Assessment of a Low Profile Planar Antenna for a Wireless Sensor Network Monitoring the Local Water Distribution Network

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Abstract

This paper presents an assessment on the suitability of a low-profile planar antenna for a Wireless Sensor Network (WSN) application monitoring the water supply at Fire Hydrants (FHs). The antenna must have a low profile so that it can be mounted on the FH lid; it must have an omnidirectional radiation pattern so that it can communicate with base stations at low elevations; and it must operate in the 2.4 GHz Industrial, Scientific and Medical (ISM) band. Measurements show that for the majority of the 2.4 GHz ISM band, the antenna has a return loss of at least -10 dB and efficiency greater than 60 %.

For the FH WSN assessment, the antenna was deployed as a transmitter mounted on the FH lid above the underground FH chamber and a vertically polarised monopole antenna mounted on a mast at various specified heights above ground level was used to measure the received power as a function of distance. The path loss results were compared with those from a previous deployment, where the FH antenna was located in the FH chamber, and it is found that using the low-profile antenna reduced the path loss by at least 10 dB over the measured transmitter and receiver separation.

I Introduction

It has previously been identified that an important application for Wireless Sensor Networks (WSNs) is monitoring the pressure, acoustic noise, turbidity and flow rate of the local water distribution network via sensors located within Fire Hydrant (FH) chambers [1–3]. In the FH

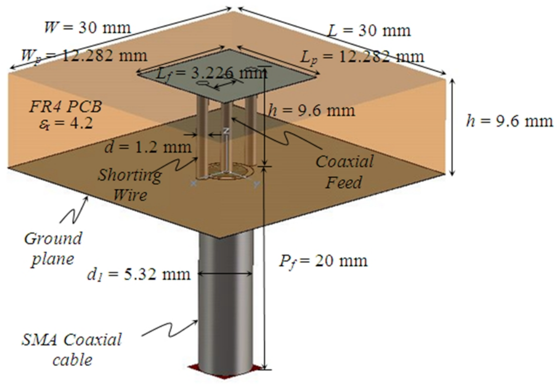

Figure 1: Printed patch-type antenna.

application the antenna must communicate with above ground base stations (BSs) mounted on nearby buildings (i.e., at low elevations above the horizontal). Current civil FH water supply infrastructure has located the wireless sensor node antenna within the below ground FH chambers that have lids made of cast iron [1] which results in poor communication with the above ground BS (owing to the metal components within the chamber, and its assymetric layout mean it is unlikely that the FH will have an omnidirectional radiation pattern). Therefore we propose that it would be desirable to have a low-profile over-ground antenna mounted on the cast iron lid to address this problem. Lin et al [1] also identify the 2.4 GHz Industrial Scientific and Medical (ISM) as the prefered band of operation, and we are especially interested in the performance between 2.4 and 2.48 GHz, i.e., the band covering the *802.15.4* channels [4] used by many WSNs such as the Memsic MICAz [5].

We therefore specify three requirements for the antenna: firstly that it must be low profile, so we can mount it on the FH lid; secondly it must have an omnidirectional radiation pattern, so that it can communicate effectively to the low elevation BSs; and thirdly it must operate between 2.4 and 2.48 GHz. High profile omnidirectional antennas such as monopoles, oriented for uniform radiation in horizontal directions on the surface of the Earth are widely used for terrestrial wireless communication networks. However, they are not suitable for the aforementioned WSN monitoring applications due to their high profile nature. Hence, simple planar antennas with monopole-like vertically polarised omnidirectional radiation patterns are ideal for this ap-

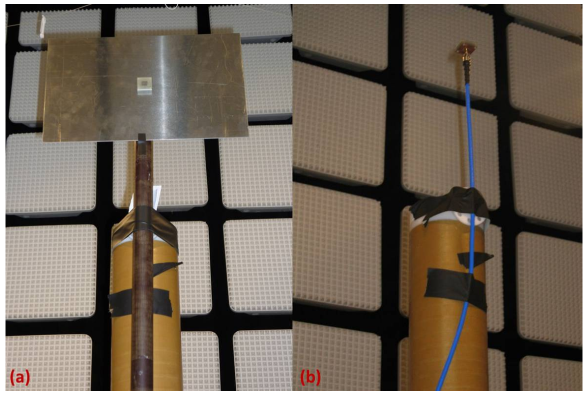

Figure 2: (a): Printed patch-type antenna with antenna stood 1 mm off ground plane; (b) Printed patch-type antenna without ground plane.

plication. To this end, we have identified a low-profile printed patch-type antenna, based on those proposed by Delaveaud *et al* [6]; Conway *et al* [7], [8]; and Chandran *et al* [9] as the ideal candidate. The developed printed patch-type antenna is shown in Figure 1; it operates between 2.4 – 2.48 GHz and consists of a ground plane and patch metallisation on a dielectric substrate, a coaxial feed probe connected to the centre of the patch through the ground plane, a dielectric substrate, and two ground shorting vias offset from the feed. The antenna shorting via placements have been optimised for operation above a metallic ground plane having the same dimensions as the FH lid (see Figure 2 (a)), and the chosen dielectric is FR4, so that it can be manufactured using standard PCB processing methods. In this work, we aim to assess the effectiveness of our antenna for the FH application.

The remainder of the paper is organised as follows: In Section II we characterise the antenna and compare the result to the simulations undertaken during the design process; in Section III we assess the effectiveness of the antenna when deployed at the FH; and finally conclusions are drawn in Section IV.

II Characterisation of the Antenna

The objective of the characterisation is to confirm that the antenna operates between 2.4 and 2.48 GHz with the desired omnidirectional radiation pattern and with high efficiency. The mea-

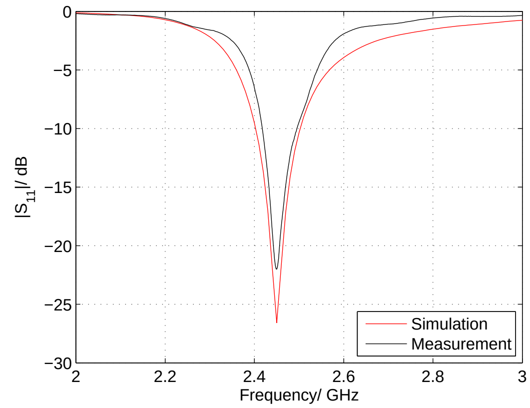

Figure 3: $|S_{11}|$ of patch antenna without ground plane.

surements were undertaken in the UK National Physical Laboratory (NPL) Small Antenna Radiated Testing (SMART) range [10], [11] and compared to simulations performed using CST Microwave Studio [12]. The antenna design has taken into account that when deployed at the FH it will be mounted on an additional ground plane (see Figure 6-(c)), therefore the characterisation takes place both with and without the ground plane, as shown in Figure 2. Figure 3 shows the S_{11} characterisation of the antenna, and we observe a reasonable agreement between simulation and measurement results. We require that the return loss is at least -10 dB [13], and we can see that this is the case for the majority of the required operating band (2.42 – 2.48 GHz).

To calculate the radiation efficiency we performed a three dimensional radiation pattern measurement of the antenna in the SMART range to find the antenna directivity (we then measure the antenna gain using substitution method with a reference gain antenna and finally evaluate the efficiency with the measured directivity and gain). We see in Figure 4 that the efficiency is between 60% and 73% throughout the band, which is acceptable for most wireless applications.

Figures 5 (a) and 5 (b) show the E-plane cuts for the antenna both with and without ground plane respectively. We note that the ground plane has the effect of 'pushing' the direction of maximum radiation away from the horizontal to approximately 40^o above the horizontal. We can also see that there is some discrepancy between simulation and measurements for the case

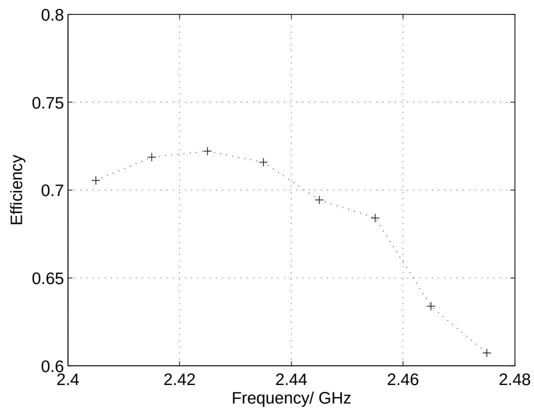

Figure 4: Antenna radiation efficiency without ground plane.

without the ground plane, however with the ground plane in place the agreement is very good. A possible explanation for this is that the ground plane reduces the effect of the cable, which was not included in the simulation.

It is required that when deployed at the FH (i.e., mounted on the ground plane) the antenna radiation pattern is omnidirectional. We can see from the H-plane cut shown in Figure 5 (d) that this is indeed the case. Figure 5 (c) shows that the radiation pattern is also omnidirectional without the ground plane.

III Fire Hydrant WSN Assessment

We undertook propagation measurements to evaluate the performance of the low profile antenna in the actual FH water supply infrastructure. Figure 6 shows the measurement set-up. Note that this shows a prototype only, and for a finished product the problem of how to integrate the antenna such that its protrusion does not cause practical problems (such as tripping) must be addressed. The aim is to measure the received signal power as a function of separation between a vertically pointing receiving half wavelength dipole antenna located at various specified heights above ground level and the designed transmitting low profile antenna located on the lid of the FH. The receive antenna is mounted at heights of 2.14 m, 4.14 m and 6.29 m above ground level and the received signal power measurements were recorded while pushing the trolley at an

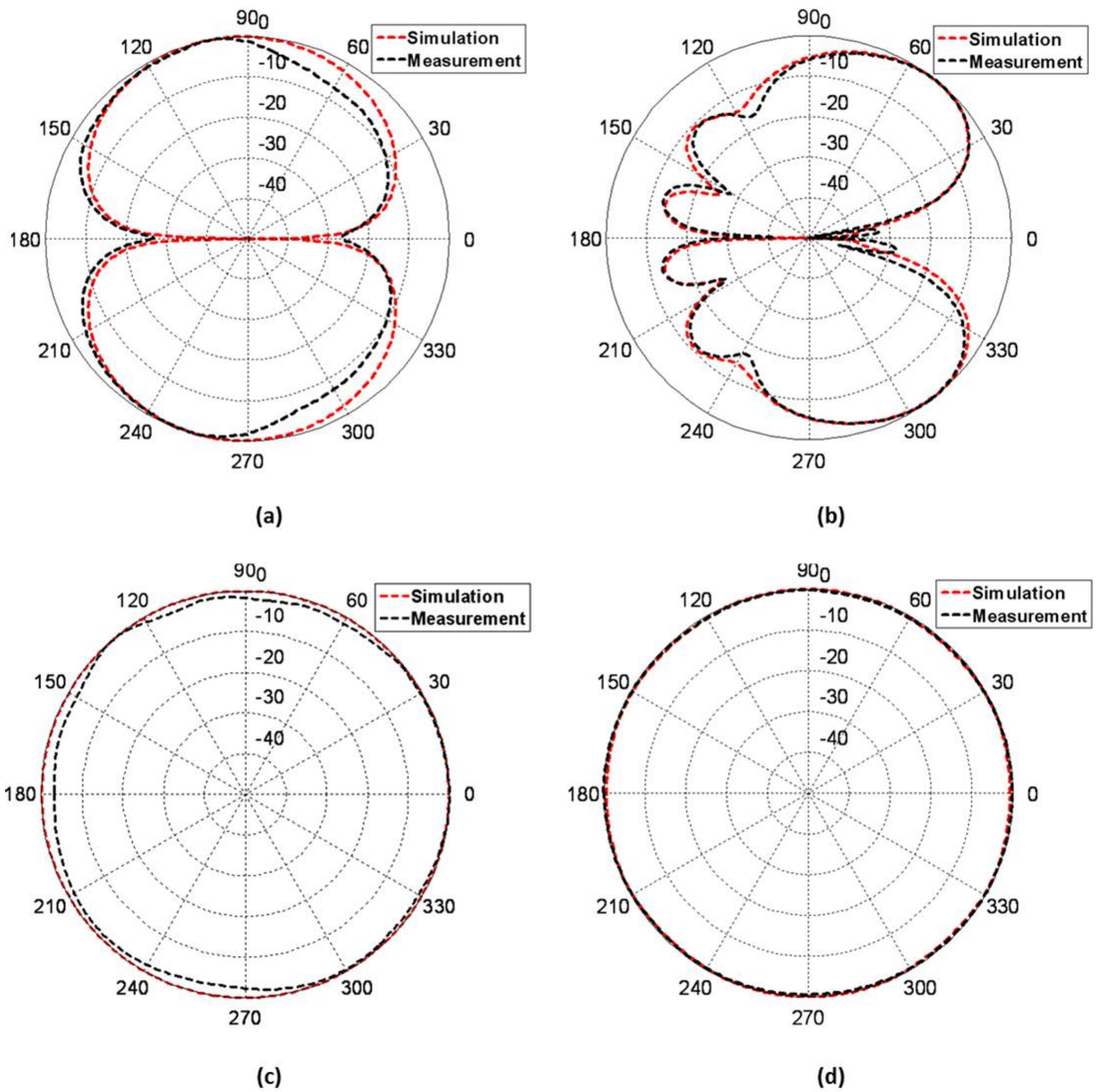

Figure 5: (a) E-plane co-polar cut without the metallic ground plane; (b) E-plane co-polar cut with the metallic ground plane, antenna stand-off 1 mm; (c) H-plane co-polar cut without the metallic ground plane; (d) H-plane co-polar cut with the metallic ground plane, antenna stand-off 1 mm;

approximately constant velocity. Note that the trolley velocity is low (slow walking pace) and the purpose of moving the trolley is to characterise the propagation between the FH and a stationary BS as a function of distance (as opposed to between the FH and a mobile antenna). To investigate the effectiveness of reducing the FH antenna peak gain angle, two transmit antenna

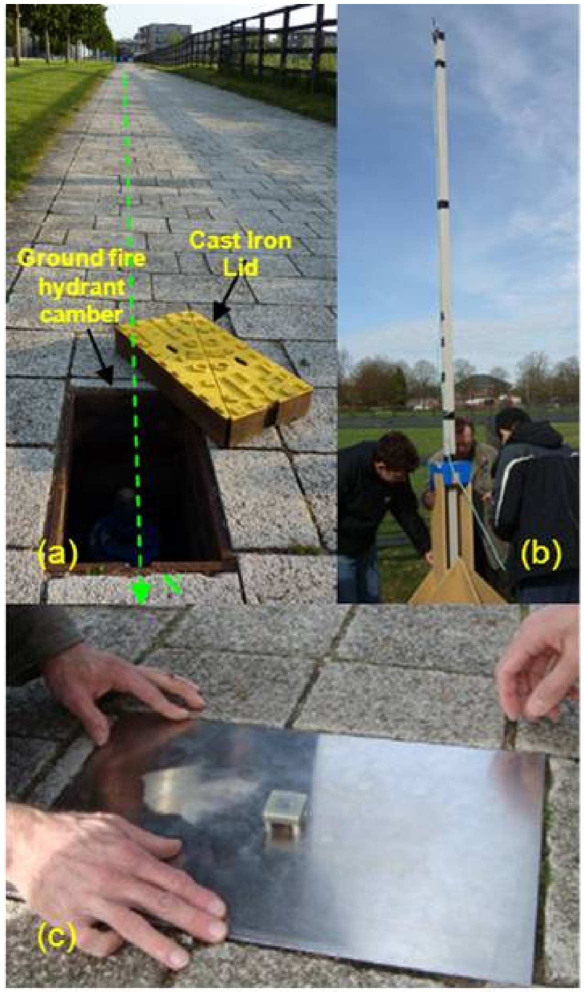

Figure 6: (a): The fire hydrant measurement environment; (b)- the experimental set-up at the receiving antenna on a trolley mounted mast; (c)- the designed transmitting low profile antenna mounted on a metallic ground plane that replaces the original cast iron FH lid.

configurations are studied, namely, 1 mm stand-off (i.e., the antenna mounted directly on the metallic ground plane) or 10 mm stand-off (i.e., the antenna 10 mm above the metallic ground plane). The transmitter unit comprises a battery powered signal source operating at 2.485 GHz (note that this is marginally outside of the specified 2.4 – 2.48 GHz range, however this is not crucial).

From the flat-earth model, we expect to see a slope with gradient of -40 dB/decade of received signal with distance, at sufficiently large distances from the transmitter [14]:

$$\left(\frac{P_R}{P_T}\right) = G_T G_R \left(\frac{h_T h_R}{d^2}\right)^2, \tag{1}$$

where P_R and P_T are the received and transmitted powers, respectively, G_R and G_T are the receive and transmit antenna gains, respectively, h_R and h_T are the receive and transmit antenna heights above the plane, respectively and d is the separation distance between the transmitter and receiver.

The path loss (PL) is defined as in [1]:

$$PL_{(dB)} = P_{T(dBm)} + G_{T(dB)} + G_{R(dB)} - P_{R(dBm)}. \tag{2}$$

We set $G_{T(dB)} = 0$, i.e., we treat the gain of the low-profile antenna as zero, as we are interested in its performance as part of the channel (i.e., contributing to the path loss), we use the standard dipole gain of 1.76 dBi for the receive antenna gain.

Plots of path loss as a function of distance are shown in Figure 7 (a) and (b) for 1 mm and 10 mm stand-offs respectively with a receiver height of 2.14 m. The slope gradients, found using linear regression, are -36.75 dB/decade, and -38.5 dB/decade for stand-offs of 1 mm and 10 mm respectively, indicating that we have achieved a good performance with both antenna configurations. We note that for greater receiver antenna heights, the transition to pure 4^{th} order propagation does not occur until larger antenna separations, and we observe in our measurements that the best match to the theoretical result (i.e., closest to -40 dB/decade slope) is achieved at the lowest receiver antenna height, i.e., 2.14 m. (for comparison, Figure 8 shows the path loss as a function of distance for the receiver height of 6.29 m, which has a gradient of 24.8 db/decade and 22.1 dB/decade for stand-offs of 1 mm and 10 mm respectively).

As well as verifying that our antenna configuration has a reasonable agreement with the expected theoretical results, we can also compare the received signal power to that measured in the previous FH WSN deployment, where the antenna was located in the FH chamber itself. We compare our results to those presented in [[1] Figure 7 '2m Antenna Height North'], observing

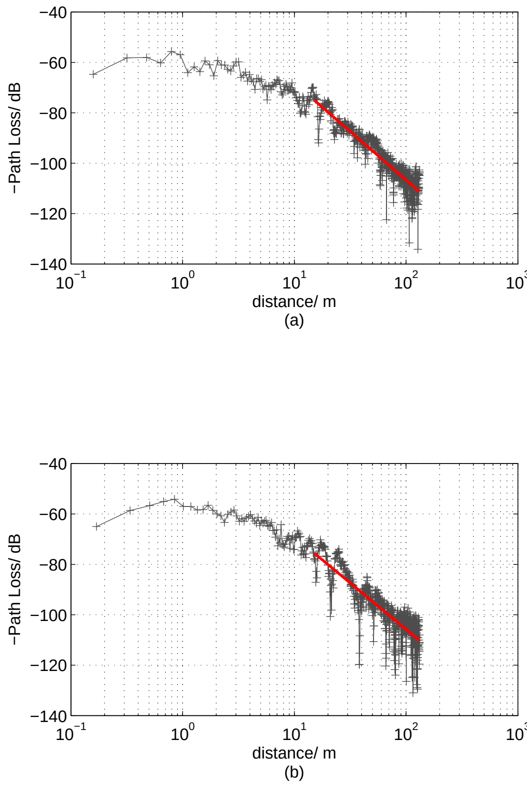

Figure 7: (a) 2.14 m receive antenna height, 1 mm stand-off between transmitter and ground plane; (b) 2.14 m receive antenna height, 10 mm stand-off between transmitter and ground plane.

that we have obtained a reduction in path loss of approximately 10 dB. Note the subsequent measurements [15] show that the path loss with the antenna located in the FH chamber may be even greater than that given in [1], therefore we can say that we have achieved a path loss reduction of at least 10 dB. In [1], it is shown that a transmit power of 19 dBm would be required to achieve their specified range of 73 m – 100 m. Using the low-profile antenna could potentially lead to a reduction in transmission power of 10 dBm, which would significantly reduce power consumption, and enable a wider variety of wireless sensor motes to be used.

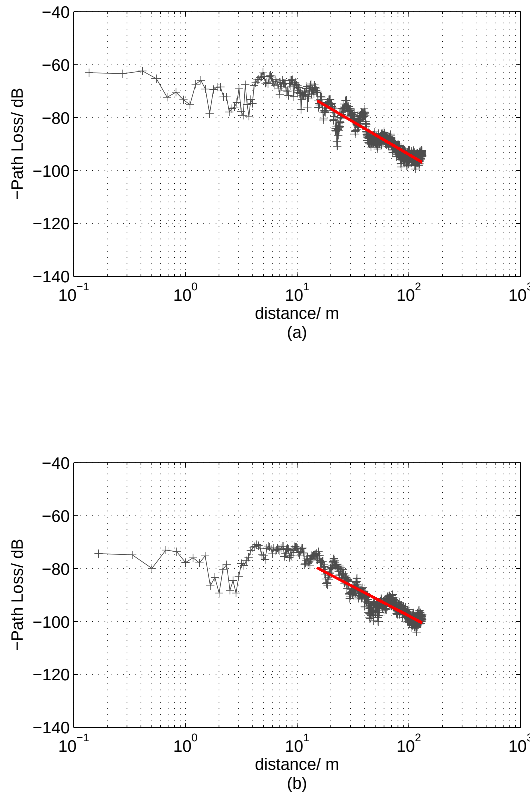

Figure 8: (a) 6.29 m receive antenna height, 1 mm stand-off between transmitter and ground plane; (b) 6.29 m receive antenna height, 10 mm stand-off between transmitter and ground plane.

IV Conclusion

In this paper we have assessed the performance of a compact low-cost, low profile planar antenna for operation in the 2.4 GHz ISM band, to be deployed in WSNs monitoring the water supply at FHs. We have confirmed that this antenna has the required properties of an omnidirection radiation pattern and high efficiency. Channel characterisation measurements with the antenna deployed in a FH demonstrate its suitability for such applications. Furthermore we have shown that a reduction in path loss of at least 10 dB is achieved compared to the previously arrangement, where the WSN antenna was located in the below ground FH chamber. Having demonstrated a proof of concept, further work is now required to robustly integrate the antenna as part of the FH lid.

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