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Antenna design for a massive multiple input environmental sensor network☆

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ABSTRACT

This article describes the design and simulation of a pair of antennas on a small PCB with minimal coupling for a massive multiple input sensor network. The two antennas are planar inverted-F antennas (PIFA) that are fed with microstrip feed lines. The critical design factors are minimizing mass while creating ISM band and GPS L1 band antennas and developing data transmission schemes for maximum usage of all communication channels. The designed board is a 60 mm diameter, 0.6 mm thick circular FR4 board that weighs approximately 5 g.

1. Introduction

Currently, atmospheric researchers rely heavily on remote sensing technologies such as satellites to predict the weather; however, there is a tremendous need for additional in-situ measurements to improve weather models and create more accurate forecasts. Current in-situ measurements for hurricane reconnaissance primarily rely on devices known as dropsondes. The dropsondes have a terminal velocity of 11 m/s at sea level, and approximately 21 m/s at a 12 km altitude [1]. For more quiescent conditions, weather balloons carrying radiosondes [2] are launched around the globe every day to measure the properties of the atmosphere. This article showcases the antenna design and application of a novel type of atmospheric sensor which our group is developing as an alternative to these devices.

The devices will be part of a new atmospheric monitoring system known as GlobalSense [3]. The system features an ensemble of disposable airborne drifters, called environmental motes or eMotes, as can be seen in Fig. 1, that will be carried by wind currents much like naturally occurring dandelion or maple seeds. The GlobalSense system innovation is based on the continuing trend for ubiquitous sensing [4,5], also known as the Internet-of-Things [6,7], where extremely large numbers of disposable, low-cost electronic devices measure various parameters and communicate that data in different formats and frequencies for various applications.

Once deployed from balloons or aircraft, eMotes will transmit low power signals in one of the industrial, scientific, and medical (ISM) radio bands to avoid expensive licensing requirements. The fixed or mobile receiver platforms will contain hardware and software to gather and process sensor and other data from multiple eMotes within range and store or retransmit the information to other locations. The GlobalSense system has been designed to support up to 50,000 eMotes operating simultaneously.

The GlobalSense system could benefit a wide range of applications with sensitivity to atmospheric conditions including but certainly not limited to energy, transportation, agriculture, construction, insurance, and tourism. The initial focus is on improving weather analysis and forecasting by greatly expanding the time and space density of critical weather parameters such as temperature, pressure, wind velocity, and humidity throughout as much of the relevant atmospheric volume as possible.

With the appropriate chemical sensors integrated on eMote platforms, the GlobalSense system could monitor air quality and greenhouse gases such as carbon dioxide and methane for global climate change initiatives [8,9]. Even broader applications involve measuring parameters of interest for surveillance, reconnaissance, and related applications. The modular and interoperable system design makes it relatively straightforward to integrate other sensors that have the appropriate specifications.

The current prototype eMotes have a mass around 7 g with a terminal velocity <5 m/s which provides greater dwell time in the atmosphere than typical environmental sensors. The final design goals are an eMote mass ≤1 g and a terminal velocity on the order of 1 m/s.

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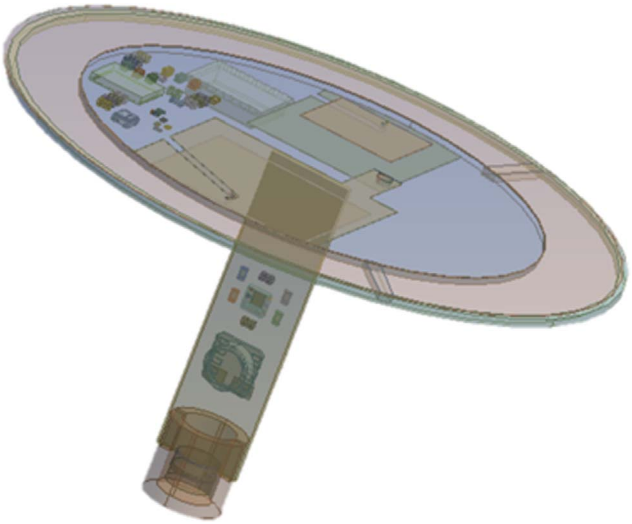


Fig. 1. CAD model of the eMote.

Given such low mass and an aerodynamic shape, eMotes can remain airborne and take measurements for hours or longer depending on atmospheric conditions and release altitude. The innovative eMote design creates an energy-efficient, long range, low power sensing device.

The eMote is designed as a cap and stem system. The antennas, along with the microcontroller and GPS receiver, are integrated into the cap along with the prerequisite passive components. The sensors are integrated into the stem with the batteries attached to the end of the stem opposite the cap. The sensors will be used to measure ambient temperature, relative humidity, pressure, and velocity. The stem board which contains the sensors will communicate using inter-integrated circuit (I^2C) communication protocol, allowing different versions of the stem to be interchanged and permitting more sensing options.

Much existing research with long range, low power sensor networks focuses on the design and optimization of the communication schemes and sensor devices [10–13], but not the antenna design. This article builds upon that research and focuses on the antenna design and implementation of the massive multiple input sensor network. The antenna design followed the typical design method of a literature search followed by simulation. The fabrication and testing of the antenna is currently in progress.

2. Antenna design

The antennas described in this article are based on the planar inverted-F antenna or PIFA. This antenna is a modification of the inverted-L antenna, which is based on the quarter-wave monopole antenna [14]. The PIFA is an ideal candidate for the eMote design as the sum of the length and width are approximately a quarter-wavelength (for the standard case) which makes it an electrically small antenna while still possessing desirable performance characteristics [14,15].

The eMote is designed to have a link margin of 10 dB at a range of 50 km. Therefore, the two antennas will need to be oriented for optimal reception and range with the top of the cap facing upward and the stem perpendicular to the ground. The antennas are oriented so that the main lobe of the ISM band antenna points down and the main lobe of the GPS antenna points up. This orientation could be modified for optimal reception depending on the receiver location.

Fig. 2 shows the antenna board designed in ANSYS HFSS. The smaller patch is the GPS antenna, the larger patch is the ISM antenna, and the large, slotted copper segment is the ground plane. The antenna board is made of FR4 with a relative permittivity of 4.4. The cap is a 60 mm diameter circular PCB that is 0.6 mm thick. Similarly, the stem is a 0.6 mm thick 11 mm by 40 mm rectangular PCB with a plastic battery compartment attached to the bottom. The two boards are connected with a four pin header that passes the V+, ground, I^2C clock, and I^2C data lines to the cap board.

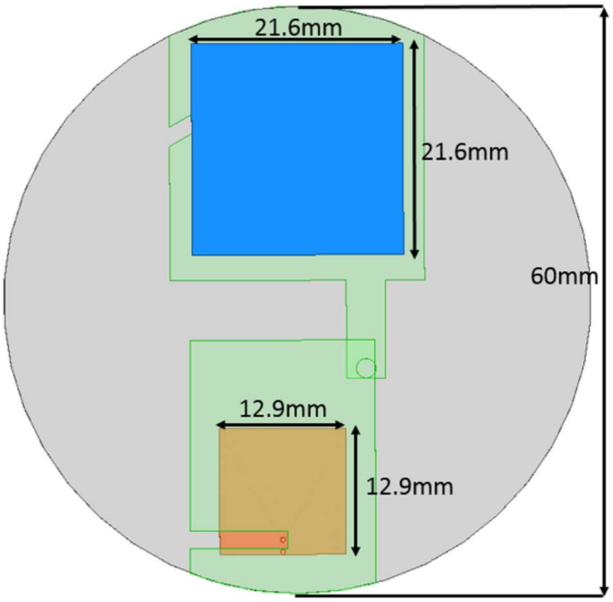


Fig. 2. Antenna board layout in HFSS with dimensions shown.

A standard, wire-fed PIFA with an air gap between the radiating element and the ground plane has a bandwidth of approximately 4%–12% [16]. When the PIFA is built on a PCB, the bandwidth decreases. Additional decreases in bandwidth are seen when the height of the feed pin shrinks [14], where the height of the feed is determined by the PCB thickness. A major design constraint was the mass of the eMote. A board thickness of 0.6 mm was selected as a trade-off between rigidity and mass.

Unlike a traditional PIFA which is fed through a coax or similar method, these antennas are fed with 50 Ω microstrip lines. The feed lines are terminated at the feed vias which connect to the radiating patch. In order to achieve this design, the ground plane is cut, creating a meandering design. The meandering design allowed the antenna to operate effectively with the reduced board thickness [17] and allowed the antenna size reduction that was desired [18].

3. Antenna performance

The data will be transmitted to the receiver over the 902 to 928 MHz ISM band. To verify the antennas bandwidth, the voltage standing wave ratio (VSWR) is shown in Fig. 3. For the ISM band antenna at the 915 MHz design frequency, the VSWR is 1.14 and the bandwidth is 901 – 927.6 MHz, which is 2.9% of the design frequency. Additionally, the VSWR is less than 2 for the range of 906–922 MHz for the ISM band antenna. For the GPS antenna, the bandwidth is significantly smaller as a percentage of the design frequency. Therefore, for the range of 1.563–1.587 GHz, the VSWR is below 1.5 with a VSWR of 1.15 at the design frequency.

The directivity plots of the two antennas shown in Figs. 4 and 5 demonstrate the appreciable gain. The ISM band antenna's pattern is more isotropic than the GPS antenna's pattern. This characteristic should allow for a more robust communication link in most directions excluding the center null located in the middle of the ground plane. Ideally the center null will face upward away from the receiver if the eMote is falling through the atmosphere as intended. The maximum directivity is approximately 6.5 dB.

The GPS antenna has a more bulbous pattern. This pattern is

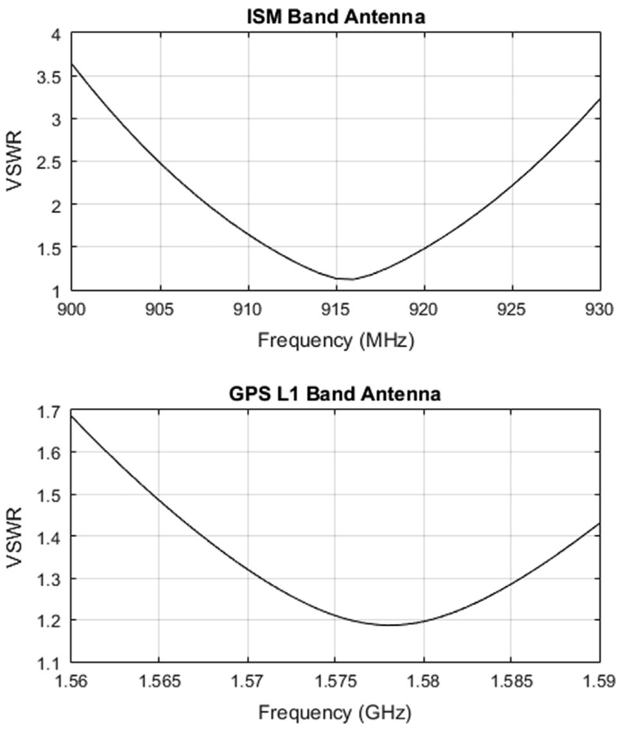


Fig. 3. Simulated VSWR plots of the designed antennas.

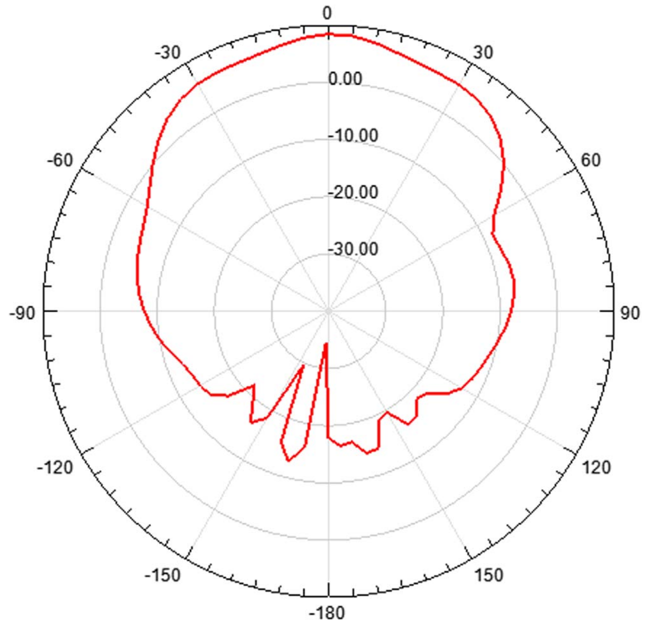


Fig. 4. Simulated directivity of the ISM Band Antenna in dB.

deemed acceptable since the maximum gain is desired to be upward toward the GPS satellites. The near nulls in the ±90° direction are due to the reflections at the edges of the dielectric. The theory for this behavior has been previously outlined [19]. Additionally, the design of the ground plane to extend further past the edges of the antenna will lead to the more bulbous pattern [20].

As can be seen from Fig. 6, there is little coupling between antennas. The graph illustrates that the S12 is approximately −45 dB in the ISM band and approximately −31 dB in the GPS band.

4. eMote as a massive multiple input system

The greatest challenge in the implementation of a large-scale eMote network is management of incoming data. In order to improve battery life and the simplicity of design, the eMote modules have been designed only to transmit and never receive any off-probe commands. Due to this design choice and scaling limitation on communications [21], the organization of the eMote probes into a coherent wireless network must be accomplished through careful time and frequency scheduling [22]. In order to configure a large number of eMotes to communicate in a coherent pattern without cross-talk or data loss, a scheduling algorithm is used to assign a time slot and communication channel based on each probe's unique ID number. Each probe uses time data received from GPS satellites to ensure that its time slot will be correctly aligned with other eMotes. This transmission scheme can be combined with multiple receivers in the base station scanning the channels in parallel time slots, as shown in Fig. 7, to achieve total recovery of all data transmissions. The decision to have separate receivers scanning channels rather than an individual receiver for each channel was made due to the former method being more adaptable. Additionally, the

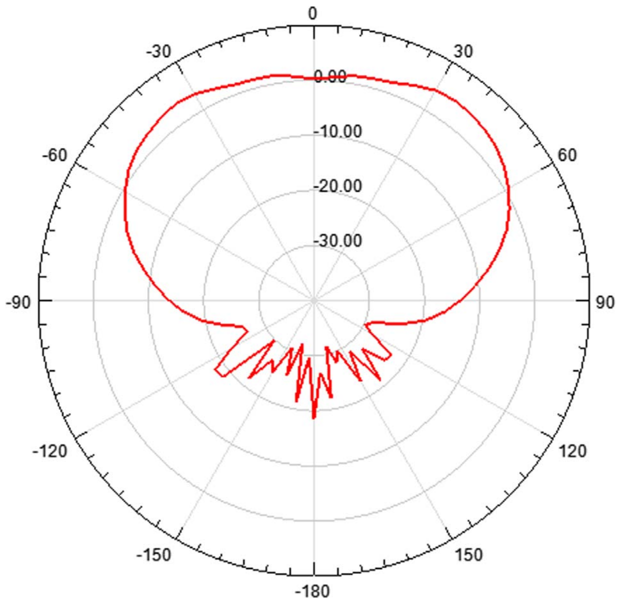


Fig. 5. Simulated directivity of the GPS L1 Band Antenna in dB.

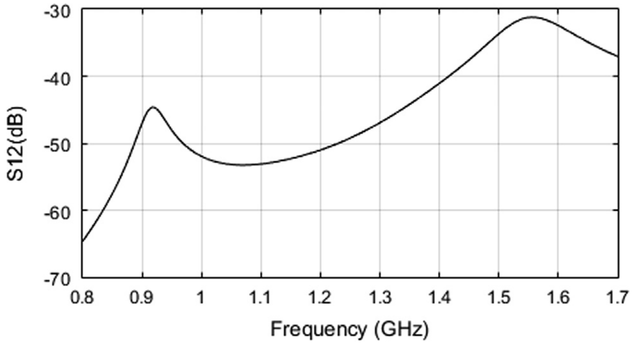
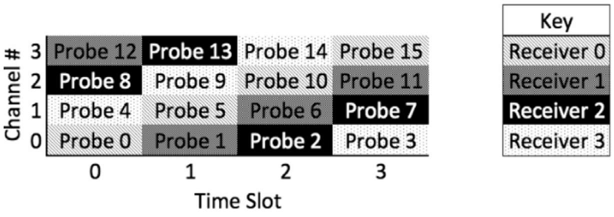


Fig. 6. Simulated plot of S12 in dB.



Channel #				
3	Probe 12	Probe 13	Probe 14	Probe 15
2	Probe 8	Probe 9	Probe 10	Probe 11
1	Probe 4	Probe 5	Probe 6	Probe 7
0	Probe 0	Probe 1	Probe 2	Probe 3
	0	1	2	3

Time Slot

Key
Receiver 0
Receiver 1
Receiver 2
Receiver 3

Fig. 7. Channel and time slot staggering example with 15 eMotes.

latter method poses the possibility of all communications on a single channel being lost if a single receiver malfunctions, whereas the same problem would be slightly mitigated in the parallel scanning methodology by other receivers occasionally receiving data points from the affected channel. Also, the absence of an eMote ID in the received data will show which channels and time slots were corrupted from accidental cross-talk and environmental conditions. Testing with small batches of eMote probes in adjacent time slots on the same communication channel can be used to verify the validity of scheduling algorithms based on GPS time data and the overall reliability of this communication scheme.

5. Conclusion

Progress has been reported on the GlobalSense system featuring low-power, drifting airborne probes called eMotes for in-situ atmospheric monitoring. Data from such a system, deployed on a routine basis, can benefit a wide range of applications including weather and atmospheric modeling.

The antennas described in this article are a novel design and implementation of PIFAs on a small, circular substrate. They are designed so the eMote can receive GPS signals and transmit sensor and GPS data to a base station. The eMotes are designed to be lightweight and maximize drag, thereby minimizing terminal velocity which translates into more in-situ data points.

The current effort will be extended to include antenna fabrication, performance testing, and verification that antenna simulations agree with test results. Also, there will be tests to verify that eMotes perform at the desired ranges and that the communication protocols work as designed. Following an initial test and verification phase, a dual-band PIFA (or other microstrip antenna) will be designed. The dual band antenna will allow the rigid FR4 portion of eMote cap to shrink, thereby lowering overall the mass of the device. Mass reductions are critical to achieve the overall eMote mass (1 g) and terminal velocity (1 m/s) design specifications.

The final goal of this project will be to demonstrate the complete Global Sense system with an ensemble of one hundred eMotes released at low altitude and multiple receivers collecting data from each one.

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References

[1] Vaisala, Vaisala dropsonde rd94 (2010) URL ⟨http://www.vaisala.com⟩.

[2] M. Divakarla, C. Barnet, M. Goldberg, E. Maddy, W. Wolf, L. Flyn, X. Xiong, J. Wei, L. Zhou, X. Liu, Validation of atmospheric infrared sounder temperature and water vapor retrievals with matched radiosonde measurements and forecasts, J. Geophys. Res. 111 (D9)http://dx.doi.org/10.1117/12.694116.

[3] J. Manobianco, Global environmental mems sensors (gems): A revolutionary observing system for the 21st century, Phase II Final Report URL ⟨http://www.niac.usra.edu/files/studies/final_report/842Manobianco.pdf⟩.

[4] M.J. OGrady, G.M.P. OHare, N. Hristova, S. Keegan, C. Muldoon, Ubiquitous sensing: A prerequisite for mobile information services, Proceedings of the 1st ERCIM Workshop on eMobility WWIC2007 (2007) 119–130.

[5] S. Lohr, Smart dust? not quite, but we are getting there, New York Times⟨http://www.nytimes.com/2010/01/31/business/31unboxed.html⟩.

[6] M. Chui, M. Löffler, R. Roberts, The internet of things, McKinsey Quarterly.

[7] J. Gubbi, R. Buyyab, S. Marusica, M. Palaniswami, Internet of things (iot): a vision, architectural elements, and future directions, Future Gen. Comput. Syst. 29 (7) (2013) 1645–1660. http://dx.doi.org/10.1016/j.future.2013.01.010.

[8] D. Crisp, C.E. Miller, P.L. DeCola, NASA orbiting carbon observatory: Measuring the column averaged carbon dioxide mole fraction from space, J. Appl. Remote Sens. 2(1), 023508. http://dx.doi.org/10.1117/1.2898457

[9] D. Wunch, Coauthors, et al., Calibration of the total carbon column observing network using aircraft profile data, J. Atmos. Meas. Techn. Discuss. 3 (2010) 1351–1362.

[10] G.J. Pottie, W.J. Kaiser, A survey on sensor networks, IEEE Commun. Mag. 40 (8) (2002) 102–114. http://dx.doi.org/10.1109/MCOM.2002.1024422.

[11] G.J. Pottie, W.J. Kaiser, Wireless integrated network sensors, Commun. ACM 43 (5) (2000) 51–58. http://dx.doi.org/10.1145/332833.332838.

[12] J. Polastre, R. Szewczyk, D. Culler, Telos: enabling ultra-low power wireless research, Fourth International Symposium on Information Processing in Sensor Networks http://dx.doi.org/10.1109/IPSN.2005.1440950.

[13] J. Rabaey, J. Ammer, T. Karalar, S. Li, B. Otis, M. Sheets, T. Tuan, Picoradios for wireless sensor networks: the next challenge in ultra-low power design, Solid-State Circuits Conference http://dx.doi.org/10.1109/ISSCC.2002.993005.

[14] W.L. Stutzman, G.A. Thiele, Antenna Theory and Design, 3rd Edition, John Wiley and Sons, Inc., 2013.

[15] A.T. Gobien, Investigations of low profile antenna designs for use in hand-held radios, Master's thesis, Virginia Tech, 2006.

[16] R. Feick, H. Carrasco, M. Olmos, H. Hristov, PIFA input bandwidth enhancement by changing feed plate silhouette, Electron. Lett. 44 (15) (2004) 921–922. http://dx.doi.org/10.1049/el:20045276.

[17] M.F. Abedin, M. Ali, Modifying the ground plane and its effect on planar inverted-f antennas (PIFAs) for mobile phone handsets, IEEE Antennas Wirel. Propag. Lett. 2 (1) (2003) 226–229. http://dx.doi.org/10.1109/LAWP.2003.819669.

[18] J.-S. Kuo, K.-L. Wong, A compact microstrip antenna with meandering slots in the ground plane, Microwave Opt. Technol. Lett. 29 (2) (2001) 95–97. http://dx.doi.org/10.1002/mop.1095.

[19] A.K. Bhattacharyya, Effects of ground plane and dielectric truncations on the efficiency of a printed structure, IEEE Trans. Antennas Propag. 39 (3) (1991) 303–308. http://dx.doi.org/10.1109/8.76326.

[20] M.-C. Huynh, W. Stutzman, Ground plane effects on planar inverted-f antenna (pifa) performance, IEE Proc. Microwaves Antennas Propag. 150 (4) (2003) 209–213. http://dx.doi.org/10.1049/ip-map:20030551.

[21] J. Manobianco, Globalsense: A new atmospheric observing system featuring innovative airborne probes, NOAA SBIR Phase I Final Report Available from Mano Nanotechnologies, Inc., URL ⟨http://www.mano-nano.com⟩.

[22] J. Yick, B. Mukherjee, D. Ghosal, Wireless sensor network survey, Comput. Netw. 52 (12) (2008) 2292–2330. http://dx.doi.org/10.1016/j.comnet.2008.04.002.