SPIDA: A Direction-Finding Antenna for Wireless Sensor Networks

Martin Nilsson

Swedish Institute of Computer Science (SICS),
Box 1263, SE-164 29 Kista, Sweden

Abstract. This paper presents the design, signal processing, and field measurements of SPIDA, a direction-finding antenna for the 2.4 GHz ISM band, intended for both communication and localization in wireless sensor networks. The main design goals for the antenna were small size, low production cost, low power consumption, low signal processing requirements, and low interfacing complexity. The most expensive part of SPIDA is its SMA connector. The RF-stage power consumption is the same as for a whip antenna. The angle-of-arrival can be computed from received-power measurements through a simple formula using on the order of ten multiplications. Controlling the direction of the antenna by a microprocessor requires only a pair of digital output pins. When field tested with the TI CC2500 radio chip, the RMS error for the uncalibrated antenna was less than 12° up to 100 m distance, covering nearly the full receiving range of the antenna at 1 mW transmitter output power. A distinguishing feature of the SPIDA antenna is the absence of side lobes, despite using a manufacturing-friendly and cost-conscious sparse ground plane.

Keywords: direction finding, antenna, parasitic elements, angle of arrival, localization, wireless sensor network.

1 Introduction

There are many potential uses for directional antennas in wireless sensor networks (WSN). For instance, the directivity can be used for economizing transmitted power, and it can also be used for localization, where a useful piece of information is the angle of arrival (AOA, a.k.a. direction-of-arrival, DOA) of a transmission. Many direction finding (DF) antennas have been proposed, including loop, Adcock-pair, pseudo-Doppler, and phased-array antennas [1, 2, 3], but they often have properties unsuitable for WSN applications, which demand small and inexpensive antennas, but are not allowed any complex circuitry nor computationally heavy signal processing.

In this paper, we describe SPIDA, *Sics Parasitic Interference Directional Antenna*, which satisfies the basic requirements of electronically steerable directional antennas for WSN (fig. 1). SPIDA was primarily developed for localization applications (i.e. concurrent communication and AOA measurements), but it can also be used for

P.J. Marron et al. (Eds.): REALWSN 2010, LNCS 6511, pp. 138–145, 2010.

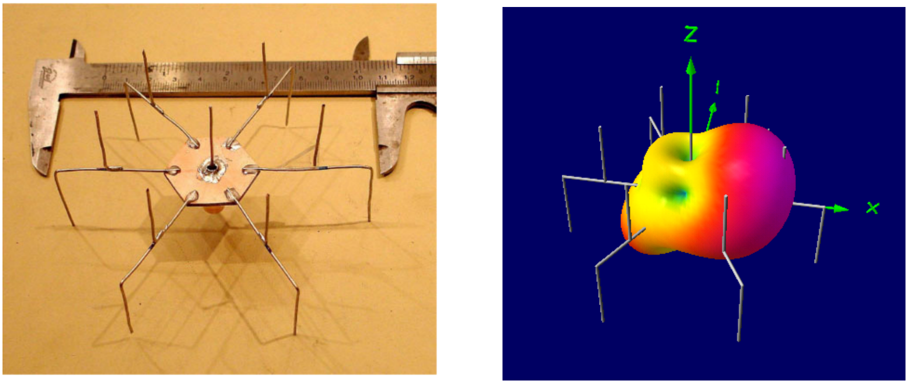

Fig. 1. (Left). The SPIDA antenna. In this setup, the rightmost parasitic element is isolated, while the others are grounded. The central element is a conventional monopole. **(Right).** The main lobe of SPIDA is quite smooth, as computed by 4Nec2 simulation.

enhancing transmission and reception in software-controllable directions. This paper focuses on the direction finding aspects of the antenna.

Radio direction finding antennas can compute AOA by measuring either the amplitude (power) of the incoming signal, or the phase (or both). An advantage of measuring the phase is that it is less affected by noise, compared to amplitude. However, RF phase measurement needs more advanced electronics with a highly stable timebase. Since this is presently difficult to achieve for an inexpensive WSN node, we have restricted the scope to amplitude measurements.

This paper is organized as follows: In the next section, we describe the design of SPIDA. In the following section, we describe how AOA data can be extracted from RSSI readings. In section 4, we describe the experimental setup and the measurement results. Section 5 concludes the paper.

2 The SPIDA Design

One of the major requirements of an antenna for WSN is small size. A fundamental fact of antenna theory says that an antenna cannot be much smaller in diameter than the wavelength [4]. If smaller, the efficiency drops dramatically. Since the 2.4-GHz ISM band can probably be considered a representative standard frequency for WSN applications, corresponding to a wavelength λ of approximately 120 mm, we can expect the antenna to be of roughly this size as well.

SPIDA, first conceived in [3], is a kind of *Electronically-Switched Parasitic-Element* (ESPE) antenna.. The ESPE principle was first published in 1979 [5], and has subsequently been developed further [6, 7]. An ESPE antenna consists of a central monopole, surrounded by a number of monopole-like parasitic elements spaced approximately $\lambda/4$ apart. In its simplest form, the parasitic elements are switched between ground, when they operate as reflectors, and isolation, when they operate as directors. In a more advanced form, the reactance between the elements can be controlled. This can be done by biasing a capacitance diode with a controlled DC voltage.

An attractive property of the ESPE antenna is that the parasitic elements are not involved in the active RF chain. The ring of parasitic elements on a ground plane can be added as a sleeve around an existing monopole, and each parasitic element can be controlled by a digital microprocessor output. The ESPE antenna is well suited to WSN applications, thanks to its small size and simplicity.

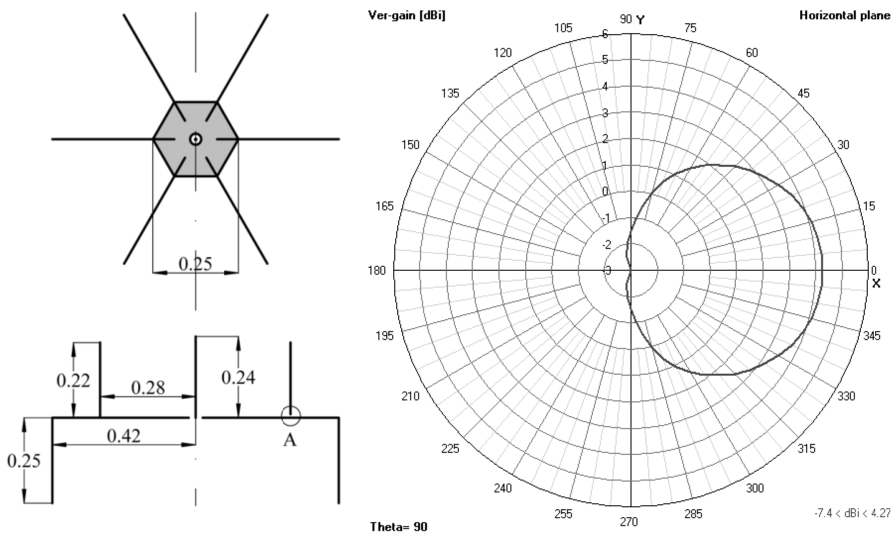

Fig. 2. (Left). Dimensions of SPIDA. Measures are in wavelengths. The directivity is controlled by isolating one element (A) in the preferred direction. **(Right).** Horizontal plane gain pattern computed by 4Nec2. The pattern has the desirable rounded shape.

Physical construction. The main distinguishing feature of SPIDA is its *sparse ground plane*. After extensive simulations it was found that this sparse ground plane gives the antenna a smooth main lobe without significant side lobes, which seems counter-intuitive from the viewpoint of classical antenna design. The absence of side lobes is highly desirable for the purpose of efficiently extracting AOA data from amplitude (RSSI) readings (cf. section 3 below).

SPIDA consists of a 3cm-diameter hexagonal disc made of ordinary copper-clad FR-4 circuit board, on which six legs made of standard 1-mm copper wire have been soldered as ground plane. No solid ground skirt is used. An SMA-connector is mounted centrally on the disc. The WSN node can be attached directly to this connector, eliminating the feed line.

The parts cost for SPIDA is dominated by the SMA connector (~10 USD in single quantities). The antenna can be built in a short time, and can be easily tuned, thanks to the active and passive elements being ordinary copper wires, which can be bent and cut with good precision after soldering. The antenna does not require any additional amplifier beyond that needed by the central monopole. The parasitic elements can be switched at low frequency, without consuming DC power.

Nominal characteristics. The antenna was initially developed and optimized using the 4Nec2 antenna simulation package [8, 9]. The nominal performance, as indicated by this program, is an antenna gain of approximately 4 dBi and a front-to-back ratio of 11 dB. The main lobe is smooth (fig. 1, right) and the gain (in dB) in the horizontal plane is nearly an offset circle (fig. 2, right). Since the antenna is supposed to be useful throughout the 2.4-GHz band (2400-2480 MHz), the antenna impedance varies, and it is not possible to design a fixed impedance matching circuit perfect throughout this frequency range. On the other hand, since the distance between the antenna and the RF output amplifier is normally much shorter than the wavelength in a WSN node, the need for precise impedance matching is relaxed.

Interfacing. The SPIDA antenna measured uses a fixed directing element and fixed reflecting elements, but normally, the elements are switched between ground and isolation under program control.

An advantage of ESPE antennas greatly simplifying implementation is that the control of this switch is not part of the RF path, and can be done arbitrarily slowly. There are three common methods for implementing the switch [10]. The traditional method uses PIN diodes, consuming a bias current, and a fair number of additional components. A more recent approach uses GaAs pHEMT transistors, requiring fewer discrete components, but such transistors are relatively expensive. Recently, however, inexpensive CMOS RF switches have become available, e.g. ADG902 from Analog Devices and BGS12A from Infineon, rendering the interfacing of SPIDA close to trivial. The CMOS switches consume practically no quiescent DC current and require no additional components. An interface for SPIDA using ADG902 was built and evaluated by Öström et al. [11].

In order to control the switches from a microprocessor, one digital output is required for each switch. If an external shift register is used, a pair of digital outputs suffices, one for data and one for clock output.

3 Signal Processing

A WSN node possesses only limited resources in terms of time and power for signal processing in order to extract AOA data from a transmission. For this reason, it is crucially important that the lobes can be formed so that efficient signal processing algorithms can be applied. The ideal pattern in this respect is an offset circle, since the received power then approximates a cosine as a function of the AOA, and the AOA can be estimated as the phase of that cosine. For this case, there is a highly efficient computational method, which extracts the phase of a sine wave with a known frequency [12]. Suppose that P_k, $0 \le k < N(=6)$ is the power measured when parasitic element k is isolated (i.e. becomes a director). Let

$$S = \sum_{k=0}^{N-1} \sin\left(\frac{2\pi k}{N}\right) P_k$$
$$C = \sum_{k=0}^{N-1} \cos\left(\frac{2\pi k}{N}\right) P_k \tag{1}$$
$$A = \sqrt{S^2 + C^2}$$

Then, for the estimate α of AOA,

$$\begin{aligned} \sin\alpha &= C / A \\ \cos\alpha &= -S / A \end{aligned} . \tag{2}$$

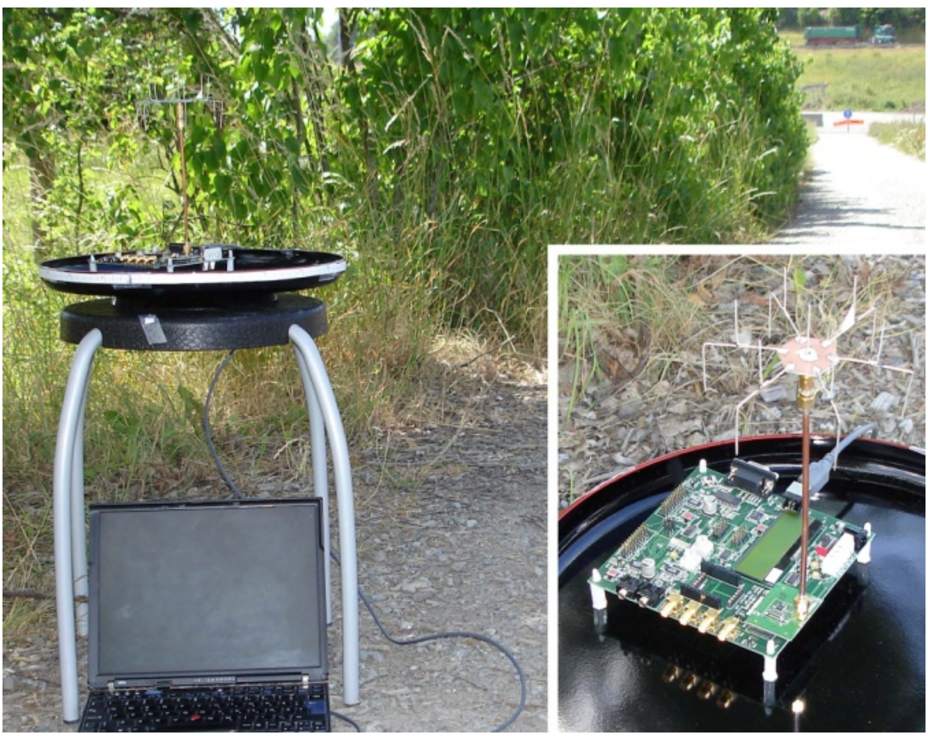

Fig. 3. Measurement setup. The receiver is in picture. The transmitter is located in the upper right corner, at the street sign at the end of the road.

4 Results

4.1 Test Setup

We measured SPIDA in outdoor and indoor experiments. For measurements, we used Texas Instruments' CC2500DK development kit [13]. This kit contains two microcontroller boards and two CC2500 radio daughter boards, together with software that can transmit test packets, and collect RSSI measurements from the CC2500 chips. SPIDA was attached to one radio board used as a receiver, while a conventional monopole was attached to the other board used as transmitter. The test software SmartRF Studio 7 was executed on two PC laptops, each connected to its own microcontroller board.

The transmitter was placed on a chair, giving the antenna a height approximately 0.5 m above ground. The transmitter was set up to continuously send packets of 24 bytes including preamble, at 2.4 kBaud on 2440 MHz. Other frequencies were also tested, but the choice of frequency appeared not to affect measurements. The transmitter output power was 1 mW. The receiver was placed on a rotating table (fig. 3), which was then placed on a chair at about the same height as the transmitter. The rotating table was rotated manually, and the average RSSI for 16 packets was recorded at 22 positions around the table. For each distance, three such series were measured and the median of the readings were taken as the final RSSI measurement. The reference direction was set by eyesight. The antenna was not calibrated or tuned in any way before measurements.

We performed a total of four experiments, measuring outdoors at distances of 20m, 50m, and 100m between transmitter and receiver, and indoors at a distance of 7m. At 100m distance, the received power was nearly down to the noise floor (~ -105 dBm) and there was considerable packet loss.

4.2 Measurement Results

The AOA estimates showed reasonably linear responses for all four experiments (fig. 4, top). The RMS error was less than 12° in all cases (table 1). The performance appears to deteriorate slowly with distance, but remains reasonable throughout the receiving range of around 100m (fig. 4, bottom). Part of the explanation for the offset error is probably the manual zero adjustment, which was not very precise.

Table 1. RMS error and received power for the test settings

Setting	AOA RMS error	Average received power
Outdoor, 20m	11.97°	-70 dBm
Outdoor, 50m	6.14°	-86 dBm
Outdoor, 100m	10.49°	-99 dBm
Indoor, 7m	11.67°	-63 dBm

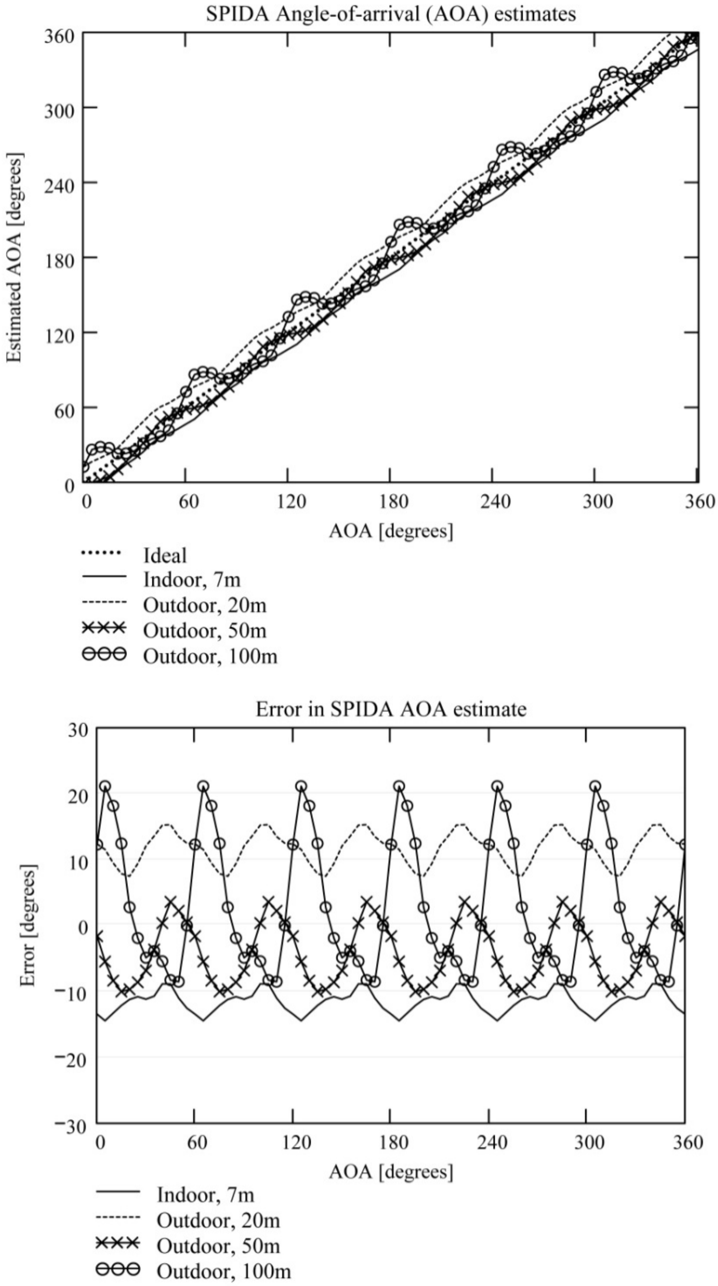

Fig. 4. (Top) AOA values show linear behavior for all distances. **(Bottom)** Error deteriorates as distance increases, but remains reasonable throughout receiving range.

5 Conclusions

We did not make great efforts to find noise-free locations for measurements, but the indoor measurements did require an adjustment in order to avoid a noisy location in the neighborhood of a WLAN access point. In general, one should expect indoor AOA measurements to be difficult and require redundancy. We first tried outdoor measurements in a soccer field, which failed, probably because a surrounding metal fence created a nearly homogeneous radiation pattern. Anyway, the RMS error of 12°, which must be considered low for the circumstances, indicates that the simple SPIDA approach may indeed be viable in many situations.

Acknowledgments. This work was carried out within the SICS Center for Networked Systems, funded by VINNOVA, SSF, KKS, ABB, Ericsson, Saab Systems, TeliaSonera and T2Data.

References

1. American Radio Relay League: The ARRL Handbook for Radio Communications (2009) ISBN 0-87259-146-8
2. Carr, J.J.: Practical Antenna Handbook, 4th edn. McGraw-Hill, New York (2001) ISBN 0-07-137453-3
3. Nilsson, M.: Directional antennas for wireless sensor networks. In: Proc. 9th Scandinavian Workshop on Wireless Adhoc Networks (Adhoc 2009), Uppsala, Sweden, May 4-5 (2009)
4. Hansen, R.C.: Electrically Small, Superdirective, and Superconducting Antennas. John Wiley, Chichester (2006) ISBN 978-0-471-78255-1
5. Harrington, R.F.: Switched Parasitic Antennas for Cellular Communications. IEEE Trans. Antennas and Propagation AP-26(3), 390–395 (1978)
6. Thiel, D.V., Smith, S.: Reactively controlled directive arrays. Artec House, Inc., Boston (2002) ISBN 1-58053-154-7
7. Schlub, R., Lu, J., Ohira, T.: Seven-Element Ground Skirt Monopole ESPAR Antenna Design From a Genetic Algorithm and the Finite Element Method. IEEE Trans. Antennas and Propagation 51(11) (2003)
8. Voors, A.: 4Nec2: Nec-based antenna modeler and simulator (2010), `http://home.ict.nl/~arivoors/`
9. Burke G.J., Poggio, A.J.: Numerical Electromagnetics Code (NEC): Method of Moments.Lawrence Livermore Laboratories, USA. Technical Report UCID-18834 (1981)
10. RF CMOS SPDT Switches. Infineon Application Note No. 175 (2009)
11. Öström, E., Mottola, L., Voigt, T.: Evaluating an Electronically Switched Directional Antenna for Real-world Low-power Wireless Networks. In: Proc. Int. workshop Real-world wireless Sensor Networks, Colombo, Sri Lanka, December 17-19 (2010)
12. Rauch, L.L.: On Estimating the Phase of a Periodic Waveform in Additive Gaussian Noise - Part I. NASA DSN Progress report 42-45 (1978)
13. CC2500DK Development Kit User Manual 1.4 (Rev. C). Texas Instruments (2007)