Towards An Ultra-Low-Power Electronically Controllable Array Antenna for WSN

A. A. Lysko[1]

Abstract – **This paper discusses steps towards a low-power beam-switching array antenna suitable for wireless sensor network (WSN) applications. Such an antenna will help to improve the signal to noise ratio (SNR), and thus throughput, latency and other important wireless network performance parameters. The power consumption is a factor critical for the long autonomous operation of battery-powered WSN nodes, and has thus been given special attention.**

A prototype was manufactured and has demonstrated a good match between the simulated and experimentally measured gain and return loss. The power consumption of the RF electronics was also measured and found to be below 1.1 mW.

1 INTRODUCTION

The wide range of opportunities offered by wire-free connectivity, remote access to data, simplified configuration, and mobility, has been steadily growing the demand for wireless solutions [1].

An antenna is an essential component of any wireless system. It interfaces between the waveguides, such as a coaxial cable or microstrip line, and the information conveying medium, air. From a system engineering point of view [2], the main criteria for an antenna to be suitable for a particular wireless system include impedance match for the frequency band of interest, antenna gain. The impedance match determines the ability of the antenna to transfer the signals it receives into radiating current, and may be considered as affecting the behaviour of a wireless system in isolation. On the other hand, the antenna's ability to focus the radiation, indicated by its gain, also determines how the wireless system interacts with the environment. This includes the communication range of the system, ability to withstand interference, and generation of interference. In a non-sparse wireless network, the relation to interference, inclusive of network's self-interference, usually determines the throughput of the wireless network [3]. For example, a high gain antenna can help to maximize the signal to noise ratio and thus achieve the best possible throughput (e.g. [4] reports 10x improvement), and lowest latency.

In a wireless network, especially for where a manual configuration may not be desirable, e.g. mobile networks, or where the network's nodes are unreliable, e.g. due to unreliable power, the direction of the beam may need to be changed. This requires mechanical or electronic control of the beam formed by the antenna.

In the domain of wireless sensor networks (WSN) [5], especially for those WSN deployed in open, especially in remote locations [6] or rural areas [7], there is often a strong need to keep the power consumption to a minimum. This can permit to run battery powered nodes in a network for a long time.

2 SELECTING THE PARASITIC ARRAY

The recently developed fully digital arrays [8], [9] are both very expensive and extremely power hungry, as they require a lot of digital electronics. Even the traditional electronically controlled phased array antennas based on phase shifters are still relatively expensive due to a high count of the radio frequency (RF) components. The mechanically steerable antennas are also unsuitable because of their susceptibility to environmental damage.

The parasitic array technology is on the other hand a technology offering a low RF component count and nearly the same configurability as the more conventional phased arrays. The research into parasitic array antennas started with [10] and has by now received considerable attention, for example [11], [12], [13], [14], [15]. In a parasitic array antenna, there is usually one element which is connected to the RF port, and many parasitic elements. The purpose of the parasitic elements is to adjust the phase of the fields to produce the beam of desired shape. A well known example of a parasitic array antenna is Yagi-Uda antenna [16].

In order to control the shape of the beam, e.g. to change the direction of the beam, the loads attached to the parasitic elements may be varied.

In practice, these control elements may have limited capabilities restricting the control of the beam, and may require optimization [17]. The control can be done discretely or continuously. The nearly continuous variation of the load allows for more accurate control. However, the electronic loads, together with the passive and active electronics controlling them, determine the power consumption due to the array itself. To be able to produce a fine voltage control, one usually requires a digital to analogue converter (ADC). In addition, one may

[1] Meraka Institute, Council for Scientific and Indistrial Research (CSIR), Pretoria, 0001, South Africa,
e-mail: alysko@csir.co.za, tel.: +27 12 841 4609, fax: +27 12 841 4720.

require additional chips to interface several ADCs, altogether adding to the cost and power consumption.

3 ANTENNA AND ITS DESIGN

The antenna under consideration in this paper is designed as a 2.4 GHz parasitic array antenna using radio frequency (RF) switches [18] with very low power consumption. The parasitic elements are set equidistantly around a circle. The design builds upon our previously reported results, e.g. [19], [17].

The design started with preparing a printed circuit board (PCB) layout for the RF switch. The layout is shown in Figure 1. The design was made to minimize the lengths of the paths between the antenna and the pole of the switch, and between the throw of the switch and the grounding. The capacitance of the open circuited state was minimized by maximizing the spacing to the neighbouring elements with metallization.

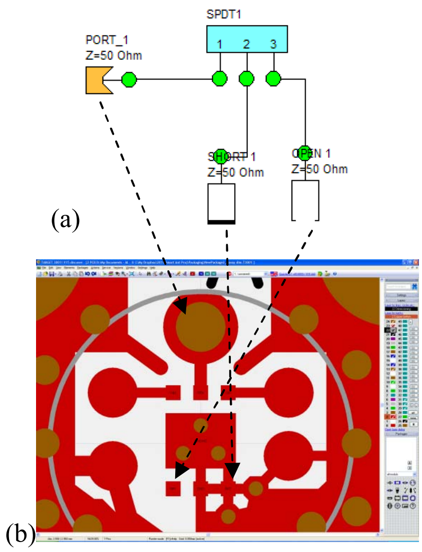

Figure 1: (a) Idealized connection between antenna port (PORT_1) and the two ports of the SPDT RF switch (short- and open-circuited, respectively). (b) Print-screen of the metallization layer for the RF switch with 6 pads connected to a via for monopole, Vcc, control, ground and not connected (NC).

This layout was analysed and numerically modelled to identify the parasitics associated with the loads for the RF switches and connecting circuitry. The commercial program WIPL-D [20], [21] as well as own codes [22], [23] were used.

There were several components to include: (a) open circuit state load of the RF switch, (b) short circuit state load of the RF switch, and (c) the connection between the switch and the monopole antenna.

(a) The determination of the open circuit state was the most challenging due to fine nature of the effects due to parasitic capacitance, as for example shown in Figure 2.

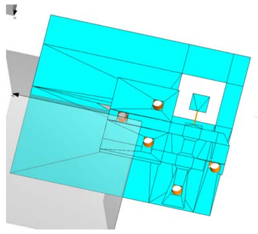

Figure 2: Modeling the open-circuiting a port of SPDT switch. The yellow line represents the countour of numerical measurement.

The model was found to be sensitive (e.g. 40% change for a different way of excitation). Nevertheless, at 2.4GHz, the small value (0.01 pF for vacuum), even if multiplied by the dielectric constant of the actual substrate of 3.38, value of the parasitic capacitance can be considered small compared to the effects due to the RF switch itself.

(b) Modeling parasitic inductance in short-circuiting a port of SPDT switch was done using lumped model from [17].

(c) The determination of the parasitic inductance due to grounding through short microstrip lines and vias is shown in Figure 3 and was in two alternative ways. Approximating the lines and vias with wires as inductors lead to an estimate of 0.46 nH. Usage of WIPL-D [20], illustrated in Figure 3, gave a close figure of 0.63 nH.

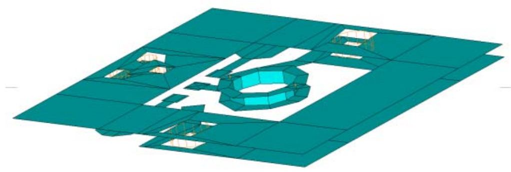

Figure 3: Modelling the connection between the RF switch and monopole antenna.

The obtained models were put together, as illustrated with Figure 4a, and also compared against several other models considered (not included into this paper). The plot in Figure 4b shows that the non-ideal termination reflected via different models seems to have a relatively low impact. The switch introduces losses. The most important effect seems to be due to the inductivity in the path connecting the switch to the antenna (creating the rotation of the curves).

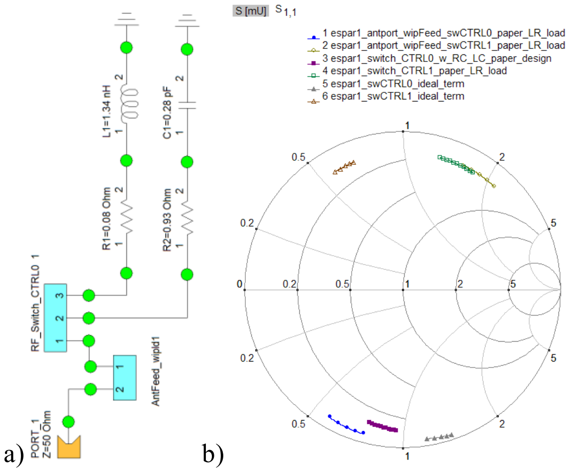

Figure 4: Combined model of SPDT RF switch connecting the antenna to unideally open/short-circuited ports (a). Comparison of results of several models (b). This includes an ideal termination of the switch.

This model was then simplified to represent the open and short circuit termination loads for the antenna with +90 Ω and -33 Ω, respectively, and then used to determine optimal dimensions of the antenna, in a manner similar to [17]. Out of the all possible states for all the RF switches connected to all the parasitic elements, a much smaller number of unique states have been identified, thus reducing the amount of required modelling significantly.

3 PROTOTYPE AND MEASUREMENTS

The prototype of the antenna was made of individual 12mm x 12mm PCB-assembled elements shown in Figure 5a/b and mounted on a 50cm x 50cm aluminium ground plane, as displayed in Figure 5c. Three parasitic elements were positioned around a circle, at 90°, 180°, and 270°, with respect to the direction of origin, and at radius of 37.8 mm from the centre. The length of the active element was 27.5 mm, whilst the length of the parasitic elements was left at 58.56 mm? 38mm.

Samples of the comparison of the measurement and simulation results are shown in Figure 6. The figure displays a good match between the measured and simulated radiation patterns. The simulated impedance match shows the correct profile, with worse performance than the measured data shows. This may indicate that the additional tuning of the models may be required.

3.1 Power consumption

Power consumption by the switch [18] was measured using Agilent U1242B in an environment with temperature 21.3±0.3°C. The control current was found to be below the measurement capabilities of U1242B (0.1μA). The highest power consumption P was for the logical state 1 and estimated using the calculated uncertainties, as

$$P = (2.725\text{V} \pm 0.1\text{ V})\cdot(132.4\mu\text{A} \pm 1.1\mu\text{A}) = 361\mu\text{W} \pm 16\mu\text{W}$$

Thus, the 3-element array consumes less than 1.1 mW, which is excellent considering that the RF switches can handle up to 32 mW of RF power (at 1 dB point), sufficient for most WSN applications.

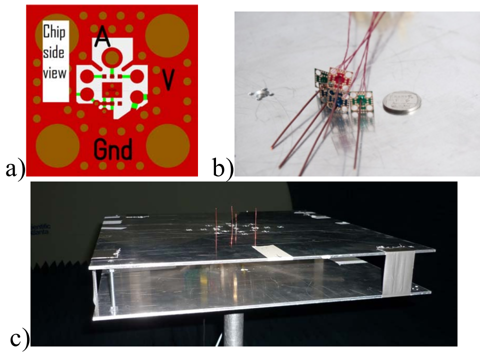

Figure 5: a) SPDT switch assembly for terminating a parasitic element, b) manufactured controllable parasitic elements, c) gain pattern measurement set-up for horizontal/H-plane.

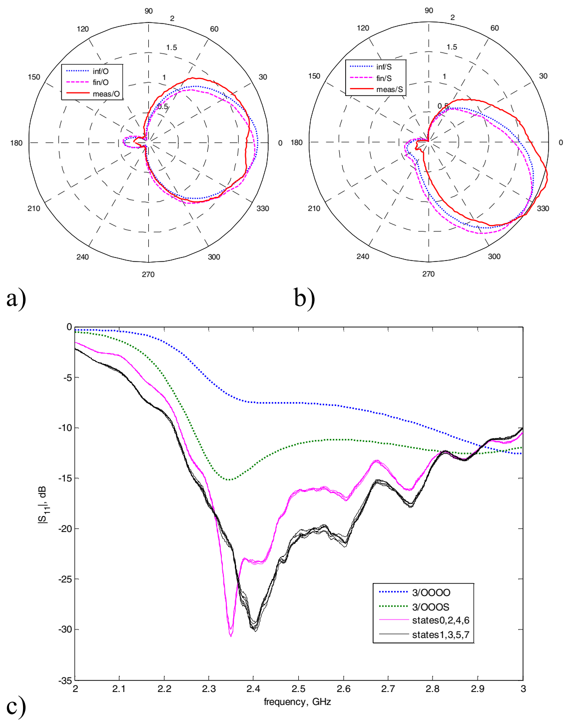

Figure 6: (a) Normalized gain pattern simulated with infintite (inf) and finite (fin) ground plane vesrus measurements (meas) for states 0 (a) and 1 (b). (c) Impedance match simulated (OOOO/OOOS) and measured (#). The OOOO corresponds to the state 0. The OOOS corresponds to the state 1.

4 CONCLUSION

The paper discusses parts of the design and measurements for a prototype of a low power antenna suitable for energy sensitive applications, such as wireless sensor networks. The antenna manufactured showed a good impedance match and directivity performance, as well as excellently low power consumption of 1.1 mW.

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