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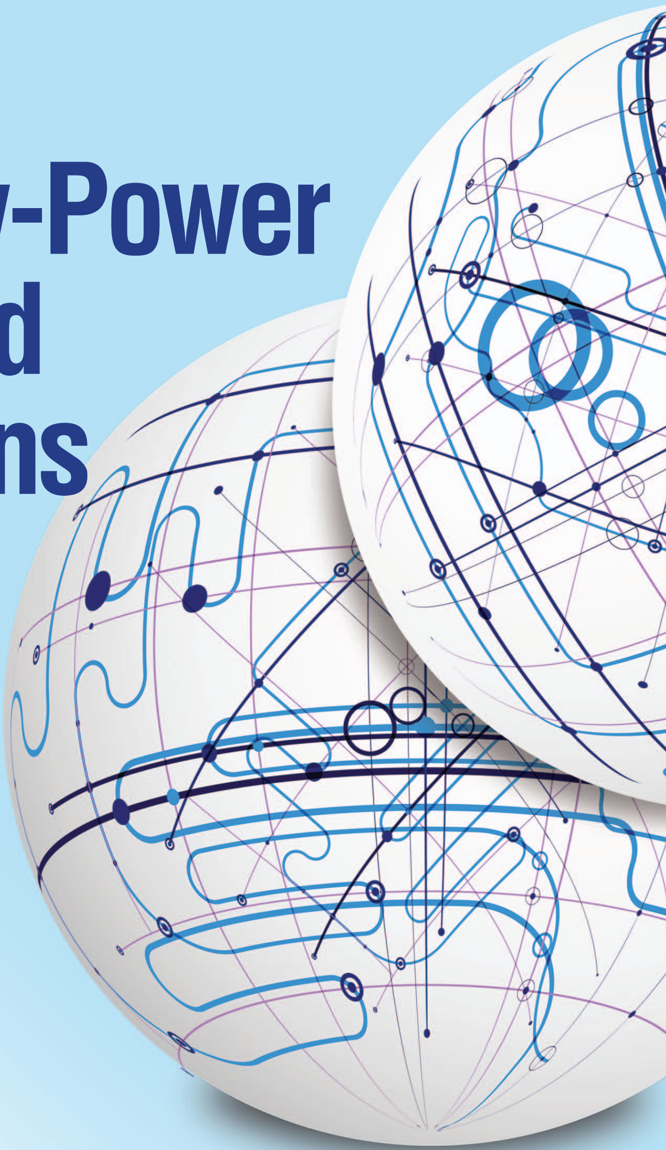
A Survey of Low-Power Transceivers and Their Applications

Johannes Blanckenstein, Jirka Klaue, and Holger Karl



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Abstract

In wireless sensor networks (WSNs) energy efficiency and communication reliability are often conflicting requirements. Additionally, some application areas such as industrial automation or infrastructure monitoring impose strict latency bounds. Low-power receivers ($<1\,\mathrm{mW}$ power consumption) together with adapted MAC protocols have the potential to meet these diverse requirements. We present an overview of state-of-the-art low-power receivers and relate their characteristics to requirements for different application areas. We compare low-power receivers to duty-cycled transceivers and present applications depending on them. For this, we use power consumption, sensitivity, and data rate as key performance figures for low-power receivers. Based on the characteristics of the applications we derive guidelines for using low-power receivers instead of duty-cycled transceivers.

I. Introduction

Industrial process automation and infrastructure monitoring require dependable wireless sensor networks. These application areas demand not only energy efficiency but also reliable and timely data communication. Several Medium Access Control (MAC) protocols are developed to specifically fulfill these demands. A thorough review about such mission-critical protocols and their limitations is given in [1].

A common way to reduce the energy consumption is to turn off the transceiver periodically. Such a duty cycling can lead to increased delay and a less reliable communication, which contradicts the requirements dictated by mission-critical applications. To overcome these limitations there are several efforts to develop low-power receivers together with appropriate protocols. The idea is to have receivers with such a low power consumption that it becomes feasible to keep them turned on all the time. Depending on the target application such a receiver can fulfill a variety of functions; among others, it can be used as a "classical" receiver or as a wake-up receiver (WUR). As the name indicates, a WUR is used to wake up

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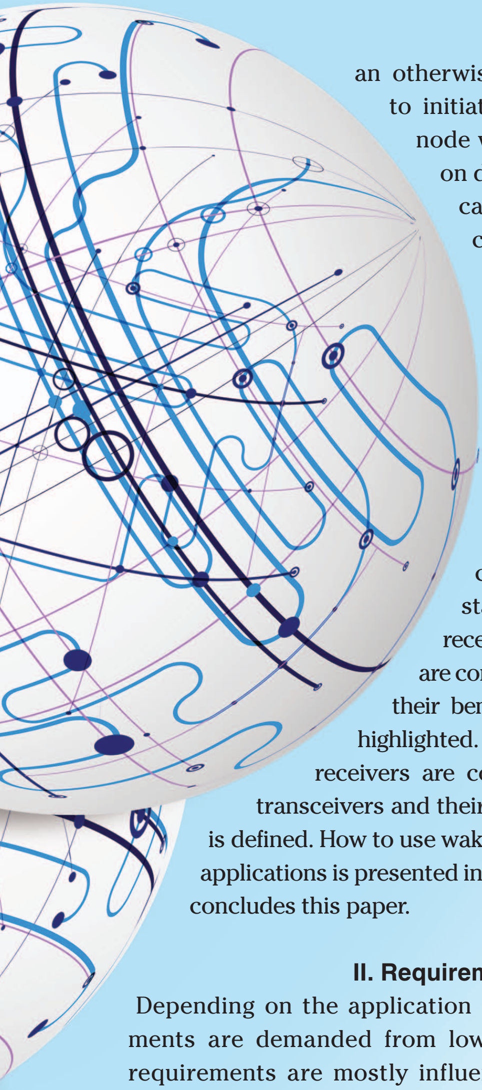

an otherwise powered-down node to initiate appropriate tasks. A node will thus be woken only on demand and not periodically, which can decrease communication delay and can enable more time-critical protocols.

The paper is structured as follows: Section II gives an overview about different requirements for low-power receivers, which are depending on the application area. In Section III, state-of-the-art low-power receivers are presented. They are compared to each other and their benefits and limitations are highlighted. In Section IV, wake-up receivers are compared to duty-cycled transceivers and their best field of application is defined. How to use wake-up receivers in specific applications is presented in Section V, and Section VI concludes this paper.

II. Requirements

Depending on the application area, different requirements are demanded from low-power receivers. The requirements are mostly influenced by the communication range, the channel characteristics, the message flow, and the available energy. All these requirements have a direct impact on the key performance figures for low-power receivers. Communication range and channel characteristics directly influence the necessary receiver *sensitivity*, and the message flow influences the necessary *data rate*. To improve either one of them, more energy has to be spent. Hence, the available energy is the limiting factor for all receiver designs; typically a very low *power consumption* is essential.

The requirements for four representative scenarios will be inspected: the aeronautical case, the wireless body area network (WBAN), smart metering, and industrial applications.

A. Aeronautical Use Case

One challenge for wireless sensor networks in the aeronautical case is the high density of wireless sensor nodes [2]. The quantity of sensor nodes within an aircraft can easily reach 1000 or more. Figure 1 shows possible locations for sensor nodes within an aircraft, together with corresponding applications.

It is challenging to consolidate all these applications and their sensor nodes within one common network. With that many nodes, a typical CSMA protocol ceases to be feasible and a more sophisticated protocol has to be used. In [2] a possible solution is presented; it uses a TDMA protocol with special reliability features. However, this protocol is developed for periodic applications and, therefore, in its present implementation not very well suited for event-triggered applications. For such cases, currently, duty-cycled transceivers are used to wake up the nodes at pre-determined points in time and then to start the protocol. For many applications, such a wake-up is only necessary once a day and therefore a very long duty cycle is used and a very low energy consumption is possible. Due to a very low duty cycle the introduced latency of the system is very high (> 10 s) while the responsiveness of the system has to be in the order of 200 ms, such a low duty cycle is not feasible.

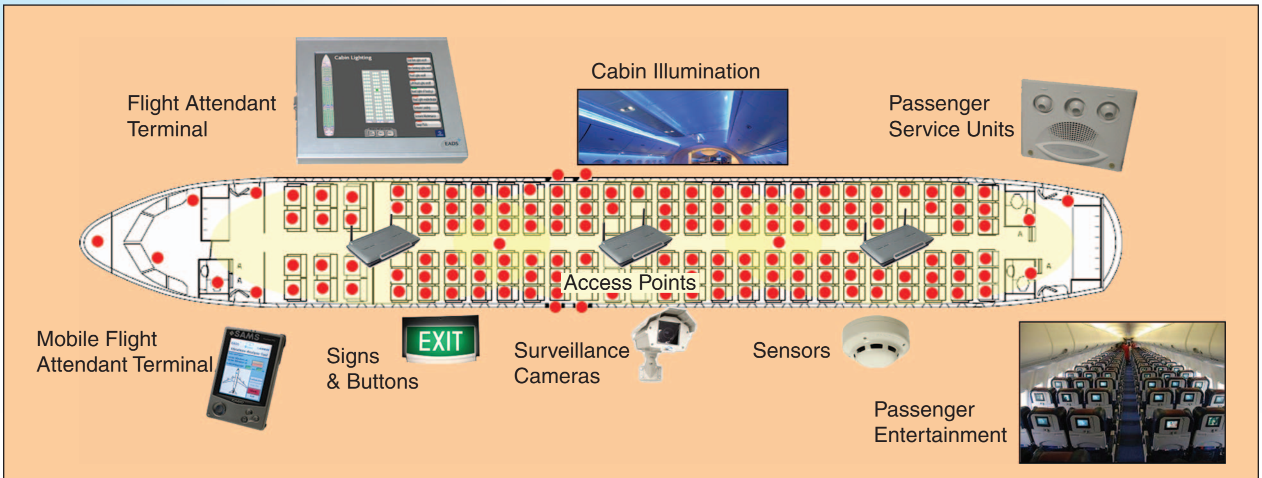

Figure 1. Placement of sensor nodes within an aircraft, together with their corresponding applications.

To make the system autonomous, the power supply for the nodes is provided by an energy harvester [3] in combination with a power management board [4]. Such an energy harvester can provide up to 23J per flight. With two flights a day and an efficiency of 54% of the power management board [4], only 288 μW are available on average. When the nodes are woken up, they have to start a measurement and transmit these values to a common sink. Measuring can consume a lot of energy, therefore, the available average power is further reduced to around $100\,\mu$W. Additionally, channel measurements [2, 5–8] suggest a minimum required sensitivity of -80 dBm to support a communication range of 10 m.

Hence, the requirements for a low-power receiver in the aeronautical case are an average power consumption below $100\,\mu$W, a sensitivity better than -80 dBm, and a delay below 200 ms.

B. Wireless Body Area Network (WBAN)

A WBAN consists of devices that are all located in close vicinity of the human body. Typical applications for WBANs are in health care or in the multimedia sector. Latré et al. [9] give an overview of WBANs in general and the requirements resulting from their applications. As stated there, a WBAN will consist of around 20–50 sensor nodes, which are used to monitor bodily functions like heartbeat or body temperature, as well as to connect multimedia devices like microphones or head-mounted displays. Those devices can have very different needs for data rates in the region of only a few kb/s; to several hundreds of kb/s; in sum the demands can reach a few Mb/s.

The advantage of low-power receivers in WBANs can be twofold: either a low-power receiver is used for low data rate applications and will replace a "normal" receiver, or it is used as a wake-up receiver to initiate a possible high data rate communication. Either way, the power consumption needs to be very limited. For example, some health care devices are implemented inside the human body, like insulin reservoirs or pacemakers. It is clear that with such devices a regular battery change is no option. Additionally, because the devices are implemented inside the body, there is a strict size constraint for the nodes, e.g., it is not possible to use large batteries. Therefore, the power consumption has to be as low as possible.

The short communication distance of about 1 m that the devices have to cover can help to keep the power consumption low. In [10] a large measurement campaign was conducted to model the behavior of WBAN channels. A stochastic channel model was derived from it where each link is considered separately. The highest path loss was found around 50 dB, with all radio links on the front side of the body. With a path loss in the region of 40–50 dB the sensitivity requirements for low-power receivers are lessened; a sensitivity of -40 dBm would be enough to receive a signal transmitted with 0 dBm. Without the need to have a high sensitivity even more energy-efficient designs can be implemented.

C. Smart Metering

Another field of application for low-power receivers is in smart metering and home automation. In both cases, radio communication takes place inside a building and the requirements for both are similar. The maximum communication distance is typically about 15 m, but it has to be differentiated if the communication takes place on the same floor or across multiple floors. At a distance of 15 m for both cases the path loss is in the same order of magnitude but at shorter distances the multiple-floor scenario has a larger path loss than the same-floor scenario. In [11] a channel is characterized for both cases. A path loss of around 100 dB was measured at a distance of 15 m. At 10 m a path loss of 100 dB was measured for the multiple-floor scenario and a path loss of 80 dB for the same-floor scenario. A similar behavior is described in [12] for the same-floor scenario.

Therefore, a low-power receiver for these applications has to have a high sensitivity. With a maximum allowed effective radiated power (ERP) of 25 dBm in the European 868 MHz band, a receiver should have at least a sensitivity of -75 dBm to be able to receive packets at a distance of 15 m. But commercially available transceivers normally have an output power around 0 dBm. To generate an output power of 25 dBm typically a discrete power amplifier has to be used. Assuming a high efficiency of 50%, additional 28 dBm($= 631$ mW) has to be spent to reach these high output power levels. Since a very high output power is rarely possible for low-power devices, a higher sensitivity should be used.

The required data rates for home automation/smart metering applications are moderate but the acceptable delay for a communication might be more demanding. If human interaction is involved, a latency larger than 0.5 s might not be tolerable. The allowed maximum energy consumption for the smart metering/home automation area depends heavily on the specific application. For some devices, like heat or electric meters, the battery has to provide enough energy for around 10 years, and because of that, large and expensive batteries have to be provided. Reducing the energy consumption of the communication system can reduce the overall costs immensely.

D. Industrial Applications

Control loops have the strictest requirements in the industrial applications field. Not only are they loss-intolerant but also delay-intolerant. For control loops, a maximum allowed delay in the order of 25 ms is common.

The wireless channel for industrial applications is similar to the one for the smart metering/home automation applications. The big difference is the target communication distance of 100 m. In [13] a characterization for the industrial indoor channel is done. There, three types of topographies are distinguished: line-of-sight (LOS), obstructed line-of-sight (OBS) with light surrounding clutter, and obstructed line-of-sight with heavy surrounding clutter. For these three topologies channel measurements were done in three different bands, at 900 MHz, at 2.4 GHz, and at 5.2 GHz. From these measurements 9 different channel characteristics were derived, three for each frequency band and three for each topology, respectively.

In [13], it was argued that the log-distance path loss model is applicable for each characteristic and the corresponding path-loss exponents n and the path loss values $PL(d_0)$ at a reference distance $d_0 = 15\,\text{m}$ were derived. When comparing the path loss at a distance of 100 m for the three topologies at 900 MHz, it was verified that the path loss behaved as assumed. The smallest path loss was observed in the LOS case with 98 dB, followed by the OBS with light surrounding clutter with 100 dB. The biggest path loss was observed in the case of OBS with heavy surrounding clutter with 110 dB. For the 2.4 GHz band the behavior was similar with 100 dB, 101 dB, and 112 dB, respectively. Assuming again a maximum transmit power of 25 dBm, a minimum sensitivity of −85 dBm is necessary.

In industrial applications bigger devices and therefore bigger batteries might be possible, but the total cost of the system has to be kept as small as possible. A receiver that fulfills the sensitivity and delay requirements while fulfilling the strict energy consumption demands can help to lower the overall system and operation cost.

E. Summary

Depending on the application scenarios the requirements for low-power receivers differ. For some scenarios a very high sensitivity is necessary whereas in other scenarios a high sensitivity is not essential. As will be shown in Section III, power consumption, sensitivity, and data rate are competing features and can be traded against each other; depending on the scenario these values have to be carefully chosen.

In Table 1 estimates for the system requirements for low-power receivers are given. These values are reference points for the system development and shall help to categorize low-power receivers; they are not meant to be strict, fixed limits for the system requirements. As can be seen, the highest requirement for sensitivity is given in the industrial case, closely followed by the aeronautical and smart metering applications. Only WBAN applications have a moderate sensitivity requirement owing to the short communication distance. The delay and data rate requirements are closely coupled; a very low data rate leads to a high communication delay which can be challenging. In some receiver concepts a data rate of only several hundred bits per seconds is possible; for instance, if 100 bytes have to be transmitted at a data rate of 1 kb/s this would lead to a minimum delay of 800 ms. Hence, the data rate of the low-power receivers have a direct impact on the possible minimum communication delay. The industrial case has the most stringent delay requirements. Regarding the data rate, WBAN applications have the highest demand because of possible multimedia applications and also the strictest requirements for power consumption.

Generally, industrial applications have the highest sensitivity and delay demands while still requiring a very low power consumption. Aeronautical applications have slightly lesser sensitivity demands but at the same time stricter power consumption demands. Smart metering applications have lessened overall system requirements. Lastly, for WBAN applications a very low power consumption is clearly the most important factor, which can be met by providing only a moderate sensitivity.

III. Low-Power Receiver

Several concepts for low-power receivers are available [14–58], differing in complexity and performance.

Table 1.
Requirements for low-power receivers.

	Communication Distance	Sensitivity	Power Consumption	Data Rate	Delay	Payload Size
Aeronautical case	10 m	−80 dBm	100 µW	250 kb/s	200 ms	10 to 100 byte
WBAN	1 m	−40 dBm	10 µW	1000 kb/s	1000 ms	5 to 4000 byte
Smart metering	15 m	−75 dBm	100 µW	10 kb/s	500 ms	10 to 100 byte
Industrial	100 m	−85 dBm	200 µW	250 kb/s	25 ms	10 to 200 byte

Generally, industrial applications have the highest sensitivity and delay demands while still requiring a very low power consumption. Aeronautical applications have slightly lesser sensitivity demands but at the same time stricter power consumption demands. Smart metering applications have lessened overall system requirements.

A. Technology

The technologies used for low-power receivers vary over a wide range; from simple passive energy detection to envelope detection with several correlation stages. Each technology has its own advantages and disadvantages. Depending on the requirements for the low-power receivers, the best technology has to be selected carefully. Some are better for high data rates, others for high sensitivity or very low power consumption.

1) Modulation

The first distinctive feature is the chosen modulation format. Most of the concepts use either amplitude modulation in its binary form On-Off-Keying (OOK), or they use Frequency-Shift-Keying (FSK). Only four of the presented concepts differ here. The concept presented by Le-Huy et al. [50] uses binary Pulse-Width-Modulation (PWM), while the concept by Marinkovic et al. [28] uses a multi-stage approach beginning with an OOK modulated signal followed by a PWM symbol. The other concepts use Phase-Shift-Keying (PSK); Yan et al. [57] use the binary form BPSK and Lee et al. [51] use the quaternary form Quadrature-Phase-Shift-Keying (QPSK), which could also be implemented as two parallel BPSK demodulators.

The advantage of FSK (and also PSK) over OOK is that it is less susceptible to noise and fading. Additionally, because of the constant power level of the carrier, the amplifier design is simpler with FSK and there is no need for an adaptable threshold to decide which symbol was received. OOK has the advantage of overall implementation simplicity which can be transferred into energy efficiency. For instance, just a simple envelope detector can be used to detect if the carrier frequency is turned on. Such a detector can easily be implemented by using a diode and a resistor-capacitor oscillator circuit as a bandpass filter. All the concepts that have a power consumption below 10 μW are using OOK. This can be seen in Figure 2.

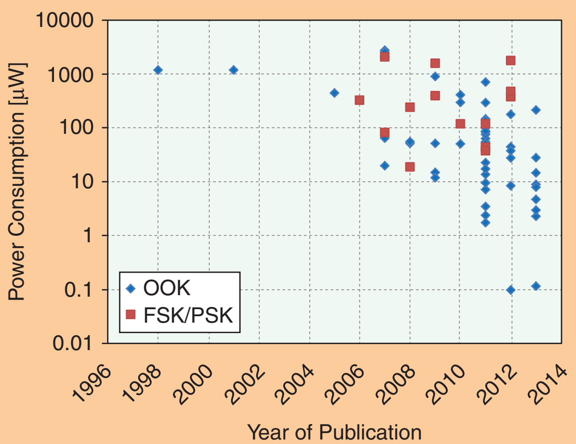

Figure 2. Power consumption of the low-power receivers using the OOK [14–47] and FSK/PSK [48–58] concepts.

2) Implementation

The second distinctive feature is the implementation of the concept. Several variants are used: super-regenerative receivers, superheterodyne receivers, injection-locked local oscillators (LO), envelope detectors with or without an intermediate frequency (IF), and in two cases envelope detectors followed by purely analog correlation stages.

The concepts in [14, 15, 20, 27, 32, 36, 43, 44, 47, 48] are using a super-regenerative receiver design. They all have a data rate above 100 kb/s with a sensitivity varying over a broad range. Two designs [22, 35] are using envelope detectors followed by purely analog non-coherent correlators and, thus, are able to reach very low power consumption values. Five concepts are using duty cycling [18, 25, 29, 30, 46], where [18, 29, 30, 46] are duty cycling even within a bit having an ON time in the range of only 100 ns. This reduction in sampling time decreases the power consumption to a level of several μW at a low data rate ($<$ 1 kb/s) without increasing the latency due to duty cycling. The concepts in [45, 53, 57, 58] are using injection-locked oscillators for either creating a power efficient "virtual LO" or creating a power efficient FSK/PSK demodulator. The concepts in [18, 21, 31, 33,] are using an uncertain IF architecture where the LO can vary in the range of 100 MHz from its desired frequency and therefore can be implemented more power-efficiently. In [25, 41, 52, 57] no IF is used, the symbols are demodulated directly which again can simplify the receiver design immensely. A very power-efficient design is possible but at the cost of a low sensitivity and the need of an external surface acoustic wave (SAW) filter.

Regardless of the particular specifications of the designs, the commonly important characteristics of all low-power receivers are *power consumption*, *data rate*, and *sensitivity*. None of these technologies can clearly be identified to outperform the others in all of these characteristics. All parts of a receiver strongly influence its performance; the interaction between them accounts for the overall power consumption. Therefore, all the low-power receivers will be compared with each other regardless of the specific technology.

B. Comparison

1) Sensitivity vs. Power Consumption

Firstly, the power consumption of the low-power receivers is related to their sensitivity. If possible, the sensitivity is measured at a bit error rate (BER) of 10^{-3}; due to correlation stages, for some concepts the sensitivity can only be measured at packet error rate (PER) levels because their functional principle makes no information available at BER level. This has to be kept in mind when comparing the sensitivity levels. The supply voltages vary in the range of 0.4V–3V. Some concepts use multiple supply voltage levels, meaning the actual power consumption might be higher due to the necessity of voltage converters when implementing the concepts on a communication platform.

The behavior of some concepts is adjustable, therefore, these receivers will have several connected data points in the figures. The data points of some concepts—[29, 30] in Figure 3 and [24, 53] in Figure 4—describe a vertical line, suggesting that one receiver setting outperforms all the others. However, this advantage is only valid for the examined parameters. As can be seen in the corresponding figure, there is no receiver setting which outperforms all the others. Nevertheless all data points are drawn to indicate that several receiver settings are feasible, even if they draw a vertical line.

As can be seen in Figure 3, it is very hard to reach a power consumption smaller than 10 µW. Only nine concepts [22, 28–30, 34, 35, 40, 45, 46] are below that level, where [35, 40] reach an outstanding power consumption around 100 nW. All those concepts can meet the moderate sensitivity demands for the WBAN applications.

2) Data Rate vs. Power Consumption

Secondly, the data rate of the receivers is related to their power consumption. Depending on the concepts, different coding techniques are used. Some designs [19, 34, 42] use Manchester coding to be able to recover the clock signal from the data. With Manchester coding the net data rate is only half of the gross data rate. Other designs [16, 22, 28–30, 34, 35, 37, 43, 50] use spreading techniques to increase the sensitivity or to distinguish between codes. Here, the net data rate is in the order of the spreading factor smaller than the gross data rate. In the figures, gross data rates before spreading, correlation, coding, etc. are shown.

As can be seen, it is hard to reach high data rates while keeping a low power consumption. Only ten designs [17, 21, 32, 33, 41, 43, 48, 54, 57, 58] reach a data rate of at least 1 Mb/s. From those only three [33, 41, 57] have a power consumption smaller than 200 µW.

Regarding the requirements in Table 1, it can be seen that for the aeronautical and the WBAN case no low-power receiver concept fulfills the power consumption, sensitivity, and data rate requirements. For the industrial case only [53] and for the smart metering case only

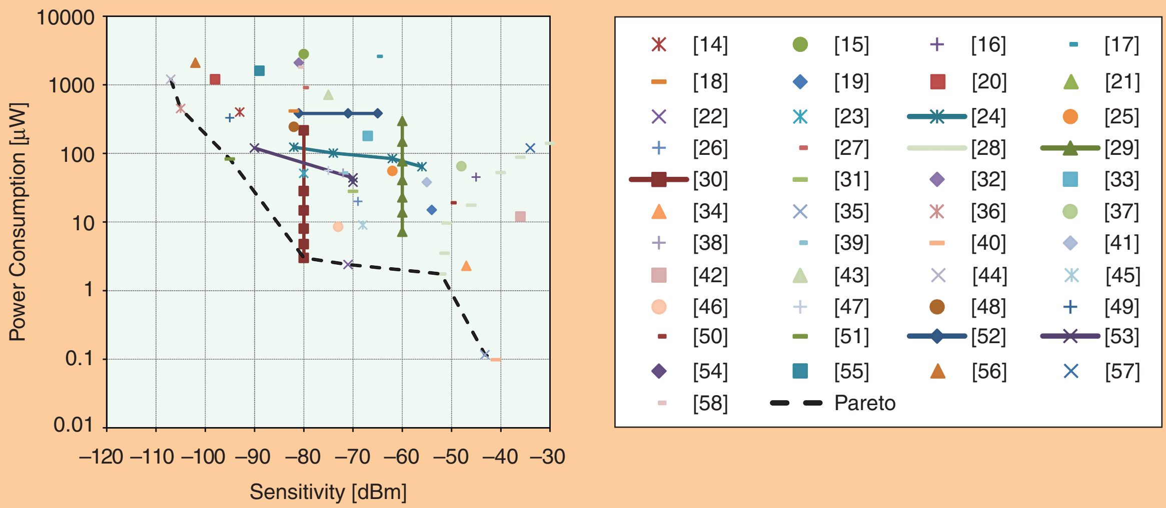

Figure 3. Sensitivity of the low-power receivers vs. their power consumption together with Pareto front.

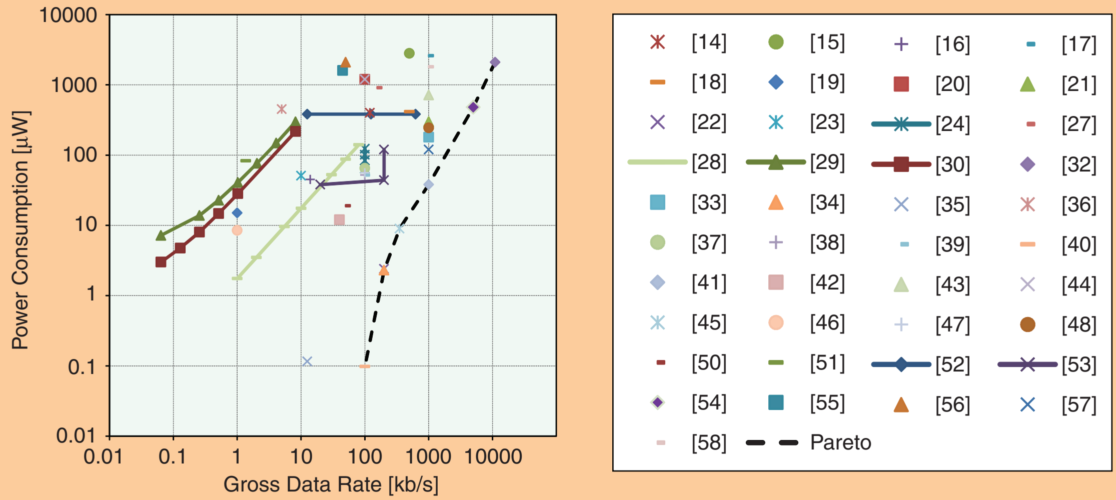

Figure 4. Gross data rate of the low-power receivers vs. their power consumption together with Pareto front.

[23, 47] fulfill all three requirements at the same time. The characteristics of these concepts would be sufficient to fulfill the sensitivity and data rate demands of those applications while reducing the power consumption dramatically.

For the aeronautical and for the WBAN scenarios currently no low-power receiver concept fulfills all the requirements to replace the main receiver of the system. However, a low-power receiver implemented as a wake-up receiver can have advantages over duty-cycling a main transceiver: either the overall power consumption and the communication delay can be reduced or at least the communication delay can be reduced while maintaining the same power consumption a duty-cycled transceiver would generate. The following section addresses this aspect more thoroughly.

IV. Wake-Up Receiver vs. Duty-Cycled Receiver

A common way to reduce the power consumption of a wireless node is to turn off all devices that are currently not used and to duty-cycle its transceiver. With a decreasing duty cycle the power consumption in the receiver is decreased, but, at the same time, the mean communication delay is increased.

In Figure 5 the periodic behavior of a duty-cycled receiver is depicted. The duty cycle follows $(T_{\mathrm{on}}/T_p)\cdot 100\%$, where T_{on} is the time the transceiver is turned on and T_p is the duration of the period. In this case the receiver has a duty cycle of 25%. The receiver is only able to receive a packet correctly if the transmit duration $T_d \leq T_{\mathrm{on}}$ and the packet is transmitted during the ON time of the receiver, which means that only the third packet in Figure 5 can be received correctly. It is only possible to communicate with a duty-cycled node in certain time frames; the period P equals the maximum additional communication delay before this frame arrives. Thus, there is a trade-off between power consumption and communication delay.

Additionally, when duty cycling, an overall more complex communication protocol is needed. To keep the communication delay as low as possible, the transmitting node either has to know beforehand at which time its communication partner is listening or it has to transmit the packet several times until it is certain that a listening slot of the receiving node is met. In the first case, the synchronous schedule, the packet has to be sent only once, but the clocks of all nodes have to be kept synchronous. In order to do this, additional communication has to be done which complicates the communication protocol and might result in higher power consumption for the transmitting node. In the second case, the asynchronous schedule, clocks do not have to be kept synchronous. In order to keep a low communication delay the packets have to be transmitted several times, which also increases the power consumption for the transmitting node. Hence, duty cycling not only increases the communication delay but might increase the power consumption for the transmitting node as well.

Following formula can be used to estimate the mean power consumption for a duty-cycled receiver.

$$P_{\mathrm{mean}} = \frac{P_{\mathrm{switch}}\cdot T_{\mathrm{switch}} + P_{\mathrm{on}}\cdot T_{\mathrm{on}} + P_{\mathrm{off}}\cdot T_{\mathrm{off}}}{T_p} \tag{1}$$

When calculating the power consumption, the switching time T_{switch} from the OFF state to the ON state is not negligible. According to Equation (1) the mean power consumption for two commercially available state-of-the-art transceivers is calculated for varying duty cycles.

The first transceiver considered is the Atmel AT86RF212 [59], which implements IEEE802.15.4 for the 700/800/900 MHz band. The second transceiver considered is the Nordic Semiconductor nRF51822 [60], which implements Bluetooth LE (2.4 GHz band). The second device is a System-on-Chip, which comprises a transceiver and a microcontroller but only the transceiver figures are taken into account. Both devices implement very different physical layers but both are optimized for low-power communication. For IEEE802.15.4 the 20 kb/s and 40 kb/s BPSK modulation as well as the 250 kb/s O-QPSK modulation is considered. For the nRF51822 the 1 Mb/s Bluetooth LE as well as the proprietary 250 kb/s and 2 Mb/s GFSK modulation is considered.

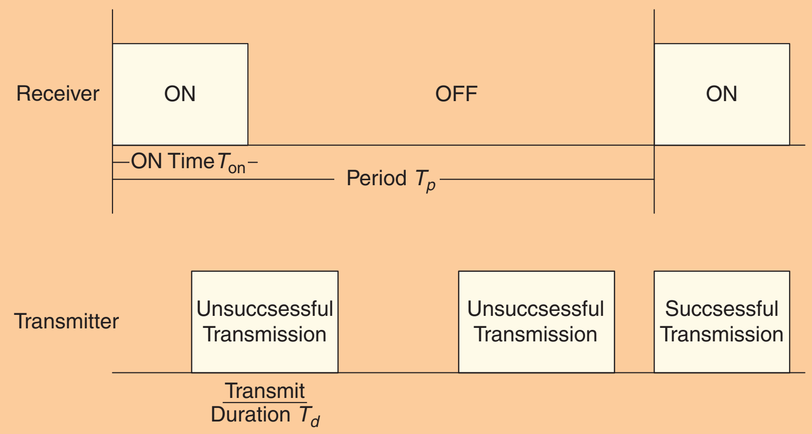

Figure 5. A 25% duty-cycled receiver, together with a transmitter that is sending three packets until a successful transmission occurs.

In Table 2 the characteristics for the different operation modes are shown. Regardless of the underlying physical layer, the sensitivity decreases with an increasing data rate while maintaining roughly the same power consumption. Within the duration T_{on} it has to be possible to transmit at least a packet header with address information. Because of the different protocols this leads to a different quantity of necessary bits; 144 bits for IEEE802.15.4 and 80 bits for Bluetooth LE. Hence, the packet length and therefore the minimum ON time T_{on} is different for each protocol.

Using these characteristics from Table 2, in Figure 6 the mean power consumption of the commercially available transceivers are depicted together with wake-up receivers with a power consumption below 200 µW. The delay in the case of WURs is equal to the time it takes them to send a wake-up message. For designs [16, 22, 28–30, 34, 35, 37, 50] that use spreading techniques with fixed spreading factors, the amount of bits to send is predefined. For other designs, we assume that a wake-up message consists of 32 bits with the delay being directly proportional to their data rates.

With an increasing duty cycle period—while keeping the duration T_{on} constant—the mean power consumption for both commercially available radios decreases. Using a higher data rate decreases the sensitivity of the devices but does not change the power consumption. Hence, a shorter necessary ON time reduces the mean power consumption for a fixed duty-cycle period. Until a certain limit—a period of about $10s$ for the Bluetooth LE radio and around $100s$ for the IEEE802.15.4 radio—the mean power consumption curves decrease linearly in the log-log scale. After the limit, the basic load of the devices becomes predominant, the mean power consumption values approach the device-specific horizontal asymptote.

A similar predominance effect can be observed when increasing the data rate. The necessary ON time will be reduced accordingly, but the switching time T_{switch} does not change. Hence, the switching time will become the predominant factor when a certain data rate, respectively necessary ON time is reached. Further increasing the data rate will not significantly decrease the mean power consumption.

Hence, duty cycling a radio decreases its mean power consumption but only until a data rate dependent threshold is reached. Then the mean power consumption approaches an horizontal asymptote.

As can be seen, all WUR concepts perform better than the commercially available transceivers regarding delay and power consumption. All of the concepts fulfill

Table 2.
Characteristics for commercially available transceivers.

	Data Rate	Sensitivity	P_{on}	P_{off}
AT86RF212	20 kb/s	−110 dBm	30.36 mW	0.66 µW
	40 kb/s	−108 dBm	30.36 mW	0.66 µW
	250 kb/s	−101 dBm	30.36 mW	0.66 µW
nRF51822	250 kb/s	−96 dBm	41.58 mW	1.98 µW
	1 Mb/s	−91 dBm	42.90 mW	1.98 µW
	2 Mb/s	−85 dBm	44.22 mW	1.98 µW

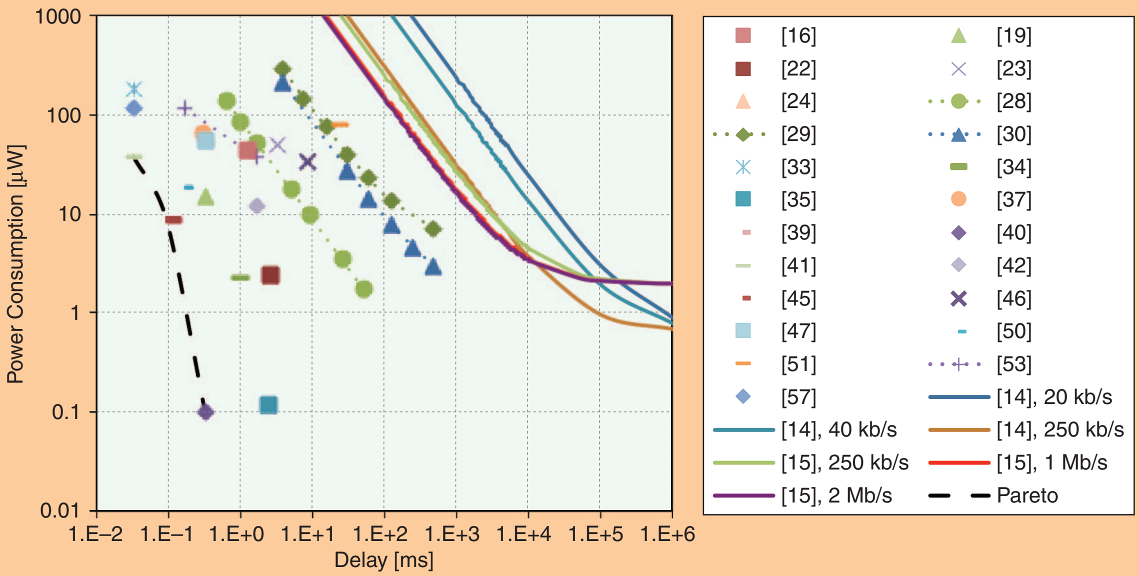

Figure 6. Wake-up delay of low-power receivers [16, 19, 22–24, 28–30, 33–35, 37, 39–42, 45–47, 50, 51, 53, 57] with a power consumption below 200 µW together with duty-cycled transceivers Atmel AT86RF212 [59] and Nordic Semiconductor nRF51822 [60]; Pareto front included.

the delay requirements given in Table 1. Considering the sensitivity requirements as well, only a subset remains. For the aeronautical case only three concepts [23, 30, 51] fulfill the requirements, for the industrial only one [51]. A duty-cycled nRF51822 with a data rate of one or two Mb/s also meets the industrial requirements, but only with a sensitivity worse than the concept in [51].

For an application with a delay restriction of 1 s, a duty-cycled transceiver is an option. The mean power consumption is in the order of 10 µW to 100 µW with a sensitivity of −90 dBm to −110 dBm. This increase in sensitivity can improve the reliability of the communication system which outweighs the additional effort for the more complex communication protocol.

V. Using Wake-up Receivers

The most promising application for low-power receivers is to replace a "normal" receiver. If used for all communication purposes, the low-power design can yield the most energy savings. However, as outlined in Section III-B, low-power receivers do not meet all requirements for all applications. Another operational area is to use a low-power receiver as a wake-up receiver. The low-power receiver will not be used for communication itself but for initiating the communication via another receiver. Since the main transceiver does not have to be periodically duty-cycled, it can be kept turned off as long as no communication is required; it will be turned on only on demand.

This behavior can be seen in Figure 7. In the first case, the unsynchronized communication with a duty-cycled receiver is depicted in its simplest form. Once a communication demand arises, the transmitter wants to start communicating and repeatedly sends the data packet. This repetition must continue for the length of the duty cycle period to assure the meeting with the ON phase of the duty-cycled receiver. In the second case, instead of sending the data packet directly, first a wake-up message is transmitted. This message indicates the receiving node that a data packet will follow and therefore it will turn on its receiver. In this case, using a wake-up receiver will not only decrease the idle listening time but also shorten the mean communication delay.

This is beneficial in a typical aeronautic application: on the ground, the status of simple switches has to be evaluated. To accomplish this the monitored switch can be connected to a sensor board, which currently is using a duty-cycled transceiver. With this system, the status of one switch can be polled within one second while only consuming $< 100\,\mu W$ on average. Using a wake-up receiver instead, the communication delay could be decreased by approximately one magnitude at the same power consumption. This increases the responsiveness of the system immensely; it is possible to inquire the status of several switches in the same time as only one with a duty-cycled transceiver.

Polling devices is not the best solution for a large number of devices. Gordon et. al [61] present a more

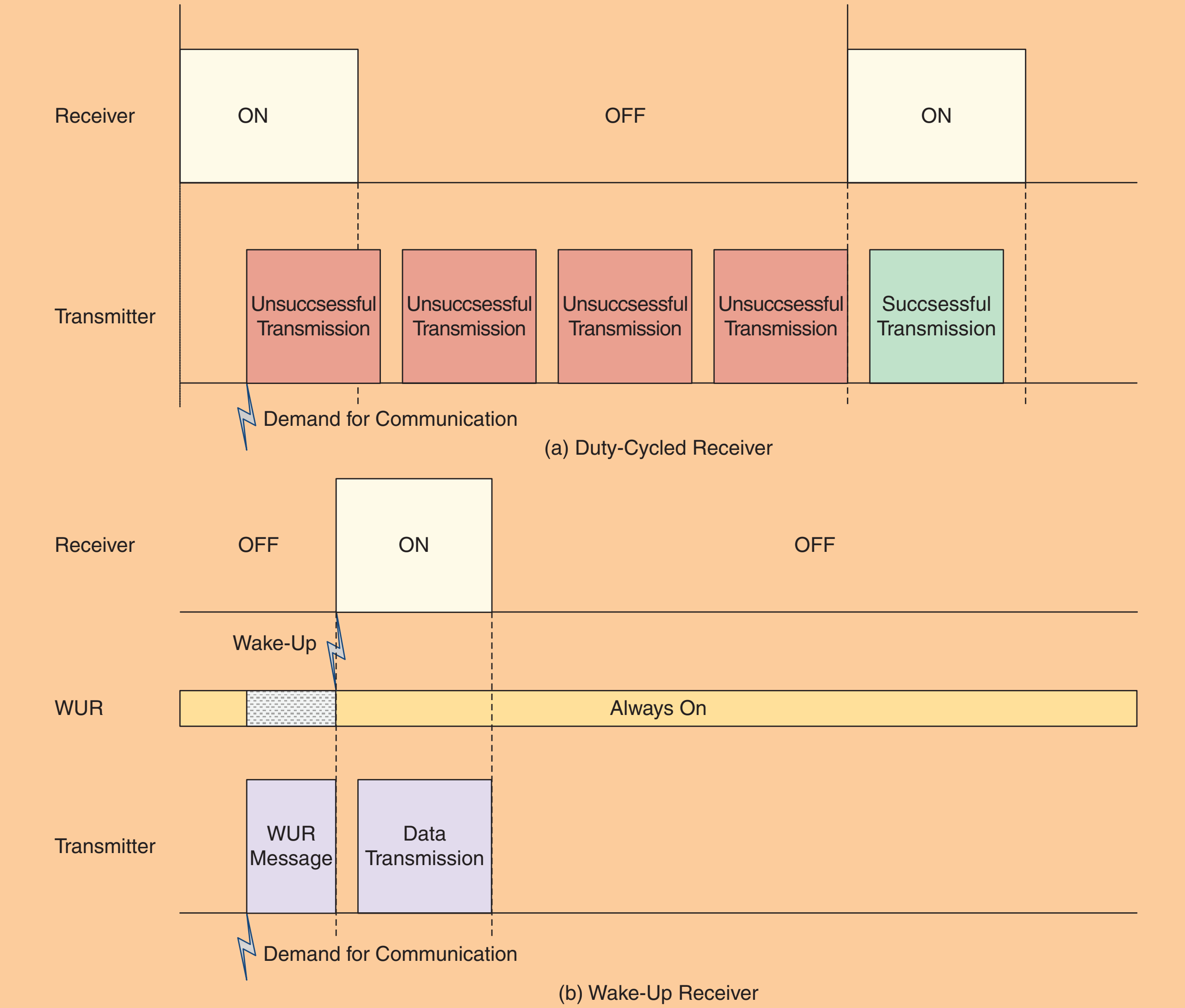

Figure 7. Different communication approaches: (a) when using a duty-cycled transceiver, and (b) when the communication is initiated with a WUR message.

sophisticated protocol where acknowledged wake-up messages are used to initiate, for example, a TDMA protocol. In doing so, the time to inquire the status of a large amount of sensors can be reduced roughly by half. A similar approach is pursued in [62], where many temperature values have to be monitored. To reduce the power consumption, sensor nodes measuring similar readings are clustered together. Only one of them is representing the cluster and is transmitting the actual reading. Wake-up receivers are used to establish the clusters in an energy efficient way and to inform about changes.

VI. Future Research and Conclusion

The development over the last 10 years showed a clear improvement of the performance of low-power receivers. The power consumption dropped from 1 mW to almost only 100 nW, hence, a factor of 10000. Still there are no designs available which fulfill the combined requirements for energy consumption, sensitivity, and data rate for the aeronautical and for the WBAN applications. If the performance improvement continues to proceed, concepts for all application areas should be available soon.

Currently there are few applications which depend on the usage of a low-power receiver/wake-up receiver. Many applications could clearly benefit from using a wake-up receiver; either because of a reduced power consumption or because of a smaller communication delay. Some applications will only be enabled when using a low-power receiver. With the high potential for reducing the energy consumption, protocols that are dependent on wake-up receivers are expected to arise.

Depending on specific application requirements, it is already possible to replace a "normal" receiver with a low-power receiver. If the low-power receiver characteristics do not yet meet the requirements for the applications, they can be used as wake-up receivers, which, by keeping similar power consumption values, drastically reduces the communication delay in comparison with duty-cycled systems.

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