Energy improved wake-up strategy for wireless sensor networks

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Abstract

The available energy of wireless sensor nodes is limited due to the fact that they often operate on batteries and due to their small size. One approach to reduce power consumption of wireless sensor nodes, is to reduce their active time. This can be done by duty cycling or by using a wake-up strategy as presented by Gamm et al. 2012. In this approach, a node is inactive until it gets awaken by another node or an external event. The energy efficiency of the wake-up strategy depends on the energy consumed per wake-up message. In this paper we investigate the wake-up messages introduced by Gamm et al. 2012 to develop a method to reduce their duration from 13.2 ms to 2.26 ms, which corresponds to an energy saving of around 83 %. To examine sensitivity and wake-up range of the wake-up receiver for messages of different durations four message types of different lengths are tested. For three types, the receiver reaches a sensitivity of -50 dBm and a range of 45 meters. Using the shortest type of message, the wake-up range is around 30 meters.

1 Introduction

Long-term monitoring of infrastructures such as bridges and buildings may be as long as 50 or 100 years [1]. It can be done with the help of wireless sensor networks (WSNs) that consist of many sensor nodes which are often installed at places that are hard to reach [2]. As a consequence of this, wireless sensor nodes should be self-powered units that are easy to attach to existing structures [1]. This implies small units which are typically powered from batteries [3] with a limited amount of energy. The sensor nodes are often left unattended over long periods or placed in remote areas where replacing of the batteries is not feasible [3].

To realize long lifetimes, the power consumption of a WSN has to be minimized [3]. Wireless sensor nodes need energy for sensing, data processing and communication [4]. A source to safe energy are energy efficient communication protocols [4] such as adapted Medium Access Control (MAC) and routing protocols. Many WSN deploy contention based MAC protocols such as S–MAC (Sensor–MAC) or X–MAC [5] which have scheduled time slots for listening and sleeping periods [4]. Energy is saved during sleeping periods, and communication is handled during listening periods. To establish a communication link between two nodes, their active phases have to be synchronized. This is usually achieved by sending synchronization messages between the nodes [4]. Due to the periodical cycling of sleep and listen periods this mechanism is also called duty cycling [5]. One drawback of duty cycling is, that energy is wasted on receiver side for idle listening and on sender side for sending of preamble messages [5].

Another approach to reduce energy consumption in a WSN is the so called on-demand communication approach [4]. In this approach, wireless sensor nodes have no synchronized listening and sleeping phases [4]. Instead, the nodes are listening permanently in a low energy consuming stand-by state and wake up to full functionality only after receiving a wake-up message [4] or if a sensor produced a trigger. In terms of energy consumption, this can be more favorable than duty cycling based protocols if communication happen infrequently [6].

The wake-up receiver presented in [6], implements an on-demand wake-up scheme that consumes only 2.78 µA in idle stand-by mode [6]. When powered from a 950 mAh capacity battery the stand-by lifetime of this node would be around 33 years in ideal conditions [6]. In a real world scenario, the lifetime is shorter due to self-discharge of the batteries, sensing and data processing tasks and communication from an to other nodes. The energy consumption during sending and receiving is around 15 mA and as such much higher than the power consumed during idle listening. From this it becomes clear, that the lifetime of a sensor node that utilizes the on-demand communication approach is directly dependent on the energy costs of the wake-up messages. By reducing these costs it is possible to decrease the power consumption in a WSN and therefore to increase its lifetime.

In the following we introduce a wireless sensor node based on the wake-up receiver presented in [6, 7] in Section 2. In Section 3 we investigate the wake-up messages and present a method to shorten their duration. The concepts of Section 3 are tested and verified in the laboratory and in a field test which is described in Section 4. Conclusions and Outlook are presented in Section 5.

2 Wireless Sensor Node

The sensor node used in this paper is based on the principles introduced and tested in [6, 7] which combine the

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advantages of fast communication, small antennas and the low power consumption of stand-by listening [6]. A schematic of the node can be seen in Figure 1. It uses a 868 MHz main communication radio and a separate 125 kHz wake-up receiver to implement the wake-up functionality. The 125 kHz wake-up message is modulated on the 868 MHz carrier frequency by On Off Keying at 250 kbps. The antenna is connected by a switch either to the main radio or to the wake-up receiver. The wake-up receiver responds to the modulated signal which is obtained from the 868 MHz signal by impedance matching, rectifying and low pass filtering. In case the wake-up receiver detects a valid input signal it creates an output signal that is fed into the microcontroller. Here it triggers an interrupt that stops the sleeping mode. The microcontroller then toggles the switch so that the antenna is connected to the main radio and is ready to receive or transmit communication messages.

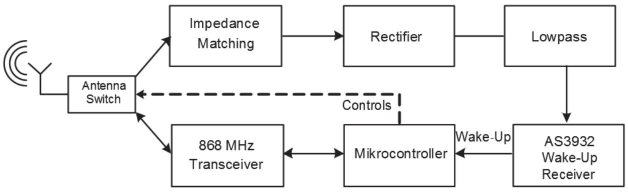

Figure 1 Schematic drawing of the wireless sensor node [6].

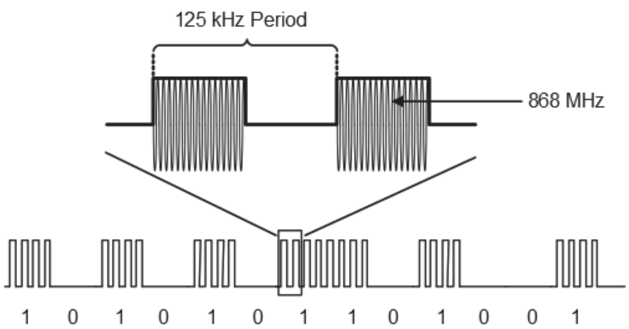

Figure 2 The 125 kHz message is modulated on the 868 MHz carrier signal by On Off Keying at 250 kbps. Figure from [6].

2.1 Hardware

The hardware of this sensor node is basically the same as presented in [6] where more details on each components can be found.The node presented here uses a 32 bit ARM Cortex M3 type EFM32 microcontroller from Silicon Labs [8] running at 14 MHz. In energy saving mode, it has an energy consumption of around 0.2 µA and in active mode around 2.2 mA [8] which is comparable to the energy consumption of the Texas Instruments MSP430 microcontroller used in [6]. The 32 bit EFM32 microcontroller achieves a higher computational power than the 16 bit MSP430 which can be of advantage when processing sensor data.

The main radio of the node is a CC1101 transceiver from Texas Instruments that has a current consumption of around 30 mA during sending with 10 dBm and around 17 mA during listening at 868 MHz [8]. The antenna is a $\lambda/2$ monopole antenna with 2 dBi antenna gain. The low frequency wake-up receiver is the AS3932 from Austriamicrosystems with a variable bit rate from 1024 to 8192 bps [9] and a 16 bit wake-up address. In listening mode it draws 2.7 µA [9].

2.2 Lifetime

The lifetime of a wireless sensor node may be investigated following the method introduced in [10]. We define an interval T_{int} consisting of T_s and T_{idle}. T_{idle} is the time when the node is sleeping and T_s is the time when the node is sending a wake-up message. T_s is equal to the lengths of messages A, B, C and D. To calculate a lifetime we also need a specific amount of stored energy Q_b, for example a small battery with a capacity of 230 mAh. From the previous section we know the power consumption I_{idle} of the node when it is sleeping and I_s when it is sending. Equation 1 can be used to calculate the lifetime of a sensor node for different intervals T_{int} [10]:

$$T_{life} = \frac{Q_b T_{int}}{(T_s I_s + (T_{int} - T_s) I_{idle})} \tag{1}$$

The lifetime of a wireless sensor node is also influenced by so called *false wake ups*. False wake ups may happen due to multipath propagation or more general due to noise that wakens the receiver falsely. Another possible source of false wake ups are interpretation errors of the pattern match algorithm where the receiver reacts on an address that is not his own and falsely wakes up.

Since both scenarios reduce the lifetime of a sensor node we introduce factor K to describe this behavior:

$$K = \frac{n_{false}}{T_{meas}} T_{awake} \tag{2}$$

Where n_{false} are the number of detected false wake ups during measurement interval T_{meas}. T_{awake} is the time that the microcontroller needs to go to sleep after a false wake up. Multiplying K by T_{int} gives the time T_{false}. This is the time a wake-up receiver spent in active mode due to false wake ups during time interval T_{int} based on the counted false wake ups during time interval T_{meas}. Given this, Equation 1 may now be written as:

$$T_{life} = \frac{Q_b T_{int}}{(T_s I_s + (T_{int} - T_s - T_{false}) I_{idle} + I_{awake} T_{false})} \tag{3}$$

where I_{awake} is the current consumption of the microcontroller in active mode.

3 Wake-up Message

The AS3932 reacts on a specific wake-up message as can be seen in Figure 3 from [9]. The message consists of the *Carrier Burst*, the *Preamble* and the both optional *Pattern* and *Data*. The *Carrier Burst* has to be 550 µs long and may

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be as long as 16 bit. The *Preamble* length must be between 4 and 40 bits including the *Pattern* that is a 16 bit address used to distinguish different receivers. The length of one bit and the maximal length of the *Carrier Burst* depend on the set bit rate of the AS3932. The duration of one bit can be calculated by using Equation 4:

$$T = \frac{1}{BR} \tag{4}$$

where T is the bit length and BR the bit rate. The length of a wake-up message can be calculated by summing the number of Carrier Burst, Preamble and Pattern bits and multiplying them by bit length T.

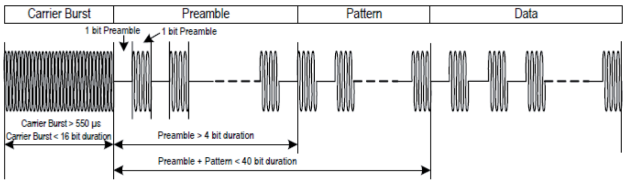

Figure 3 Pattern that has to be sent to wake-up the AS3932. The address pattern and the data bits are optional. Figure taken from [9].

3.1 Wake-up Sensitivity

To measure sensitivity S, a measurement setup as described in [6] and sketched in Figure 4 can be used. Two nodes are connected by coax cables through an adjustable attenuator. One node is configured as receiver the other as sender. The sender sends wake-up messages to the receiver that counts each wake up. By adjusting the variable attenuation A the receiver will finally reach its sensitivity limit and stop waking up. Sensitivity S can be calculated by subtracting attenuation A from transmit power P_S. Attenuation A_t of cables and connectors must also be taken into account and have to be subtracted, too. Equation 5 describes this relation:

$$S = P_S - A - A_t \tag{5}$$

After transforming sensitivity S from dBm to received power P_R in Watt, the maximal wake-up range r can be calculated by using Friis free-space equation [11]:

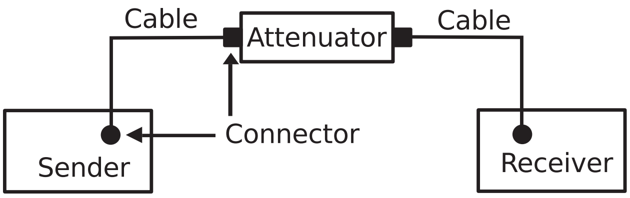

Figure 4 Schematic drawing of a measurement setup to determine the sensitivity of a wireless sensor node.

$$r = \frac{c}{4\pi f}\sqrt{\frac{P_S G_S G_R}{P_R}} \tag{6}$$

where c is speed of light, f the sender frequency, G_S and G_R the antenna gains of sender and receiver and P_S the transmit power.

Another important factor that influences the transmission range is the clearance of the first Fresnel zone as most of the energy of a propagating radio wave is carried inside it [12]. Its maximal radius R can be calculated using Equation 7 [12]:

$$R = \frac{\sqrt{\lambda d}}{2} \tag{7}$$

Here d is the distance between sender and receiver and λ the wavelength.

4 Experimental Analysis

To verify the concepts introduced in the sections above, sensitivity and wake-up range were measured in the laboratory and in a field test. For that purpose, four wake-up messages A, B, C and D were defined. The parameters of the messages are shown in Table 1. Message A is identical to the message used in [6]. It is sent at a bit rate of 2730 bps. Messages B, C and D have different lengths for carrier burst, preamble and pattern. They were sent at a bit rate of 8192 bps. To realize an address length of 4 bit the 12 lower bit of the address pattern were set to zero, that is only the four upper bits of the address field of the AS3932 were configured.

Msg.	DR [bps]	C. B. [bit]	Preamb. [bit]	Pattern [bit]	Length [ms]
A	2730	8	12	16	13.2
B	8192	8	12	16	4.4
C	8192	8	12	4	2.9
D	8192	4	10	4	2.2

Table 1 The table shows the relevant parameters (Data rate, Carrier Burst, Preamble, Pattern and Length) of messages A, B, C and D that were used to determine sensitivity and range of the wake-up receiver.

4.1 Wake-up Sensitivity

The wake-up sensitivity was measured as described in Section 3.1. Each message A, B, C and D was sent 500 times at 10 dBm transmit power. Table 2 shows the detected wake ups at different attenuations. The experiment shows, that the messages are just detected by the receiver at an attenuation of 59 dB. According to Equation 5, this results in a sensitivity of -50 dBm by assuming 1 dB attenuation of cables and connectors. Using Equation 6 the maximal wake-up range for this receiver can be calculated to 55 m.

4.2 Wake-up Range

Following the laboratory measurement, the wake-up range was examined in a field test. The test consisted of a sender and a receiver placed at distances d from each other at 1.15 m above ground. The sender sent each of the above defined messages A, B, C and D 500 times at 10 dBm output power and the receiver counted each successful reception. Figure 5 shows the received wake-ups against the dis-

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Att. [dB]	Rec A	Rec B	Rec C	Rec D
50	500	500	500	500
57	500	500	500	499
58	500	500	476	475
59	500	500	467	475
60	45	36	94	93
61	0	0	0	0

Table 2 Received (Rec) wake-ups at different attenuations for messages A, B, C and D each sent 500 times.

tance. It can be seen that the curves for messages A, B and C follow the same tendency with a maximum wake-up range of around 45 meters. Above 45 meters, the nodes still wake up but with a decreased probability. The wake-up range of message D is only around 30 meters which is probably due to the short carrier burst and preamble. Also multipath propagation might disturb the correct reception of messages. The differences of the wake-up range measured in the field test and in the laboratory are probably due to attenuations in the first Fresnel zone that has a maximal radius of around 2 meters according to Equation 7 in case sender and receiver are 45 meters apart and sending at 868 MHz.

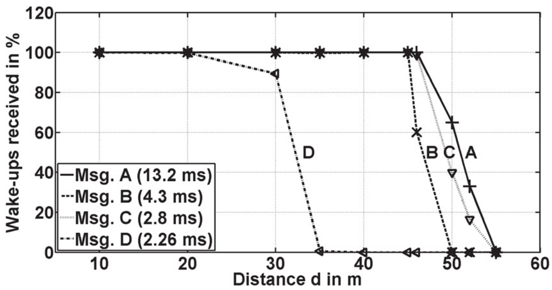

Figure 5 In the field test detected wake-ups against distance between sender and receiver for messages A, B, C and D. Each message was sent 500 times in row.

4.3 False Wake-ups

As introduced in Section 2.2, it can happen that the wake-up receiver awakes falsely. As false wake ups increase the energy consumption of a wireless sensor node we set up a test similar to that shown in Figure 4 to examine the effect of false wake ups due to noise more closely and in respect to the influence that the length of the wake-up messages has on it. The sender sent a 125 kHz On Off Keying modulated signal of 20 ms duration every 75 ms. The signal was without any specific pattern to simulate a 125 kHz noise signal. Around 632 packages were sent in a period of 60 seconds. The attenuation was hold fix around the sensitivity limit at 60 dB. The receiver was successively configured to react on messages A, B and C and counted each wake up. Figures 6, 7 and 8 show the histograms of the false wake ups including a lognormal fit of the data. The receiver counted all detections during 60 second intervals. By inspecting the means that are 90, 65 and 129 for messages A, B and C it can be seen that increasing the data rate does not lead to significantly more false wake ups, but limiting the address does.

The conditions of this test resemble a worst case scenario that are far away from any real world example but demonstrate that false wake ups can happen and care should be taken when using messages of certain lengths. In some cases it will be better to invest more energy into longer carrier burst, preamble and pattern sequences to reduce false wake ups and to create more safety. In other applications, short and fast transmissions may be the right solution. It is also possible to further optimize the settings of the AS3932 to increase its robustness against noise which was not done here.

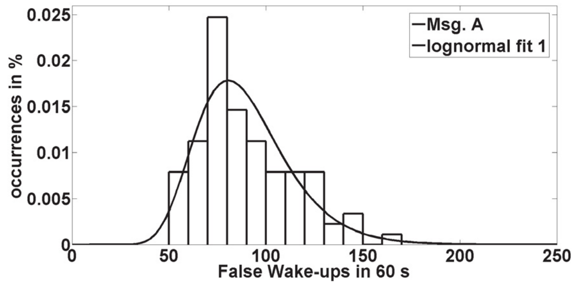

Figure 6 Lognormal fit of false wake-ups with mean around 90. Receiver reacts on message A.

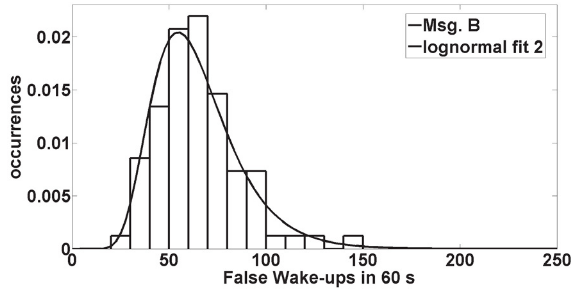

Figure 7 Lognormal fit of false wake-ups with mean around 65. Receiver reacts on message B.

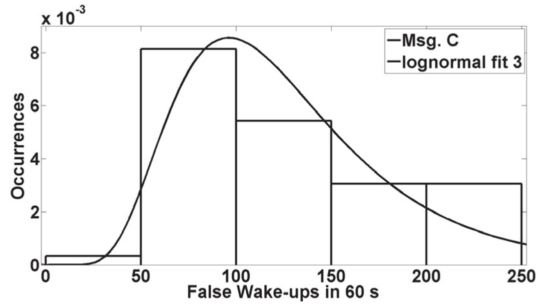

Figure 8 Lognormal fit of false wake-ups with mean around 129. Receiver reacts on message C.

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5 Results and Discussion

The important question, if the approaches presented above increase the lifetime of a wireless sensor node may be answered by investigating the lifetime according to Equation 1 of Section 2.2. Figure 9 shows the gain of short wake-up messages against the lifetime of a wireless sensor node. Investigated are messages A, B, C and D at intervals T_{int}. The plot is normalized to message A. It can be seen that short wake-up messages increase the lifetime, especially for intervals T_{int} from around 1 to 10 seconds where the lifetime is increased by a factor between three and six depending on the message type. For T_{int} in the range up to 100 seconds, the lifetime is approximately doubled. For bigger intervals, the stand-by current of the sensor node dominates more and more and the gain of shorter wake-up messages decreases.

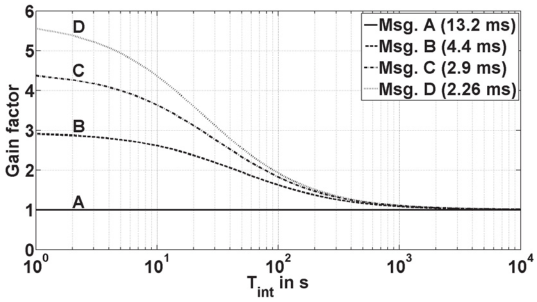

Figure 9 Gain in lifetime of a wireless sensor node if sending a wake-up message of type A, B, C or D each T_{int} interval. Normalized to message A.

Following the results of Section 4.3, false wake ups could relativize or even reverse the gain of short messages. To examine this, Equation 3 was used together with the results presented in Section 4.3. Figure 10 shows the gain of messages A, B, C and D if the number of false wake ups n_{false} are 90, 65 and 129 for messages A, B, C and D for a measurement interval T_{meas} of 60 seconds. This represents the results of the worst case scenarios for messages of types A, B and C found in Section 4.3. We assume that T_{awake} equals 1 ms and a node consumes 2.2 mA during this time, as introduced in Section 2.1. It can be seen that even under this conservative consumption the gain is still positive for messages C and D until T_{int} gets greater than 50 seconds and for message B until T_{int} gest greater than 100 seconds. For T_{int} greater than 100 seconds the lifetime decreases for all types of messages due to the false wake ups. From this we can conclude that very short messages with limited address space should primarily be used in WSN with frequent communication where a WSN benefits most from energy reduced wake-up messages. Using high data rates also increases the lifetime of WSN with infrequent communication.

6 Conclusion and Outlook

The advantages of wake-up receivers as presented in [6] are low stand-by currents and on-demand capability that

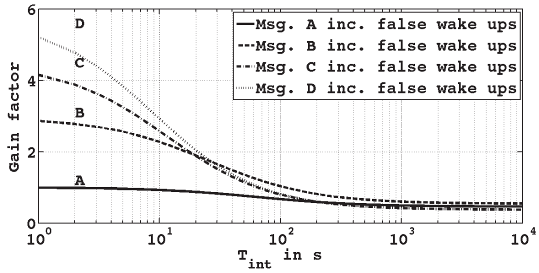

Figure 10 Gain in lifetime of a wireless sensor node if sending a wake-up message of type A, B, C or D each T_{int} interval including false wake ups. Normalized to message A.

lead to low latencies and long lifetimes in wireless sensor networks. In this paper we introduce a method to reduce the duration of wake-up messages from 13 ms to 2.3 ms by using high data rates at the receiver and by limiting the address space to 4 bit. Four test messages were defined and investigated with respect to receiver sensitivity and wake-up range. With a laboratory test it was demonstrated that there is almost no visible difference in sensitivity and wake-up range for messages sent and received at high data rates. A field test showed that shorter addresses are more susceptible to influences like noise and multipath propagation. We also investigated to what extent false wake ups may influence the lifetime of a wake-up receiver and conclude that very short wake-up messages are primarily useful in close distance wireless sensor networks with frequent communication. Here, fast wake-up messages can increase the lifetime of a wireless sensor node almost by a factor of six. Increasing the data rate and using long carrier burst, preamble and pattern is beneficial also for wireless sensor networks with infrequent communication.

The results presented here can be used to develop medium access control protocols that are able to adapt the length of wake-up messages to the radio signal strength or to the false wake up rate of wake-up receivers.

7 Acknowledgments

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8 References

[1] P. C. Chang, A. Flatau, and S. Liu, “Review paper: health monitoring of civil infrastructure,” *Structural health monitoring*, vol. 2, no. 3, pp. 257–267, 2003.

[2] V. A. Kottapalli, A. S. Kiremidjian, J. P. Lynch, E. Carryer, T. W. Kenny, K. H. Law, and Y. Lei, “Two-tiered wireless sensor network architecture for structural health monitoring,” in *Smart Structures and Materials*, pp. 8–19, International Society for Optics and Photonics, 2003.

[3] B. Sahoo, S. Rath, and D. Puthal, "Energy efficient protocols for wireless sensor networks: A survey and approach.," *International Journal of Computer Applications*, vol. 44, 2012.

[4] M. Enzinger, "Energy-efficient communication in wireless sensor networks," *Sensor Nodes–Operation, Network and Application (SN)*, vol. 25, 2012.

[5] M. Buettner, G. V. Yee, E. Anderson, and R. Han, "X-mac: a short preamble mac protocol for duty-cycled wireless sensor networks," in *Proceedings of the 4th international conference on Embedded networked sensor systems*, pp. 307–320, ACM, 2006.

[6] G. Gamm, M. Kostic, M. Sippel, and L. M. Reindl, "Low–power sensor node with addressable wake–up on–demand capability," *International Journal of Sensor Networks*, vol. 11, no. 1, pp. 48–56, 2012.

[7] J.-M. Boccard, A. Bannoura, O. Gorgis, G. Gamm, and L. Reindl, "Slot antenna packaging for infrastructure monitoring based on wake-up transceiver strategy," in *Wireless Sensor (ICWISE), 2013 IEEE Conference on*, pp. 84–89, IEEE, 2013.

[8] Silicon Labs, 400 West Cesar Chavez Austin, TX 78701 USA, *EFM32GG232 DATASHEET*, June 2013. Rev. 1.10.

[9] ams AG, Tobelbader Strasse 30 8141 Unterpremstaetten Austria, *AS39323D Low Frequency Wakeup Receiver*. Rev. 1.4.

[10] G. Gamm, *Sensorknoten mit Ultra Low Power Aufweckempfänger*. PhD thesis, Department of Microsystems Engineering (IMTEK) Laboratory for Electrical Instrumentation, Georges-Koehler-Allee 103, 79110 Freiburg, 2013.

[11] T.-I. Kvaksrud, "Range measurements in an open field environment," *Texas Instrum. Incorporated, Dallas, TX, Design Note DN018*, 2008.

[12] D. B. Green and A. Obaidat, "An accurate line of sight propagation performance model for ad-hoc 802.11 wireless lan (wlan) devices," in *Communications, 2002. ICC 2002. IEEE International Conference on*, vol. 5, pp. 3424–3428, IEEE, 2002.

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