Energy efficient communication solutions based on wake-up receivers

Heikki Karvonen and Juha Petäjäjärvi

1. Introduction

Wireless sensor networks (WSN) and wireless body area networks (WBAN) have enormous amount of possible use cases in various fields. For example, environmental monitoring, healthcare, smart buildings and smart cities are taking advantage of low-power sensor nodes which provide data to Internet of Things (IoT) as a part of fifth generation (5G) systems. Typically, wireless transceiver consumes most of the sensor nodes' energy resources [1]-[6], therefore a careful design must be performed for communication techniques and protocols, in order to enable that the WSNs and WBANs can be deployed for long periods of time without battery replacement or recharging. Indeed, a huge amount of research work has been carried out to improve the energy efficiency by optimizing protocols using a layered and cross-layer approach [7].

In this chapter the focus will be on energy efficient communication solution that can be achieved by using an intelligent hierarchical network architecture which can be used to effectively utilize heterogeneous devices collecting different types of sensor data from the patient's body or environment, performing autonomous networking and providing data for the data bases of the IoT. In the hierarchical network case, energy consumption can be decreased by utilizing a wake-up concept that enables to keep the devices at a sleep mode as long as possible. Hierarchical architecture will be introduced in Section 2. There are two different types of concepts that can be used to enable the wake-up between different hierarchical layers of the architecture: duty-cycling based radios and wake-up receiver (WUR) usage. The wake-up concept needs a joint design of physical and medium access control (MAC) layers. The wake-up concept design issues will be discussed in Section 2b and a generic wake-up radio based MAC (GWR-MAC) protocol will be introduced in detail in Section 2c.

Different types of state-of-the-art WUR solutions that can be used to enable wake-up concept will be introduced, and their future research directions are outlined, in Section 3. Energy efficiency comparison results for a GWR-MAC based hierarchical WSN architecture and conventional duty–cycle MAC based WSN are introduced in Section 4 to show that the WUR based networking has remarkable potential to improve energy efficiency particularly in the target scenarios where events occur rarely. WSN and WBAN devices long lifetime will make the applications more user-friendly and therefore it will foster wide-spread deployments. Once the number of WSNs providing sensor data for the data bases of the IoT is increased, the possibilities of horizontal deployment of different type of applications will be enormous. It has been estimated that 50 billion devices and objects will be connected to the IoT by 2020 [8]. For example, wireless medical networks have enormous possibilities to improve quality and effectiveness of healthcare [9]. Examples of envisaged applications that can be built by utilizing the described intelligent hierarchical architecture will be outlined in Section 4.

2. Hierarchical Architecture

The wireless sensor network architectures can be divided roughly into two categories: flat and hierarchical. In the flat architecture case, which is the traditional approach, all the network nodes are at the same level and they have similar roles from the communication point of view and typically also similar characteristics. In the hierarchical network case, the nodes have different characteristics and roles at different hierarchical layers. The flat network structure is simpler but it cannot provide efficient communication, especially when the network is composed of a large amount of nodes. The hierarchical network structure has been found to provide more efficient communication in the case of heterogeneous networks since the nodes' operations can be designed so that the overall performance will be improved in comparison with a flat architecture.

At the early stage of the WSN research, the target applications included a homogeneous set of sensor devices, which were performing a simple sensing task and reporting sensor observations to a central (sink) node. That star-topology is still valid for many WSN applications. However, the development has led to an emergence of heterogeneous networks which include different types of devices with varying capabilities, enabling the implementation of more versatile application scenarios. Support for heterogeneous devices is needed in WSNs for energy efficiency, scalability and quality of service (QoS) purposes. The network of a heterogeneous set of devices must be designed carefully to enable efficient and reliable operation. The previously proposed hierarchical architectures can be divided into intra-network and in-network approaches. In the intra-network approach, the main design goal is efficient communication between the WSN and backbone, see, e.g., [73] and [74]. The in-network approaches of WSNs typically limit to two-tier topologies, where the higher tier (gateway) collects data and forms connection to a backbone network. The lower tier nodes can be simpler and they save energy by communicating directly, in a star-topology fashion, only with the gateway [10]. Several WSN protocols, e.g., ZigBee [11] and Z-Wave [12], make a distinction between a routing (full function device (FFD)) and a non-routing (reduced function device (RFD)) device. However, that approach also allows clustering of nodes and designating only one node at a time as an energy-consuming higher tier node (cluster head) [13], [14]. The multi-tier architectures are typically designed for a specific application, e.g., hospital environment [15], traffic monitoring system [16], surveillance [17], environmental monitoring [18], smart home [19], or underwater acoustic sensor networks [20].

Hierarchical network's total energy consumption can be decreased by taking carefully into account the characteristics of the heterogeneous devices at different layers of the architecture. Different types of devices' functionalities must be designed so that communication and sensing requirements can be met while maintaining the low energy consumption. From communication's energy consumption point of view, it is important to maximize the length of the nodes' sleep mode and minimize the number of retransmissions. That is particularly important in a heterogeneous network for the higher tier nodes which are the most power consuming. In addition, long sleep modes are also important for a simple low-power nodes to improve their lifetime.

Intelligent hierarchical architecture for heterogeneous WSNs will be introduced in Section 2a. To enable energy efficiency by putting the nodes into the sleep mode, the heterogeneous hierarchical network requires a method for awakening the nodes when required from the application point of view. For that purpose, duty cycle-based radio is the traditional approach while wake-up receivers have started to gain more and more research attention in recent years. Both approaches will be discussed in Section 2b. A generic wake-up radio based MAC protocol will be introduced in Section 2c.

a. Architecture for a heterogeneous network

Network architecture based on hierarchical levels of intelligence and usage of wake-up concept has been introduced [58]. It can be used in various WSN and WBAN application scenarios which include different type of devices. The wake-up functionality is seen as a long lifetime enabler, particularly for the wireless long-lasting (e.g., medical, surveillance, structural, environmental and industrial) monitoring systems, which have many possible application scenarios in both private and public sectors. Due to a very wide application space, the hierarchical architecture is designed to be flexible, and scalable to varying configurations [58]. Therefore, a high-level architecture which is independent of the specific implementation techniques (e.g., radio interfaces) is defined in order to enable that different application developers have flexibility to choose the most suitable implementation technique. The proposed high-level architecture can be used as a starting point for the network design. In the discussed hierarchical network case the nodes are categorized into different architectural layers based on their capabilities and functionalities. The high-level architecture and the functionalities offered at the different layers are illustrated in Figure 1.

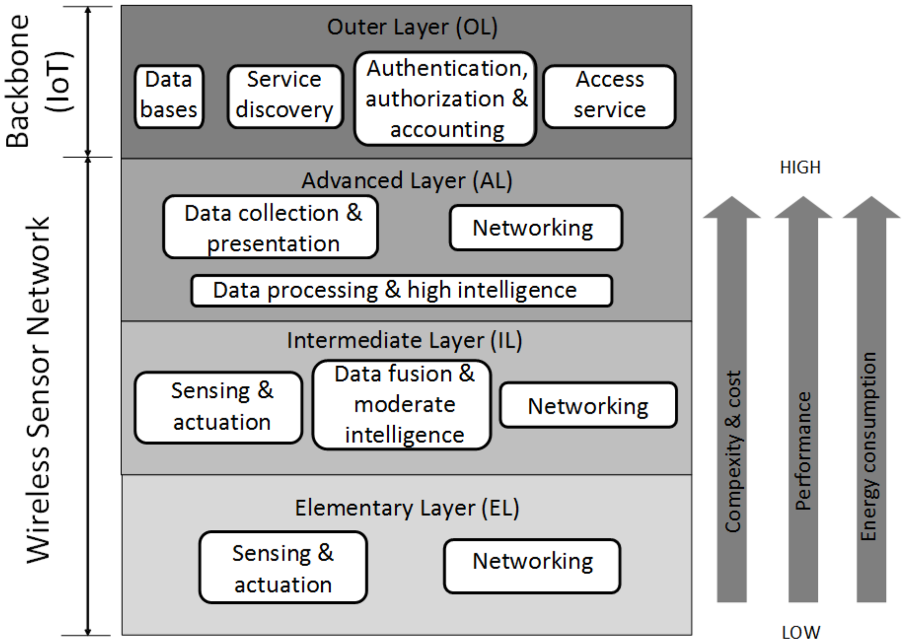


Figure 1. High-level architecture for a hierarchical network with heterogeneous devices.

In this design, the hierarchical layers of the architecture are named to be meaningful as follows: elementary layer (EL), intermediate layer (IL), advanced layer (AL) and outer layer (OL). The complexity, cost, capabilities and performance of the devices at different layers increase from the bottom to the top. Consequently, the devices at the lowest layer consume less energy than the devices at the higher layers. The objective of the intelligent hierarchical design is to decrease the overall energy consumption by using the low-complexity devices for continuous event monitoring and data collection while keeping the more power consuming higher layer devices in the sleep mode as long as possible. The elementary layer nodes will wake up the higher-complexity devices only when required. The EL devices are usually simple sensor nodes providing basic sensing and possibly also actuation services. However, the devices at the lowest layer are elementary from the application service point of view since they provide the essential data about the monitored event or object. The networking services offered by the EL nodes are communication with the devices at the intermediate layer, and in the mesh network case, the EL sensor nodes can communicate also with each other. The simplest service which elementary layer node can offer is just to send a simple message containing, e.g., a body temperature or environment humidity value sensed by the node. The intermediate layer nodes have more capabilities and they can offer higher performance functionalities and sensing, such as performing electrocardiography (ECG) or recording a video. The IL nodes may also perform data aggregation for information collected from EL nodes and make decisions based on the data by using, e.g., pattern recognition algorithms. Therefore, the intermediate layer nodes can decide whether a sensed event is so critical that also the advanced layer needs to be awakened. The IL nodes offer important networking services by communicating both with upper and lower layer devices. The advanced layer nodes are the most intelligent devices in the architecture, and they will eventually collect all the relevant data from the lower layers and make intelligent decisions, process data and act as a gateway between the WSN and the backbone network. Therefore, AL devices must provide adequate service interfaces so that the application data can be offered to the end-user through backbone. The outer layer is the backbone (public or private) infrastructure providing wireless and/or wired communication, (e.g. broadband or cellular network) back-end systems and applications servers. Since this layer is not part of the actual wireless sensor network architecture, it is called outer layer in this design.

Figure 2 illustrates an example of application scenarios that was implemented, by University of Oulu and Technical University of Tampere, to verify the introduced hierarchical architecture principle. Sub-network 1 illustrates a WSN where the sensor nodes (TelosB [21]) collect data from the office environment and send it to the embedded computer (FriendlyARM [22]), which forwards the data to the desktop computer with an Ethernet connection to the backbone network (Internet). Sub-network 2 illustrates a surveillance WSN where the sensor nodes (TUTWSN [23]) detect movements in the monitored area and wake up a wireless local area network (WLAN) camera node to record a video once the moving object has been sensed. The WLAN camera node sends the video to an embedded computer, which forwards the data to the backbone network (Internet). An authenticated end-user can access the data from different sub-networks through the Internet and receive, e.g., automatic alarms about intruders in the monitored area. In medical applications, this type of network with tailored sensors could for example monitor elderly or Parkinson decease patient at home environment and provide alarms for the patient itself and for the nursing staff at hospital when movements are detected in unusual or dangerous areas. Patient's WBAN can be also implemented using hierarchical architecture principle. The information collected by WBAN would provide useful information about the patient state for example when the monitoring network has triggered the alarm and caught medical persons to pay attention to the patient due to detected event.

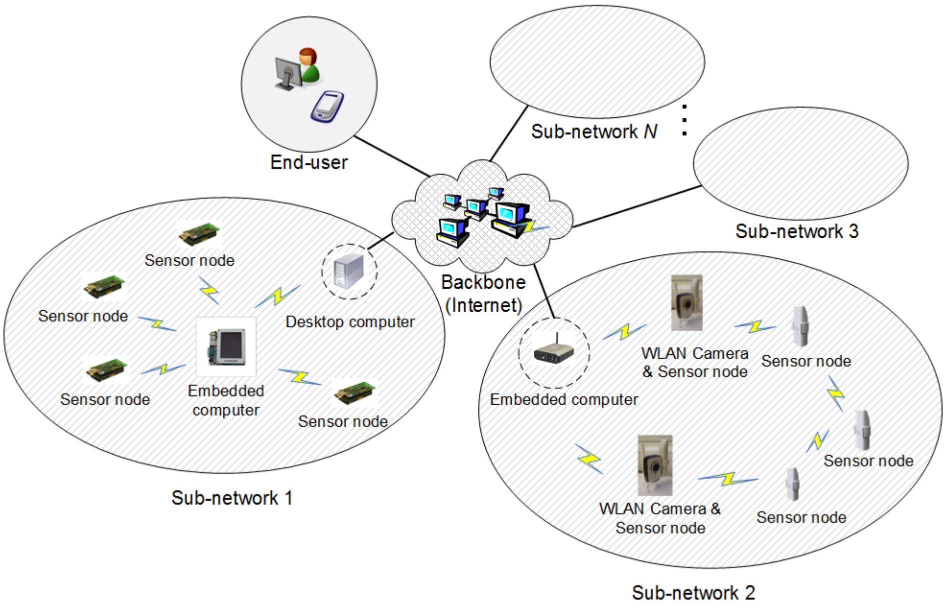


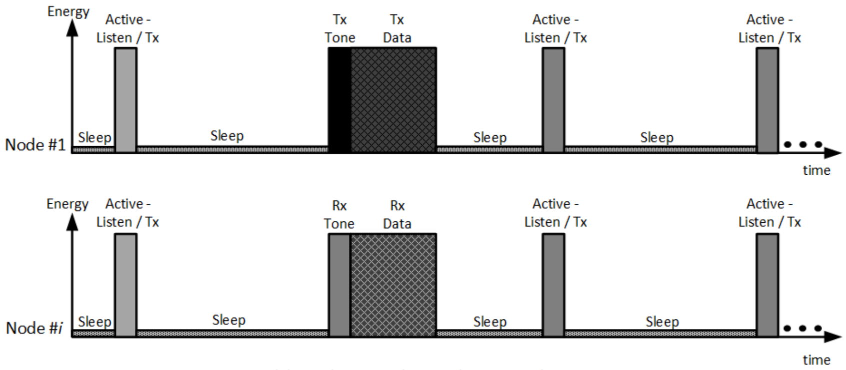
Figure 2. Distributed heterogeneous network example.

b. Wake-up concept

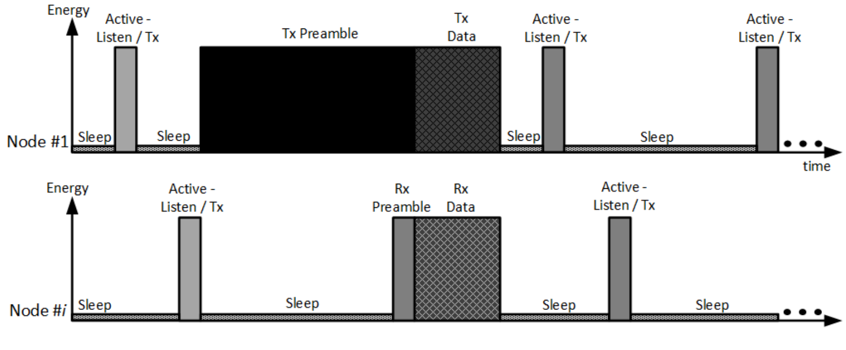
As was described above, the idea of the energy efficient hierarchical architecture is to keep the most power consuming nodes in a sleep mode as long as possible. For that purpose, there is a need for a low-power wake-up concept, which can be implemented by using a specific wake-up receivers or by using a duty-cycled MAC protocol.

The design of wake-up concept must take into account physical and MAC layer characteristics. The wake-up signal transmitted through the physical medium must be designed to enable that it can be detected by using low power consuming components at the WUR, which design options are discussed in detail in Section 3. There are different types of MAC protocols which try to improve energy efficiency. Their efficiency depends on the application characteristics since different types of networks require different types of solutions. Indeed, the scalability and adaptability to network changes are important MAC protocol design objectives because in that way the protocol performance can be ensured in many type of scenarios. MAC protocols must be designed to take care of the packet collision avoidance, idle listening and overhearing with minimum control overhead. Packet collisions must be avoided to keep the number of retransmissions low. Idle listening occurs when radios listen to the channel redundantly, when there are no incoming transmissions. Retransmissions and control overhead decrease data throughput and increase energy consumption because redundant bits need to be transmitted. Consequently, the available sleep time of the sensor nodes also decreases. Overhearing should be avoided so that only the target nodes will receive and decode the packets.

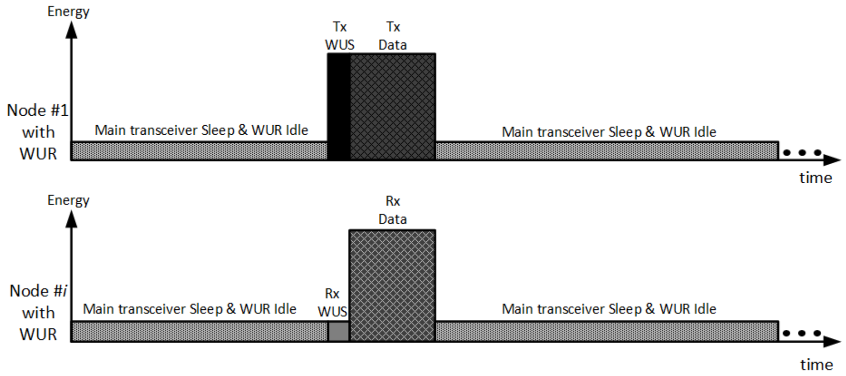
Most of the proposed sensor network MAC protocols are duty-cycle based, i.e., the radios have a sleep / awake scheduling which they are following. The MAC protocols can be divided into synchronous and asynchronous categories. Duty-cycling principle is illustrated in Figure 3 (a) for synchronous case, and in Figure 3 (b) for asynchronous case. Synchronous protocols schedule the sleep / awake periods so that the nodes which are expected to communicate with each other are awake at the same time. Synchronous protocols typically require a centralized control and use clustering of nodes, and inside each cluster there is a common sleep / awake schedule which is controlled by the cluster head. Asynchronous protocols include methods for communications between the nodes which have different sleep / awake schedules.



(a) Synchronous duty-cycling principle



(b) Asynchronous duty-cycling principle



(c) Wake-up radio principle

Figure 3. Principle for a) synchronous duty-cycling, b) asynchronous duty-cycling and c) wake-up radio based MAC.

Asynchronous communication is enabled by using a sender or receiver initiated communication. In the sender initiated case, the data source will send a preamble before data transmission. Once the receiver detects the preamble, it will continue the listening to receive the data packet that will follow the preamble, as illustrated in Figure 3 (b). If the receiver does not detect a preamble, it will go back to the sleep mode. In the receiver initiated case, the receiver will use probing to query for potential transmissions. In each case, the idle listening will occur if there is no incoming transmission when the nodes wake up to listen to the channel according their schedule. Idle listening is expensive from the power consumption point of view because the transceivers should be in the sleep mode as much as possible in order to save power.

Recently, wake-up radio-based MAC solutions have gained attention due to their energy efficiency superiority, particularly in applications with rare events and transmissions [59] - [62]. The wake-up radio principle has been illustrated in Figure 3 (c). In this case the data transceiver can be in the sleep mode until there is incoming data packet to be received from some other node. The WUR of the source node will notify the target node(s) by sending a wake-up signal (WUS). After receiving the WUS, target node’s WUR will trigger wake-up of the main transceiver for data packet reception.

Duty cycle-based MAC protocols work well in many WSN applications but not in applications where the monitored events, and communication, occur rarely. A drawback of the duty-cycle approaches is idle listening, which increases energy consumption and should thus be avoided if possible. I.e., the duty-cycle radios (DCR) will listen to the channel unnecessarily if the event reporting frequency is lower than the duty-cycle. Idle listening can be decreased by setting the duty cycle very low when the traffic load is low. Adaptive duty-cycle protocols have been proposed for that purpose. However, low duty-cycle will increase the communication delay and may not be able to satisfy the application requirements.

Wake-up receivers [26]–[57] can be used to avoid the idle listening problem while allowing energy-efficient and low latency operation. The wake-up receiver is continuously able to detect the wake-up signal when it is in the ultra-low-power standby mode. The communication delay can be avoided when the event occurs and there is data to transmit. Therefore, WURs have potential to decrease energy consumption in comparison with duty-cycle radio-based networks. WUR design approaches will be discussed in more details in Section 3.

c. A generic-level WUR-based MAC for hierarchical architecture

A generic WUR-based MAC (GWR-MAC) protocol which is based on dual-radio approach is introduced here to enable idle listening avoidance in sensor network applications [59]. In the dual-radio node architecture case, nodes include wake-up receiver and main data radio, as illustrated in Figure 4. The GWR-MAC protocol is not restricted to any specific WUR technology or data radio technology. Two different options for the wake-up procedure are defined for the GWR-MAC protocol: source-initiated and sink-initiated. The data transmission period of GWR-MAC can be implemented by using different types of channel access methods, as will be explained below.

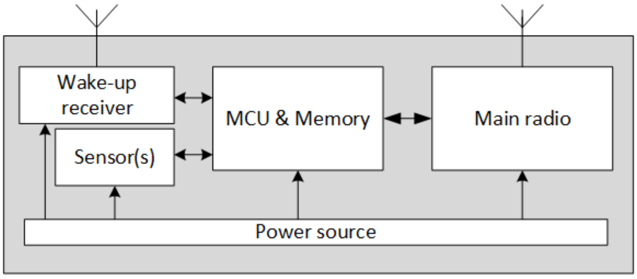


Figure 4. Sensor node architecture for dual-radio approach.

In the source-initiated mode, the sensor node(s) will wake up the sink node from the sleep mode by transmitting a wake-up signal (WUS), as illustrated in Figure 5. To decrease the probability of WUS collisions, a random (or predefined) delay for WUS transmissions can be used. The WUR of the sink node will receive the WUS and generate a wake up via microcontroller (MCU) to the main radio. The sink node's main radio will then broadcast a beacon (BC) message to initiate transmission period for the sensor node(s) according to the channel access procedure, which can be based on different methods suitable for different scenarios. The beacon message is, at the same time, an acknowledgement to the sensor node(s) that the WUS has been received by the sink. If the sensor node does not get the beacon message, it will retransmit the WUS after a random back-off period. The WUS transmission procedure is therefore similar to the Aloha channel access with a random (or predefined) delay for the first transmission. Once the beacon message is received, the sensor node(s) will send the data packet(s) to the sink during the transmission period by using the channel access method informed in the beacon message. This mode of the GWR-MAC protocol is therefore a combination of the source-initiated wake-up procedure and following channel access control method for the transmission period.

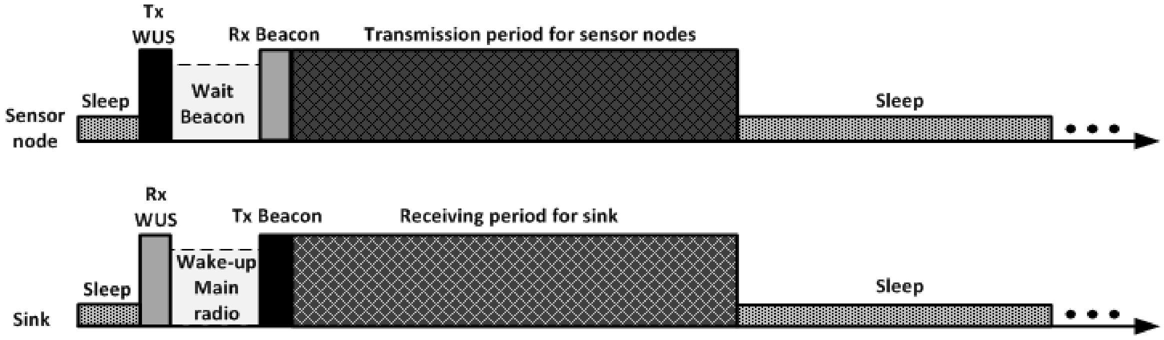


Figure 5. Source-initiated mode of the GWR-MAC protocol.

In the sink-initiated mode, illustrated in Figure 6, the sink node will wake up the sensor nodes from the sleep mode by sending the WUS using broadcast, uni-cast or multi-cast. It depends on the used WUR technology whether it is possible to use addressing to wake up only certain sensor nodes or whether broadcast should be used. When the sensor node receives the WUS, it will send an acknowledgement (ACK) message to the sink. The sink node knows that the WUS has been detected correctly and sends the beacon containing information about the following transmission period. Data transmissions are then performed during the transmission period, and once they are finished, all the nodes have entered the sleep mode.

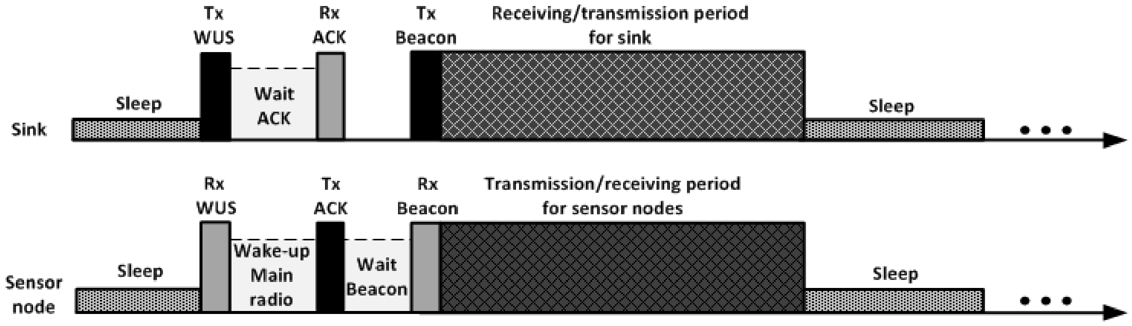


Figure 6. Sink-initiated mode of the GWR-MAC protocol.

Typically, the data flow is from the sensor nodes to the sink node. However, the transmission period can also be dedicated to the sink node to transmit data to the sensor node(s), if, for example, a wireless software update or reconfiguration of sensor node(s) requires it. Therefore, in Figure 6, it is illustrated for the sink-initiated case that the transmission period can be dedicated to the sensor node(s) or to the sink node to transmit data packets. The sink node can determine in the beacon the upcoming transmission period channel access mechanism, timing and scheduling information. Different channel access methods can be used for the transmission period management. When the transmission period is finished, all the nodes have entered the sleep mode and the next transmission period will take place after the next wake-up procedure.

For the transmission period channel access, one option is to use a contention-based MAC. In that case, the nodes compete for channel access and transmit packets according to the contention-based MAC principle. For example, in the Aloha case, nodes transmit when they have a packet to transmit. If the packet is not successfully received, then the retransmission policy defines either that the packet is discharged or retransmitted. For example, in the Aloha case, the unsuccessful packet will be retransmitted again after a random back-off period if the ACK is not received during a certain time. In addition, other contention-based methods, e.g., carrier sensing multiple access with collision avoidance (CSMA/CA), etc. can be used during the transmission period. Another option is to use contention-free scheduled methods, e.g., time division multiple access (TDMA) based protocols, guaranteed time slots defined in the IEEE Std 802.15.4 ([24], [25]) and scheduled access mode of the IEEE Std 802.15.6 [75] or ETSI SmartBAN MAC [76]. The requirement for the usage of contention-free methods is that the sink node assigns dedicated time slots for each sensor node. The sink node does not have information about which nodes have a packet to transmit, and therefore the channel resources may be wasted. In the ideal contention-free case, collisions will not occur if the nodes are perfectly synchronized and follow the schedule.

The described GWR-MAC protocol principle is suitable for different types of application since it defines a bi-directional wake-up procedure between the sensor nodes and the sink. In addition, it enables the usage of different channel access methods for the transmission period. The described GWR-MAC is a general-level framework for short-range networks which take advantage of the wake-up radios. It depends on the application scenario which mode of the GWR-MAC protocol should be used. For example, in some applications only the source-initiated case may be used, and then only the sink node should be equipped with a WUR. In some scenarios, there can be a need that only the sink node must be able to wake up sensor nodes. In that case, the sink-initiated mode would be used and only the sensor nodes must be accompanied with a WUR. Some application scenarios require both modes of the GWR-MAC protocol. In such cases all the network nodes must be equipped with a WUR and data radio as was illustrated in Figure 4. In recent years WUR based MAC solutions have gained researchers attention and other similar type of solutions, which can be used in a hierarchical network context, have been recently discussed and reviewed in [61] and [62].

3. Wake-up receiver solutions

Wake-up receiver designs have progressed substantially in the last decade and they might be utilized in various IoT applications in the near future. The current designs consume power well below 100 µW which is already over hundred times less than a typical commercial RF transceiver designed for WSNs consumes. Low power consumption enables a node to listen the channel constantly for years with a single coin size battery. But due to the tradeoff between power consumption and sensitivity, sensitivities of WURs are usually considerably worse compared to commercial RF transceivers. Consequently, to reach the WUR and the RF transceiver of the node, more transmit power is needed to transfer a wake-up signal to the WUR than to transmit data to the RF transceiver.

Receiver design includes always tradeoffs regarding, e.g., data rate, power consumption and sensitivity. The two main performance comparison metrics of the proposed solutions have been power consumption and sensitivity, followed by data rate. In some works, energy per bit is also used as a comparison metric. However, utilized wake-up packet lengths are usually only few bytes in size so receiver's active power consumption becomes more important than energy per bit. Also due to the small size of the wake-up packet, it is transmitted reasonably fast even with low data rates. Below will be discussed in more details the different receiver architectures that can be used for wake-up signal detection. Furthermore, future research directions will be outlined.

a. Wake-up receiver architectures

Data receivers typically use direct conversion (DiCo) architecture, but due to the challenges of flicker noise and DC offset, they are rarely used in WURs. Also common superheterodyne receiver architecture has been proposed to be used as a wake-up receiver. However, in those solutions duty-cycling is often employed and active power consumptions of different superheterodyne solutions are significantly more than in WURs based on other architectures. Due to the demanding requirements of power consumption and sensitivity, receiver designers have proposed many different receiver architectures for WUR purposes. Figure 7 shows block diagrams of most common architectures, which are based on RF envelope detection (RFED), uncertain-intermediate frequency (IF), matched filter, injection-locking, superregenerative oscillator and sub-sampling.

Being the most straightforward option for energy detection, the RFED architecture is the most commonly used solution. In the RFED based receivers, local oscillator (LO) is not needed since the envelope of the RF signal is detected and signal is therefore directly down converted to baseband. The envelope is detected from a wide bandwidth. Therefore, incoming signal is band pass filtered in order to ensure low-noise at the envelope detector input.

Accurate RF synthesizers typically consume too much power to be used in WURs. The uncertain-IF receiver architecture utilizes synthesizer that consume low-power at the cost of poor frequency stability. After the signal is down converted, the signal is located in a wide frequency range. Wideband amplification is typically used to improve SNR followed by envelope detection.

Majority of WURs use narrowband wake-up signals even though in-band interference is a major challenge for receiver architectures that are based on received signal power. With a spread spectrum technique, the signal is spread in frequency domain, which makes it more resistant against interference due to spreading gain that will be achieved by dispreading the signal at the receiver. To dispread the spread spectrum signal energy efficiently, e.g., passive surface acoustic wave (SAW) matched filter can be used. Low-power consumption is achieved at a cost of sensitivity due to high insertion losses of the SAW matched filter.

Receiver based on injection-locking architecture has an oscillator that locks to a received carrier frequency if it is close to oscillator's natural oscillation frequency. If injection-locking does not occur, but the carrier frequency disturbs the oscillator, it will be seen at the oscillator output. This is called injection-polling. Hence, injection-locking receivers are usually used to detect frequency shift keying (FSK) modulated signals.

The superregenerative receiver is based on power detection. Oscillation start-up time in a superregenerative oscillator correlates with the received signal strength. By detecting time difference between oscillation start-up times, a simple low-power receiver that has large gain can be built. Superregenerative oscillator architecture block diagram in Figure 7e has a low noise amplifier (LNA) at the front-end, because it is needed to isolate feed through from oscillator to antenna and it also amplifies the signal. It depends on superregenerative receiver characteristics that how much oscillator emits to surroundings. If emission is larger than regulations allow, isolation must be implemented. LNA can be added at the front-end of other architectures as well that would give gain at the cost of power consumption. Typically in WURs, amplification is rather done at IF than in RF because it is more power friendly.

Sub-sampling based receiver architecture down converts the signal with a discrete-time sampler instead of with a continuous-time mixer. Input signal is mixed with harmonic components in the discrete-time sampler, producing replicas in multiple frequencies that gives more freedom to select appropriate IF.

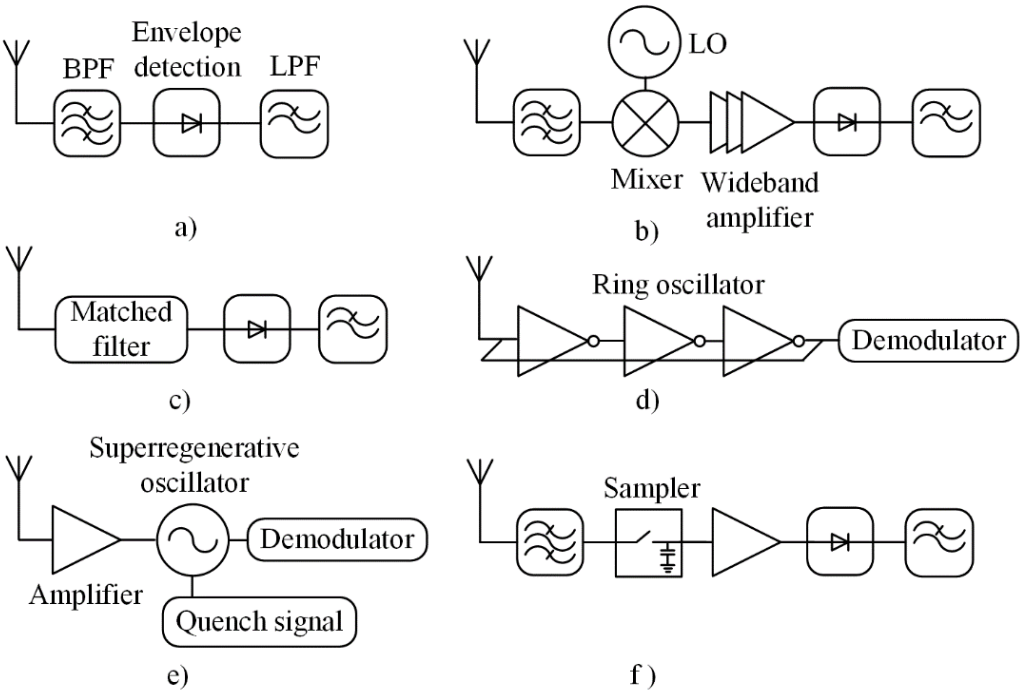


Figure 7. Typical wake-up receiver architectures: a) RF envelope detection, b) uncertain-IF, c) matched filter, d) injection-locking, e) superregenerative oscillator and f) sub-sampling.

Different WUR designs are compared in Figure 8, where the trade-off between sensitivity and power consumption is clearly illustrated. At the moment, there is no superior architecture which would be clearly more suitable for WUR purposes in comparison to other solutions.

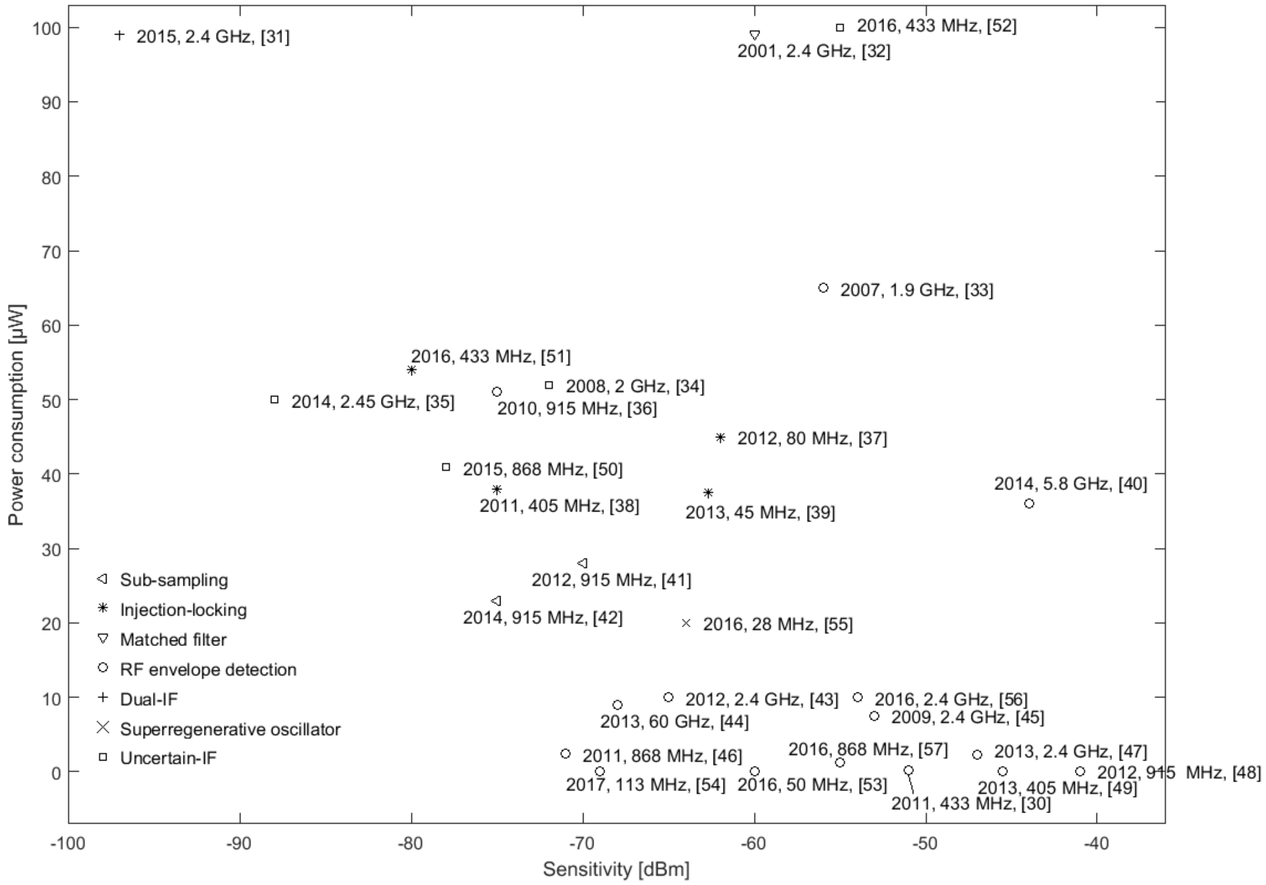


Figure 8. Comparison of wake-up receivers and their architectures.

b. Future research directions

WUR sensitivities vary from -40 dBm to around -90 dBm in designs that have active power consumption less than 50 µW. Whereas, typical commercial short range transceiver usually has sensitivity at least of -95 dBm. Therefore, there is still work to be done to reach the gap between WURs and data transceivers. If the wake-up range is lower than the data radio range, the usage of wake-up signaling will require higher node density in the network or higher transmit power. The gap becomes even larger issue if one would like to integrate WURs to low power wide area network (LPWAN) sensor nodes. In the LPWAN, wireless communications range outdoors can be over 10 km [63] and in indoors one base station can cover a large real-estate [64]. Whereas, in a traditional WSN communications range of the sensor node is usually some tens of meters [65]. Figure 9 shows main differences between the WSN the LPWAN. An application for the LPWAN where utilizing the WUR would be beneficial could be, e.g., remote patient monitoring. Sensor nodes can be configured to report periodically patient's well-being directly via a remote base station which enables that patient does not need to carry gateway device. In normal conditions, sensor nodes can be configured to transmit patient's vital data to the base station couple of times per day but if the patient's physical condition has some alarming signs, and doctor needs data more frequently, the wake-up receiver usage enables that the reporting frequency could be changed with low latency. It is expected that this kind of situation occurs rarely, therefore it is assumed to be more energy efficient to use nodes that are equipped with the WUR instead of using duty-cycling base MAC protocol. In order to achieve 10 km range with transmit power according to regulations, commercial LPWAN transceivers are operating in sub 1 GHz bands and they are designed to be highly sensitive. For example, SX1272 transceiver by Semtech [66] achieves sensitivity of -137 dBm at data rate of 300 bps. Semtech is part of the LoRa alliance [67], which is targeting to standardize solution for the LPWAN.

Another important player in the LPWAN field at the moment is Sigfox [68]. Sigfox's technology compliant transceivers such as the AX5043 by Axsem [69] has similar performance than the SX1272. Most of the WURs found from the literature have much higher data rates, from 100 kbps to 350 kbps. One direction for future WUR research could be therefore the sensitivity improvement at the cost of data rate. Since the length of the wake-up packet is usually in the order of few bytes, the wake-up signal can be transmitted sufficiently fast even with low data rates while maintaining energy efficiency.

The world is rapidly evolving into a networking society where more and more wireless devices communicate with each other. Gartner, a technology research and advisory firm, estimated in 2014 that there will be 26 billion IoT based devices in 2020 [70]. ABI Research, a technology market intelligence firm, estimated the number of devices to be 30 billion [71] and Cisco estimate is that 50 billion devices and objects will be connected to IoT by 2020 [8]. These estimates show that the IoT market will be huge. Assuming that most of the devices will be wireless, number of radios can be even higher since a device might be equipped with multiple radios. More wireless devices mean that there will be more interference, but on the other hand new millimeter wave bands will be exploited that will ease the situation. More interference will be harmful, especially for the RF envelope detection architecture since it is based on energy detection. This should be taken into account while planning future research activities related to the WURs.

Wake-up signal generation and transmission is often neglected in the WUR design and energy efficiency performance evaluation. However, since OOK is the most common modulation method being used, it can be generated with most of the commercial transceivers. Also, data rate can be usually configured to match receiver's rate. In the LPWANs, the base stations are already being installed all around the world by SigFox and the Lora alliance, therefore the hardware changes would be expensive. In order to make WURs a widespread technology in the future, integrating WURs to existing and future IoT networks should get more attention in the research.

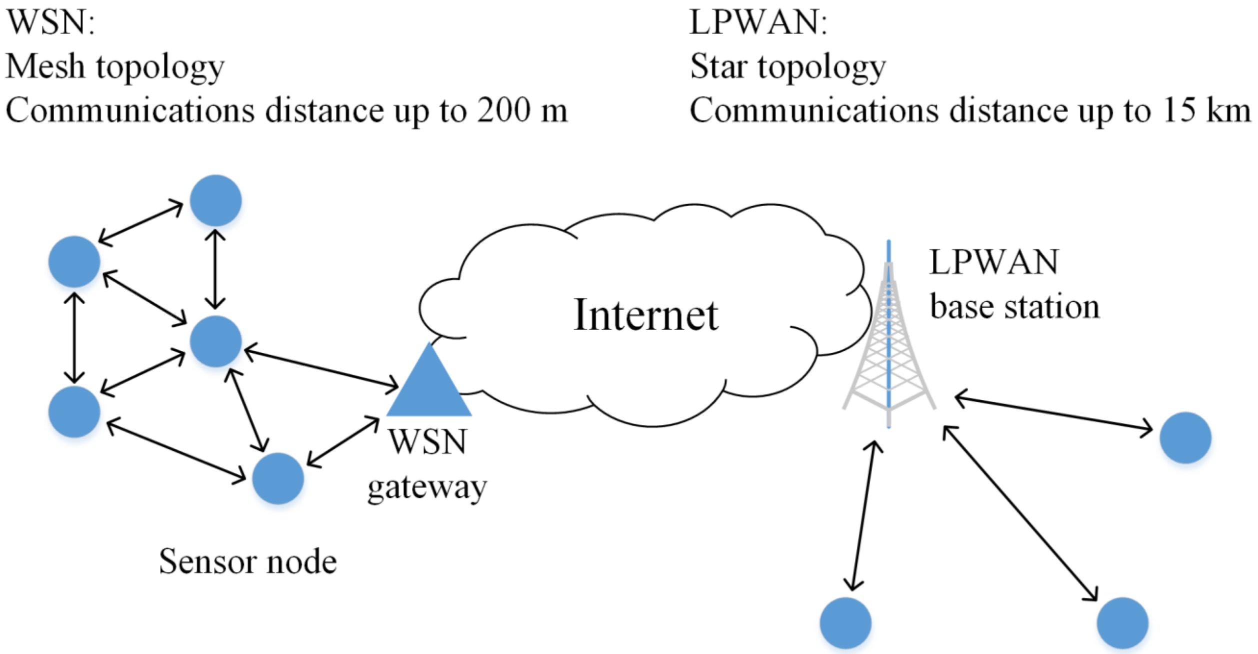


Figure 9. Main differences between the WSN and the LPWAN.

4. Energy efficient target scenarios

a. Application scenarios

The hierarchical architecture is scalable for various application scenarios which are deployed using heterogeneous devices. However, wake-up radio based hierarchical architecture is targeted especially to applications which require communication rarely and in addition require a low latency reaction to events.

A very good example is an area surveillance network. In that case the motion detection sensor (e.g. passive infrared (PIR)) nodes are continuously monitoring the environment to detect intruder movements in the sensing area. Once the event is detected, sensor nodes must be able to report event rapidly. In the energy efficient hierarchical architecture case it means that the next layer in the hierarchy must be awakened with a very low delay. If the event is detected to be critical, also the highest layer will be awakened and alarm will be generated to the user through the backbone. Another example is structural monitoring of, e.g., bridges or buildings. In that case the condition of the monitored structure can be queried rarely. On the other hand the sensor nodes can send alarm if some critical changes have been detected. Also in that case the sensor nodes can perform continuous monitoring and wake-up the higher layer node only when required in order to enable long lifetime for the network nodes. Hierarchical wake-up radio based architecture can be as well utilized for WBAN and industrial applications. In WBAN case the wake-up radios could be equipped for instance to implants and on-body nodes which must have very long lifetime once installed in to human body. In industrial applications to WUR based nodes can be installed to monitor, e.g., pipe valves or certain parts of engines. For military and critical infrastructure scenarios there also are many use cases for hierarchical WUR based network architecture since there is a need for different types of long time monitoring applications, e.g., for surveillance, reconnaissance and security purposes. Figure 11 summarizes example applications and communication and sensor technologies that can be used in their implementation.

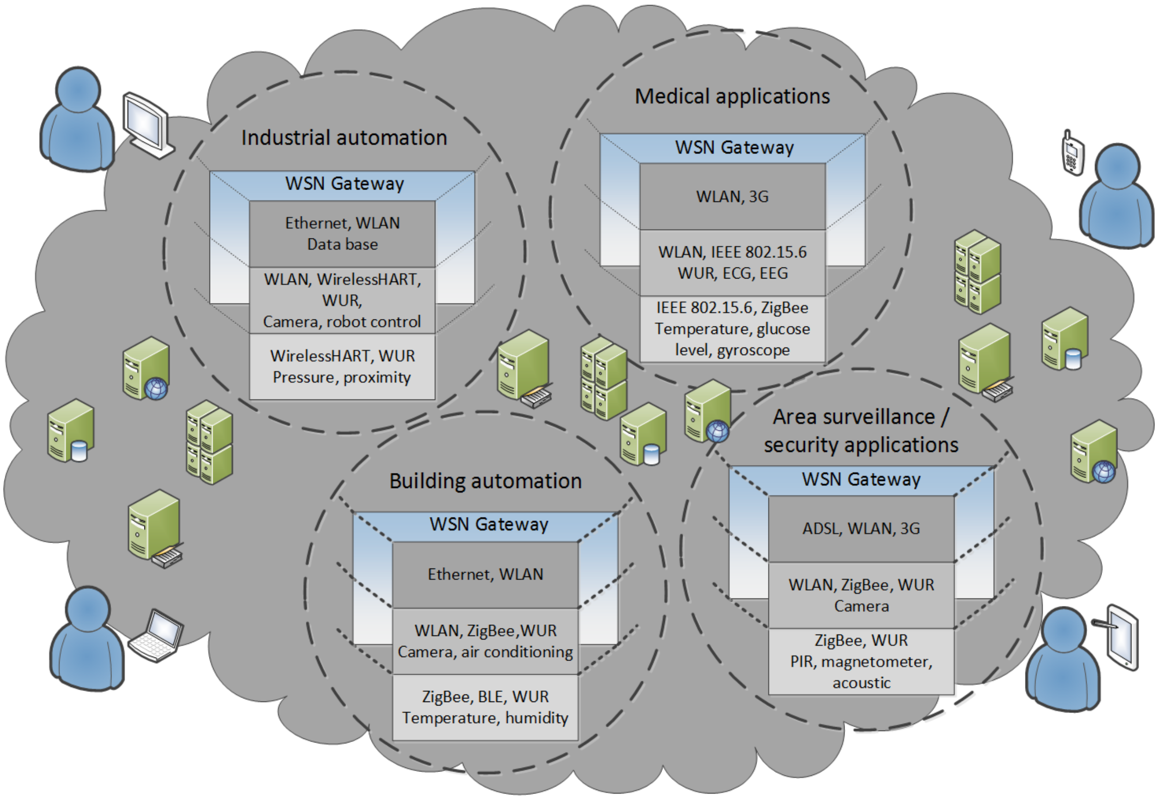


Figure 10. Examples of hierarchical WSN architecture application areas and techniques.

b. Energy efficiency comparison of wake-up mechanisms

This section introduces an energy efficiency comparison of the WUR- and DCR-based wake-up mechanisms discussed in Section 2b. The intelligent hierarchical operation is assumed for both WUR and DCR approaches, i.e., the lower-layer devices of the hierarchical architecture are performing continuous sensing and will wake up the higher layers when required. At first, the comparison is done with different duty-cycle and event-frequency values in a typical surveillance scenario for critical infrastructure protection, which corresponds with the case of sub-network 2 in Figure 2. For both approaches, source-initiated communication is assumed, i.e., the focus is on the scenario where the sensor nodes have sensed something and trigger the wake up of the higher layer. The used analytical model can also be applied to other WSN scenarios with layered hierarchical architecture but in that case the detailed assumptions must be adjusted to match the particular application under evaluation. As an example of that, energy comparison results for a two-tier WBAN case using a sink-initiated of GWR-MAC will also be introduced in this section. In addition, in the end of section, results for wake-up receiver design tradeoff affect to energy consumption will be discussed.

In the DCR approach, each layer’s low-power transceivers need to wake up and sleep according to a predefined schedule. It is assumed that the nodes in each network layer have low-power radios (e.g., IEEE Std. 802.15.4-based) for duty cycling to enable the wake-up mechanism. In the DCR-based network case, the transmitter sends a detected event (DE) message in order to inform the node at a higher layer that it should stay awake. If a higher-layer node receives a DE message during the duty cycle listening, it will stay on, send an ACK message and wait for a data transmission.

In the WUR-based network, the wake-up signals are used to activate the other layers when needed. The GWR-MAC protocol introduced in Section 2c is used in the WUR-based networks. In the surveillance network case, the lower-layer transmits the wake-up signal and the higher-layer node sends back a beacon message, as described in the GWR-MAC protocol’s source-initiated mode definition. Then the lower-layer nodes can send their data to the higher-layer node. The same GWR-MAC wake-up procedure is used for the elementary layer to wake up the intermediate layer and the intermediate layer to wake up the advanced layer. In the WBAN example case, the sink-node transmits a WUS to a sensor node when it needs to be awakened to receive a message. Once awaken, the sensor node will send acknowledgement back to the sink. The sink node will then send data (or control) message back to the sensor node(s).

Authors have originally proposed an analytical model, which can be used to compare the energy efficiency of the GWR-MAC based and conventional duty-cycle MAC (DCM)-based networks as a function of number of events in a hierarchical network for surveillance scenario [58].The energy efficiency comparison takes account of the energy consumption of the nodes’ core components: micro-controller unit, transceiver and sensors. A low-power micro-controller has typically the active, standby, and sleep modes. The transceiver has the transmit (Tx), receive (Rx), idle and sleep modes. The active, Tx and Rx modes are the most energy consuming parts. Therefore, it is important to put the nodes into the sleep mode when possible. The sensing component consists of sensors and A/D converters. The sensing component has different modes, which affect energy consumption, e.g., sensor warm-up, active mode and settle time of the A/D converter. The dominating energy consumption factors of each transceiver’s components are taken here into account: wake-up signaling, data transmission and reception, and MCU and sensor active mode current consumption. The relevant energy consumption characteristic, affecting the WUR and DCR energy efficiency comparison, are then addressed. However, energy consumption during network initialization and run-time management (e.g., communication required for synchronization and routing) are not taken into account.

The energy efficiency equation for the WUR and DCR network comparison is defined as [7], [58]

$$\eta(\varepsilon,\lambda,t,\beta)=\frac{\min(E(\varepsilon,\Lambda,t,\beta))}{E(\varepsilon,\lambda,t,\beta)}, \tag{1}$$

where E is the network energy consumption over time period t, ε is the number of events during t, λ is duty-cycle and β is bit error probability. In this case the event means that nodes have a data packet to send for a hub about the sensed event. In (1), the minimum of E is calculated over the duty-cycle value set $\Lambda = (0,1]$. Note that $\Lambda = 1$ corresponds to the WUR case since the receiver is listening the channel continuously. The metric introduced in (1) defines the maximum energy efficiency to be one and enables comparison of the WUR and DCR based networks.

The total energy consumption during the operation time, t, as a function of number of events and bit error probability, for WUR-based network layers (EL, IL and AL) can be calculated as

$$\begin{aligned}
&E_{WUR}^{EL}(\varepsilon,t,\beta)=E_{s}^{EL}(t)+E_{MCU}^{EL}(\varepsilon,t)+E_{TX,WUS}(\varepsilon,t,\beta)+E_{wait,BC}(\varepsilon,t)+E_{RX,BC}(\varepsilon,t)\\
&+E_{C}(t)+E_{TX,D}^{EL}(\varepsilon,t,\beta)+E_{clk}(t)\\[1em]
&E_{WUR}^{IL}(\varepsilon,t,\beta)=E_{s}^{IL}(t)+E_{MCU}^{IL}(\varepsilon,t)+E_{TX,WUS}(\varepsilon,t,\beta)+E_{TX,BC}(\varepsilon,t)+E_{wait,BC}(\varepsilon,t)\\
&+E_{RX,BC}(\varepsilon,t)+E_{RX,WUS}(\varepsilon,t,\beta)+E_{C}(t)+E_{clk}(t)+E_{TX,D}^{IL}(\varepsilon,t,\beta)+E_{RX,D}^{IL}(\varepsilon,t,\beta),\\[1em]
&E_{WUR}^{AL}(\varepsilon,t,\beta)=E_{MCU}^{AL}(\varepsilon,t)+E_{RX,WUS}(\varepsilon,t,\beta)+E_{TX,BC}(\varepsilon,t)+E_{C}(t)+E_{clk}(t)\\
&+E_{TX,D}^{AL}(\varepsilon,t,\beta)+E_{RX,D}^{AL}(\varepsilon,t,\beta)
\end{aligned} \tag{2}$$

where $E_{\mathrm{TX,WUS}}$ is the energy consumption of wake-up signal transmissions, $E_{\mathrm{RX,WUS}}$ is the energy consumption of wake-up signal receptions, $E_{\mathrm{TX,BC}}$ is the energy consumption of beacon transmission, $E_{\mathrm{wait,BC}}$ is the energy consumption of beacon listening, $E_{\mathrm{RX,BC}}$ is the energy consumption of beacon receptions, E_{C} is the constant energy consumption of WUR and E_{clk} is the energy consumption of the clock needed to maintain the time synchronization. E_{s}^{x} is the energy consumption of sensing, E_{MCU}^{x} is the energy consumption of MCU, $E_{TX,D}^{x}$ and $E_{RX,D}^{x}$ are the energy consumption of data transmissions and receptions, respectively, calculated separately for each layer (i.e., x is EL, IL or AL).

The total energy consumption during t, as a function of number of events, duty-cycle percentage and bit error probability, for DCR-based network layers (EL, IL and AL) can be calculated as

$$\begin{aligned}
&E_{DCR}^{EL}(\varepsilon,\lambda,t,\beta)=E_{s}^{EL}(t)+E_{MCU}^{EL}(\varepsilon,t)+E_{RX,DC}^{EL}(\lambda,t)+E_{clk}(t)+E_{TX,DE}^{EL}(\varepsilon,t,\beta)\\
&+E_{RX,BC}^{EL}(\varepsilon,t,\beta)+E_{TX,D}^{EL}(\varepsilon,t,\beta)\\[1em]
&E_{DCR}^{IL}(\varepsilon,\lambda,t,\beta)=E_{s}^{IL}(t)+E_{MCU}^{IL}(\varepsilon,t)+E_{RX,DC}^{IL}(\lambda,t)+E_{clk}(t)+E_{RX,DE}^{IL}(\varepsilon,t,\beta)\\
&+E_{TX,BC}^{IL}(\varepsilon,t,\beta)+E_{TX,DE}^{IL}(\varepsilon,t,\beta)+E_{RX,BC}^{IL}(\varepsilon,t,\beta)+E_{TX,D}^{IL}(\varepsilon,t,\beta)+E_{RX,D}^{IL}(\varepsilon,t,\beta),\\[1em]
&E_{DCR}^{AL}(\varepsilon,\lambda,t,\beta)=E_{MCU}^{AL}(\varepsilon,t)+E_{RX,DC}^{AL}(\lambda,t)+E_{clk}(t)+E_{RX,DE}^{AL}(\varepsilon,t,\beta)+E_{TX,BC}^{AL}(\varepsilon,t,\beta)\\
&+E_{TX,D}^{AL}(\varepsilon,t,\beta)+E_{RX,D}^{AL}(\varepsilon,t,\beta)
\end{aligned} \tag{3}$$

where λ is the duty-cycle percentage, $E^{x}_{RX,DC}$ is the energy consumption of channel listening according to the duty cycle, $E^{x}_{TX,DE}$ and $E^{x}_{RX,DE}$ is the energy consumption of DE message transmission and reception, respectively, when *x* is EL, IL or AL. Depending on the dyty-cycling based MAC protocol features, the DE message can be replaced, e.g., by using a preamble before the data packet.

By multiplying the energy consumption of different layers nodes at WUR based network (eq. (2)) and DCR based network (eq. (3)) with the number of nodes at each layer, the network total energy consumption during operation time, *t*, can be easily derived. Interested reader can find more details about the network energy consumption derivation from [7] and [58].

Figure 11 shows network total energy consumption comparison results, which are calculated using the parameters chosen to represent typical values for nodes equipped with WUR, IEEE St. 802.15.4 and IEEE Std. 802.11b communication interfaces and sensors, as described for the surveillance scenario. The number of nodes at the elementary layer is 100, and the number of nodes at the intermediate layer is 10, i.e., there is in average 10 sensor nodes assumed to be associated with one IL node, which acts as a coordinator node for the sensor nodes. It can be seen that in the WUR-based network, energy consumption is drastically lower with the whole range of studied duty-cycle values when the event frequency is low. For the lowest number of events case, the energy consumption gain of the WUR approach is more than two orders of magnitude in comparison with a DCR with λ = 5%. For the highest number of events per hour, DCR has energy consumption gain of 12% with the smallest duty cycle percentage value. More details about the analytical model, parameters and results can be found from [58].

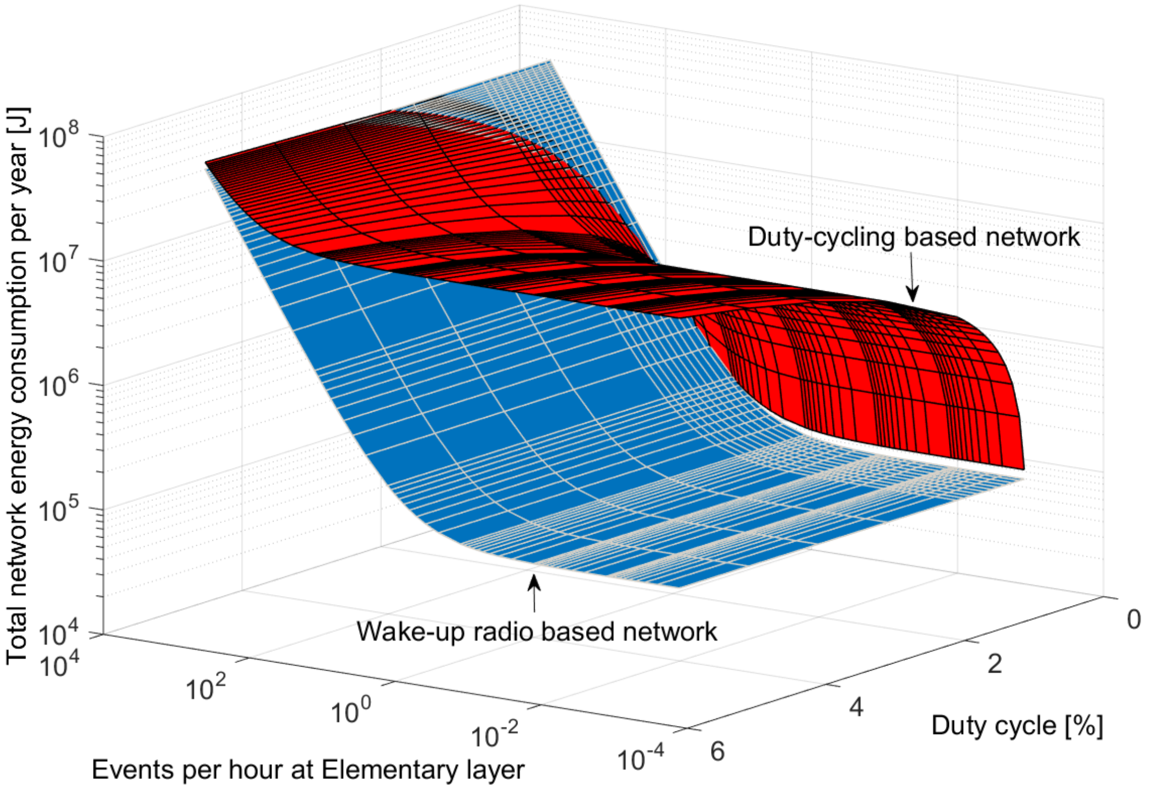


Figure 11. Network energy consumption comparison as a function of event per hour and duty cycle.

In [60] and [77] authors have shown that hierarchical architecture and its analytical energy efficiency model introduced in [58] can also be applied for WBAN scenario. Further, in [65] the wake-up radio and DCR based network energy consumption comparison is discussed in WBANs case. Here are shown WUR and DCR energy efficiency comparison results which are calculated using four different WUR parameters, which are shown in Table 1. Typical state-of-the-art performance values are used in WUR1 and WUR2 for power consumption and sensitivity. WUR3 sensitivity is set to be same as for duty-cycled radio (DCR) transceiver [72]. In the WUR4 case the assumption is that sensitivity can be improved by using very low data rate while remaining very low Rx mode power consumption. In the calculations have been assumed that data packet payload is 255 bytes and communication is error free ($\beta = 0$). More details about the used analytical model can be found from [60].

The energy efficiency comparison results for WUR and DCR based WBANs as a function of number of events per hour is presented in Figure 12. It can be observed that the GWR-MAC based network outperforms the DCM based network's lowest duty cycle (λ = 0.5%) case when the number of events is less than 12 per hour. When compared to DCM network with λ = 3%, the GWR-MAC based approach is more energy efficient if the number of events is below 60 per hour. The results for different WURs shows that WUR's Rx mode power consumption has remarkable effect to the total energy efficiency since it is continuously listening the channel to detect wake-up signals. The WUR1 based network features lowest sensitivity for wake-up receiver. However, it is the most energy efficient when $\varepsilon < 12$, even though it requires highest power used by the transmitter. WUR3 case has the highest Rx mode power consumption, which leads to drastically lower energy efficiency if events occur rarely. This observation highlights the importance of constant mode power consumption (Rx mode) minimization for wake-up receivers. All the studied WUR cases lead to higher energy efficiency than DCR approach when the number of events is less than 12 per hour. When the number of events increases above 12 per hour, the energy consumption of data communication starts to dominate in the network overall energy consumption and the difference between WUR's energy efficiency is not visible anymore. Furthermore, it can be observed that if sensitivity of WUR can be improved by decreasing the data rate that will lead to energy efficient solution for very rare event cases. When the event frequency increases, the longer transmission and reception duration will cause lower energy efficiency in comparison to higher data rate WUR solutions. From the results of Figure 12 can be concluded that the WUR based approach is drastically more energy efficient than duty-cycle based approach when the event frequency is low.

Table 1. Parameters used for different radios in the energy efficiency comparison.

Radio	Sensitivity	Tx power	Data rate	Power consumption	
				Tx mode [72]	Rx mode
WUR1	-70 dBm	0 dBm	200 kbps	52.2 mW	5 µW
WUR2	-80 dBm	-10 dBm	200 kbps	33.9 mW	10 µW
WUR3	-95 dBm	-25 dBm	200 kbps	25.5 mW	50 µW
WUR4	-95 dBm	-25 dBm	300 bps	25.5 mW	5 µW
DCR	-95 dBm	-25 dBm	971 kbps	25.5 mW	56 mW [72]

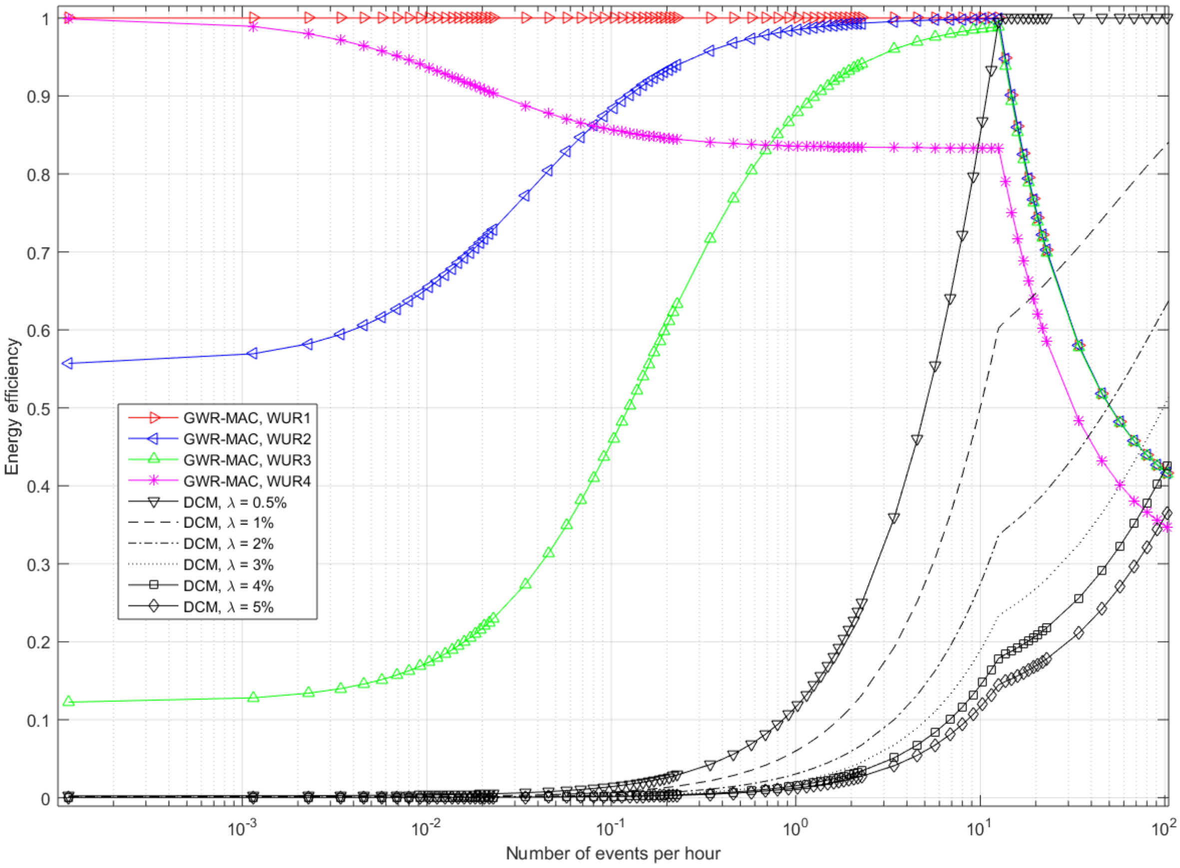


Figure 12. Energy efficiency comparison for WUR based and DCM based hierarchical network.

In [77] has been proposed a dual-radio solution combining an ultra wideband (UWB) communication and wake-up receiver (UWB-WUR) for WBANs. A dual-radio approach for asymmetric communication links is based on wake-up receiver usage so that sensor nodes will include IR-UWB in transmit-only mode for data transmissions (uplink), and WUR is used for control message receptions from the hub node (downlink). Solution enables that idle listening will not occur at the sensor nodes which presumably can improve energy efficiency especially when the downlink traffic does not occur often. Therefore, the solution introduced in [77], takes advantage of sink-initiated wake-up procedure which was introduced in Figure 6. Energy consumption and energy efficiency of the UWB-WUR solution has been studied by the authors in [77]. Results will be shortly introduced here and more details of the energy consumption calculation can be found from [77]. Figure 13 shows the energy consumption comparison for UWB-WUR approach and the DCR approach based on duty cycling in the WBAN case. Results are given for different duty cycle values between 0.3% and 2.5% and error-free transmissions has been assumed for both approaches. It can be observed that UWB-WUR approach consumes less energy until the number of wake-ups per year increases to approximately to three per minute. After that point the DCR network with the lowest duty cycle consumes less energy.

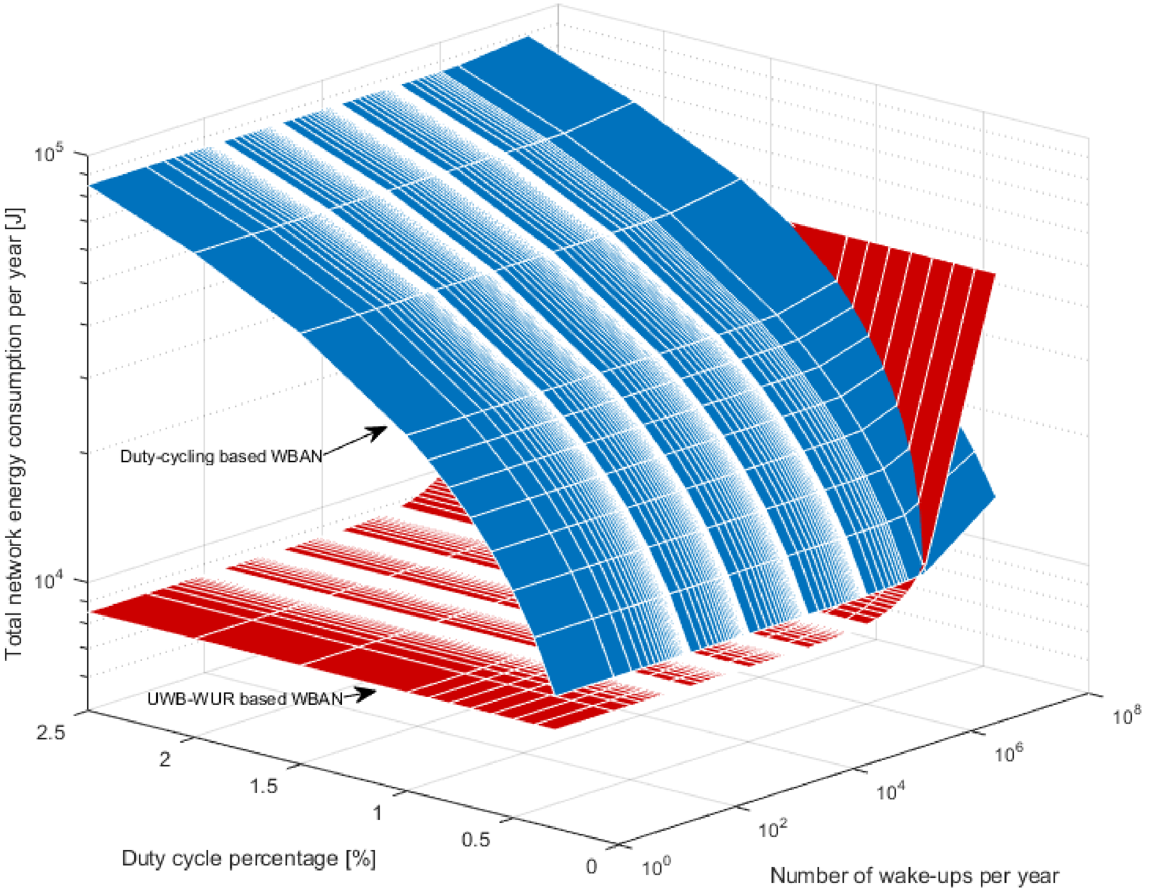


Figure 13. Energy consumption comparison of UWB-WUR based approach and duty-cycling based approach for WBAN.

Figure 14 shows energy consumption comparison for a link where TX node sends a WUS to a receiver node (WUR). For the WUR, different parameter settings are used to find out how the energy savings that can be achieved by performing tradeoff between WUR data rate and sensitivity. Three different WUR settings are evaluated in the results of Figure 14: 1) WUR with data rate R = 1 kbps and required transmitter's power consumption P_{Tx} = 12 mW; 2) WUR with R = 50 kbps and P_{Tx} = 24 mW; 3) WUR with data rate R = 200 kbps and P_{Tx} = 45 mW. The rationale behind these parameter values is that low data rate wake-up receiver can be designed to be more sensitive. Therefore, for more sensitive WUR solution, a lower transmit power is required to achieve successful wake-up signal detection. For example, in [72] it is shown that transmitter's power consumption is halved when output power is reduced by 25 dBm. In the abovementioned WUR settings, the sensitivities varies so that the setting 1) corresponds to most sensitive receiver and setting 3) is the least sensitive. The results of Figure 14 are calculated for a single link taking into account TX and RX energy consumption. From the results of Figure 14 it can be observed that when the number of wake-ups is more than ten per hour, the energy consumption of wake-up link with lowest data rate performance starts to increase. The rationale is that, since the data rate is low, the wake-up signal transmission and reception take more time and their contribution to energy consumption starts to be remarkable, even the required transmission power is lowest for that WUR parameter setting. It can be observed that when the number of wake-ups is high, the highest data rate wake-up link consumes least energy, even the required transmit power is highest for that WUR setting, because it has the lowest sensitivity. Therefore, the results of Figure 14 illustrate that it is important to take into account the WUR design factor in order to minimize the energy consumption that depends on how frequently the wake-ups are needed in the particular network. Further details of the model that can be used to calculate the results of Figure 14 can be found from [77].

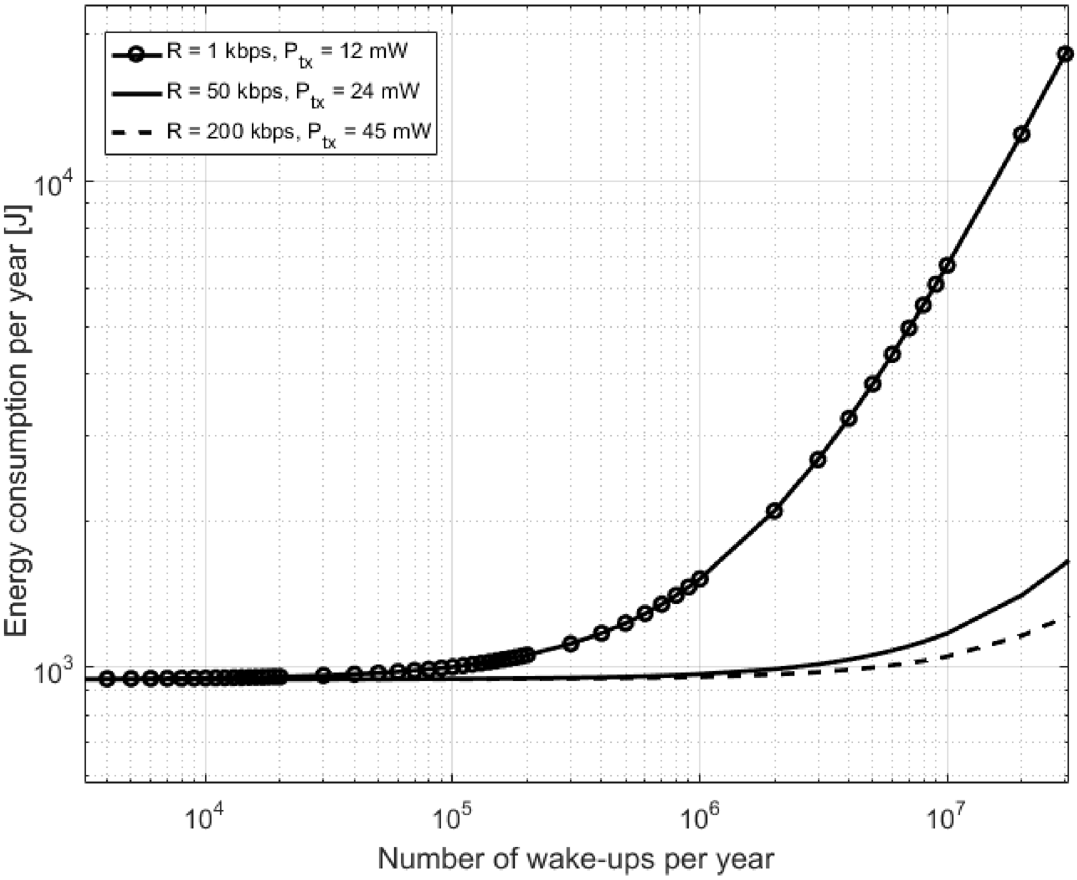


Figure 14. Energy consumption comparison for a Tx-Rx link when using different parameter setting for WUR.

5. Summary

Hierarchical architecture for wireless sensor network and wireless body area network which can be used to provide data to Internet of Things was discussed in this section. Introduced architecture is designed to enable the deployment of multiple different technologies in the same network. Therefore it can be used for different type of monitoring scenarios, e.g. sensors networks for monitoring of environment and building structures, as well as for many other types of WSN and WBAN applications. Functionalities for different layers are designed so that the network can fulfill its' requirements with low-power operation. Energy efficiency is achieved by utilizing a wake-up signaling which can be used to activate the layers only when required. A generic wake-up radio based MAC protocol designed for hierarchical architecture was introduced. GWR-MAC protocol includes a bi-directional wake-up procedure and data transmission period which channel access method can be selected depending on the application characteristics. Different wake-up receiver architectures were introduced and future research directions were outlined. Architecture's energy efficiency performance results were shown for a typical area surveillance scenario and WBAN case. Results show that WUR based networks has remarkable potential to improve energy efficiency, in comparison to traditional duty-cycle operation, in the case of low event rate applications. Comparison for different WUR parameter settings is also made in this section to illustrate the WUR's data rate and sensitivity tradeoff affect to energy consumption. The DCR approach was found to be more energy efficient only when sufficiently low duty cycle is combined with a high number of events. However, in many practical solutions, the duty cycle is fixed and must be large enough to handle the worst-case traffic. Duty cycle should be changed dynamically when the event frequency changes in order to save energy. Furthermore, the very low duty-cycle operation would require very strict synchronization in order to enable that transmissions would be done exactly at correct times according to the duty cycle. Strict synchronization maintenance will cause additional energy consumption. The wake-up radio research area is still quite unexplored even it has gained researchers attention in recent years. Therefore the purpose of the hierarchical architecture with GWR-MAC protocol is to enable more efficient usage of WURs in WSNs and WBANs, and to foster future research and development.

References

[1] Raghunathan V, Schurgers C, Park S & Srivastava M (2002) Energy-aware wireless microsensor networks. IEEE Signal Processing Magazine 19(2): 40–50.

[2] Ares BZ, Park PG, Fischione C, Speranzon A & Johansson KH (2007) On power control for wireless sensor networks: System model, middleware component and experimental evaluation. In: Proc. European Control Conference, pp. 1–8.

[3] Hohlt B, Doherty L & Brewer E (2004) Flexible power scheduling for sensor networks. In: Proc. Third International Symposium on Information Processing in Sensor Networks. IPSN 2004, pp. 205–214.

[4] Demirkol I, Ersoy C & Alagoz F (2006) MAC protocols for wireless sensor networks: a survey. IEEE Communications Magazine 44(4): 115–121.

[5] Anastasi G, Conti M, Francesco MD & Passarella A (2009) Energy conservation in wireless sensor networks: A survey. Ad Hoc Networks 7(3): 537 – 568.

[6] Action Nechibvute, Albert Chawanda, and Pearson Luhanga, “Piezoelectric Energy Harvesting Devices: An Alternative Energy Source for Wireless Sensors,” Smart Materials Research, vol. 2012, Article ID 853481, 13 pages, 2012. doi:10.1155/2012/853481

[7] Karvonen H., "Energy efficiency improvements for wireless sensor networks by using cross-layer analysis," Ph.D. thesis, University of Oulu, Finland, March 2015.

[8] D. Evans, “The Internet of Things: How the next evolution of the internet is changing everything,” Cisco Internet Business Solutions Group (IBSG) white paper, April 2011

[9] Markets and Markets “Wireless Devices Market for Medical by Technology (BT/BLE, Wi-Fi, ZigBee, ANT+), Component (Sensors, ICs, Processors), Application (Monitoring, Medical Therapeutics, Diagnosis, Fitness & Wellness), and Geography – Global Forecast to 2020", Market report, December 2014.

[10]Yang J, Gao Y & Zhang Z (2011) Cluster-based routing protocols in wireless sensor networks: A survey. In: Proc. International Conference on Computer Science and Network Technology, volume 3 of ICCSNT ’11, pp. 1659–1663.

[11]ZigBee Alliance (2014). ZigBee Alliance webpage. URI: http://www.zigbee.org.

[12]Z-Wave Alliance (2014). Z-Wave alliance webpage. URI: http://www.z-wavealliance.org.

[13]Kumar D, Aserib TC & Patelc RB (2009) EEHC: Energy efficient heterogeneous clustered scheme for wireless sensor networks. Journal of Computer Communications 32.

[14]Wu M & Collier M (2011) Extending the lifetime of heterogeneous sensor networks using a two-level topology. In: Proc. IEEE International Conference on Computer and Information Technology, pp. 499–504.

[15]Slimane JB, Song YQ, Koubâa A & Frikha M (2009) A three-tiered architecture for large scale wireless hospital sensor networks. In: Proc. The International Workshop on Mobilizing Health Information to Support Healthcare-related Knowledge Work, MobiHealthInf 2009, pp. 1–12.

[16]Zhang M, Song J & Zhang Y (2005) Three-tiered sensor networks architecture for traffic information monitoring and processing. In: Proc. Intelligent Robots and Systems, IROS 2005, pp. 2291–2296.

[17]Kulkarni P, Ganesan D, Shenoy P & Lu Q (2005) SensEye: A multitier camera sensor network. In: Proc. ACM International Conference on Multimedia, MM ’05, pp. 229–238.

[18]Lopes CER, Linhares FD, Santos MM & Ruiz LB (2007) A multi-tier, multimodal wireless sensor network for environmental monitoring. Springer Link Lecture Notes in Computer Science 4611: 589–598.

[19]Zatout Y, Campo E & Llibre JF (2009) WSN-HM: Energy-efficient wireless sensor network for home monitoring. In: Proc. International Conference on Intelligent Sensors, Sensor Networks and Information Processing, ISSNIP ’09, pp. 367–372.

[20]Stefanov A & Stojanovic M (2010) Hierarchical underwater acoustic sensor networks. In: Proc. ACM International Workshop on UnderWater Networks, WUWNet’10, pp. 1–4.

[21]Crossbow (2014). TelosB datasheet. URI: www.willow.co.uk/TelosB_Datasheet.pdf.

[22]FriendlyARM (2014). FriendlyARM Mini6410 specification. URI:http://www.friendlyarm.net/products/mini6410.

[23]Kuorilehto M, Kohvakka M, Suhonen J, Hämäläinen P, Hännikäinen M & Hämäläinen T (2007) Ultra-Low Energy Wireless Sensor Networks in Practice: Theory, Realization and Deployment. John Wiley & Sons.

[24]IEEE (2011) IEEE Standard for Local and metropolitan area networks - Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs). Standard, The Institute of Electrical and Electronics Engineers, Inc. IEEE Std. 802.15.4 - 2011, Revision of IEEE Std 802.15.4-2006.

[25]IEEE Standard for Low-Rate Wireless Networks," in *IEEE Std. 802.15.4-2015 (Revision of IEEE Std 802.15.4-2011),* pp.1-709, April 22 2016.

[26]Gu L & Stankovic JA (2005) Radio-triggered wake-up for wireless sensor networks. Springer Journal on Real-Time Systems 29(2): 157–182.

[27]Van der Doorn B, Kavelaars W & Langendoen K (2009) A prototype low-cost wakeup radio for the 868 MHz band. International Journal of Sensor Networks 5(1): 22–32.

[28]Ansari J, Pankin D & Mähönen P (2009) Radio-triggered wake-ups with addressing capabilities for extremely low power sensor network applications. International Journal of Wireless Information Networks 16(1): 118–130.

[29]Petäjäjärvi J, Karvonen H, Mikhaylov K, Pärssinen A, Hämäläinen M & Iinatti J (2015) WBAN energy efficiency and dependability improvement utilizing wake-up receiver. IEICE Transactions on Communications - Special Issue on Innovation of Medical Information and Communication Technology for Dependable Society, vol. E98-B, no. 04, pp. 535-542, Apr. 2015.

[30]Marinkovic SJ & Popovici EM (2011) Nano-power wireless wake-up receiver with serial peripheral interface. IEEE Journal on Selected Areas in Communications 29(8): 1641–1647.

[31]Salazar C, Kaiser A, Cathelin A, Rabaey J (2015) A -97dBm-Sensitivity Interferer-Resilient 2.4GHz Wake-Up Receiver Using Dual-IF Multi-N-Path Architecture in 65nm CMOS. Proc. ISSCC, pp. 396 – 398.

[32]Tomabechi S, Komuro A, Konno T, Nakase H and Tsubouchi K (2001) Design and Implementation of Spread Spectrum Wireless Switch with Low Power Consumption. IEICE Trans. Fundamentals, vol. E84-A, no. 4, pp. 971 – 973.

[33]Pletcher N, Gambini S and Rabaey J (2007) A 65 µW, 1.9 GHz RF to digital baseband wakeup receiver for wireless sensor nodes. Proc. CICC, pp. 539 – 542. DOI: 10.1109/CICC.2007.4405789.

[34]Pletcher N, Gambini S and Rabaey J (2009) A 52 µW wake-up receiver with -72 dBm sensitivity using an uncertain-IF architecture. IEEE Journal of solid-state circuits, vol. 44, no. 1, pp. 269 – 280. DOI: 10.1109/JSSC.2008.2007438.

[35]Bryant C, and Sjoland C (2014) A 2.45GHz, 50uW wake-up receiver front-end with −88dBm sensitivity and 250kbps data rate. Proc. European Solid State Circuits Conference (ESSCIRC), pp. 235 – 238. DOI: 10.1109/ESSCIRC.2014.6942065.

[36]Xiongchuan H, Rampu S, Xiaoyan W, Dolmans G and de Groot H (2010) A 2.4 GHz/915 MHz 51 µW wake-up receiver with offset and noise suppression. Proc. ISSCC, pp. 222 – 223. DOI: 10.1109/ISSCC.2010.5433958.

[37]Joonsung B and Hoi-Jun Y (2012) A 45µW injection-locked FSK Wake-Up receiver for crystal-less wireless body-area-network. Proc. A-SSCC, pp. 333 – 336, 2012. DOI: 10.1109/IPEC.2012.6522693.

[38]Pandey J, Shi J and Otis B (2011) A 120 µW MICS/ISM-band FSK receiver with a 44 µW low-power mode based on injection-locking and 9x frequency multiplication. Proc. ISSCC, pp. 460 – 462. DOI: 10.1109/ISSCC.2011.5746397.

[39]Hyunwoo C, Joonsung B and Hoi-Jun Y (2013) A 37.5 µW body channel communication wake-up receiver with injection-locking ring oscillator for wireless body area network. IEEE Trans. on circuits and systems I: Regular papers, vol. 60, no. 5, pp. 1200 – 1208. DOI: 10.1109/TCSI.2013.2249173.

[40]Choi J, Lee IY, Lee K, Yun SO, Kim J, Ko J, Yoon G, Lee SG (2014) A 5.8-GHz DSRC transceiver with a 10-µA interference-aware wake-up receiver for the Chinese ETCS. IEEE Trans. MTT, issue 99, pp. 1 – 15. DOI: 10.1109/TMTT.2014.2362118

[41]Moazzeni S, Cowan GER and Sawan M (2012) A 28 µW sub-sampling based wake-up receiver with -70 dBm sensitivity for 915 MHz ISM band applications. Proc. ISCAS, pp. 2797 – 2800. DOI: 10.1109/ISCAS.2012.6271891.

[42]Moazzeni S, Sawan M and Cowan GER (2014) An ultra-low-power energy-efficient dual-mode wake-up receiver. IEEE Trans. on circuits and systems I: Regular papers, issue 99, pp. 1 – 10. DOI: 10.1109/TCSI.2014.2360336.

[43]Kuang-Wei C, Xin L and Minkyu J (2012) A 2.4/5.8 GHz 10 µW wake-up receiver with −65/−50 dBm sensitivity using direct active RF detection. Proc. A-SSCC, pp. 337 – 340. DOI: 10.1109/IPEC.2012.6522694.

[44]Wada T, Ikebe M, Sano E (2013) 60-GHz, 9-µW wake-up receiver for short-range wireless communications. Proc. ESSCIRC, pp. 383 – 386. DOI: 10.1109/ESSCIRC.2013.6649153.

[45]Durante MS and Mahlknecht S (2009) An ultra low power wakeup receiver for wireless sensor nodes. Proc. STA, pp. 167 – 170. DOI: 10.1109/SENSORCOMM.2009.34.

[46]Hambeck C, Mahlknecht S and Herndl T (2011) A 2.4µW Wake-up Receiver for wireless sensor nodes with −71dBm sensitivity. Proc. ISCAS, pp. 534 – 537. DOI: 10.1109/ISCAS.2011.5937620.

[47]Nilsson E and Svensson C (2013) Ultra low power wake-up radio using envelope detector and transmission line voltage transformer. IEEE Journal on Emerging and Selected Topics in Circuits and Systems, vol. 3, issue 1, pp. 5 – 12. DOI: 10.1109/JETCAS.2013.2242777.

[48]Roberts NE and Wentzloff DD (2012) A 98nW wake-up radio for wireless body area networks. Proc. RFIC, pp. 373 – 376. DOI: 10.1109/RFIC.2012.6242302.

[49]Seunghyun O, Roberts NE and Wentzloff DD (2013) A 116 nW multi-band wake-up receiver with 31-bit correlator and interference rejection. Proc. CICC, pp. 1 – 4. DOI: 10.1109/CICC.2013.6658500.

[50]Armas ET, Ramos-Valido D, Khemchandani SL and del Pino J (2015) A 40.9 µW high sensitivity wake-up radio for wireless sensor networks using uncertain-IF architecture. Proc. DCIS, pp. 1–6. doi: 10.1109/DCIS.2015.7388585

[51]Chen SE and Cheng KW (2016) A 433 MHz 54 µW OOK/FSK/PSK compatible wake-up receiver with 11 µW low-power mode based on injection-locked oscillator. Proc. ESSCIRC, pp. 137-140. doi: 10.1109/ESSCIRC.2016.7598261

[52]Thanh PN, Tuan KN and Dong XM (2016) A 100-µW wake-up receiver for UHF transceiver. Proc. ICICDT, pp. 1-4. doi: 10.1109/ICICDT.2016.7542049

[53]Nikoofard A and Mandal S (2016) An 11.5 nW broadband wake-up RF receiver with −60 dBm sensitivity at 50 MHz. Proc. ISCAS, pp. 2787-2790. doi: 10.1109/ISCAS.2016.7539171

[54]Jiang H et al. (2017) A 4.5 nW wake-up radio with -69 dBm sensitivity. Proc. ISSCC, pp. 416-417. doi: 10.1109/ISSCC.2017.7870438

[55]Petäjäjärvi J, Mikhaylov K, Karvonen H, Vuohtoniemi R, Iinatti J (2016) Superregenerative wake-up receiver with 20 µW power consumption for human body communications. Proc. NTMS, pp.1.5.

[56]Cheng KW, Lin JS and Chen SE (2016) Reference-less ultra-low-power wake-up receiver with noise suppression. Proc. URSI AP-RASC, pp. 994-997. doi: 10.1109/URSIAP-RASC.2016.7601309

[57]Magno M, Jelicic V, Srbinovski B, Bilas V, Popovici E and Benini L (2016) Design, Implementation, and Performance Evaluation of a Flexible Low-Latency Nanowatt Wake-Up Radio Receiver. IEEE Transactions on Industrial Informatics, vol. 12, no. 2, pp. 633-644. doi: 10.1109/TII.2016.2524982

[58]Karvonen H., Suhonen J., Petäjäjärvi J., Hämäläinen M., Hännikäinen M., and Pouttu A., ”Hierarchical Architecture for Multi-Technology Wireless Sensor Networks for Critical Infrastructure Protection” Springer Wireless Personal Communications Special Issue on Intelligent Infrastructures, vol. 76, no. 2, pp. 209-229, 2014. DOI: http://dx.doi.org/10.1007/s11277-014-1686-2.

[59]Karvonen H., Petäjäjärvi J., Iinatti J., Hämäläinen M., Carlos Pomalaza-Ráez “A Generic Wake-up Radio based MAC Protocol for Energy Efficient Short Range Communication,” IEEE PIMRC Workshop: The Convergence of Wireless Technologies for Personalized Healthcare, Sep 2-5, 2014, Washington DC, USA.

[60]Karvonen H., Petäjäjärvi J., Iinatti J., Hämäläinen M., "Energy Efficient IR-UWB WBAN using a Generic Wake-up Radio based MAC Protocol", the Third Ultra Wideband for Body Area Networking Workshop (UWBAN-2014), Co-located with the 9th International Conference on Body Area Networks (BodyNets-2014), Sep 29 - Oct 1, 2014, London, UK.

[61]J. Oller, I. Demirkol, J. Casademont, J. Paradells, G. U. Gamm and L. Reindl, "Has Time Come to Switch From Duty-Cycled MAC Protocols to Wake-Up Radio for Wireless Sensor Networks?," in *IEEE/ACM Transactions on Networking*, vol. 24, no. 2, pp. 674-687, April 2016.

[62]F. Z. Djiroun and D. Djenouri, "MAC Protocols With Wake-Up Radio for Wireless Sensor Networks: A Review," in *IEEE Communications Surveys & Tutorials*, vol. 19, no. 1, pp. 587-618, Firstquarter 2017.

[63]Petäjäjärvi J, Mikhaylov K, Pettissalo M, Janhunen J and Iinatti J (2017) Performance of a low-power wide-area network based on LoRa technology: Doppler robustness, scalability, and coverage. SAGE International Journal of Distributed Sensor Networks, 13(3), 1–16. doi:10.1177/1550147717699412

[64]Petäjäjärvi J, Mikhaylov K, Yasmin R, Hämäläinen M and Iinatti J. (2017) Evaluation of LoRa LPWAN technology for indoor remote health and wellbeing monitoring. Springer International Journal of Wireless Information Networks, 24(2), 1–13. doi:10.1007/s10776-017-0341-8

[65]Petäjäjärvi J, Mikhaylov K, Vuohtoniemi R, Karvonen H and Iinatti J. (2016) On the human body communications: Wake-up receiver design and channel characterization. EURASIP Journal on Wireless Communications and Networking, 2016(179), 1–17. doi:10.1186/s13638-016-0674-5

[66]Semtech, SX1272 datasheet: SX1272/73 - 860 MHz to 1020 MHz Low Power Long Range transceiver.

[67]LoRa Alliance, https://www.lora-alliance.org/

[68]Sigfox company webpage, https://www.sigfox.com/

[69]Axsem, AX5043 datasheet: Advanced high performance ASK and FSK narrow-band transceiver for 70-1050 MHz range.

[70]Gartner, “Gartner Says the Internet of Things Installed Base Will Grow to 26 Billion Units By 2020”, Press release, Jan. 2nd, 2014.

[71]ABI Research, “More Than 30 Billion Devices Will Wirelessly Connect to the Internet of Everything in 2020”, Press release, May, 2013.

[72]Texas Instruments, CC2420 datasheet: 2.4 GHz IEEE 802.15.4/Zigbee-ready RF Transceiver.

[73]Buratti C & Verdone R (2008) A hybrid hierarchical architecture: From a wireless sensor network to the fixed infrastructure. In: Proc. Wireless Conference, EW 2008.

[74]Khan Z, Catalot D & Thiriet J (2009) Hierarchical wireless network architecture for distributed applications. In: Proc. Wireless and Mobile Communications, ICWMC ’09, pp. 70–75.

[75]IEEE Std. 802.15.6 - 2012, “IEEE Standard for Local and metropolitan area networks - Part 15.6: Wireless Body Area Networks,” The Institute of Electrical and Electronics Engineers, Inc, Standard, 2012.

[76]ETSI TC SmartBAN, “Smart Body Area Networks (SmartBAN); Low Complexity Medium Access Control (MAC)”, TS DTS/SmartBAN(14)006001r5, Dec 2014.

[77]H. Karvonen, J. Petäjäjärvi, V. Niemela, M. Hämäläinen, J. Iinatti and R. Kohno, "Energy efficient UWB-WUR dual-radio solution for WBANs," *11th International Symposium on Medical Information and Communication Technology (ISMICT)*, Lisbon, 2017, pp. 64-68.