Chapter 2
Wireless Body Area Networks

There has been a lot of research into Wireless Body Area Network; see for example the surveys presented in by [4] and [8]. In a WBAN, sensors are placed on or near the body. Each node needs to be very small; hence it can only have a small battery. Additionally, it is impractical or even impossible to replace the batteries on a regular basis. Alternatively, the node can make use of energy harvesting. In both cases the power consumption needs to be very low. This is one of the biggest challenges in the design of WBAN nodes and can only be achieved by making use of the special properties of WBANs.

In this chapter different sensor network aspects and reported WBAN applications are analyzed and summarized. Additionally, several MAC protocols are compared using the WBAN properties. Since low power consumption is of primary importance, the sensor node energy consumption of the different MAC-layers are compared. With the energy consumption models, the solution space is examined. At the end of the chapter the receiver requirements are obtained.

2.1 Wireless Sensor Network Properties

The power consumption of wireless sensor nodes can be greatly reduced by optimizing the nodes with respect to network symmetry, synchronization, scale and packet rate.

Firstly, the network symmetry has a big impact on the system design. In a symmetric network the wireless sensor nodes have similar power supply and processing power. On the other hand, in an asymmetric network there can be large differences between nodes. In other words, the network is heterogeneous. Body Area Networks usually are asymmetric [4]. In such a network at least one node has a bigger power supply and more processing power, and can take over energy-consuming tasks from the low-power simple sensor nodes.

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Additionally, the network size is an important network property. Unlike environmental sensor networks, a WBAN is inherently small-scale. The maximal distance between two nodes is less than 10 m, and each network has less than 100 nodes [3]. In such a small network, it is more power efficient to use single-hop communication instead of multi-hop.

Since the network is small-scale, asymmetric and single-hop, a star topology is suitable, which is used by most WBANs [2, 4]. In a star topology there is only one master node which manages the network. Since the master has a bigger power supply it can transmit with higher power and acts as a gateway to the outside world. The rest of the network consists of low-power, simple sensor nodes. Additionally, the master can be used for in-band interference avoidance. Firstly the master node manages the network and makes sure that only one sensor node is active at any given moment. Secondly, the master can implement carrier sensing to reduce collisions with other networks operating in the same band.

Finally, the packet rate λ and maximal allowed link setup latency T_{lat} are important in WBAN design. When the packet rate is low and the allowed network latency is high, the nodes can sleep for very long periods to save power. In such a network the network does not have to stay synchronized the entire time, because there is enough time to synchronize before each transmission. Since the network does not need to be kept synchronized in the long pauses between two consecutive packages, the synchronization overhead is reduced. On the other hand, when the latency needs to be very low or when the packet rate is very high, there is no time to synchronize the network before every transmission. A more in-depth analysis of network synchronization, with special attention for the MAC layer, is given in the next section.

2.2 MAC Layer Energy Consumption Model

Before data can be transferred between two nodes, they need to be synchronized. This can be achieved in either of two ways: synchronize the network just before the data transfer takes place, or keep the network synchronized continuously. The first case is an asynchronous or contention-based network; the sensor nodes ask for permission to start transmitting or the master node polls the sensor nodes for data when needed. The latter type is a synchronized, or schedule-based network, i.e. each node knows when it can transfer the data, for example in a Time Division Multiple Access (TDMA) protocol.

The MAC-layer protocol, and therefore synchronization type, has a big influence on the power consumption. Depending on the type of synchronization, power is wasted because of:

- idle listening,
- overhearing,
- synchronization overhead.

In an asynchronous network the idle listening and overhearing penalties can have a big influence on the power consumption. Since each node does not know when it needs to listen for incoming data it needs to listen regularly even when there is no data present. Additionally, a node also does not know when other nodes do get a transmission slot. Therefore, the sensor nodes can overhear packets meant for another node and react on it. Examples of asynchronous MAC protocols targeted towards sensor networks are B-MAC [7] and X-MAC [1].

The idle listening can be reduced by adding a very-low-power receiver to the wireless sensor node. The receiver only listens for WUCs from the master node and wakes-up the rest of the sensor when needed. Additionally, this Wake-up Receiver can reduce the overhearing penalty when an address is added to the WUC. It is only beneficial to add a WURx, when its power consumption is less than the idle listening and overhearing penalties.

On the other hand, in a synchronous network, the master needs to assign slots to nodes and the nodes need to listen for synchronization beacons. This synchronization overhead consumes power. Furthermore, when the synchronization between a sensor node and the network master is lost, the node needs to listen continuously for the next synchronization beacon.

Within this section the power consumption of each type of network synchronization is modeled. The energy consumption of the node is calculated per received packet, taking into account the maximally allowed link-setup latency T_{lat}, the number of nodes N_{node} and the average packet rate λ. The energy needed to transmit the data is not taken into account since it is equal for both synchronization schemes.

Firstly, address coding and required address length are discussed. Next, the traffic statistics and generic radio model are presented. The radio and traffic model are used to obtain the energy consumption models for the different network types. These models are eventually used in the following sections to explore the design space and determine in what cases which network type is optimal.

2.2.1 Address Coding

Each node has a unique address to reduce the overhearing penalty. The node correlates the received address with its own address, and compares the result to a threshold. If the correlation is higher than the threshold, the node is woken up.

Although maximum likelihood decoding leads to more reliable results than correlation decoding, it is also much more complex and power consuming. Therefore, correlation decoding is chosen. Correlation coding is very similar to minimum distance or Hamming codes.

A correlation decoding function can be implemented power efficiently by NXOR operations,

$$C = \sum_{n=1}^{l} a_n \text{ NXOR } r_n \, , \tag{2.1}$$

where l is the address length, r_n the received address bit and a_n the address bit of the node. The output of the correlation function is the number of correct bits, and the maximal value is l. The minimum number of bits that differ between two addresses is called the Hamming distance, and is denoted by M. A code can correct $\lfloor \frac{1}{2} (M-2) \rfloor$ errors and detect $(M-1)$ errors. It is better to choose an odd Hamming distance M, since it can correct as many bits as a longer code with distance $M+1$. The correlator threshold T has to be in the range: $l - M \leq T < l$ to make sure the node wakes up only if its own address is received. In practice, noise will induce bit errors which can lead to a missed wake-up call or a false wake-up, with probabilities p_{miss} and p_{false} respectively.

2.2.1.1 Number of Nodes

The maximum number of addresses, and therefore sensor nodes, depends on the address length l and the minimal number of different bits between two addresses M. It is impossible to give an exact number of possible addresses, this problem is known as the sphere packing problem; the number of available addresses is equal to the number of spheres with diameter M that can be packed in a l dimensional space where each dimension has only two states: "0" or "1".

However, an upper bound can be given: the number of addresses with Hamming distance M (N_{nodes}) is less than the total number of nodes divided by the number of nodes in a sphere with radius $\lfloor \frac{M-1}{2} \rfloor$. The radius is rounded half down, since the number of bits is integer and the radius of two neighboring addresses should be less or equal to the Hamming distance between the addresses. The radius is the Hamming distance divided by two, since the distance between the centers of two equally sized and neighboring spheres is the sum of their radii.

The total number of possible unique nodes without taking into account the Hamming distance is

$$N_{nodes,max} = 2^l \, , \tag{2.2}$$

and the number of addresses in a sphere with radius $\lfloor \frac{M-1}{2} \rfloor$ is

$$N_{nodes,sphere} = \sum_{n=0}^{\lfloor \frac{M-1}{2} \rfloor} \binom{l}{n}. \tag{2.3}$$

Combining the total number of nodes and the nodes per sphere, an upper bound on the number of nodes with Hamming distance M is

$$N_{nodes} \leq \frac{2^l}{\sum_{n=0}^{\lfloor \frac{M-1}{2} \rfloor} \binom{l}{n}}. \tag{2.4}$$

2.2.1.2 Coding Performance

A WUC is missed when the correct address was sent but the output X of the correlator is smaller than the threshold T. Noting that the bit errors have a binomial distribution with success probability p and number of trials n, and the probability of a single bit error is given by p_e, the miss probability is

$$p_{miss} = P(X \leq T \mid p = 1 - p_e, n = l). \tag{2.5}$$

Additionally, the probability a WUC is missed after N_{WUC}^{+} attempts is

$$p_{wuc,miss} = p_{miss}^{N_{WUC}^{+}}. \tag{2.6}$$

It is more difficult to calculate the false wake-up probability than the packet miss probability. The probability of a false wake-up is highest when a 'neighboring' address with Hamming distance M is received; this case is taken as a conservative false wake-up estimation. Since the distance is equal to M the received and actual addresses share $l - M$ bits. It is assumed that the false wake-up probability when a non-neighboring address is send is negligible.

The false wake-up event can be divided in two independent events: a false wake-up with all the shared bits correctly received, and one with the shared bits containing bit errors. The false wake-up probability is the sum of the probabilities of these two events. Assuming none of the shared bits change and only the unique bits change, the node is woken up when bit errors change $T - (l - M)$ unique bits and p_{false} is

$$p_{false}\Big|_{\text{No shared bits change}} = P(X > T - (l - M) | p = p_e, n = M) \tag{2.7}$$

$$\times P(Y = 0 | p = p_e, n = l - M), \tag{2.8}$$

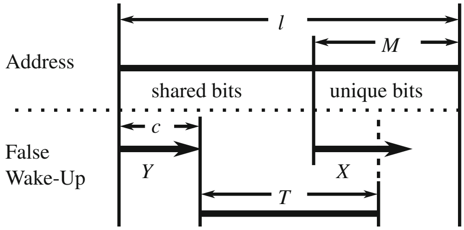
where X specifies the number of unique bits that change and Y specifies the number of shared bits that change, see Fig. 2.1. When c shared bits change also c extra unique bits have to change. The probability on this event is

$$p_{false}\Big|_{\text{c shared bits change}} = P(X > T + c - (l - M) | p = p_e, n = M) \tag{2.9}$$

$$\times P(Y = c | p = p_e, n = l - M). \tag{2.10}$$

The maximal number of changed shared bits is by definition smaller than the number of shared bits

Fig. 2.1 Address coding and the false wake-up event



$$c < l - M. \tag{2.11}$$

Additionally, for a false wake-up to occur,

$$c + T < l, \tag{2.12}$$

should hold, see Fig. 2.1. Combining these bounds, c is bound by

$$c < \min\{l - M, l - T\}. \tag{2.13}$$

No longer assuming that only the shared bits can change, p_{false} becomes

$$p_{false} = \sum_{c=0}^{\min(l-M,l-T)} P(X > T + c - (l - M)|p = p_e, n = M) \tag{2.14}$$

$$\times P(Y = c|p = p_e, n = l - M). \tag{2.15}$$

When the bit error probability is less than 1 % and the address length is large enough, e.g. larger than 10, p_{false} can be approximated

$$p_{false} \approx P(X > T - (l - M)|p = p_e, n = M)P(Y = 0|p = p_e, n = l - M). \tag{2.16}$$

The approximation error is less than 0.4 % when $l = 10$ and $p_e = 1\,\%$.

It is clear that the probabilities p_{miss} and p_{false} depend on the address length and the BER. Depending on the application the threshold T can be changed to sacrifice p_{miss} for p_{false} or vice versa. Here we assume that both probabilities need to be low, thus the threshold T is chosen in a way to equate both error probabilities. Taking into account that most WBAN have less than 100 nodes [3] and a BER of 10^{-3}, Fig. 2.2 gives the error probabilities as a function of the address length. For the minimal address length both p_{miss} and p_{false} are less than 1 %, which is already acceptable. Adding extra bits decreases both the probabilities. However, the effect on the energy dissipation will be negligible since the error is already very low. Taking a Hamming distance of 3, an address length of 10 bits is good enough.

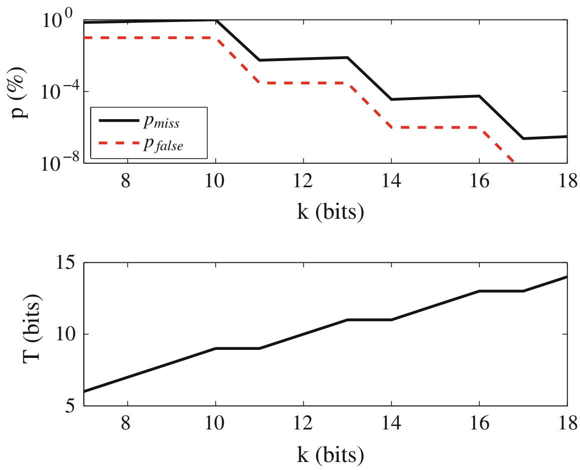


Fig. 2.2 p_{miss}, p_{false} and T as function of the address length l for a network of 100 nodes and a BER of 0.1 %. T is chosen in a way to equate both error probabilities

2.2.2 Radio Model

The state-transition diagram of a generic radio is shown in Fig. 2.3, and the corresponding parameters are listed in Table 2.1. The initial start-up behavior is not shown; it is assumed that the radio is already initialized and that the main radio starts in the sleep state. There are two radios depicted in the diagram: the main radio and the WURx. Since the wake-up receiver is optional, it is placed outside the main radio whose states are depicted within the large dashed rectangle. The additional WURx can trigger the main radio to wake up or go into receive mode depending on the current state of the main radio.

The states with a solid line are stable radio states, i.e. the radio can be in these states for an arbitrary amount of time. The dotted lines are transition states, and the time spent in this state is given within brackets. Furthermore, the power consumption in each state is given outside the states.

In the sleep mode the radio is in its lowest power down state, while in the standby mode the receiver consumes more power. On the other hand, the radio can wake-up faster from the standby mode than from the sleep mode. Therefore, using the sleep mode can be disadvantageous because the energy needed for waking up might be larger than the energy saved by staying in the sleep mode instead of the standby mode. In the following sections the conditions for which the sleep mode is advantageous are analyzed.

Some radios may not provide a sleep and standby mode or may not need settling time between receive and transmit modes. T_{wake} should be set to zero in the former case and T_{set} should be set to zero in the latter case. When the radio is always on and does not need to settle, both of the parameters should be set to zero.

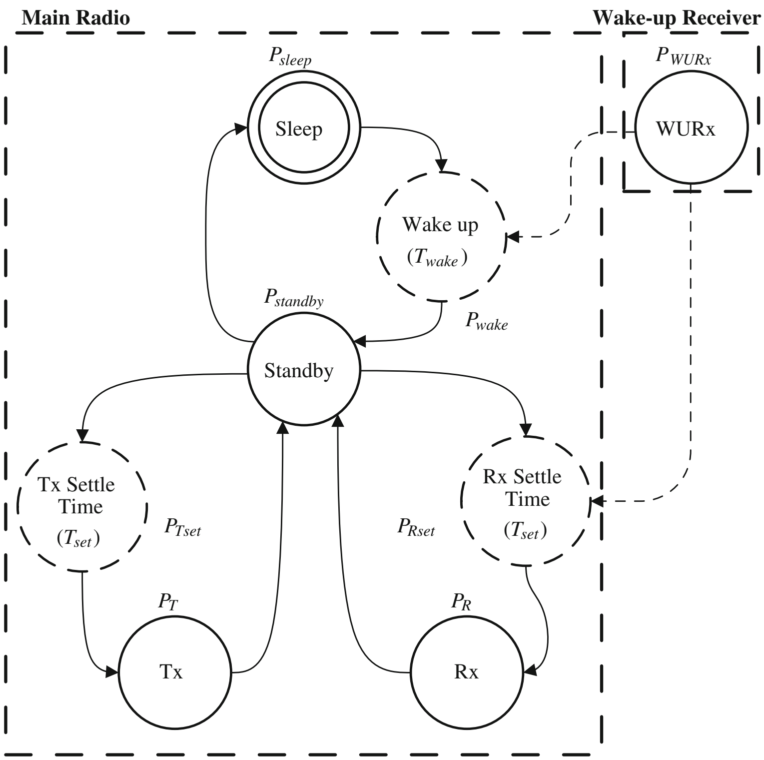


Fig. 2.3 General radio state-transition diagram

Table 2.1 Radio platform parameters

Parameter	Explanation
T_{wake}	Switching duration: sleep → Standby
T_{set}	Switching duration: settling period when switching to Rx or Tx
P_{sleep}	Power consumption in sleep mode
$P_{standby}$	Power consumption in standby mode
P_R	Power consumption in receive mode
P_T	Power consumption in transmit mode
P_{Rset}	Power consumption when switching to Rx mode.
P_{Tset}	Power consumption when switching to Tx mode
P_{wake}	Power consumption when switching between sleep and standby mode
ΔP_x	Power increase in mode x compared to sleep mode $P_x - P_{sleep}$
k	Length of minimal packet in bits. Used for: sync, ACK, WUC
R_b	Bit rate of main radio

Table 2.2 List of the used asynchronous (top) and synchronous (bottom) MAC layer packet statistics

Statistic	Probability/Value	Explanation
μ_{WUC}	$\approx \frac{1+p_{miss}}{1-p_{miss}}$	Average number of WUC transmissions per received packet
$p_{ACK\geq 1}$	$1 - p_{miss}^{N_{WUC}^{+}}$	Probability that the sensor node transmits at least one ACK packet
$p_{FACK\geq 1}$	$\approx p_{false}$	Probability that the sensor node transmits at least one false ACK packet
μ_{ACKx}	$\approx \frac{p_{miss}}{1-p_{miss}}$	Average number of retransmitted acknowledgments per received packet
μ_{FACKx}	$\approx p_{false}\left(N_{WUC}^{+} - 1\right)$	Average number of retransmitted false acknowledgments per received packet and node in the network
μ_{slot}	$\approx \frac{1-p_{miss}^{N_{WUC}^{+}}}{1-p_{miss}}$	Expected number of TDMA slots per received packet

In this book the Nordic nRF24L01 radio chip is used in the application analysis, but the radio parameters are general enough to allow for other radios.

2.2.3 Network Statistics

In an asynchronous network the master node transmits WUCs and waits for the node to transmit an Acknowledgment (ACK). When a WUC or Acknowledgment (ACK) packet gets missed with probability p_{miss}, they need to be retransmitted. However the maximum number of transmissions is limited to N_{WUC}^{+}; after this number of transmissions the transmitter quits and the wake-up process has failed. In each WUC a counter value is transmitted which specifies the number of transmissions left. Using this counter value the receiver knows exactly how many times it can try to transmit an acknowledgment. The node will transmit the acknowledgments until either the connection is set-up or the maximum number of transmissions is reached.

It is also possible for the node to wake up when a WUC is received which was meant for another node: a false wake up. After such an event the node starts transmitting False Acknowledgment (FACK) packets. The false wake-up event leads to the overhearing penalty previously mentioned. The probability of a false wake up is given by p_{false}.

Table 2.2 gives a list of asynchronous and synchronous MAC layer packet statistics expressed as functions of p_{miss}, p_{false} and the maximal number of transmissions N_{WUC}^{+}. The probabilities and statistics are derived in appendix A.

The synchronous MAC protocol is discussed in-depth in Sect. 2.2.6. The expected number of TDMA slots per received packet is given by μ_{slot}, which is very similar to the expected number of wake up calls. The variable μ_{slot} is derived in Appendix A.4

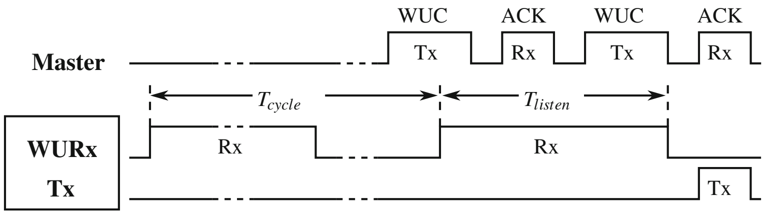


Fig. 2.4 Wake-up event for a WURx-enhanced MAC protocol

and is approximately

$$\mu_{slot} \approx \frac{1 - p_{miss}^{N_{WUC}^{+}}}{1 - p_{miss}}, \tag{2.17}$$

assuming $N_{WUC}^{+} > 1$ and $p_{miss} \lesssim 1\,\%$.

2.2.4 WURx-Enhanced Asynchronous Network

In the WURx-enhanced scheme, a WURx is added to the sensor node, which is used to listen for wake-up calls and waking up the sensor node when needed. There are two sub-categories of the WURx-enhanced MAC scheme: with and without main receiver. When the node needs to receive a lot of data and the low bit rate of the WURx is not sufficient an additional receiver can be added at the cost of higher power consumption. When the node is woken-up it transmits an acknowledgment and the data transfer can commence. Figure 2.4 shows a simplified overview of a wake-up event when the WURx enhanced scheme is used. To save power the WURx can be duty-cycled when the latency requirement allows for it, as is shown in the figure. The duty cycle period is chosen as long as possible to minimize the power consumption. Additionally the master needs to be able to transmit N_{WUC}^{+} calls within the latency requirement. Therefore, the cycle period is chosen equal to the latency requirement T_{lat} divided by the maximum number of attempts, i.e.

$$T_{cycle} = \frac{T_{lat}}{N_{WUC}^{+}}. \tag{2.18}$$

A detailed wake-up cycle is shown in Fig. 2.5. The radio parameters correspond with the parameters used in the radio state model depicted in Fig. 2.3. The wake-up periods are only present when the nodes go to the deep sleep mode. To ensure that the WURx will also wake up the node when the listen cycle starts in the middle of a WUC packet, at least two WUCs have to fit within the listen period T_{listen},

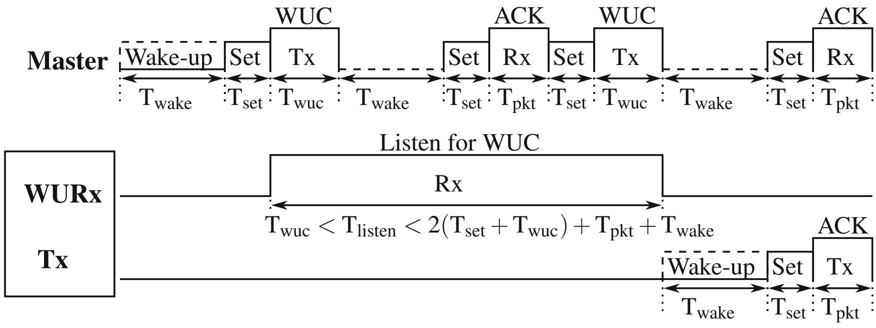


Fig. 2.5 Detailed view of a wake-up event

$$T_{listen} > 2\,(T_{set} + T_{wuc}) + T_{pkt} + T_{wake}. \tag{2.19}$$

Additionally, the listen period can never be longer than the complete cycle

$$T_{listen} \leq T_{cycle}, \tag{2.20}$$

and the duty cycle ratio η, the fraction of time a sensor node is active, is

$$\eta = \frac{N^{+}_{WUC} T_{listen}}{T_{lat}} \tag{2.21}$$

$$= \frac{T_{listen}}{T_{cycle}}. \tag{2.22}$$

The packet lengths k of the WUC and ACK are assumed to be equal. However, the bit rates of the main radio R_b and WURx R_{bw} can be different and therefore the WUC and ACK packet duration can be different,

$$T_{wuc} = \frac{k}{R_{bw}} \tag{2.23}$$

$$T_{pkt} = \frac{k}{R_b}. \tag{2.24}$$

A lower bound on the required R_{bw} is obtained by combining (2.19) and (2.20)

$$R_{bw} \geq \frac{2k}{T_{cycle} - 2T_{set} - T_{wake} - T_{pkt}}. \tag{2.25}$$

The average energy dissipation per received packet is obtained by assuming that on average each node receives the same number of packets and a packet is received every $\frac{1}{\lambda}$ s. The dissipation of the sensor node is divided in 4 parts,

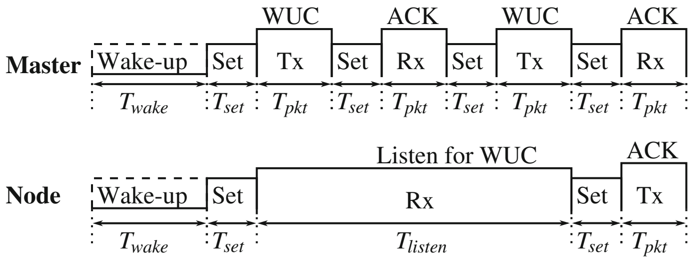


Fig. 2.6 Detailed view of a synchronization cycle for the WURx-less asynchronous MAC protocol

$$E_{node} = \frac{P_{sleep}}{\lambda} + \eta \frac{P_{WURx}}{\lambda} + \left[p_{ACK\geq 1} + p_{FACK\geq 1} \left(N_{nodes} - 1 \right) \right] E_{ACK1} \tag{2.26}$$

$$+ \left[\mu_{ACKx} + \mu_{FACKx} \left(N_{nodes} - 1 \right) \right] E_{ACKx}, \tag{2.27}$$

the first term specifies the transceiver energy consumption in sleep mode, the second term the energy consumption of the duty-cycled WURx, the third term is the energy required when transmitting the first acknowledgment and the fourth and final term specifies the energy needed for retransmitting the acknowledgments. The false acknowledgment statistics $p_{FACK\geq 1}$ and μ_{FACKx} were defined per 'other node' in the network. Therefore, they are multiplied by number of 'other nodes', or the total number of nodes minus 1. The expected number of transmitted acknowledgments and retransmitted acknowledgments are derived in Sect. 2.2.3, and the energy consumed per acknowledgment is

$$E_{ACK1} = \Delta E_{wake} + \Delta E_{Tset} + T_{pkt} \Delta P_T \tag{2.28}$$

$$E_{ACKx} = \left(T_{wake} + T_{WUC} + T_{set} \right) \Delta P_{standby} + \Delta E_{Tset} + T_{pkt} \Delta P_T \,. \tag{2.29}$$

2.2.5 WURx-Less Asynchronous Network

The asynchronous network scheme is very similar to the WURx-enhanced scheme, with the difference that the WURx is not present and the main receiver listens for the wake-up calls. Therefore, in the asynchronous MAC protocol the WUC and ACK packets duration is the same. Although this scheme consumes more power than the WURx enhanced scheme, it has benefits for systems with very strict latency requirements since the wake-up time is shorter. Figure 2.6 shows the synchronization cycle.

The energy consumption of the sensor node is similar to the WURx-enhanced case (2.26)

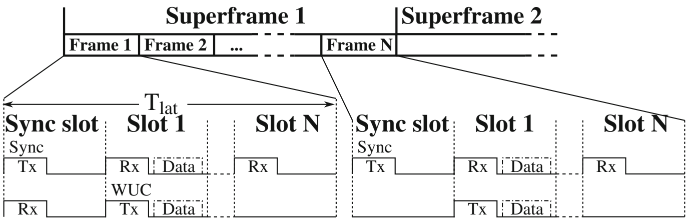


Fig. 2.7 Synchronous MAC scheme in case of a wake-up event. As an example the timing diagrams of the master and node 1 are shown

$$E_{node} = \frac{P_{sleep}}{\lambda} + \frac{1}{\lambda T_{cycle}} E_{cycle} + \left[p_{ACK \geq 1} + p_{FACK \geq 1} \left(N_{nodes} - 1 \right) \right] E_{ACK1} \tag{2.30}$$

$$+ \left[\mu_{ACKx} + \mu_{FACKx} \left(N_{nodes} - 1 \right) \right] E_{ACKx}, \tag{2.31}$$

where the values $p_{ACK \geq 1}$ and μ_{ACKx} were derived in appendix A and summarized in Table 2.2, and

$$E_{ACK1} = \Delta E_{Tset} + T_{pkt} \Delta P_T \tag{2.32}$$

$$E_{ACKx} = \left(T_{pkt} + T_{set} \right) \Delta P_{standby} + \Delta E_{Tset} + T_{pkt} \Delta P_T \tag{2.33}$$

$$E_{cycle} = \Delta E_{wake} + \Delta E_{Rset} + T_{listen} \Delta P_R. \tag{2.34}$$

2.2.6 Synchronous Network

The synchronous MAC scheme is different from the two MAC schemes mentioned in the previous sections. The main difference is that the whole network is always synchronized, whereas in the asynchronous MAC protocols the transmitter and receiver are only synchronized before a transmission. Furthermore, the system is highly asymmetric. Within this section the energy consumption of a sensor node in a low-power TDMA MAC protocol similar to [6] is presented. The energy consumption of the master node is not taken into account, since it is assumed that its power supply is much bigger than that of a wireless sensor node.

Figure 2.7 shows an overview of the synchronous scheme. The master node transmits synchronization beacons at known intervals to keep the network synchronized. Additionally, the master node assigns the time slots to the nodes in the network. Each frame is divided in multiple time slots; one for every node, within these slots only the assigned nodes can transmit their data. The nodes notify the master they have data to transmit using a wake-up call and then start sending the data.

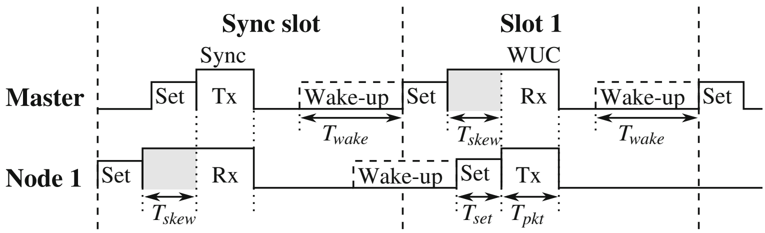


Fig. 2.8 Detailed view of the synchronous MAC scheme in case of a wake-up event with the radio state variables. The clocks of the master node and node 1 are not fully synchronized

A receiving node only needs to receive a synchronization beacon every superframe; the time between two beacons is determined by the stability of the local clock. The local clock accuracy given by Θ is expressed in ppm. The maximally allowed clock skew is given by T_{skew}, which is used as guard time. A more detailed view is shown in Fig. 2.8. Again the wake-up periods are only present when the nodes go to deep sleep mode. The gray areas are needed to deal with clock skew. The latency has to be smaller than T_{lat}, and within the latency period all the N_{node} nodes need to be able to transmit N^{+}_{WUC} wake-up calls. Therefore, the TDMA slot time is

$$T_{slot} = \frac{T_{lat}}{N^{+}_{WUC}\,(N_{node}+1)}. \tag{2.35}$$

It is assumed that the minimal time between two beacons is large enough to ensure correct transmission: $T_{beacon} \gg \frac{T_{lat}}{N^{+}_{WUC}}$. On the other hand, the maximum time between two synchronization beacons to keep the network synchronized is a function of the clock accuracy and the time reserved for the clock skew:

$$T_{beacon} \leq \frac{T_{skew}}{\Theta(\text{ppm})} 10^{6}. \tag{2.36}$$

In the following analysis we assume the time between beacons is minimal to reduce the energy consumption. The average number of beacons per received packet $\mu_{bcn/pkt}$ is

$$\mu_{bcn/pkt} = \frac{1}{\lambda T_{beacon}}. \tag{2.37}$$

When a node misses the synchronization beacon it stays in receive mode until it receives the next beacon in order to resynchronize. While resynchronizing, all the packets are lost. The probability of this event is assumed to be equal to the packet miss probability p_{miss}. If T_{beacon} is large, the resynchronization penalty is severe.

The average energy consumption of a sensor node, calculated per received packet is:

Table 2.3 Application and WURx parameters

Parameter	Value
λ	33 pkt/s
T_{lat}	30 ms
N_{nodes}	3 sensor + 1 master
p_{miss}, p_{false}	1 %
N^{+}_{WUC}	3
P_{WURx}	329 μW
R_{bw}	625 kbps

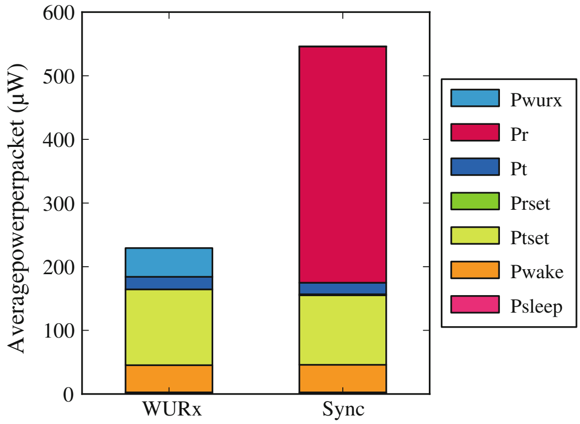


Fig. 2.9 Average power consumption per packet for the WURx-enhanced and synchronous networks

$$E_{node} = \frac{P_{sleep}}{\lambda} + \mu_{bcn/pkt} E_{sync} + p_{miss} \frac{\Delta P_R}{\lambda} + \mu_{slot} E_{slot}, \tag{2.38}$$

where

$$E_{sync} = \Delta E_{wake} + \Delta E_{Rset} + \left(T_{skew} + T_{pkt}\right) \Delta P_R \tag{2.39}$$

$$E_{slot} = \Delta E_{wake} + \Delta E_{Tset} + T_{pkt} \Delta P_T . \tag{2.40}$$

2.2.7 Application Example

In this section the average power consumption per packet is calculated for a typical application. The application resembles the Holst ECG demonstrator. It is a network of sensor nodes attached to the human body, which consists of one master node and three sensor nodes. The application parameters are listed in Table 2.3. The WURx front-end presented in Chap. 6 and Nordic radio given in Appendix B are used when comparing the power consumption in synchronous WURx-enhanced networks.

Table 2.4 WBAN network parameters

References	# nodes typ/max	Distance	Latency
[3]	$10/<100$	2m / 5m	10ms/1s setup
[5]	$6/<256$	<3m	125ms (medical) / 250ms (non-medical)

The average power consumption per packet depicted in Fig. 2.9 is calculated using the model presented in Sect. 2.2. The average power consumption needed for the synchronization is split in the different modes used in the radio model given in Fig. 2.3. The power needed to transmit the acknowledgments, consisting of P_{tset} and P_t, is the same in both cases, since the same retransmission scheme and transmitter are used. The penalty for a false wake-up in the WURx-enhanced scheme only attributes 4.5 % to the total power consumption. Thus the simple address coding scheme suffices. Moreover, the Nordic radio wake-up power P_{wake} and sleep power P_{sleep} are almost equal in both synchronization schemes. However, the power is reduced by using the WURx (P_{WURx}) to listen for wake-up calls instead of the Nordic radio ($P_{rset} + P_r$). When using the WURx-enhanced synchronization the power is reduced by 58 % when compared to the synchronous network. Note that the amount of power saved strongly depends on the packet rate λ and latency T_{lat} requirements.

2.3 Applications

Many different applications for WBAN can be found in literature. An overview of required transmission distances and latency requirements reported in the overview papers [3] and [5] are given in Table 2.4. From the given literature it can be concluded that a typical WBAN network consists of 10 nodes and the transmission distance is less than 10 m.

Furthermore, the application space of WBAN networks can be divided in three scenarios:

Multimedia: Applications in this scenario have a very high bit rate, which is not supported by the WURx. Therefore, an additional high bit rate, high power receiver needs to be added to the sensor node for the data transfer.

Active RFID: In this category, the application bit rate is relatively low and the WURx can handle the data transfer. Most data is transmitted from the low-power sensor node to the master node. Application examples are fitness sensors, medical sensors and a ‘forgotten things’ network.

Remote control: The master sends very simple commands to peripheral devices, for example to turn devices on or off, select a radio station and control hands-free devices.

The radio topologies used in the three different scenarios are depicted in Fig. 2.10. Additionally, the data transfer is schematically depicted by the size of the arrows.

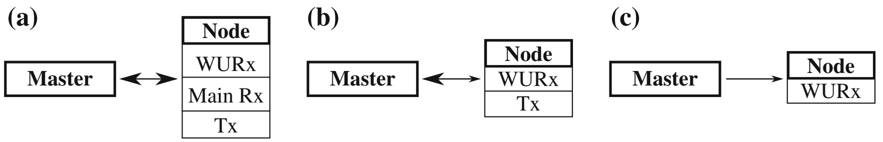


Fig. 2.10 Radio topologies used in the three different application scenarios, where the *arrow* sizes depict the amount of data transfer from master to sensor node or vice versa. **a** Multimedia, **b** Active RFID, **c** Remote control

Table 2.5 Typical WBAN application parameters as seen from the sensor node perspective

References	Scenario	Application	Sensor	Data rate
[3]	Active RFID	Fitness	Speed, distance, heart rate	<500 kbps
		Mobile	Sensor, headset, handsfree	<500 kbps
	Remote ctrl	Remote control	Headset ctrl, printers, ID	
	Multimedia	Video	Video communications	<20 Mbps
[4]	Active RFID	Medical	ECG (12 leads)	288 kbps
			ECG (6 leads)	71 kbps
			EMG	320 kbps
			EEG (6 leads)	43.2 kbps
			Blood saturation	16 bps
			Glucose sensor	1,600 bps
			Temperature	120 bps
			Motion sensor	35 kbps
			Cochlear implant	100 kbps
			Artificial retina	50–700 kbps
	Multimedia	Audio	Audio streaming	1 Mbps
[8]	Active RFID	In-body	Glucose sensor	Few kbps
			Pacemaker	Few kbps
		Medical	ECG	3 kbps
			SpO2	32 kbps
			Blood pressure	<10 bps
		Non-medical	Forgotten things	256 kbps
			Social networking	<200 kbps
		In-body	Endoscope capsule	>2 Mbps
		Non-medical	Music for headset	1.4 Mbps

In literature many WBAN applications are presented, although most of them target medical applications. A short survey is given in Table 2.5. It is interesting to note that the estimated data rate for ECG applications ranges from 3 to 288 kbps. This can partly be explained by the number of leads used. It could be that in some applications the raw data is processed locally and only the measured parameters are transmitted, thereby greatly reducing the amount of data to transmit. From the reported applications it can be concluded that most applications fall into the active-RFID category.

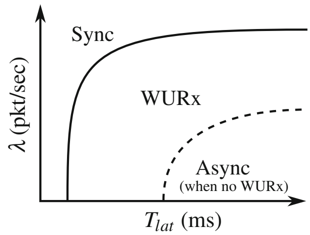


Fig. 2.11 Solution space showing the most optimal MAC synchronization scheme as a function of the latency and packet rate, note that the axes are not drawn to scale

2.4 Solution Space

Since the targeted WBAN network is asymmetric and uses a star topology, only the power consumption of the low-power sensor nodes are of concern. Furthermore, since the data transfer phase is the same for the MAC protocols, only the power consumption of the synchronization phase is taken into account.

Depending on the application parameters, one of the MAC protocols leads to the lowest power consumption of the wireless sensor nodes. The most important application parameters are the number of nodes N_{node}, packet rate λ and the maximal latency requirement T_{lat}. Even without making assumptions about the specific radios used, the solution space can be divided between the different MAC protocols. A schematic overview of these regions is shown in Fig. 2.11 (the axes are not drawn to scale).

The practical boundary conditions are not taken into account yet, they will be discussed later in this section. Three different regions can be distinguished:

Sync: In this region the synchronous scheme is the best alternative. The WURx and main transceiver in the asynchronous scheme cannot be duty cycled, either because the maximally allowed latency is too low and the radio can not wake up fast enough, or the packet rate is too high. Therefore the transceiver does not spend a lot of time in the sleep mode in the asynchronous MAC protocols, and the WURx-enhanced MAC protocol consumes a lot of power.

WURx: When the packet rate is lower and the latency is higher the WURx becomes a better alternative, since the sensor node is in sleep mode for longer periods. Additionally, a lot of time slots are assigned but not used in the synchronous TDMA protocol. Therefore, the TDMA synchronization overhead per received packet increases. Consequently, adding a WURx to the sensor node reduces the power consumption.

Async: When the latency and packet rate requirements are further relaxed, even the WURx-less asynchronous MAC protocol is more power efficient than the TDMA MAC. However, adding a WURx always reduces the power consumption as long as the WURx consumes less power than the main radio.

The WURx-enhanced protocol is the best choice when its energy consumption given by (2.26) is less than the energy consumption of the TDMA protocol given

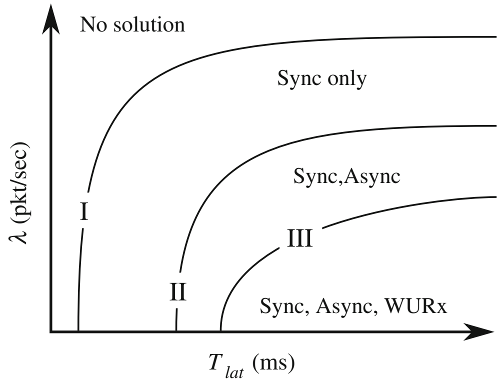


Fig. 2.12 Feasible synchronization schemes as a function of the link-setup latency and packet rate

by (2.38). After multiplying both equations by the packet rate to obtain the power consumption, and assuming $\mu_{slot} \approx 1$ and $\mu_{ACK1} + \mu_{FACK1} \approx 1$, the inequality becomes

$$P_{WURx} + \underbrace{\lambda\,(\mu_{ACKx} + \mu_{FACKx})\,E_{ACKx}}_{\text{ACK retransmission}} < \underbrace{\frac{1}{T_{beacon}} E_{sync}}_{\text{Sync overhead}} + \underbrace{p_{miss}\,\Delta P_R}_{\text{Resync penalty}} . \quad (2.41)$$

In other words, the WURx-enhanced protocol is more power efficient when its synchronization overhead is less than the TDMA overhead. Furthermore, the WURx power budget is

$$P_{WURx} = \frac{1}{T_{beacon}} E_{sync} + p_{miss}\,\Delta P_R - \lambda\,(\mu_{ACKx} + \mu_{FACKx})\,E_{ACKx}. \quad (2.42)$$

It is assumed there is only one synchronization channel. This introduces limits on the maximal number of nodes, packet rate and minimal latency requirements. The boundary conditions are schematically depicted in Fig. 2.12. Again, the axes are not drawn to scale. The boundary conditions are:

Above I; high packet rate; low latency: At a very low latency and high packet rate the channel will be utilized more than 100 %, hence there is no viable solution.

Between I and II: The synchronous TDMA MAC scheme can manage with the lowest latency, and is the only viable MAC scheme. An asynchronous MAC scheme needs additional time to listen for WUCs. Also the WURx is not viable in this region since additional time is needed for waking up the main radio after the WUC is received and the WUC itself takes longer to transmit because of the lower WURx bit rate. In the TDMA protocol at least the WUC and settling time has to fit within one time slot. Therefore in this region the following conditions hold:

Table 2.6 WBAN network parameters

Parameter	N_{node}	Packet size k	N^{+}_{WUC}	p_{miss} and p_{false}
Value	10	32	3	0.1 %

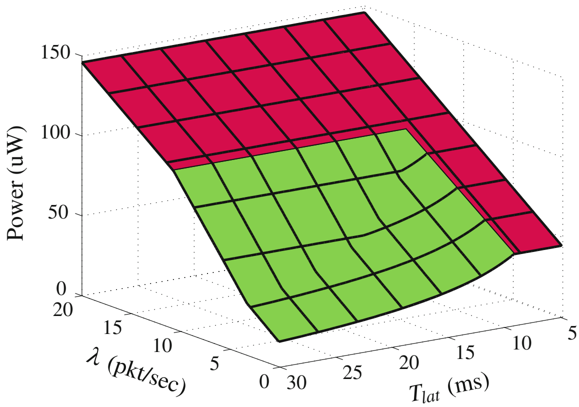


Fig. 2.13 Average synchronization power consumption using the Nordic nRF24L01 transceiver, WURx V2 and the parameters given in Table 2.6. In the *green* (*light*) area the WURx-enhanced MAC is the best choice and in the *red* (*dark*) area the synchronous TDMA MAC protocol leads to lower power consumption

$$T_{slot} > T_{pkt} + T_{set} \tag{2.43}$$

$$\frac{T_{lat}}{N^{+}_{WUC}} > (N_{node} + 1)\left(T_{pkt} + T_{set}\right). \tag{2.44}$$

Between II and III The latency requirement is more relaxed and the packet rate is lower. The WURx-less asynchronous protocol can be used when the listen period and wake-up time fits within the synchronization cycle:

$$T_{cycle} > T_{wake} + T_{set} + T_{listen} \tag{2.45}$$

$$\frac{T_{lat}}{N^{+}_{WUC}} > T_{wake} + 3T_{set} + 3T_{pkt}. \tag{2.46}$$

Below III The bit rate of the WURx is not a problem anymore, because higher latency is tolerated. Therefore the boundary condition III is the same as the boundary condition on the WURx bit rate given by (2.25), and the following holds:

$$\frac{T_{lat}}{N^{+}_{WUC}} > 2T_{wake} + 3T_{set} + T_{pkt} + 2T_{WUC}. \tag{2.47}$$

In order to calculate the average synchronization power consumption of wireless sensor nodes, the actual power consumption of the transceivers need to be known.

A typical low-power transceiver is the Nordic nRF24L01 radio chip. Its power consumption and other specifications are given in Appendix B. Additionally, the second WURx version described in Chap. 6, with a data rate of 625 kbps is used to calculate the average power consumption.

Using a typical network size of 10 nodes and the network parameters given in Table 2.6 the power consumptions shown in Fig. 2.13 are obtained. Note that the latency axis is inverted for ease of reading. The WURx-enhanced MAC protocol leads to the lowest power consumption when the packet rate is low and the latency requirement is not strict, i.e. when T_{lat} is high. In this region the sensor node can sleep for prolonged periods of time and the WURx can be duty cycled to save power. From the application Table 2.5 it is clear that many applications fit these properties.

2.5 Conclusion

In this chapter, the WBAN and WURx concepts were introduced, and a literature overview of WBAN applications was given. Additionally, the energy consumption of both asynchronous and synchronous MAC layer protocols were analyzed. The targeted WBAN applications for the Wake-up Receiver consist of a small number of nodes, approximately 10, and has a short transmission distance, i.e. less than 10 m. Additionally, the network is highly asymmetric, i.e. the master node has a large power supply and processing capability, whereas the sensor node has only a very small power supply and should be kept as simple as possible. Therefore, the network uses a single-hop star topology. Furthermore, the packet rate is low, namely less than 10 (pkt/s) and the latency requirement T_{lat} is not very strict.

MAC-layer protocols used for network synchronization have a big influence on the energy dissipation needed for node-to-node communication. Energy is wasted in the link synchronization because of:

- idle listening
- overhearing
- synchronization overhead

The idle listening energy consumption is the main contributor in asynchronous network protocols. In synchronous networks most energy is consumed in the frame synchronization, thus in the synchronization overhead. In both network types the overhearing problem can be neglected when assuming a small network size, i.e. no more than a few hundred nodes, packet error rate of less than 1 %, and address coding with a few bits Hamming distance.

In the proposed WBAN scenario the WURx-enhanced MAC scheme leads to the lowest power consumption.

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