2.4 GHz Internet-Connected Bird Feeder: The SMALL Device

The Bird Feeder Collective: Alexandros Pallaris, Oskar Bolinder, and Simon Ljungbeck

***Abstract*—We fabricated a bird feeder capable of recording sensor data and communicating this data to the internet via a custom-made antenna. This antenna is an electrically small folded meander-line antenna that operates within the 2.4 GHz ISM frequency band. The antenna is characterised, and the maximum communication range of the setup is measured. The sensors enable the bird feeder to detect infrared light at the feed-point, and measure weight.**

***Index Terms*—Student Design Contest, antenna measurements, electrically small antenna, IoT**

I. Introduction

WHAT is a bird? To a farmer looking to protect their crop seeds, a nuisance. To the man walking down the street, a part of the scenery. To a cat, a potential meal. But to the SMALL Device MK III with WiFi enabled, a bird is mere fodder for the sensor; a bird is nothing but another statistic, to be logged and reported amidst thousands of others. Birds and their feeding present a critical challenge to human society, one that man has struggled to perfect the solving of from pre-history to modern days. In this paper we present the latest in a long line of achievement, an improvement on previous solutions, a magnificent wonder of science and engineering to inspire future generations: we present "The SMALL (Self Maintained Aviator Lunch Locale) Device".

The SMALL device is a sensor-holding bird feeder (see Fig. 1) intended to connect with the internet for easy, remote, and real-time viewing of collected data. It does this over the 2.4 GHz ISM band [1] using a custom-made miniaturized antenna. Powered by a battery, this bird feeder is designed to be left outside for over a week at a time as it logs bird presence and the weight of remaining food. With a clear line of sight from the bird feeder this information can be uploaded in real time to a web-server from more than 2 km away. Plots of bird presence by hour and food weight are then available to be accessed from any device with an internet browser. This is accomplished with a combination of sensors, a custom-made antenna and chassis, and other electronic components which work in concert to make up a standalone internet-connected device.

II. The SMALL Device (Description of Measurement Capabilities)

In the design phase of the project, the following demands were taken into consideration: The bird feeder should detect bird presence accurately. All sensor data should be uploaded to a database on the internet, from at least 50 m away from any other device. The bird feeder should work in non-ideal ambient conditions, such as different weather, and be able to operate on battery-power for more than a week. And, the entire setup should be fairly simple, so as to be easily understood and reproduced.

To accomplish this, we needed a few different things:

- A base bird feeder, to feed birds and hold the electronics
- Sensors capable of detecting a bird and measuring weight
- A microcontroller to control the device, with a battery for power
- A 2.4 GHz RF module and antenna, to allow the device to connect wirelessly to the internet
- A website capable of receiving, storing, and plotting data to be viewed anywhere

We decided to 3-D print our own base bird feeder rather than modify one, to allow easy fitting of our electronics. We chose an Arduino Uno as the microcontroller, for ease of use and low power consumption [2]. We chose an RF transceiver module capable of low-power, high-range transmissions that had an SMA connector [3], allowing us to simply connect our antenna to it. Our antenna is a small PCB monopole antenna, with the roof of the bird feeder server as a ground plane (antenna design described in Section IV). For our sensors we chose a passive infrared (PIR) sensor to detect bird presence, and incorporated a load cell into the design to measure the weight of remaining food.

Fig. 1. Our finished device, the SMALL MK III (**left**), and our antenna (**right**) which is obscured by a cover in the finished bird feeder.

The PIR sensor functions by detecting changes in infrared light, which it interprets as movement. Infrared light is a type

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of electromagnetic radiation that is emitted by objects around room temperature and hotter. Warmer objects give off more infrared light, so in effect the PIR sensor can detect heat [4]. When the level of heat detected by the PIR sensor changes sufficiently, a detection is made and it will send a signal out to the microcontroller. While birds may not be particularly hot, the change in heat pattern from a bird coming to eat can be detected [5].

The load cell is built-in in such a way that the lower half of the bird feeder hangs off of it, allowing it to measure the weight and interpret any changes as changes in the amount of bird food. Since this sensor can continually send out data, the weight of birds landing and taking off could also be used to filter out false-positive detections from the PIR sensor. The microcontroller reports the weight every 30 seconds, allowing us to see any longer-term changes as food being removed or added to the bird feeder.

III. Software Implementation

Below, some of the more complicated parts are explained. All of the code and files that we used in this project can be found in Appendix A.

A. Arduino Code

One of the trickier things on the software side was that we were only able to send data from the Arduino and the ESP8266 WiFi module via the *IO2–Pin5* connection, where the signal can be either high (1) or low (0). This meant all data going to the web site needed to be manually coded in binary format. The Arduino began the data transmission to the WiFi module by sending 1 to signal that data is incoming. Next, 0 would be sent in case of a PIR detection and 1 in case of data from the weight sensor. If weight data, 12 additional bits would follow, representing the weight. This means the maximum weight that can be sent with out code is $2^{12} = 4096$ g.

B. Web Server

The web server consisted of a combination of $HTML$ documents and PHP and $JavaScript$ code. The implementation was quite straight forward. To upload data we decided to force the user/bird feeder to send a password as a parameter in the GET request. This is for security reasons, so no one can manipulate data or fill the web server memory.

The uploaded data was mainly processed on the server side by PHP code, but for the plots, $JavaScript$ was used, i.e. the graphs were constructed on the client side. The reason for this was both to decrease the working load for the web server (constructing graphics needs a lot of computer power) and because we wanted interactive graphs (for example, the user should be able to zoom in/out in the plots).

A link to the web site may be found here https://birdfeedercollective.com/

IV. Antenna Design & Measurements

A. Design

Our goal was to build an electrically small antenna operating over our chosen ISM band of 2.4-2.5 GHz [1], with which our device can connect with a receiver over 100 m away. Since our device should be placed by someone without knowledge of antennas, and may rotate during use, the antenna should radiate omnidirectionally. An antenna is considered electrically small if it can be contained within a sphere of radius a where $\frac{2\pi a}{\lambda} \ll 1$, and λ is the target wavelength [7]. For our design we have taken a bound of $\frac{2\pi a}{\lambda} = 0.5$, which for our maximum frequency of 2.5 GHz gives a maximum radius of $a = 9.54$ mm. The typical omnidirectional antenna is a dipole antenna with a size of around $\lambda/2$, or 6 cm, so we must reduce the size significantly.

Starting from perhaps the simplest concept in making a regular antenna smaller, we decided to create a meander-line antenna. Working from designs presented in literature [6], [7], we simulated and optimized many different sorts of meander-lines with different folding structures and numbers of meanders. To avoid interference from the dielectric properties of our bird feeder's structure, which could also change during use as the contained food is eaten and replaced, we decided to use a monopole design with a ground plane. Monopoles are also relatively easy to connect to our feeding coaxial cable, since it can simply connect through a small hole in the ground plane. An unfortuante drawback of a monopole design is that the radiation pattern is expected to be directed more above than below the ground plane, whereas we would prefer it to be directed mainly horizontally, but the simplicity and ease of this design convinced us to try it. The ground plane, a conducting sheet between the antenna and the rest of the device, would help to electrically hide everything behind it. Our designs were evaluated based on the bandwidth we were able to achieve when feeding with a standard coaxial cable of 50 Ω impedance, and just how small they were.

For non-folded meander lines the antenna's resistance, or the real part of the impedance, was simply too low when constrained to our small size. So we tried folding the meander-line in various ways, including moving from the simple meander-line to spirals and helixes. In the end, none of our options seemed to show significantly better characteristics than the simple once-folded meander-line. We chose this design since it is quite simple and - being flat - easy to manufacture. Our final design can be seen in Fig. 2. Excluding the ground plane, the antenna itself with the substrate fits within a sphere of radius $a = 0.92$ mm; it is electrically small.

While simulating our antenna designs, we included the bird-feeder as a dielectric load beneath the ground plane. Since the full 3-D model was too complicated to simulate, a simplified version was used where the bird feeder was approximated beneath the top section as a simple cylinder. Since we used a transceiver module that cannot connect directly to WiFi, we required a receiving antenna as well. This one was separately modelled without the bird feeder, and once optimized was slightly different to the transmitting antenna.

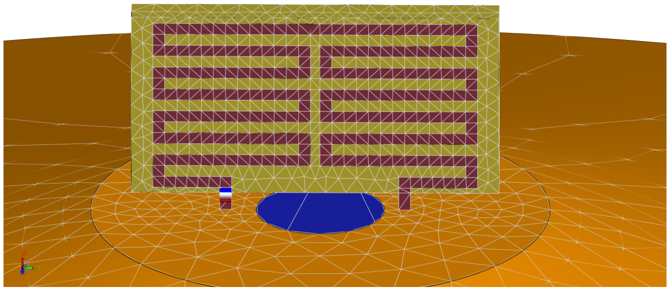

Fig. 2. Simulated structure of our folded meander-line antenna.

B. Construction

Our antennas were fabricated from a 1.55 mm thick FR4 substrate coated with a 20 μm thick copper layer. They were created with the use of a milling machine, which used a drill to first cut out the unwanted copper before cutting through the FR4 substrate to remove the antenna. They are then mounted with glue to a ground plane, and soldered together with a coaxial cable. Our completed receiving antenna can be seen to the right side of Fig. 1.

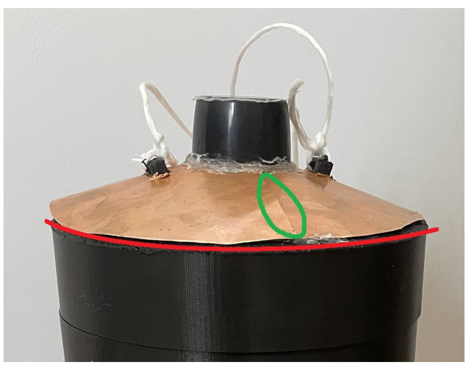

Fig. 3. The top section of our bird feeder, used for the antenna pattern measurements. The red line shows the horizontal plane, while the green circle shows the seam of the ground plane. The antenna itself is obscured by its protective plastic cover, but is positioned with its face perpendicular to the seam. The white cord is the cord from which the device is hung from a tree.

C. Measurements

To evaluate how well our finished antenna works, we measured their reflection coefficients, gain patterns, and made a practical measurement of maximum connection distance.

The reflection coefficient shows which frequencies our antennas work best at - if an incoming signal is reflected, it both does not get sent out through the antenna, and can cause problems for the electronics. For good function, we want a reflection coefficient of less than -10 dB over the frequencies that we will use it for: 2.4 - 2.5 GHz. We measured the reflection coefficients of our transmitting and receiving antennas using a virtual network analyzer, and compared with our simulations (Fig. 4). Both of our final antennas function at slightly lower frequencies than expected, presumably due mainly to differences in the way we soldered the connection with the antenna, the ground plane, and the coaxial cable as compared to the relatively simplistic simulation. Since their functional frequencies overlap and are within the WiFi band this is not a problem as we can simply restrict our electronics to that part of the WiFi frequency band.

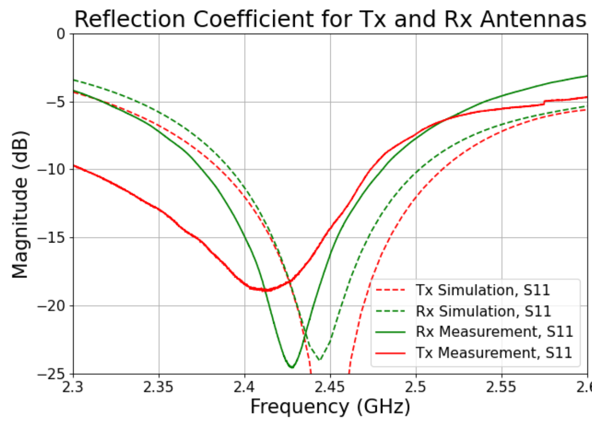

Fig. 4. Measured and simulated reflection coefficients for both our transmitting (Tx) and our receiving (Rx) antennas.

To test how well our antennas work at different angles, and to compare with our simulations, we performed a measurement of the gain pattern of the antenna. In an anechoic measuring chamber the top part of our bird feeder (Fig. 3) was strapped to a rotating machine, and we measured the transmission at different rotations with a stationary horn antenna. The results can be seen in Fig. 5.

The expected radiation pattern in the horizontal plane for a small monopole antenna is omnidirectional, similar to the simulated data in the left part of Fig. 5. The data for our antenna shows that it functions better in some directions than others, with one particularly bad angle. While not ideal, this shows that our device should be able to function if placed at a random angle, and twisting and turning in the wind. In this measurement our antenna was situated on top of a rotating pole and slightly above the measuring horn antenna - probably not ideal, but not likely to change the shape of the radiation pattern. Based on the measured pattern it seems like the asymmetries such as the seam in Fig. 3 and the holders, as well as the bumpy, rough surface of the ground plane likely contribute more to the difference between what we measured and what we simulated than expected.

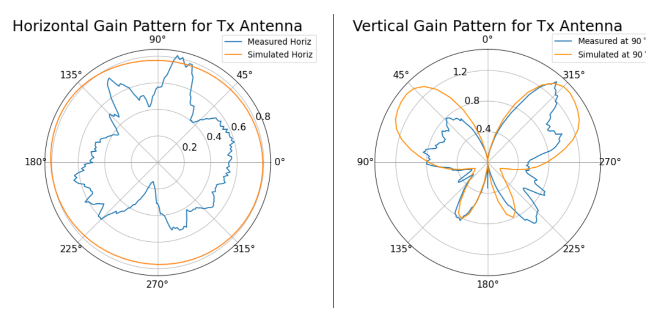

Fig. 5. Measured and simulated horizontal (**left**) and vertical (**right**) gain patterns for transmitting antenna. The horizontal plane can be seen as the red line in Fig. 3, while the vertical angles are along the seam (green circle) in Fig. 3, where 0° is upwards from the antenna, 180° is downwards. Measured data was normalized to maximum value of the simulated data to show pattern.

We also measured a vertical plane - to do this we screwed the antenna onto the side of our rotating pole during the measurement, leaving the seam of the ground plane (Fig. 3) horizontal during the measurement. As can be seen in the right part of Fig. 5 there are two null angles where we have no radiation, as expected from a monopole. Both the simulation and our measurements show another angle with bad gain just below the horizontal, and the most gain directed upwards. It is expected that a monopole's radiation pattern will tilt upward from the ground plane if the ground plane is not large compared to the wavelength [8], and with a wavelength of 12 cm ours is not. This is unfortunate as in practice the receiver and transmitter will likely be at roughly horizontal angles to each other, but although the pattern becomes bad at those angles, the antenna still functions.

D. Distance Measurements

To evaluate the range of our setup and the practical function of our antennas, we want to find the maximum distance at which our transmitter (the bird feeder itself) could connect to our receiver. We assume here ideal conditions (no losses and a clear line-of-sight). We first calculate a theoretical maximum distance based on our transceiver module's device specifications [3], starting from the Friis transmission equation [9]:

$$P_r = P_t G_t G_r (1-\Gamma_t^2)(1-\Gamma_r^2)\left(\frac{\lambda}{4\pi R}\right)^2 \qquad (1)$$

Our receiving and transmitting antennas are very similar and electrical small, so we approximate their gains as that of a Hertzian dipole: $G_t = G_r = 1.5$, and since we are calculating a theoretical maximum distance we set the reflections coefficients $\Gamma_t = \Gamma_r = 0$. P_t is the transmitted power, which for the maximum power setting can be found to be 0 dBm (1 mW), and we can find the minimum received power to be -85 dBm, or (3.16 pW) [3]. Using the largest wavelength support by the transceivers, at a frequency of 2.4 GHz, equation 1 can be rearranged to solve for the maximum distance that we expect to be able to reach:

$$R = \frac{1.5\lambda}{4\pi}\sqrt{\frac{P_t}{P_r}} = 265 \text{ m} \qquad (2)$$

For the measurement the receiving antenna was kept stationary on a hill to provide a good line-of-sight, as a person holding the transmitter walked away until the receiver could no longer receive the signal. From the VNA measurements, we expect the greatest distance to be at the frequency where the product between the two transmission coefficients is as large as possible. Since our transmitter module supports different power modes and frequencies, we set the device to scan over different combinations of those values to determine which mode is the most practical, and if the results adhere to our expectations.

However, during this test we were not able to get out of the range of our device before trees and houses began to obscure our line-of-sight, preventing us from getting further away. We ultimately determined only a lower bound on the distance at which even the lowest power setting could transmit data: 2.2 km (see Fig. 6).

Fig. 6. Satellite image of the area we used for the distance measurement, showing a black dot where we had the receiver, a green dot at the furthest spot we were able to easily reach, and a red circle with a radius of 2.2 km representing a lower bound on the range of our device.

Based on our distance measurement and equation 2, we made theoretical calculations to estimate a lower limit on range for the higher power modes. Since the lowest power mode outputs -18 dBm, at -12 dBm we have $R = 4.4$ km, at -6 dBm $R = 8.8$ km, and at the highest power mode of 0 dBm $R = 17.5$ km.

V. The Working Device

The final device is filled with bird food and hung by a string in a location where birds can reach it, such as a tree. When sensor data is taken the device immediately notifies the web server, where it can then be viewed from anywhere (see Fig. 7).

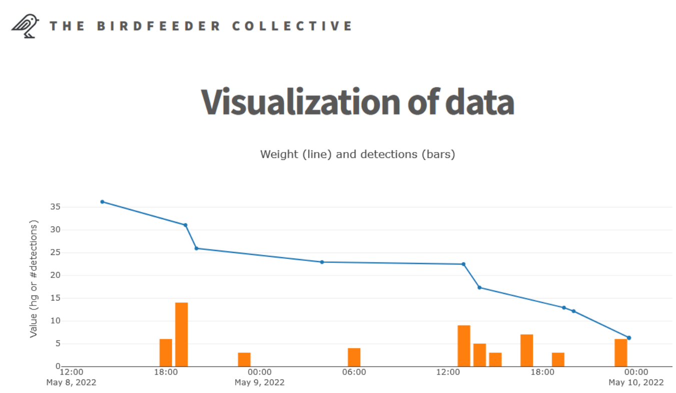

Fig. 7. A screenshot of the web site, showing a visualization of the data collected by the bird feeder. The line shows the weight of the birdfood, while the bars show the number of birds detected that hour.

VI. List of Parts and Materials Required

In table I we list the parts and materials required to duplicate this device. Many of the materials are only available in bulk, but only needed in small quantities; the bulk cost is listed. We

TABLE I
LIST OF PARTS AND MATERIALS REQUIRED AND THEIR APPROXIMATE COSTS.

Item	Cost (USD)
2x Arduino UNO	$56
PIR sensor	$10
Weight sensor	$24
ESP8266 WiFi module	$12
2x NRF24L01 module	$12
Connection Cables	$25
2x Antenna (Copper-clad FR-4)	$7
PETG 3-D printing filament	$18
Fiberglass sheet	$7
Brass sheet	$10
Web Site	$50
Total Cost	$231

obtained our materials from a combination of online ordering (mainly through Amazon), in-store purchasing (through a local Kjell & Company store), or just used someone's leftovers from previous purchases that we found in labs here. The web site was hosted using bluehost.com.

VII. CONCLUSION

We fabricated a bird feeder capable of recording bird presence and measuring food weight, as well as transmitting that data to the internet using the 2.4 GHz ISM band. A website that we setup can then be visited from anywhere to see visualizations of the data. We fed birds.

When is a bird? With the SMALL device, you can find out.

APPENDIX A
SUPPLEMENTARY FILES

The code and files used for our device can be found at: https://github.com/SL2000s/birdfeeder_pub. This page contains the 3-D models of the bird feeder structure, the antenna CAD file and structure, and the code used with the electronics.

ACKNOWLEDGMENT

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REFERENCES

[1] United States Department of Commerce, National Telecommunications and Information Administration. (2016, January). United States Frequency Allocations: The Radio Spectrum Chart [Online]. Available: https://www.ntia.doc.gov/page/2011/united-states-frequency-allocation-chart

[2] L. Miller. ”Arduino vs Raspberry Pi for Robotics.” Learnrobotics.org. https://www.learnrobotics.org/blog/arduino-vs-raspberry-pi/ (accessed April. 26, 2022)

[3] Nordic Semiconductor, nRF2401 Single Chip 2.4 GHz Radio Transciever Product Specification (2007), Retrieved from https://cdn.sparkfun.com/datasheets/Wireless/Nordic/nRF24L01_Product_Specification_v2_0.pdf on 2022/5/2.

[4] Wikipedia. ”Passive infrared sensor.” Wikipedia.org. https://en.wikipedia.org/wiki/Passive_infrared_sensor (accessed April. 24, 2021)

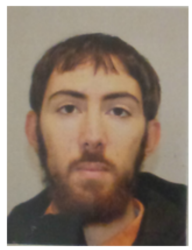
[5] Y. Siahaan, B. A. Wardijono, and Y. Mukhlis, ”Design of birds detector and repellent using frequency based arduino uno with android system,” 2017 2nd International conferences on Information Technology, Information Systems and Electrical Engineering (ICITISEE), 2017, pp. 239-243, DOI: 10.1109/ICITISEE.2017.8285503.

[6] S. R. Best, Optimization of the Bandwidth of Electrically Small Planar Antennas (2009), The MITRE Corporation, Retrieved from https://www.mitre.org/sites/default/files/pdf/09_4198.pdf on 2022/2/2.

[7] J. L. Volakis, C.-C. Chen, K. Fujimoto, “Survey of Small Antenna Theory,” in Small Antennas: Miniaturization Techniques and Applications, 1st ed. McGraw-Hill, 2010.

[8] P. J. Bevelacqua, ”The Monopole Antenna.” Antenna-theory.com, https://www.antenna-theory.com/antennas/monopole.php (Accessed Dec. 23, 2021)

[9] S. J. Orfanidis, ”Transmitting and Receiving Antennas” in *Electromagnetic Waves and Antennas*, Rutgers University (2016). Available: https://www.ece.rutgers.edu/~orfanidi/ewa/



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Oskar Bolinder is a bachelor student from Lund, Sweden who studies theoretical physics at Lund University. He is currently occupied mainly with machine learning but is looking to go into particle physics. Additionally, he is working as a mentor for students taking the introductory calculus course at the university. As a mentor he tries to present mathematics and physics in a way that is both approachable and engaging.

Simon Ljungbeck is an undergraduate student from Sweden currently studying engineering mathematics and computer science at Lund University. He has competed in both Mathematics and Physics at high-school level, and is now aiming for taking a PhD in the field of machine learning.