Measurements of an Offset Magnetic Dipole Source Using a Wireless Dual-Loaded Loop

Christopher G. Hynes and Rodney G. Vaughan

Abstract – Experimental validation is presented for the coupling to a dual-loaded loop antenna from an offset magnetic dipole source. The measurement system consists of a wireless dual-loaded loop antenna that is designed for sensing weak signals at extremely low frequencies. The antenna port signals are digitized and transmitted to a receiver using 802.15.4. The port sensor pass-band is up to 108 Hz, with a 256 samples per second sampling rate. A receiver gain of 33 dB and noise figure near 1.5 dB (3.7 nV per square root hertz input referred noise) allow measurements of port signals with amplitudes down to 3.3 μV. Experimental coupling measurements between this wireless dual-loaded loop and an offset magnetic dipole agree well with the theory.

1. Introduction

The dual-loaded loop antenna is a well-established two-port device with the combined performance of a small electric dipole and a loop antenna [1]. It can simultaneously measure a component of the electric and magnetic fields [2, 3]. When arranged as three co-located, orthogonally oriented loops, it forms what is known as a three-loop antenna system (TLAS) [4, 5]. A TLAS with a simple beamformer can measure the six components of the complete electromagnetic field. It has been used for low-frequency electromagnetic compatibility testing [6] and vector-sensing direction finding [7]. Other potential applications range from noncontact biomedical measurements, such as electroencephalograms and electrocardiograms, to earthquake prediction from precursor signals.

Two main design challenges of implementing a TLAS are achieving a large dynamic range with low noise and extracting the port signals without perturbing the antenna patterns. Using traditional metallic cables attached to the loop ports would perturb the antenna response, and using baluns or ferrites to isolate the loops is challenging to implement (i.e., bulky) at low frequencies. With currently available fiber optic systems for the ports, it is challenging to achieve good dynamic range and low noise figure [8].

Recently [9], expressions for the coupling from an offset magnetic dipole to a dual-loaded loop have been formulated and verified with simulation. This paper presents the experimental validation of the new theoretical expression using a wireless dual-loaded loop system [10]. The remainder of this paper is organized as follows. Section 2 presents the theoretical response of a dual-loaded loop to an offset magnetic dipole moment. Section 3 describes the measurement system and procedure and the results.

Manuscript received 28 February 2024.

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2. Background Theory

Kanda [2] formulated the dual-loaded loop response to an arbitrary electromagnetic field. Closed-form expressions have been established for the responses of the dual-loaded loop to incident plane waves [2, 11] to centrally located electric and magnetic dipole moments [4], and recently [9], for arbitrarily orientated offset electric or magnetic dipole moments.

A dual-loaded loop, as shown in Figure 1, is centered in the xy-plane and is electrically small and thin, such that $a \ll b, ka \ll 1$, where b is the loop radius, a is the wire radius, and k is the wavenumber. When its two ports are located at $(\pm b, 0, 0)$, the summation current from a magnetic dipole moment is well approximated by [9]:

$$\begin{aligned}
I_\Sigma &= \frac{1}{2}[I(\phi=0)+I(\phi=\pi)], \\
&\approx \frac{k\eta b^2 e^{jkR}}{4R^3(2jZ_L-\eta\pi a_0)} \\
&\times \Bigg\{ 2m_{m,z}\Bigg((1-jkR)\,{}_2F_1\left(\frac{3}{4},\frac{5}{4};1;\zeta\right) \\
&+ k^2R^2\left({}_2F_1\left(\frac{1}{4},\frac{3}{4};1;\zeta\right)-\frac{1}{\sqrt{1-\zeta}}\right)\Bigg) \\
&+ \frac{1}{R^2}((\boldsymbol{m}_m\times\boldsymbol{r}_0)\times\boldsymbol{r}_0)_z\Bigg(3(1-jkR)\,{}_2F_1\left(\frac{5}{4},\frac{7}{4};2;\zeta\right) \\
&+ k^2R^2\left({}_2F_1\left(\frac{3}{4},\frac{5}{4};2;\zeta\right)-2\,{}_2F_1\left(1,\frac{3}{2};2;\zeta\right)\right)\Bigg)\Bigg\},
\end{aligned} \tag{1}$$

where $j=\sqrt{-1}$, η is the wave impedance in the medium, Z_L is the port impedance, $\boldsymbol{m}_m = m_{m,x}\boldsymbol{u}_x + m_{m,y}\boldsymbol{u}_y + m_{m,z}\boldsymbol{u}_z$ is the magnetic dipole moment located at $\boldsymbol{r}_0 = x_0\boldsymbol{u}_x + y_0\boldsymbol{u}_y + z_0\boldsymbol{u}_z$, $\boldsymbol{u}$ denotes the Cartesian unit vectors, $(\cdot)_z$ denotes the z-component of the vector, ${}_2F_1(\cdot,\cdot;\cdot;\cdot)$ is the Gaussian hypergeometric function, and

$$\zeta = \frac{4b^2(x_0^2+y_0^2)}{R^4}, \tag{2}$$

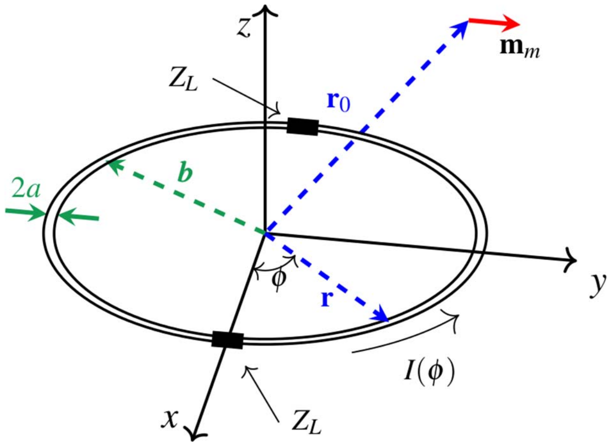

Figure 1. Dual-loaded wire loop with an off-center magnetic dipole moment source $\boldsymbol{m}_m$ [9].

$$R^2 = b^2 + r_0^2, \tag{3}$$

$$a_0 = kb\left[\frac{1}{\pi}K_0\left(\frac{a}{b}\right)I_0\left(\frac{a}{b}\right) + \int_0^{2kb}(\Omega_2(x) + jJ_2(x))dx + \frac{1}{\pi}(\ln 4 + \gamma - 2)\right], \tag{4}$$

in which Ω_2 is the Lommel-Weber function of order 2, J_2 is the Bessel function of the first kind of order 2, $\gamma = 0.5772\cdots$ is Euler's constant, and I_0 and K_0 are the zeroth order modified Bessel functions of the first and second kind, respectively. Using numerical simulations, (1) has been shown to be accurate for any magnetic dipole source location and orientation [9].

3. Experimental Results

A wireless dual-loaded loop system, whose block diagram is shown in Figure 2, is used to measure the voltages across the loop's port impedance $Z_L = R_{in} = 510\ \Omega$ [12]. The port sensors, as shown in Figure 3a, are designed to have a bandwidth of 108 Hz (sampled at 256 Hz), a gain near 33 dB, and a noise figure of about 1.5 dB (3.7 nV/$\sqrt{\text{Hz}}$ input referred noise). Once the port signals are digitized using an analog-to-digital converter (ADC), they are transmitted using parallel 2.4-GHz 802.15.4 wireless channels to a receiving computer for storage and postprocessing.

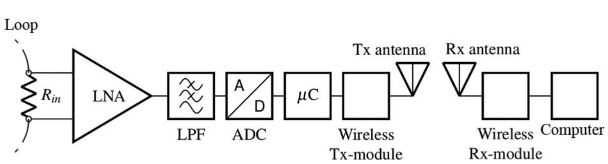

Figure 2. Block diagram of the wireless system used to collect the data from each dual-loaded loop port [12].

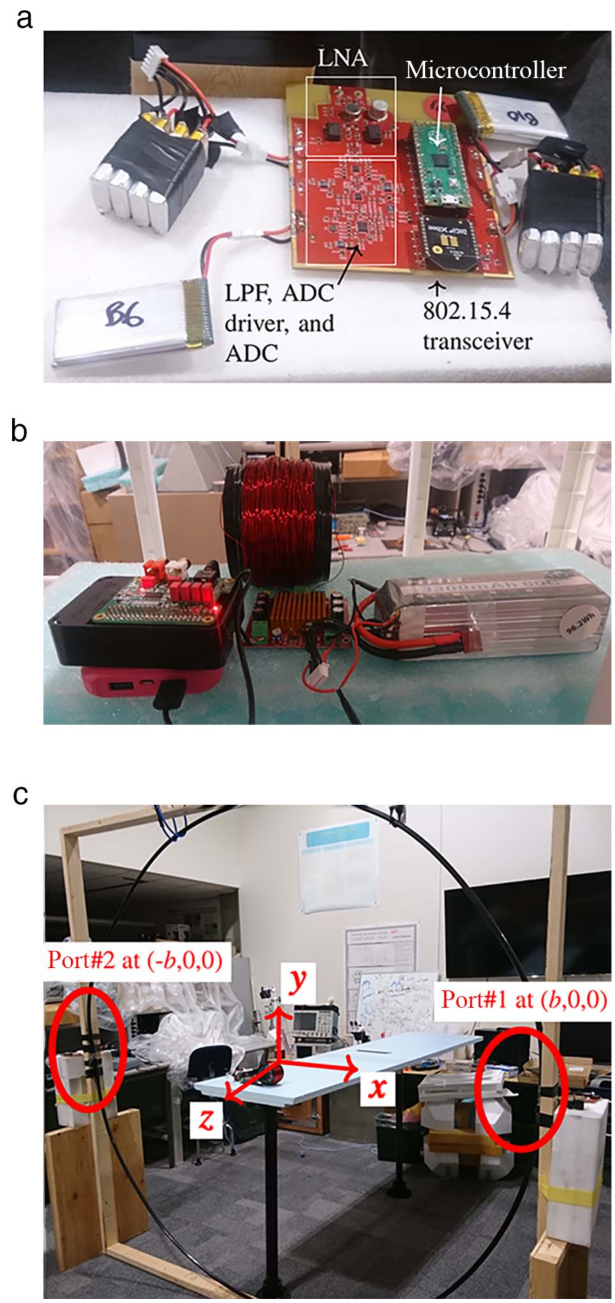

Figure 3. (a) Port sensor printed circuit board. (b) Experimental magnetic dipole source. The Raspberry Pi is shown on the left, and the audio amplifier is shown in the center. It is powered by the 22.2-V, 3300-mAh battery shown on the right. The wire loops are shown in the center background. (c) An experimental arrangement was performed when the magnetic dipole moment was located at the center of the dual-loaded loop. The shown arrangement was used to collect the data when the magnetic dipole was shifted along the x-, y-, and z-axes [10].

A 115-cm diameter loop was constructed using 1.9-cm diameter polyethylene tubing, with two parallel 18-AWG wires routed within each half-loop of the dual-loaded loop (the pair of speaker wire had their ends soldered together to reduce the resistance). The loop was supported with a wood structure, as shown in Figure 3c.

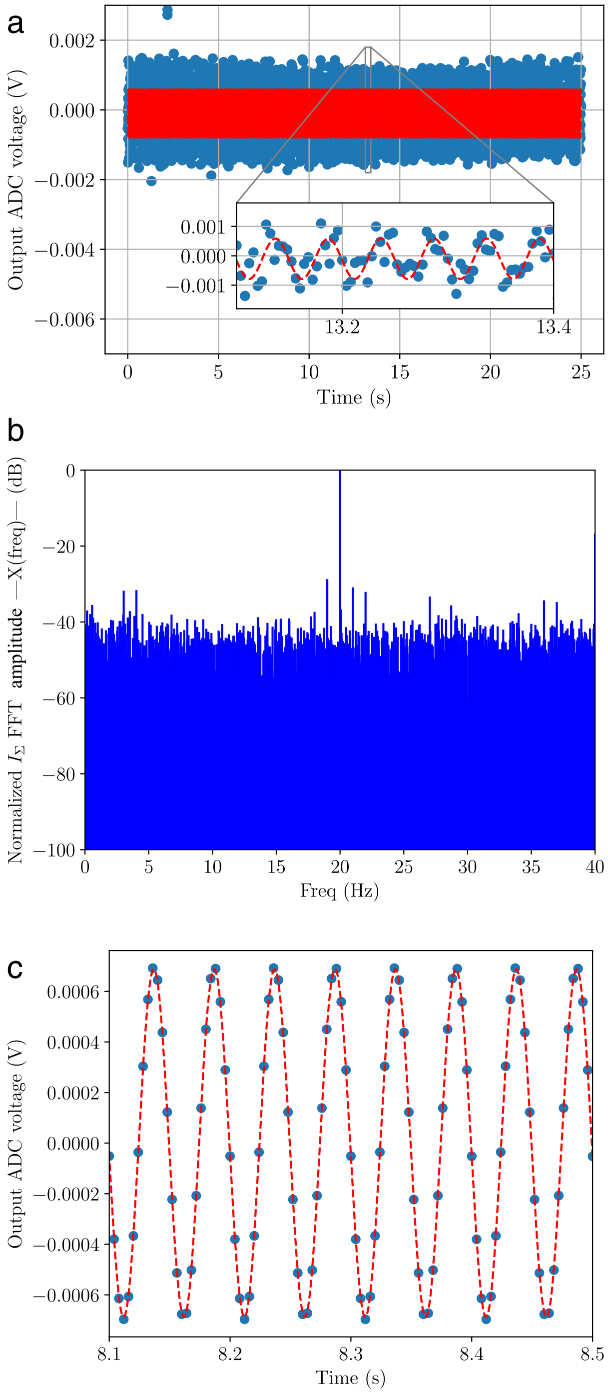

Figure 4. (a) An example of one of the weakest measured time series ADC data (in blue) captured from the dual-loaded loop sensor when the magnetic dipole is shifted along the x-axis at $x_0 = 1.5b$. The best-fit 20-Hz sinusoid is shown in red. (b) The fast Fourier transform of the data shown in (a). (c) The filtered data after applying a band-pass filter 5-Hz wide and centered around 20 Hz.

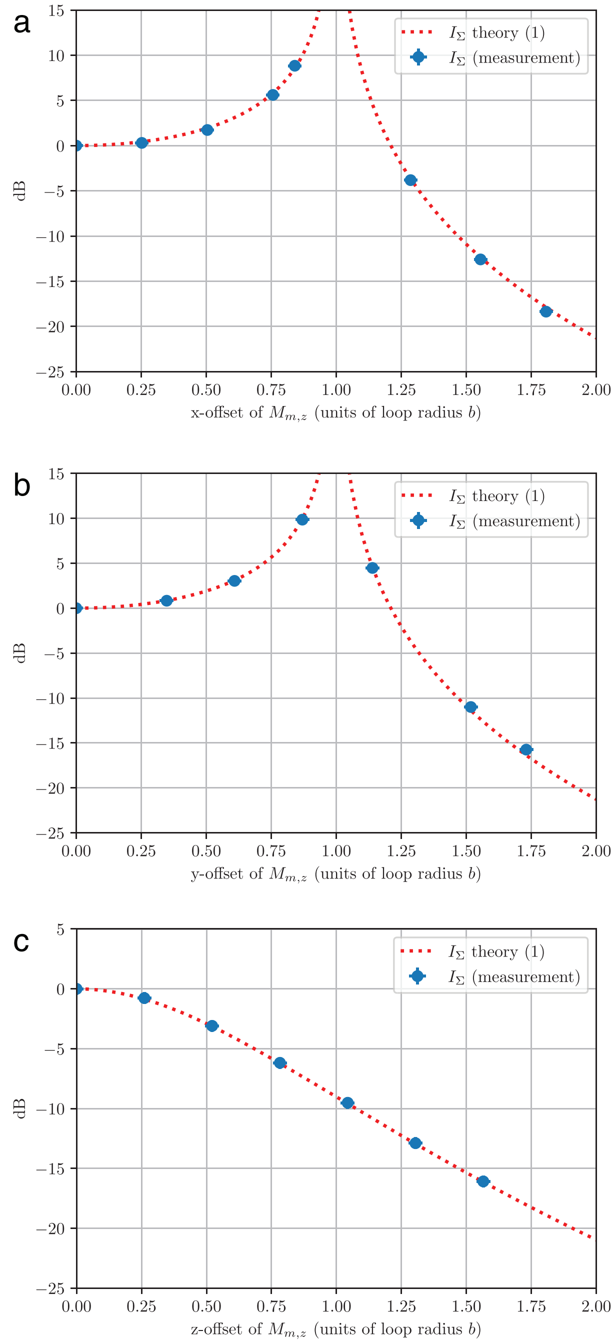

Figure 5. Theory and measurement of the dual-loaded loop's I_Σ current as a function of the magnetic dipole source's offset distance along the (a) x-axis, (b) y-axis, and (c) z-axis. The results are normalized to the value at the origin. The dual-loaded loop is centered at the xy-plane and the magnetic dipole source is z-directed. The positional uncertainty error bars are set to ±2 cm.

The magnetic dipole, seen in Figure 3b, was created by wrapping 22-AWG wire around a 10.5-cm diameter cylinder 590 times, yielding a direct current resistance of 5.7 Ω and an inductance of 10.63 mH. A Raspberry Pi microcontroller [13], powered by a USB battery, is used to generate a 20-Hz signal for the magnetic dipole. This signal is duty-cycled to allow synchronization of the received signals. The resulting current through the magnetic dipole wire has a peak amplitude of 2.0 A.

As seen in Figure 3c, the magnetic dipole is placed at the loop's center and shifted along the Cartesian axes. The magnetic dipole is supported at each location by a rigid 2.5-cm thick extruded polystyrene insulation sheet. At each dipole offset, the dual-loaded loop port sensor signals are digitized and sent in parallel via their 802.15.4 transceiver to a receiving computer that collects and processes the data streams using Python.

The measurements were performed in a laboratory environment containing strong noise signals—particularly the 60-Hz power line signal. However, a sufficient signal-to-noise ratio is available to extract the amplitude of the 20-Hz dipole signal down to 150 µV at the ADC (3.3 µV at the sensor input). An example of the time and corresponding spectra of the raw data is shown in Figure 4. The measurement data is compared with (1) in Figure 5, where a good agreement is seen. Further details on the measurement setup can be found in [10].

4. Conclusion

This paper presents the first experimental measurements for the received signal of a dual-loaded loop antenna from an offset magnetic dipole. The measurements are performed using a wireless dual-loaded loop system designed for detecting weak, extremely low-frequency signals. The port signals are sampled at approximately 256 Hz with a pass-band upper frequency of 108 Hz. The port sensors have a 33-dB gain and 1.5-dB noise figure that allowed signals down to 3.3 µV to be measured. The system corroborates recent analytical results for the coupling between a dual-loaded loop and a magnetic dipole source. With the present design, three dual-loaded loop antennas can be configured orthogonally to create a three-loop antenna system suitable for extremely low frequencies, with each loop port signal transmitted across an 802.15.4-wireless channel and processed in parallel.

5. References

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