed a standard intended for low data transfer rates of WPANs as opposite to the high transfer rates of 802.15.3. Three different transfer rates are supported; 20, 40 and 250 kbps. In 2007 subworking group *a* of 802.15.4 presented two new PHY layers that can be used for applications where the distance is measured for example. The 802.15.4*b* was chartered for clarifing the 802.15.4 base standard and came up with a solution in 2006. In Figure 6 the different 802.15 standards are depicted with its sub groups.

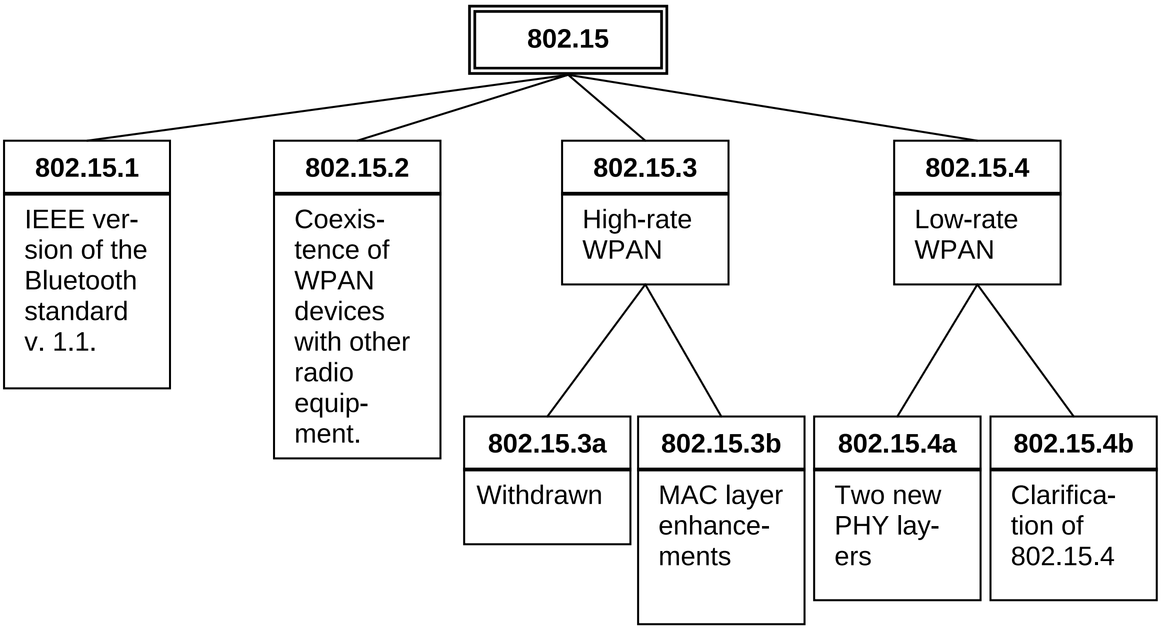

Figure 6. An overview of approved and withdrawn 802.15 standards.

As mentioned in the beginning of this section 802.15 working group has a number of not yet approved standards being in different stages of standardization. The first step towards an IEEE standard is to propose a project and this is done through a document called project authorization request (PAR), which must first be approved by appropriate IEEE board before the actual standardization process can begin. When a PAR has been approved the work with chartering a task group begins and this will in the end present a new standard. For the moment there are six approved PARs and consequently six task groups; 802.15.3*c*, 802.15.4*c*, 802.15.4*d*, 802.15.4*e*, 802.15.5, and 802.15.6. The remaining four groups within 802.15 do not have any PAR and therefore they are only interest groups/study groups; SGrfid, WNG, IGTHz, and SGvlc. The 802.15.3*c* is working on a new PHY layer intended for millimetre waves using the 57-64 GHz frequency band. The 779-787 MHz band has been opened in China and task group 4c, i.e. 802.15.4*c*, is addressing this new band. The same goes for

802.15.4*d*, which is working on a new PHY amendment addressing the frequency band between 950-956 MHz, opened up in Japan. The task group of 4*e* is working on MAC layer enhancements and compatibility issues with Chinese WPAN. Standardization of supporting mesh networking is done in 802.15.5 and WBAN is the newest working group named 802.15.6 that is going to bring a standard forward supporting networking in the close vicinity of the human body. The other groups that have not yet reached the PAR stage are; a study group on radio frequency identification systems (SGrfid), a standing committee looking into future wireless technologies (WNG), an interest group concerning communicating using THz waves (IGthz), and the last group is a study group on visible light (SGvlc).

All 802.15.*x* approved standards propose PHY and MAC layers. They do not provide any network layer, transport or application layer, implying that this has to been developed by any other party. ZigBee [9] is a company alliance providing a network and an application layer to 802.15.4 devices, see Figure 7.

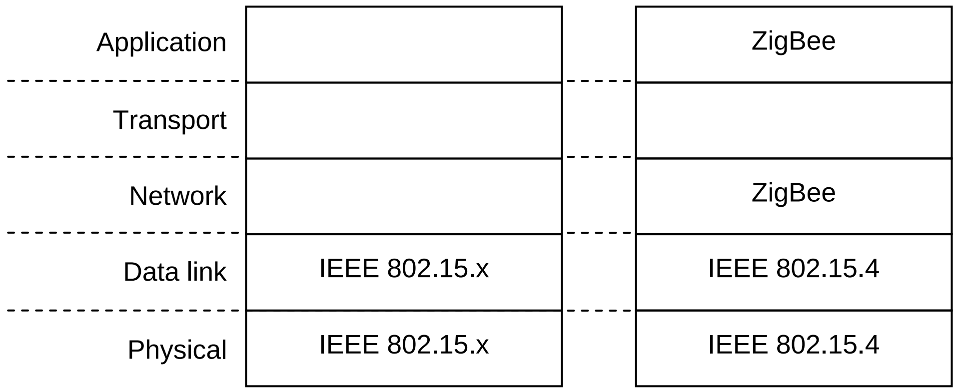

Figure 7. Show the layers that IEEE standardizes and ZigBee provides compared with the TCP/IP stack's layers.

The transport layer can be omitted and its services can be included in the application layer.

3.3 Discussion

IEEE 802.11 WLAN is not an option for WBANs because it is not intended for low-power devices even though it can be used with laptops running on batteries. But this is only a temporary solution until an electric socket is found again. The IEEE 802.15.4 standard states that it is a low-power alternative and it could be an alternative depending on what battery requirements the sensor network has.

4 WBAN for medical applications

Medical equipment is one application area for wireless body area network (WBAN) where a couple of sensors will monitor a patient's activity, e.g., electrocardiogram (ECG), electroencephalography (EEG), and report if something abnormal happens. All kinds of sensor networks put requirements on long battery life time in the sensing node. Therefore, the architecture of a sensor network intended for medical applications must be carefully designed in order to have a long life time. In Figure 9 a schematic picture over a sensor node is depicted containing a sensor, microcontroller and a transceiver.

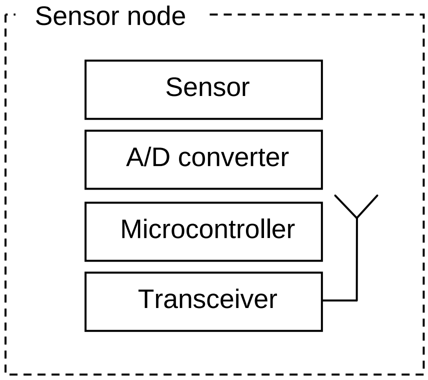

Figure 9. Schematic picture over a sensor node design.

The sensor monitors an activity and the sensor node will communicate the sensor data according to a predetermined heart beat to a more advanced node contained in the network, see Figure 2 where the sensor nodes communicate with a PDA or a mobile phone. There a three different ways of designing a sensor node with its circuitry; (1) design everything from scratch, sensor, microcontroller and transceiver, (2) design the sensor node with off-the-shelf components and (3) buy an already developed sensor node. The most expensive choice is of course (1) but the design would probably be the best suited for the application since only necessary circuits would be included. This would also result in the most energy efficient architecture because the design is optimised for one application. Choice no 3 is the fastest way to have something up running and probably the cheapest solution also. This is to recommend if the first focus is on the functionality and to test different solutions for the actual application. The middle way between the two extreme cases is of course (2) where off-the-shelf circuitry best suited for the application in question is chosen. This still requires some design of circuitry around the three main components (sensor, microcontroller, transceiver) such as resistors, capacitors etc. However, reference designs are usually found among the data sheets for the three different main components. If the sensor is digital there is no need for an A/D converter between the sensor and the microcontroller. Today, more and more digital sensors are found on the market.

There is no standard for sensor networks or WBANs and one reason for this could be the wide range of application scenarios for those networks. A standard wants to have support for as many applications as possible and the wider a standard becomes the more complex it will usually become. For a standard to attract the industry it should have support for a diverse set of applications. Sensor networks put requirements on energy-efficiency and to achieve this must all unnecessary features in the design of the sensor node be removed. To achieve long battery life time the sensor node should be kept as simple as possible and a standard can usually not be that simple and application specific. However, the IEEE has chartered a new subworking group, 802.15.6, under the 802.15 umbrella that is going to bring a standard forward intended for WBANs.

4.1 Specific absorption rate

The specific absorption rate (SAR) is an important parameter when talking about the exposure of the human body to electromagnetic fields (wireless communication is using electromagnetic waves) and it measures how much energy that the human body absorbs every second per kilo (W/kg) [22]. The SAR values for frequencies between 100 kHz-10 GHz are as follows: the mean value for the whole body is 0.08 W/kg, locally for head and trunk 2 W/kg and locally for arms and legs 4 W/kg. The absorption rate decreases when the sending unit is further away from the body. The penetration into the body is dependent on the frequency in use, e.g., a GSM phone using the 900 MHz band penetrates approx. 4 cm into the body whereas the UMTS phone using a higher frequency only penetrates 2-3 cm into the body. The maximum output power that a GSM phone is using when sending is 2 W and at most the phone can use 1/8 of the time meaning that the mean value will be 0.25 W. A 3G phone can use at a maximum 1 W and the mean value will be 0.125 W. The mobile telephone systems have a SAR value of 2 W/kg as mentioned earlier herein. Most of the energy is absorbed in tissue containing a lot of water such as skin, muscles, blood and the brain. The output power of the sending unit must be regulated so the different SAR values are not exceeded. In the next subchapter the output power together with different frequency bands will be discussed and the output power that is allowed in non-licensed bands is nowhere near the ones used in the mobile telephone systems.

4.2 Frequency bands and regulations

All radio transmission is regulated by the government within each country (i.e, in Sweden Post- och Telestyrelsen). However, there exists some harmonization between different countries on the same continent. In Europe ETSI[6] is the central organ that tries to harmonize frequencies between the different European countries. In Table 4 the available non-licensed frequency bands in Europe are given [10]. There exists more non-licensed frequency bands at higher frequencies, but these are of limited practical use at the moment and some of these non-licensed frequencies are assigned to specific applications. Non-licensed band implies that a user can utilize it as long as the restrictions on output power and duty cycle requirement are fulfilled. The output power is the maximum allowed amount of power used by the transmitter when sending and the duty cycle is the amount of time a transmitter is allowed to use the frequency band in time. Frequency bands defined as *non-specific short-range devices* are available for general. As can be seen, in Table 4, six different ranges of frequency bands are available for general use in Europe: 26.995-27.195 MHz, 40.665-40.695 MHz, 433.050-434.790 MHz, 868.0-870.0 MHz, 2400.0-2483.5 MHz and 5725.0-5875.0 MHz. The different allowed frequency band has restrictions on the output power and the duty cycle.

From Table 4 it can also be seen that some of the available license free ISM frequency bands require duty cycle operation by default. The duty cycle percentage is given as the total *On Time* within one hour (the time the transceiver is allowed to use the frequency channel), meaning that a duty cycle of 0.1% implies a channel usage of 3.6 seconds during one hour. There is also a restriction on how long the maximum time period for *On Time* for one transmission is and this is a certain percentage of the total allowed *On Time* per hour.

[6] European Telecommunications Standards Institute

Table 4. Frequency bands available for short-range communication in Europe [10].

Frequency band [MHz]	ETSI standard	Req. duty cycle	Application
26.995-27.195	EN 300 220	no	Non-specific short-range devices (42 dBµA/m @ 10 m, 1 mW EIRP)
40.665-40.695	EN 300 220	no	Non-specific short-range devices (10 mW)
402-405	EN 301 839		Medical implants (25 µW)
433.050-434.790	EN 300 220	1 mW < 100% 10 mW < 10%	Non-specific short-range devices (10 mW)
863-865	EN 301 357		Wireless Audio
868.0-868.6	EN 300 220	< 1%	Non-specific short-range devices (25 mW)
868.6-868.7	EN 300 220	< 10%	Alarms (10 mW)
868.7-869.2	EN 300 220	< 0.1%	Non-specific short-range devices (25 mW)
869.2-869.25	EN 300 220	< 0.1%	Social alarms (10 mW)
869.25-869.3	EN 300 220	< 0.1%	Alarms (10 mW)
869.4-869.65	EN 300 220	< 10%	Non-specific short-range devices (25 mW)
869.7-870.0	EN 300 220	no	Non-specific short-range devices (5 mW)
2400-2483.5	EN 300 440	no	Non-specific short-range devices (10 mW)
	EN 300 328	no	Radio LANs (10 mW, 100 mW 2400-2454)
	EN 300 440	no	Movement detection (25 mW, 2446-2454)
5725-5875	EN 300 440	no	Non-specific short-range devices (5 mW)

A minimum *Off Time* between two *On Time* events must also be fulfilled, according to the ETSI standard of operation of non-licensed short-range devices [11, 12]. See Table 5 what the different requirements of the duty cycle make on the different parameters *On Time* and *Off Time*. The fact that the transmit output power is very limited for short-range radio transceivers, less then 100 mW (typically in the range of 1 mW to 10 mW), implies that it is not the power amplifier of the transmitter that dominates the power consumption [14]. Instead the short-range transceiver’s power consumption is dominated by things such as the local oscillator, the mixer and intermediate frequency (IF) amplifiers. These parts of the transceiver are often common or similar building blocks for the receiver chain and the transmitter chain. This implies that the power consumption is similar for the reception and the transmission operations of a short-range transceiver. It is actually common that the transceiver consumes more power during reception than during transmission [15], this is due to the fact that the receiver is slightly more complex than the transmitter chain and that the power consumption of the transmitter is dependent on the transmit output power, i.e., the emitted power is negligible in comparison with the overall power consumption of the transceiver.

Table 5. Duty cycle limitations [13].

Duty cycle	Total *On Time* during one hour [sec]	Maximum *On Time* for one transmission [sec]	Minimum *Off Time* between two consecutive transmissions [sec]
< 0.1%	3.6	0.72	0.72
< 1.0%	36	3.6	1.8
< 10%	360	36	3.6

The power consumption of the receiving side is also higher due to the reception time window. A transmitter does only have to transmit at a certain point in time whereas a receiver must listen for a slightly longer time period in order to catch the transmission. In [16] there is screen dump from an oscillator showing the power consumption for sending and receiving procedures for short-range receivers in sensor networks. This screen dump also shows that the amount of power consumed for the receiving part is higher than for the sending part due to longer time windows.

The overall power consumption of a short-range receiver is typically in the range of 10 mW to 100 mW during operation [14]. The estimated life time of a ZigBee device, based on a 2.45 GHz transceiver from Freescale MC13192 [17] and a 8-bit microcontroller from ditto MC9S08GB60 [18] powered by a 3 volt LiMn coin cell, for some different telemetry applications [19], are:

- Light switch, six wakeups every day, life time approx. 10 years (not considering the self destruction of the battery).
- Water level sensor, one wakeup every hour, life time approx.1-2 years.
- Patient heart monitoring, one wakeup every 5 ms, life time approx. 1 day.

It can be concluded that even if a frequency band which not requires any duty cycling is used, it is necessary to put these transceivers into power-down mode during long time periods [14] to be able to fulfil a life time of several years. At duty cycling operation the average power consumption over time is dependent on: (*i*) the wakeup frequency of the sensor node, (*ii*) the amount of data that is transmitted at each transmission time, (*iii*) the speed which the data is transmitted with, (*iv*) the startup overhead introduced by the electronics at each wakeup, and (*v*) the protocol overhead.

4.3 Power consumption

To evaluate the power consumption a good starting point is to describe the operation in timing diagrams and then use these to calculate the average power consumption, i.e., the power consumption signature of a sensor node. The duty cycle, D, is the ratio between the *On Time*, t_{ON}, and the period of the function, t_{period}, found in Equation (1).

$$D = \frac{t_{ON}}{t_{period}} \tag{1}$$

The t_{ON} for each wakeup is equal to the sum of the processing time (including sampling the sensor), $t_{process}$, and the transmission time, t_{trans}, where t_{trans} is dependent on the number of bits, N_{bits}, sent at each transmission and the transmission rate, R_{trans}. The resulting t_{ON} is according to Equation (2).

$$t_{ON} = t_{process} + \frac{N_{bits}}{R_{trans}} \tag{2}$$

In a real implementation there are two overheads: (*i*) the overhead introduced by the electronics' start-up time/turn off time and (*ii*) communication protocol overhead. Taking into account the overhead introduced by the state switches from *off* state to *on* state and vice versa, complicates the power consumption calculations. The overhead time is introduced at the startup, t_{start}, and at the turn off, t_{stop}. In Figure 9 a simplified timing diagram for duty cycle operation is displayed.

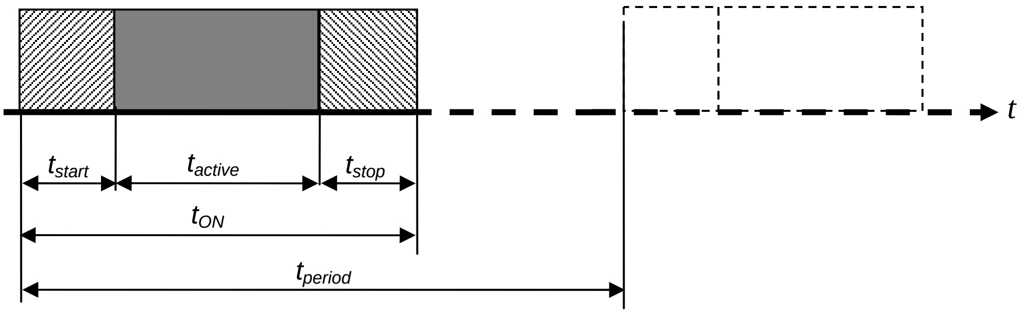

Figure 9. Duty cycling with different timing parameters.

In Equation (3) the overhead for starting and stopping the device is included. The t_{active} in Figure 9 is equal to $t_{process} + N_{bits}/R_{trans}$ in Equation (3), where N_{bits} are the total number of bits in one transmission burst (including preamble, payload and CRC), and R_{trans} is the transmission bit rate.

$$t_{ON} = t_{start} + t_{process} + \frac{N_{bits}}{R_{trans}} + t_{stop} \tag{3}$$

An important observation is that the transceiver's power consumption is often dominant, in comparison with the microprocessor [20], and large energy savings can be done by applying temporal data aggregation of several samples before the actual data transmission take place. This of course implies that it do not exist any specific response time requirements on each individual sensor sample. Furthermore, all components in the sensor node do not need to be "on" all the time during one wakeup, selective enabling of components [21] can save a lot of energy. When this is the case the situation becomes more complicated, since it is necessary to differentiate between the power consumption and the actual on time of the microprocessor, the transceiver and other components in the sensor node. The operation of all components will sum up to a power (or current) consumption signature, Figure 10.

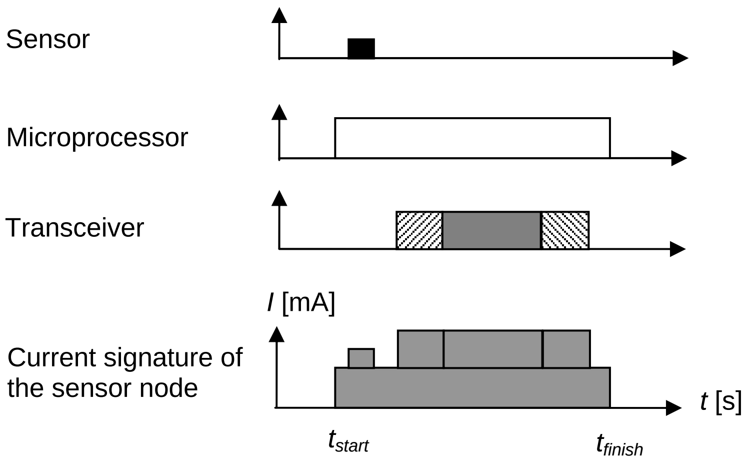

Figure 10. Power consumption signature.

The power consumption signature of the sensor node reveals the total energy consumption for each wakeup. Assuming that the signature is represented as a function of the current consumption over time, $I(t)$, the total amount of consumed charge (given in mAs)[7] of one wakeup, Q_{wakeup}, is given by integrating the current signature function $I(t)$ from t_{start} to t_{finish}, Equation (4). The current signature is easiest to capture by conducting a current consumption trace with some fast sampling instrument.

$$Q_{wake\ up} = \int_{t_{start}}^{t_{finish}} I(t)dt \qquad (4)$$

When the life time for a given battery (a specific amount of available energy) should be estimated, the available charge (often given as mAh)[8], Q_{bat}, is compared with the average current consumption (in this specific case given as mA), I. By using Equation (5) the average current consumption of the transceiver is given in mA.

$$I = \frac{Q_{wake\ up}}{t_{period}} \qquad (5)$$

By plugging the result from Equation (5) into Equation (6) the life time in years is given.

$$T_{lifetime} = \frac{Q_{bat}}{I \times 24 \times 365} \qquad (6)$$

As an example consider a transceiver where the integral of the current signature $I(t)$, is equal to 0.1 mAs, and t_{period} is equal to 10s. This gives an average current consumption of 0.01 mA[9]. Further assuming a typical coin cell battery, CR-2450 which has a capacity of delivering 500-600 mAh, the life time is in the order of 5 to 6 years (not considering the aging of the battery). This is a coarse grained estimate, the actual implementation has a large impact on how optimized the power signature becomes for a specific device, as will be shown in the next section.

[7] Milli-ampere-second is an indirect measure of the energy, representing the charge of 0.001 Columb.
[8] Milli-ampere-hour is an indirect measure of the energy, representing the charge of 3.6 Columb.
[9] This is probably an extremely low value.

4.4 Transceiver considerations

From a power consumption perspective high data rate is often preferable, since involved transceivers should be in active mode for as short time period as possible. There also exists a trade off between the range (sensitivity), data rate, and modulation scheme (complexity of the transceiver). A transceiver could be in different states; power-down, sleep, idle, and active mode. In power-down the transceiver is not fed with any power at all, which is the case for the other three modes where the transceiver consumes power. In active mode it is sending or receiving and in idle it is fully powered but is waiting for an action to take place. In sleep mode the transceiver has a shorter startup time then from a power-down mode but there is still some power fed into the transceiver to keep, e.g., the oscillator running. Different manufacturers have different types of sleep modes and it is the data sheet that can reveal the power consumption in sleep mode. If only a small amount of data (one or a couple of bytes) is sent during each wakeup, the overhead caused by the startup time may have a large impact on the total average power consumption. The startup time for the transceivers is usually not easily obtained from the technical data sheets of the different manufacturers. In [25] the startup time for a transceiver called µAMPS-1 is given and it is 470 μs. This transceiver has a transfer rate of 1 Mbps and in a sensor network where the amount of data that has to be transferred is not substantial the startup time can be a very large portion of the sending node's wakeup. If we want to transmit between 10-100 byte every wakeup with the µAMPS-1 then the transmission will take between 80-800 μs plus the startup of 470 μs. However, the overall target for short-range devices is often to achieve as small consumed energy per transmitted bit ratio. The method described in the previous section can be used to estimate the achievable life time for different transceivers. The wakeup periodicity and the type of sleep mode that is used are important design parameters, since the startup time from power down to standby often is substantial. Here there exists a trade off between periodicity and type of mode that should be used in the non active period. As a first consideration one should use power down mode during non active periods, but then the startup overhead is large at each wakeup. A second possibility is to use some low power idle mode (consumes more power then power down) during non active periods, resulting in that the startup to active mode is shorter. This design choice is directly dependent on the wake period. In the book *Ultra-Low Energy Wireless Sensor Networks in Practice* written by M. Kuorilehto et al. [26] real world sensor applications are covered together with practical advice. Here summaries of transceivers, microcontrollers etc. are found, which can be a good starting point when developing sensor networks.

4.5 Link layer considerations

The applied communication protocol stack has a direct impact on the operation sequence of the sensor node. As an example, compare a unidirectional system with a bi-directional system. If the communication between the sensor node and the PDA/mobile phone in Figure 2 is unidirectional, the sensor node only performs transmissions and the operation sequence may be equal for each wakeup. On the other hand, if a retransmission scheme is used, bi-directional communication is necessary. The event of a retransmission causes the current signature to differ; it introduces non static execution sequences. For bi-directional communication the transceiver, in the sensor node, need to perform both reception and transmission and a receive/transmit switch, which requires a longer active time. All commercial transceivers usually include an error detecting mechanism by applying a cyclic redundancy check (CRC) on the payload. If an error is detected, three different approaches are available: (*i*) accept that the payload is erroneous and use it anyway (typically done in voice applications), (*ii*) drop the data and wait for the next transmission, or (*iii*) ask for a retransmission of the data from the source. The application must be the one deciding if there should be retransmission scheme or not.

Before the sensor node is allowed to send the medium access procedure is consulted. The medium access control (MAC) is an algorithm deciding who has the right to send. Two main classes of MAC protocols are available; contention based and contention free channel access. The most common contention based channel access methods are Aloha and carrier sense multiple access (CSMA) [21]. A node employing the former mechanism will start to send immediately as soon as the node has something to send with high probability of collision with another node. In CSMA mode the node starts with listening for a time period if the channel is free during this time period the node starts to send otherwise the node has to defer its channel access to a later occasion when the channel becomes available again. All nodes in a network must obey to the same MAC rules.

For a sensor application a contention free channel access mechanism is preferable, since it does not introduce any arbitration overhead (i.e., listening period). Three straightforward methods are available for contention free channel access: *polling*, *strobing* and *cyclic broadcast*. If *polling* is applied the master in the network (e.g., BS, AP, mobile telephone, PDA) individually asks each sensor node (slave) to send an update of its status. Polling requires an incoming message and an outgoing message for each sensor node. Polling is the most precise method but least time efficient way to request information from a sensor node but it can support retransmissions. If strobing is applied the master periodically broadcasts a request to all devices for a status update. Each device responds in turn, without any individual request from the master with node 1 answering first, then 2, 3, 4 etc. If cyclic broadcast is applied all sensor nodes are configured to automatically send messages to the master on scheduled intervals, and these intervals are scheduled in such a way that no conflict occur in-between the broadcasts. Cyclic broadcast requires very good clocks at the sensor nodes, the clock drift make a strict cyclic broadcast impossible to implement if no common time source is available. Polling and strobing are the most common contention free channel access methods used, polling is used in Bluetooth and IEEE 802.15.1 [5, 8] and strobing is used as contention free channel access method in IEEE 802.15.4 [8].

Polling and strobing require approximately the same amount of active time by the sensor nodes, and the cyclic broadcasting least active time by the sensor nodes. However, since no synchronizing transmission is available from the master in cyclic broadcasting there exists an inherent problem keeping the sensor nodes from drifting apart with this scheme. This problem is present for all three schemes; a communicating pair of transceivers, a master and a sensor node, must perform a synchronized rendezvous in time. The sensor nodes should wakeup as accurately as possible to their scheduled rendezvous with the master. This is especially difficult in low-power consuming embedded systems, since the clock drift in such devices often are substantial, especially when they are put in some form of low power sleep mode for long periods. The clock drift can either be compensated with high duty cycle or large guard time. High frequency duty cycling avoids the clock from drifting apart any substantial amount, i.e. the clocks are synchronized at each wakeup. If low frequency duty cycling is used, large guard time must be used to compensate for a large clock drift in-between the nodes, see Figure 11. It is a trade off between these two parameters, where the optimization goal is to minimize the overall power consumption. The station in receiving mode must add a guard time; if the guard time is too small it may miss part or the entire transmission from the transmitting station. A typical drift value for a good clock is +/- 50 ppm, but for a low power integrated RC oscillator, often used in sleep mode, the clock drift can be in the range of +/- 1000 ppm, even when temperature calibrated [24].

All three methods for contention free channel access rely on accurate timing of the wakeup of the sensor nodes, for polling the accurate wakeup is necessary for reception of the poll from the controlling gateway/router. When strobing is applied the sensor nodes must wakeup to receive the strobe and then go to sleep until its individual transmission time occurs again. Clearly, the more accurate timing the sensor node has, the less overhead is introduced in sense of guard space. Figure 11 displays the conceptual idea of the worst case drift between the two clocks, master and the sensor node, and the necessity to add a certain guard time for a given wakeup period, t_{period}, in order for the sensor node not to miss a transmission.

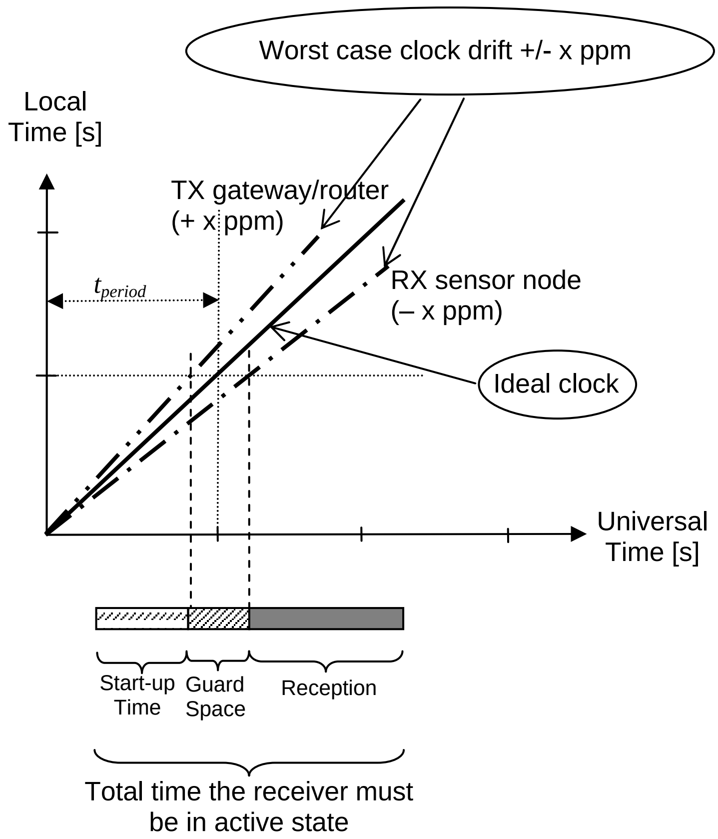

Figure 6. Clock drift at transceiver pairs, TX and RX, in sleep mode (the scale is not realistic in the graph).

The book *Protocols and Architectures for Wireless Sensor Networks* by H. Karl and A. Willig [21] is a comprehensive guide to the communication part of a sensor network.

5 Conclusion

Up to date there is no available standard for wireless body area network (WBAN) and specifically not any intended for medical applications. A WBAN intended for medical applications could be seen as a wireless sensor network since most medical applications will rely on sensors collecting data about, e.g., the heart and the brain. As such the sensor nodes must be kept simple in order to fulfil requirements on energy-efficiency and long battery life time. Things that influence the battery life time is the duty cycle of the sensing node, i.e., the active time period of the sensor node. To conserve energy the sensor node should be kept as long as possible in power-down or sleep mode. A drawback with long sleep periods is the clock drift implying that a node must also be awake longer once it wakes up due to clock drifting apart from other sensor nodes in the network making a rendezvous in time more complicated. The communication protocols within the node should be kept simple not requiring a lot of computation and also more advanced data/signal processing should be avoided in the sensor node.

The higher frequency that is used for communication the smaller antenna can be used, which is an advantage when a sensor node must have a small form factor. A single medical application using wireless communication will probably not have its own frequency band from the beginning because this is too expensive and therefore it is directed to the license-free bands; see Table 4 for a summary of these bands. However, when medical applications have found their niche it can be possible to apply for licenses in the future when it is beneficial, however, medical implants already today has its dedicated band at 402-405 MHz. The license-free bands have requirements on the output power and duty cycle. The output power, which a node can use for transmitting in the license-free bands, is quite small (<100mW) compared to for example a mobile telephone that can have peaks of 1-2 W during transmission. Therefore, the SAR value should not be of any problem in a WBAN. The higher frequency that is used the higher attenuated by the body the signal will be and this is a drawback. Here more channel measurements should be done on the human body to find out how a better signal reception could be achieved. Perhaps it is impossible to utilize higher frequencies due to the attenuation the body is causing. In Sweden the hospitals can decide to prohibit wireless networks even though they are designed according to the regulations of a certain license-free frequency band. This is due to that fact that other medical equipment could be sensitive to electromagnetic radiation. Therefore a discussion with a big hospital would be beneficial in order to determine a suitable frequency band for a WBAN.

Since there is no standard available the developer of sensor networks such as a WBAN intended for a medical application is usually directed to off-the-shelf proprietary transceivers since the design of a transceiver from scratch is very costly. One advantage with using a standard is that there is more than one manufacturer of wireless transceivers and a standard also ensures that nodes having transceivers from different manufacturer are able to communicate with each other.

It is important to find out the requirements that the sensor application has on the system, e.g., number of sensors, duty cycle, amount of data every wakeup, and from those start to find suitable sensor architecture with belonging transceiver. If the application requires a high duty cycle (i.e., wake ups often) with a small amount of data to transmit every wakeup a transceiver with low power consumption during sleeping mode is important. Whereas with a low duty cycle this is not that important since the transceiver will always power-down after a transmission. Everything boils down to have as low energy consumption as possible per transmitted bit. Energy consumption is the really weak part of a wireless sensor network since the transceiver and other hardware equipment still drain batteries. For example the startup time for a transceiver that has been in power-down mode could consume as much as three times the energy as compared when transmitting the actual bits that invoked the transceiver in first place. The actual application must be the one driving the requirements on the communication. However, the application must be designed with for example the startup time in mind. A sensor network is a true cross-layer design problem where many different areas must meet such as hardware designers, application developers and communication people.

6 Abbreviations/acronyms

CSMA	Carrier sense multiple access
FTP	File transfer protocol
HTTP	Hypertext transfer protocol
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization of Standardization
MAC	Medium access control
OSI	Open system interconnection
PHY	Physical layer
SAR	Specific absorption rate
TCP	Transmission control protocol
UDP	User datagram protocol
UWB	Ultra-wide band
WBAN	Wireless body area network
WLAN	Wireless local area network
WMAN	Wireless metropolitan area network
WPAN	Wireless personal area network
WWAN	Wireless wide area network

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