Parameter Optimization of Staircase Shaped Co-Planar Waveguide Monopole Antenna with Modified Ground Plane for Radio-Frequency Energy Harvesting Application

Alphonsos A Masius and Yan Chiew Wong
Micro and Nano Electronic (MiNE) Research Group, Centre for Telecommunication Research and Innovation, Universiti Teknikal Malaysia Melaka
ycwong@utem.edu.my

***Abstract*—Co-planar waveguide (CPW) fed monopole antenna is a compact wideband antenna that is easy to fabricate and integrate with any RF circuitry. However, this antenna often suffers low gain and modifications are needed to create a deep resonance. In this work, a compact CPW fed monopole antenna is designed and optimized to resonate at 5.85 GHz Wi-Fi frequency band for RF energy harvesting application. The proposed antenna with a small size of 40 mm × 30 mm × 1 mm is composed of a staircase shaped radiating element fed by a CPW feed line, and an inverted stair-style ground. The antenna yields a high gain of 4.152 dB and wide bandwidth of 1.63 GHz or 27.86% impedance bandwidth. The optimization of the length of feedline and ground radiating elements through parametric sweeps show the most significant improvement of performance in terms of gain. The surface current is evenly distributed across the antenna with a higher concentration on the feeding area and edges of the main patch due to the stair-case shape and optimization of the feedline's length. The performance of the antenna is evaluated for feasibility in energy harvesting application using Friis transmission approximation and it was found that the antenna has an average of 34.77% improvement in received power when compared to a reference antenna with the same size and operating frequency. The monopole antenna proposed in this work manages to have a high gain while maintaining miniature size without the need of any parasitic material.**

***Index Terms*—High Gain Miniature Antenna; Low Profile Antenna; RF Energy Harvesting.**

I. INTRODUCTION

Over the centuries, researchers have gain better understanding of the forms of energy thus new ways for energy to convert from one form to another is revealed. This enables vast development in industrial and technology that leads to modern lifestyles nowadays. However, in every industrial process and everyday technology, a small amount of energy is being unintendedly loss into the environment in the form of heat, light, sound, vibration, or electromagnetic waves [1]. The energy leaked into the environment is referred to as ambient energy. The ambient energy is usually very low and in a form that is not readily available for use. It needs to be harvested, collected, and stored into a form that can be readily used for an intended application through a specialized method referred to as energy harvesting [2].

Energy harvesting generally refers to the collection, conversion, and storage of ambient energy into electrical energy. In this study, we focus on the harvesting of electromagnetic energy, also known as radio-frequency (RF) energy. RF energy originates from the RF signals emitted in wireless communication systems. Nowadays, wireless communication system has become so essential that it is no longer possible to separate it from our daily life. A massive range of electronic devices is being interconnected through wireless communication system which gives rise to the Internet of Things [3] which we are experiencing today. As a result, RF energy is being broadcasted abundantly into the free space which in turn provides free resources for ambient RF energy harvesting [4]–[6].

Antenna is used as a capturing device to detect and collect the ambient RF energy. It is the primary element in RF energy harvesting system as it determines the sensitivity of the system to capture the surrounding RF signals [7]. A more sensitive system means that the system can be activated at lower energy level, which is essential as the power level of the RF energy in ambient is already very low [8]. Therefore, it is crucial to design a high gain antenna for RF energy harvesting purposes. The overall antenna dimension must also be considerably small. This is due to the fact that the advancement in semiconductor industry has led to smaller electronic circuitry, thus we don't want the antenna to be a design constraint for a miniature system.

In this paper, our interest is in the design of compact co-planar waveguide (CPW) fed monopole antenna for RF energy harvesting at 5.85 GHz Wi-FI band. CPW fed monopole antenna is a compact wideband antenna that is easy to fabricate and integrate with any monolithic microwave integrated circuits (MMIC's) communication devices [9][10]. However, this antenna often suffers low gain [11] and modifications are needed to create a deep resonance. Thus, we focus on ground plane modifications of a staircase shaped monopole antenna to increase gain at 5.85 GHz Wi-FI band for energy harvesting applications.

II. DESIGN METHODOLOGY

Figure 1 shows the geometry of the CPW stair-case shaped antenna. The antenna is modelled and simulated on Computer Simulation Technology (CST) Microwave Studio by using ROGERS RO5880LZ epoxy dielectric substrate with a dielectric constant, εr= 1.96, tangent loss, tan δ= 0.002 and substrate's thickness, h, of 1.0 mm. As shown in the figure, the staircase radiating elements consists of eight rectangles of lengths L1, L2, L3, L4, L5, L6, L7, L8 and widths W1, W2, W3, W4, W5, W6, W7, and W8. The ground plane consists of combination of eight rectangles of lengths L9, L10, L11, L12, L13, L14, L15, L16 and widths W9, W10, W10, W11, W12, W13, W14, W15, and W16 on both sides of the transmission line, Lf. The gap between the main patch to the ground is given as d, while the strip width of the CPW is labelled as Wf and the gap of the CPW is labelled as G. The substrate length, Lp is 40 mm and its width, Wp is 30 mm. This gives the total dimension of the antenna of only 40 mm × 30 mm × 1 mm.

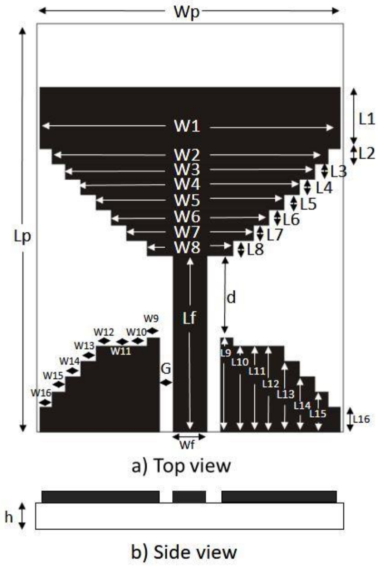

Figure 1: The geometry of the CPW antenna

The design process started by calculating the feedline strip width (Wf) of the CPW using standard equations for 50-ohm impedance [12] as shown in Equation (1) – (2). The length of the feedline, Lf is quarter wavelength (λ/4) at 5.85 GHz. Then, Equation (3) – (6) are used to approximate the first width (W1) and length (L1) of the CPW radiating element [13][14].

$$\frac{wf}{t} = \frac{2}{\pi}\left[B - 1 - \ln(2B - 1) + \left\{\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon r}\right\}\right] \quad (1)$$

$$B = \frac{377\pi}{2Z_o\sqrt{\varepsilon_r}} \quad (2)$$

$$W = \frac{c}{2f_o\sqrt{(\mathcal{E}_r+1)/2}} \quad (3)$$

$$L = \frac{1}{2f_o\sqrt{\mathcal{E}_{reff}}\sqrt{\mu_o\mathcal{E}_o}} - 2\Delta L \quad (4)$$

ΔL is given as:

$$\Delta L = 0.412\, h\, \frac{(\mathcal{E}_{reff}+0.3)(\frac{W}{h}+0.364)}{(\mathcal{E}_{reff}+0.258)(\frac{W}{h}+0.8)} \quad (5)$$

and $\mathcal{E}_{reff}$ is given as:

$$\mathcal{E}_{reff} = \frac{\mathcal{E}r+1}{2} + \frac{\mathcal{E}r-1}{2}\left(1 + 12\frac{h}{W}\right)^{-1/2} \quad (6)$$

where:

wf = width of microstrip feedline
t = height of substrate
c = speed of light
f_o = center frequency
μ_o = relative permeability of air
ε_o = relative permittivity of air
ε_r = relative permittivity/dielectric constant of substrate

The calculated value of length L1 and width W1 are used to find the values of the next L2, L3, L4, L5, L6, L7. L8, L9 and W2, W3, W4, W5, W6, W7, and W8 through parametric study. The next length, L2 is reduced from L1 through parameter sweep function to optimize the antenna gain and bandwidth, and is repeated for the next corresponding lengths (L3, L4, L5, L6, L7, L8 and L9) until no further significant increase in gain and bandwidth are detected. The ground patch is a mirror image of the main patch. The value of Wf and d are then optimized through parameter sweep to obtain a resonant frequency at 5.85 GHz. *G* is obtained through parametric sweep and optimized to obtain the most significant gain and bandwidth, while still maintaining a wide enough space for fabrication consideration.

III. RESULTS AND DISCUSSIONS

Table 1 shows the original (calculated) and optimized parameters for lengths, widths, d, and G at 5.85 GHz.

Table 1
The original and Optimized Antenna Parameters

Parameter	Original (mm)	Optimized (mm)
L1	6	6
L2 – L8	NA	1.5
L9	12.95	9.5
L10	11.4	8.4
L11	9.9	8.4
L12	8.4	8.4
L13	6.9	6.9
L14	5.4	5.4
L15	3.9	3.9
L16	2.4	2.4
W1	29.4	29.4
W2	27.0	27.0
W3	24.4	24.4
W4	21.4	21.4
W5	18.4	18.4
W6	15.4	15.4
W7	12.4	12.4
W8	8.4	8.4
G	1.345	1.0
Lf	12.81	17.25
Wf	3.31	3.31
d	2.8	8.05

During the optimization, it is observed that decreasing L9 shifted the resonant frequency to the right and vice versa, and the value of d corresponding to L9. Wf is optimum at the calculated value while increasing it worsen the matching at 50-ohm. The antenna shows significant increases in gain and depth of resonance when Lf is increased from 12.81mm to 15.75mm. However, when Lf is further increased to 17.25mm, the depth of resonance decreases but the resonance frequency shifted closer to 5.85 GHz and the gain is further increased. This shows that the length of feedline greatly impacts the impedance matching of the antenna. The return loss of the antenna must be below -10 dB to ensure the proposed antenna can achieve at least 90% matching efficiency [15]. The return loss of the optimized and original antenna design is shown in Figure 2. It is shown that the optimized antenna has a wide bandwidth of 1.63 GHz ranging from 5.21 GHz to 6.84 GHz. In contrast, the original design has a bandwidth of 1.4 GHz thus the optimized antenna shows 7.6% bandwidth improvement. The gain at 5.85 GHz is 4.152 dB which is higher than most monopole antennas [9].

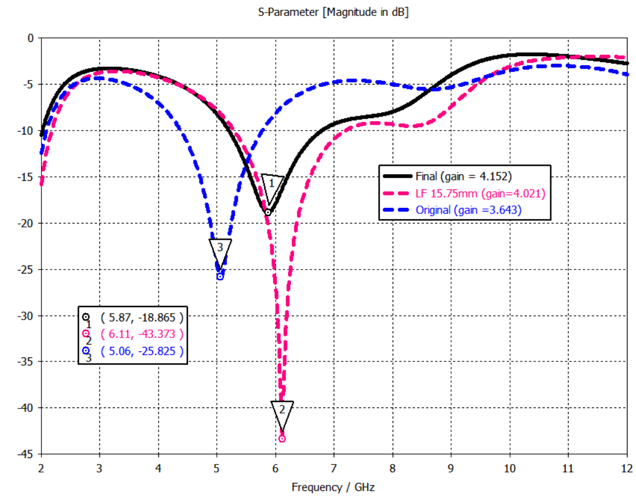

Figure 2: Return Loss of the Optimized and Original Antenna Design

A detailed comparison in size and simulated gain between the proposed antenna and reference antennas can be seen in Table 2. With such gain, this enables energy harvesting in close distance between the antenna and base station, according to the Friis equation as stated in [16], which will be further discussed later. The proposed antenna is small in size with overall dimension of 40 mm × 30 mm × 1 mm. From Table 2, it is seen that the proposed antenna is not the smallest available, but the gain difference is significantly higher than all of the listed reference antennas.

Table 2
Comparison of Several Reference Antennas in Terms of Size and Simulated Gain

Ref.	Size (mm^2)	Frequency (GHz)	Simulated Gain (dB)
[17]	21 x 33 = 693	5.8	2.5
[18]	38 x 30 = 1140	5.5	2.5
[19]	40 x 30 = 1200	5.8	1.0
[20]	40 x 40 = 1600	5.8	3.5
[21]	36 x 26 = 936	5.8	2.2
Proposed	40 x 30 = 1200	5.85	4.152

Figure 3(a) shows the simulated 3-D radiation pattern and surface current distribution of the proposed antenna. The surface current is distributed evenly across the antenna, and higher current concentrations are seen at the feeding area and edges of the main patch. This is due to the stair-case shape that provides structural disturbance and optimization of the distance between the main patch and the ground which improves the performance of the antenna at 5.85 GHz. The antenna gain is highest in the horizontal plane, as seen in Figure 3(c). From both the polar plot in Figure 3(c) and 3(d), it can be seen that the intensity of the radiated power goes into two directions, 180° and 0°/360°, which means the antenna has a bi-directional radiation pattern. At the 90° (horizontal) plot, the half-power bandwidth is 65.2° wide with approximately 1.15 dB gain. Meanwhile, the half-power bandwidth at the 0°/360° (vertical) plot is 125.5° with approximately 0.4 dB gain.

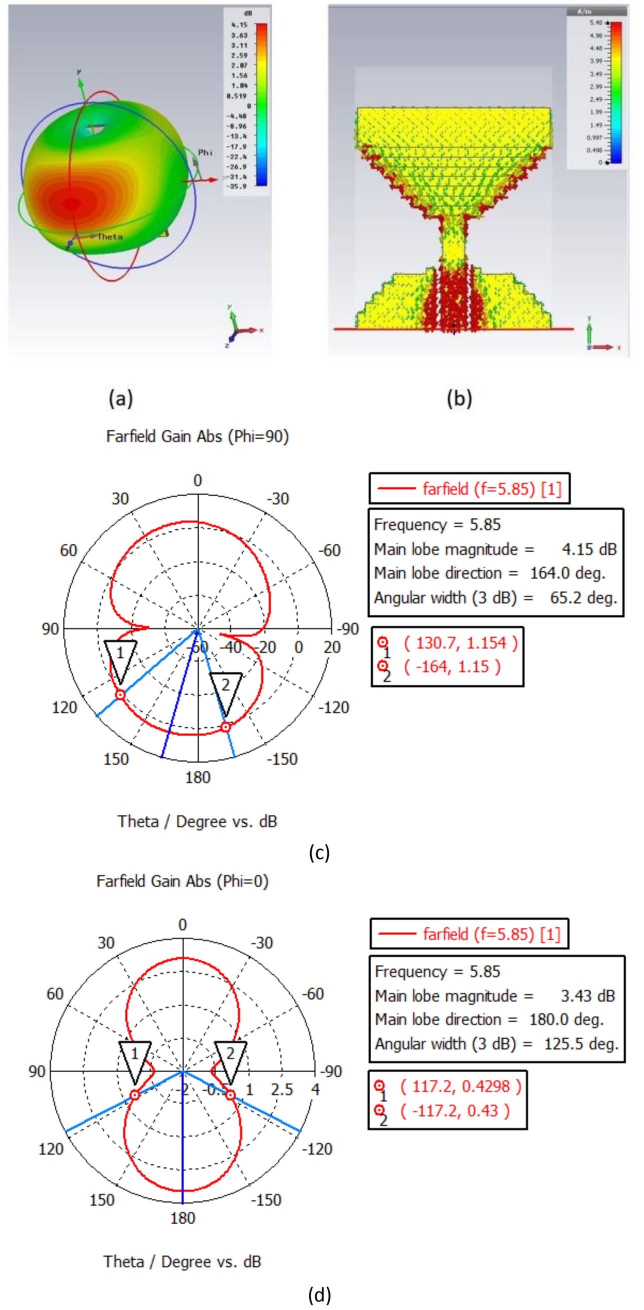

Figure 3: (a) The simulated radiation pattern, (b) the surface current distributions of the proposed CPW fed antenna, (c) horizontal polar plot, and (d) vertical polar plot.

IV. Approximation Of Received Power Using Friis Transmission Equation

To show that the simulated gain is feasible for close distance RF energy harvesting at 5.85 GHz, the Friis Transmission Equation (7) can be used to approximate the received power from the antenna at some distance given a transmission frequency and antenna gains. The received power of the proposed antenna is compared to the received power of a reference antenna with the same size and operating frequency [19] as seen previously in Table 2.

$$P_{rx}\,(dB) = P_{tx} + G_{tx} + G_{rx} + 20\log 10\left(\frac{\lambda}{4\pi Dr}\right) \quad (7)$$

where:

P_{rx} = received power at the antenna (dBm)
P_{tx} = transmitted power (dBm)
G_{tx} = transmitter gain (dB)
G_{rx} = receiver gain (dB)
D_r = distance between transmitter and receiver (m)
λ = wavelength in transmission medium

At 5.85 GHz, according to [22], the transmitted power is 30 dBm (maximum Wi-FI router transmit power allowed at 5.85 GHz), with transmitter gain of 7 dB and using the simulated gain of the proposed antenna (4.152 dB) and the gain of the reference antenna (1 dB), the received power according to the Equation (7) at varying distance are as seen in Table 3.

From Table 3, it is seen that the power received decreases over the distance. However, the power received by the proposed antenna at short distance should be enough for powering low power sensors or to be stored in storage device such as super capacitor. Overall, the proposed antenna has 34.77% improvement in term of received power compared to the reference antenna.

Table 3
The Calculated Received Power of the Proposed Antenna and Reference Antenna at Various Distance

Distance (m)	Received power of reference antenna (dBm)	Received power of reference antenna (μW)	Received power of optimized antenna (dBm)	Received power of optimized antenna (μW)	Improvement of proposed antenna
1	-9.791	104.9	-6.639	216.8	34.78 %
2	-15.81	26.23	-12.66	54.21	34.78 %
4	-21.83	6.558	-18.68	13.55	34.77 %
6	-25.35	2.915	-22.20	6.023	34.77 %
8	-27.85	1.64	-24.70	3.388	34.76 %

V. CONCLUSIONS

This paper focuses on optimizing the lengths of feedline and ground radiating elements of a CPW fed stair-case shaped antenna to increase gain at 5.85 GHz Wi-FI band. It was shown that by modifying the monopole to a staircase-shape, more parameters can be created, thus, this provides more flexibility in optimizing the parameter which might be worth to consider in future design. The antenna is low-profile with dimension of only 40 mm × 30 mm × 1 mm with gain of 4.152 dB which is higher than most monopole antennas with the same size range. It covers a bandwidth of 1.63 GHz or 27.86% impedance bandwidth with 7.6% bandwidth improvement compared to the original unoptimized design. The proposed antenna also shows high feasibility for close distance energy harvesting from Wi-FI routers and is easy to fabricate.

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