# Using Antenna Diversity to Improve Wake-up Range and Probability

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**Abstract**— In this article we present polarization diversity in the wake-up path of a low-power wireless sensor node. Due to antenna diversity, the node shows an improved wake-up signal strength and optimized sensitivity in a multipath propagation environment. We verify the design using simulations and different measurement setups. The resulting combined antenna signal has a gain of +3 dB when both diversity antennas receive the same signal strength. In this case, the wake-up receiver has an improved sensitivity around −53.7 dBm. Furthermore, we introduce a smart antenna for the communication link by using just one extra antenna switch. The proposed design can be used for any wake-up receiver of this kind.

## 1. INTRODUCTION

Wireless sensor networks (WSNs) are used in various applications like environmental monitoring, child education, smart manufacturing, infrastructure monitoring and many others. A WSN usually consists of many small self-powered sensor nodes that measure their environment and communicate data to other nodes or a base station [1]. Recently, more and more WSN consist of wake-up receivers, that reside in a low-power stand-by state until they receive a wake-up signal [2]. Only after receiving this signal, or a sensor event, they wake-up to full operation, which can be more favorable in respect to energy consumption, than duty-cycling [3]. The low-power wake-up sensor nodes presented by [3, 4] use the AS3932 low-power wake-up receiver that listens permanently to a 125 kHz signal which is modulated on an 868 MHz carrier frequency and demodulated by using a rectifier and a low-pass filter. Changing between communication and low-power wake-up listening is realized with a antenna switch.

In this article, we present a wake-up node, based on the node presented by [4]. The newly designed node uses polarization diversity in the wake-up path which is motivated in Section 2. The node shows an improved wake-up signal sensitivity and reliability in multipath propagation environments. We show that almost no additional active parts are needed in Section 3. The general design and its performance are tested by using simulations and different measurement setups which is summarized in Section 4. Finally, the results are discussed in Section 5 followed by conclusions and outlook in Section 6.

## 2. BACKGROUND

In general, wave propagation cannot be seen as free-space propagation. Several phenomena such as reflection, diffraction, scattering, and doppler fading has to be taken into account [5]. Due to these phenomena, it is likely that a signal from one antenna reaches another antenna over several paths with its associated path lengths and attenuations. As a result, many copies of one signal reach the antenna after different delays, where they superimpose each other destructive or constructive [5]. Using antenna diversity helps to mitigate these fading effects [7], since one assumes that signals are independent from each other, if they are received by uncorrelated antennas. Hence, if one antenna does not receive a signal due to fading, the other (uncorrelated) antenna will likely still receive the signal [7]. Polarization diversity is one of the typical methods of diversity, since there is no spatial separation of the antennas required [7]. When using diversity systems, combining the output signals of several antennas leads to increased signal strengths at the receiver [6] and improves the communication reliability. Figure 1 shows the generalized block diagram of an antenna diversity system introduced in [8]. Here, each of the $M$ antennas is connected to the cophasing and sum circuitry through its associated amplifier $G_i$. The output voltage $V_o$ is the combination of the $M$ antenna signals and can be calculated as [8]:

$$V_0 = G \sum_{i=1}^{M} g_i V_i \tag{1}$$

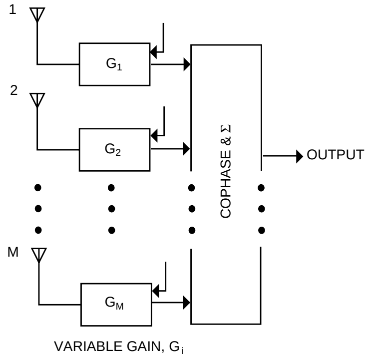


Figure 1: Generalized diversity block diagram from [8].

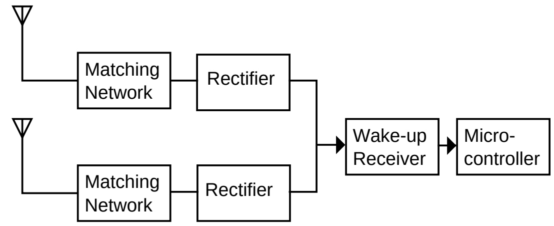


Figure 2: Block diagram of low-power wake-up receiver featuring antenna diversity. Each diversity branch consists of antenna, matching network and rectifier.

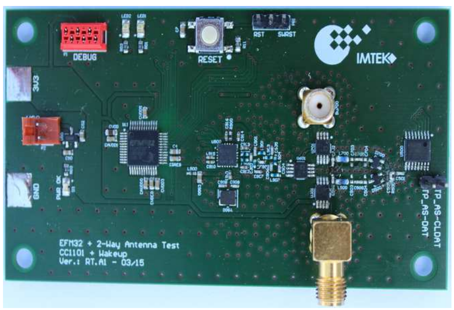


Figure 3: Wireless sensor node for two diversity antennas.

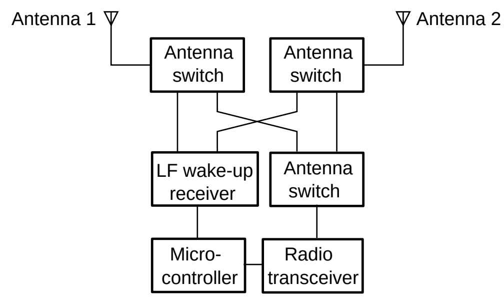


Figure 4: Schematic layout of the wireless sensor node with wake-up diversity and smart communication antenna system.

where $g_i$ is a gain factor specific to the $i$-th antenna and $V_i$ its corresponding output voltage. The cophasing and sum circuitry in Figure 1 is used to process the multiple antenna signals. This additional power consumption limits its use for wireless sensor networks [9]. Figure 2 shows the block diagram of the multiple antenna system proposed in this paper. The signals of the diversity antenna are rectified before they are combined. Due to this, the signals are in phase as long as the two antennas are not a half wavelength apart of each other, which is very unlikely for a 125 kHz signal. This means that summing of the signals can be done without further processing of the signals according to Equation (1).

## 3. HARDWARE

Figure 3 shows the sensor node used in this work which is basically the same as introduced in [4]. The node uses a 32 bit ARM Cortex M3 type EFM32 microcontroller from Silicon Labs running at 14 MHz. The controller has an energy consumption of around 0.6 µA in energy saving mode and in active mode around 2.2 mA. The communication radio is a CC1101 transceiver from Texas Instruments that draws a current of around 30 mA when sending with 10 dBm output power and around 17 mA during listening at 868 MHz.

To feature multiple antennas, the board is equipped with two antenna ports, which are connected to an ADG918 antenna switch from Analog Devices. By inserting a third antenna switch, a smart communication antenna system is realized. Due to the three extra antenna switches, the node has an additional power consumption of less than 3 µA compared to the power consumption of the node presented in [4]. Figure 4 shows schematically the signal paths on the board to realize wake-up diversity and smart antenna system for the communication link. The low frequency wake-up receiver is the AS3932 from Austriamicrosystems with a typical sensitivity of 100 µV RMS and a 16 bit wake-up address.

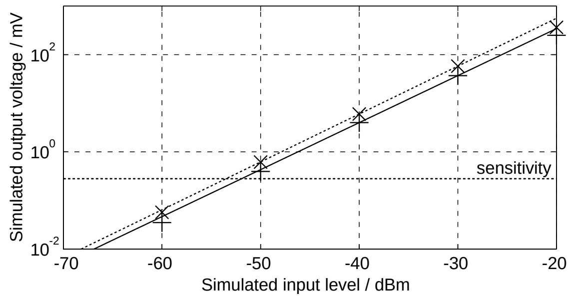


Figure 5: Simulated output voltage of the rectifier with one (solid line) and two antennas (dashed line) connected to the system. The typical sensitivity of the low-frequency receiver AS3932 is given as dotted line.

Table 1: Output voltage of rectifier at decreasing input signal levels with different antenna configurations

| Input level | Simulation (mV) | | Measurement (mV) | | |
|---|---|---|---|---|---|
| (dBm) | one antenna | two antennas | straight antenna | angular antenna | both antennas |
| −10 | 839 | 1055 | 1050 | 1036 | 1190 |
| −20 | 250 | 364 | 234 | 228 | 316 |
| −30 | 37 | 58 | 26.9 | 26.1 | 52.1 |
| −40 | 4 | 6 | 2.76 | 2.69 | 5.49 |
| −45 | - | - | 0.90 | 0.90 | 1.78 |
| −50 | 0.4 | 0.62 | 0.31 | 0.31 | 0.59 |
| −55 | - | - | 0.12 | 0.14 | 0.22 |
| −60 | 0.04 | 0.06 | 0.07 | 0.08 | 0.10 |
| −65 | - | - | 0.05 | 0.06 | 0.06 |

## 4. SIMULATION AND MEASUREMENTS

To test the general performance of the diversity path, we simulated the circuit with Agilent Advanced Design System[1] in transient simulation mode. Figure 5 shows the simulated output voltage of the rectifiers versus the antenna input power as can be seen in Table 1. Figure 5 shows the simulated output of the rectifier with one active input signal (solid line) and with both antenna ports powered simultaneously (dashed line). Both simulations show the expected exponential behavior of the diodes over the input level range. Accordingly, the data was fitted with an exponential function of the form $y = a\exp(bx)$. For the simulation with one active port $a = 29464$ and $b = 0.223$ and with two active ports $a = 52422$ and $b = 0.227$. Figures 5, 6 and 7 show the theoretical sensitivity of the low-frequency wake-up receiver AS3932 as dashed line. By investigating the intersection of the theoretical sensitivity with the fitted data, it can be seen that the sensitivity of the system with one simulated antenna is around −51.9 dBm and with two antennas around −53.5 dBm. The difference between the two simulated sensitivities is around 1.6 dB which is less than the expected 3 dB according to Equation (1).

To measure the rectified output voltage on the sensor node, two test-setups were used. At first, a signal generator was connected to the antenna ports of the board, feeding them consecutively with a 868 MHz signal at different input levels. Since both measurements achieved almost equal results, Figure 6 shows the output voltage over the input level for the straight antenna, only. An exponential function was used to fit the measurement data, superimposed on a constant noise level, that is $y = a + b\exp(cx)$ with $a = 0.043$, $b = 26\,734$ and $c = 0.23$. The theoretical sensitivity of the AS3932 intersects the fitted curve at −50.6 dBm. The circle in Figure 6 shows the sensitivity measured by using the AS3932 receiver: when the receiver did not further react to the input signals its sensitivity limit was reached. For one powered antenna it was found at −51.3 dBm. All simulated and measured sensitivities for one antenna fit very well to the results found by [3, 4].

In a second step, a second signal generator was connected to the other antenna input port also feeding it with a 868 MHz signal. Figure 7 shows the data curve fitted with an exponential function of the form $y = a + b\exp(cx)$ with $a = 0.031$, $b = 45\,410$ and $c = 0.226$. Here again, $a$ shows the noise-level of the measurement. The intersection of the fitted curve and the theoretical sensitivity

[1]Agilent Technologies, Inc., 1985–2014.

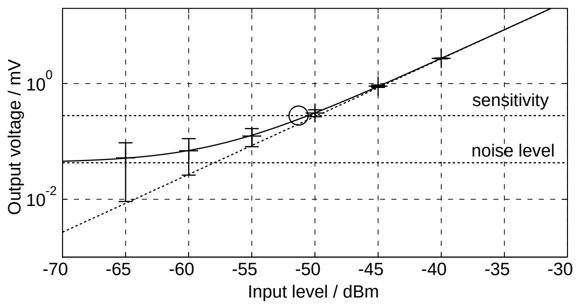


Figure 6: Measured voltage at the rectifier output with one active antenna. Typical sensitivity of the AS3932 and noise-level are given as dotted lines, the circle shows its measured sensitivity.

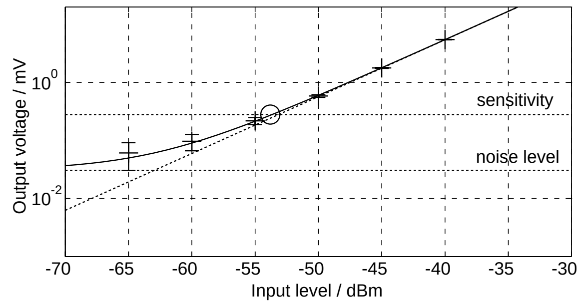


Figure 7: Measured voltage at the rectifier output with two active antennas. Typical sensitivity of the AS3932 and noise-level are given as dotted lines, the circle shows its measured sensitivity.

Table 2: The table shows the power levels of a pulsed 868 MHz signal required to wake-up the wireless sensor node in a multipath environment for different antenna configurationsk, including diversity.

| spot | straight antenna (dBm) | angular antenna (dBm) | diversity (dBm) |
|---|---|---|---|
| 1 | −4.2 | −16.3 | −17.1 |
| 2 | −7.7 | −3.9 | −9.1 |
| 3 | +0.3 | +4.8 | −0.7 |
| 4 | +4.8 | −1.1 | −3.6 |
| 5 | −0.4 | −4.0 | −5.8 |
| 6 | −8.2 | −10.8 | −13.2 |

Table 3: The table shows the wake-up sensitivities of the wireless sensor node achieved by simulation, measurement of the rectified voltage and by feeding the AS3932 with a 868 MHz input signal.

| | Sensitivity one antenna (dBm) | Sensitivity two antennas (dBm) |
|---|---|---|
| Simulation | −51.9 | −53.5 |
| Voltage measurement | −50.6 | −53.7 |
| 868 MHz input signal | −51.3 | −53.8 |

line is at −53.7 dBm. The point where the AS3932 did not longer sense the input signal was found to be at −53.8 dBm, depicted as a circle in Figure 7. This is a gain of around 3 dB compared to the system with one antenna. Table 1 shows the simulated and measured data that was used in Figures 5, 6 and 7.

To test the wake-up diversity of the wireless sensor node, we did several measurements in a laboratory with multipath propagation. A signal generator was used to send a pulsed 868 MHz signal at a defined power level. The node was placed in the laboratory and the sending power of the signal generator was decreased until the wake-up receiver did not further detect the signal. This test was repeated with different antenna configurations at six different spots in the laboratory. Table 2 summarizes the measurement results. It is visible that higher power levels are required to wake-up the receiver using single antenna configurations than by using multiple antennas, which reflects the assumptions and measurements of above.

## 5. DISCUSSION

Table 3 summarizes the wake-up sensitivities of the wireless sensor node introduced in Section 3. The results were achieved by simulation, measurement of the output voltage of the rectifiers and by feeding the AS3932 with a pulsed 868 MHz input signal. It can be seen that the sensitivity resulting from the simulation of one antenna is a little higher than the sensitivities measured at the real system. This effect is probably due to the not included substrate and microstrip lines which introduce extra capacities. It can also be seen, that the sensitivities of multiple antennas compare very well to the expected values according to Equation (1). The results for two antennas are around 3 dB above the results for one antenna. The laboratory measurements summarized in Table 2 clearly show the benefits of antenna diversity in a multipath environment.

## 6. CONCLUSION AND OUTLOOK

In this paper we presented a low-power wireless sensor node with wake-up receiver featuring polarization diversity in the wake-up path, which makes it suitable for wireless sensor networks in a multipath environment. We showed that there are almost no further active components needed to combine the signals of multiple antennas in this design. We discussed polarization diversity in the wake-up path, by using simulations and measurement setup. We showed that polarization diversity can double the signal strength at the receiver input and that the sensitivity of the wake-up receiver can be improved by 3 dB from −51.6 dBm to −53.7 dBm when both diversity antennas receive a full signal. Measurements performed in a multipath environment with different antenna configurations show the benefits of antenna diversity and underline the assumptions made before. Further, and more elaborated multipath environment measurements will be done in the future to support the first results presented here.

## ACKNOWLEDGMENT

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