Inverted F Type Antenna Design for the Cattle Activity and Estrus Detection Sensor Module

Youchung Chung

Department of Information and Communication Engineering, Daegu University, Kyungsan, Kyungbook 38453, Korea; youchung@daegu.ac.kr; Tel.: +82-53-850-6638

Abstract: In this paper, an inverted F type antenna (IFA) for ZigBee communication of a sensor board has been designed and optimized, and it replaces the chip antenna on an RF (Radio Frequency) module that is not performing well enough for the ZigBee communication. The sensor board detects cattle behavior and identifies the breeding (estrus) period and transmits the data to the main station by the RF (Radio Frequency) module and IFA antenna. The proposed and optimized TRx (transmitting/receiving) IFA antenna of the ZigBee communication module has a return loss of $-19\,\text{dB}$ and a gain of 1.6 dB at 2.45 GHz. The size is about 2.5 $\times$ 0.5 cm in width and vertical length, and the height is 0.55 cm. The strength of signals with the chip antenna and the IFA antenna have been measured and compared. There is about a 20 dB enhancement with the IFA antenna compared to the chip antenna. The antenna is designed and applied to the RF transmission and reception (TRx) module. This antenna and sensor module can be applied to livestock in general as well as cattle.

Keywords: inverted F type antenna; antenna of ZigBee; sensor module antenna

1. Introduction

As the livestock industry becomes larger, the management of livestock is automated, and the livestock are managed by attaching sensors. In order to monitor the activity of livestock, a gyro sensor is installed on the body of livestock, and gyro data are collected. With the collected data, it is possible to predict the movement of livestock and the health and temperature of the livestock. In order to detect movement, a gyro sensor and a small TRx module are mounted on the mainboard to collect data from sensors installed on the body of livestock in a ranch or cage through wireless communication. The size of the RF module is also small because the size of the mainboard mounted on the body of livestock must be small. Usually, a small ceramic chip-type antenna is used by RF TRx module companies, which is for short-distance communication and is easy to use in development but not in actual ranches or cages. Since the return loss of the ceramic chip antenna is not good, and the loss of the ceramic antenna is large, the distance between transmission and reception is short. Thus, the inverted F antenna (IFA) for the ZigBee (IEEE 802.15.4 standard) communication-based module was designed.

IFA is well known and has been introduced in various textbooks [1,2] and articles [3,4]. The basic forms of IFAs and ways to design IFAs are introduced by Refs. [1–4]. Ref. [3] shows a basic single-band small IFA antenna of 1.9 GHz, and Ref. [4] shows an IFA of dual-band 2.4 and 5 GHz for a wireless LAN antenna [5,6]. The planar inverted F antenna (PIFA) was introduced in the articles [5–9]. Refs. [5,6] show the design of a dual-band PIFA, and a quad-band antenna was introduced in Ref. [7] with the combination of PIFA and a folded dipole antenna. The broadcasting dual-band (DVB-H UHF; 470–862 MHz, L; 1452–1492 MHz) is composed of a PIFA and another dual-band (WLAN 11 b; 2.4–2.5 GHz, 11 a; 5.15–5.8 GHz) is composed of a folded dipole antenna [7]. In Ref. [9], an ultra-wideband (UWB) frequency range (3.1 to 10.6 GHz) and a nearly omnidirectional radiation pattern are achieved with smaller than previous UWB PIFAs. A lumped equivalent circuit model of PIFA has been applied to the design of the PIFA, and the performance of PIFA (return loss, bandwidth,
gain, and efficiency) is improved with the additional open stub in the radiating element of the PIFA [10].

The IFA antenna is designed to be small in size to resonate at 2.45 GHz, the ZigBee frequency, considering the size and space of the communication module case and PCB (Printed Circuit Board) board. The RF sensor module equipped with an IFA antenna can grasp the behavior and habits of livestock by measuring the movement and momentum of livestock through a wireless network with an acceleration or tilt sensor. In addition, the purpose is to identify the breeding (estrus) period from the collected data and to individually tailor breeding and fertilization to livestock.

2. Antenna Design and Installation

On the left side of Figure 1, a movement sensor module and mainboard in the form of a livestock necklace is mounted on the belt and installed on the neck of the livestock. The mainboard (58 × 68 mm), sensor, and RF module are shown in the center of Figure 1. On the right side of Figure 1, the necklace on which the sensor module is mounted is hung around the neck of the animal. The gyro sensor on the mainboard detects the movement of livestock, and the mainboard transmits the movement data to the base station through the ZigBee RF transmission and reception module with a monopole or high-gain patch antenna based on the size of the ranch. The ZigBee HbeePro-20C RF module (red dotted line box in Figure 1) for general development has a ceramic chip antenna for short range such as 1 m transmission and reception, and the return loss of the antenna is quite bad for use over a long distance (10–100 m) such as in a ranch as an antenna. Therefore, the antenna for the RF module should be developed in consideration of the size of the case, the size of the mainboard, the size of the RF module, and the location of the antenna feeding point.

![Figure 1. Cattle necklace-shaped sensor board and case.](image)

In the base station, wireless sensor data of all livestock are collected, and it is possible to predict and manage the health status of livestock and various livestock-related data based on the collected data. The low 8 kb/s data can be analyzed and displayed by a mobile or computer, and the result can be informed in advance to the owner. Daily or weekly data collected continuously and analysis of the data makes it possible to predict the future and various outcomes such as health status, breeding period, and activity status of cattle.

Figure 2 shows the RF transmission/reception module and a small chip antenna for short-distance communication installed on the top of the RF module. The chip antenna is connected to the feeding point of the PCB of the RF module. The size of the RF module is about 20 × 25 mm, and the size of the feeding point is 4.4 × 1.5 mm, as shown in Figure 2. The left side of the feeding point is + and the right side is ground. The distance between the feeding point and ground is fixed as 2–2.4 mm as shown in Figure 2 and the ground. Therefore, the feeding position, size, and relative location of the +/- location are fixed.

The general structure of an IFA antenna is shown in Figure 3 [11]. The IFA antenna is similar to a bent mono-pole antenna parallel to a ground plane used in wireless communication. A bent monopole antenna is fed from an intermediate point a distance from the grounded end. The design has some advantages over a simple monopole: the height of the antenna is shorter than the equivalent monopole and more compact. The impedance matching is easier, controlled by changing the distance between the feed line and ground position, and does not require any other extra matching components. The summation of
the length of \( L \) and \( H \) should be \( \lambda/4 \) of the ZigBee frequency of 2.45 GHz, which is about 31 mm. The \( H \) controls the capacitance of the antenna and \( L \) controls the inductance of the antenna and frequency of resonance. The case of the mainboard shown in Figures 1 and 4 has only 5 mm space clearance from the feeding point to the cover of the mainboard. The location of the RF module is a corner of the mainboard, as shown in Figures 1 and 4. \( L \) in Figure 2 equals \( L_1 + L_2 \) in Figures 4 and 5.

Based on the location of the RF module on the mainboard and the feeding point of the antenna in Figure 2, the proposed antenna shape and location should be the upper...
part of the RF module, as shown in Figure 4. The antenna starts from the feeding point, which is the right-top of the RF module, and it extends straight out to the left side of the RF module. Since the size of the RF module is 20 × 25 mm and the calculated proposed length of the antenna is about 31 mm, the length of the antenna is longer than the width of the RF module. Therefore, the 5–10 mm out of the total length of the antenna should be bent down, as shown in Figure 4. There is a 4 mm notch for pushing the RF module down to the mainboard to secure the RF module from vibration and movement, since the connection between the RF module and the mainboard is very important to communicate and transfer the data to the base station. Therefore, the proposed antenna should have the size of the feeding point as shown in Figure 2, and the height and location of the antenna are fixed as shown in Figure 4 with the polypropylene cover.

3. Simulation and Measurement

The antenna simulation model with CST is shown in Figure 5. According to all the limitations related to the size, height, and location of the module and notch of the cover, the lengths of all the parameters of the antenna for simulation are shown: 20 < L1 < 25 mm, L2 < 30 mm, 3 < h < 5.5 mm, w = 3 mm, the gap between feeding and the ground is about 2–4.4 mm on the FR4 board. The width of antenna w is not as sensitive as the other parameters. The optimization of each parameter value to match the antenna to the frequency of the ZigBee 2.45 GHz, and the parameters are adjusted within the limitations of all parameters. The simulated and optimized parameters of the antenna are L1 = 20, L2 = 5, height h = 5.5 mm, and gap = 4 mm.

The simulated results of the antenna are shown in Figure 6 with the variation of length of L2. The results of the return loss of the antenna when the length of L1 = 20 mm and length of L2 vary from 5 to 8 mm. As the length of L2 increases, the resonant frequency of the antenna shifts to the lower frequency, as expected. The optimum of L2 is 5 mm when L1 = 20 mm and h = 5.5 mm. The optimized total length of the proposed IFA antenna L1 + L2 + h is about 31.5 mm, which is close to the theoretical length of the IFA antenna of about 31 mm, which is λ/4 of the ZigBee frequency of 2.45 GHz.

![Figure 6. Variation of S11 due to the length of L2.](image)

The simulation result |S11| of the proposed antenna is shown in Figure 7 with the given parameters, as the length of L1 + L2 + h = 31.5 mm. The S11 of the proposed antenna is −17 dB at 2.45 GHz. The measurement results of S11 with the cover and without the cover of the cases are shown in Figure 8. Since the antenna has been designed with the cover shown in Figure 4, the measurement result with the cover is better than the result without the cover of the module. It shows that the S11 is −19.45 dB with the cover and −14.4 dB without the cover, as shown in Figure 8.
Figure 6. Variation of S11 due to the length of L2.

Figure 7. Scheme 11 of the proposed IFA antenna of the sensor module.

Figure 8. Measured return loss of the fabricated IFA antenna of the sensor module (a) with the cover of the module and (b) without the cover of the module.

The simulated antenna radiation 3D patterns with antenna design coordinates are shown in Figure 9a, and radiation patterns of x-z and x-z planes are shown in Figure 9b,c with the antenna structure. The antenna is designed on the x-y plane, and Figure 9a shows the 3D antenna radiation pattern matched to antenna coordinates. The maximum gain is 1.6 dBi in the z-axis −17 degrees direction, as shown in Figure 9a. The reason the antenna pattern is tilted is that the ground plane does not exist in the Y direction of the antenna, so it is tilted about −17 degrees toward the ground. In Figure 9c, the gain at 180 degrees is about 1.5 dBi, and the gain at 0 degrees is about 1.3 dBi. The reason why the gain of the 180 degrees part shows a greater gain than the 0 degree part is that the vertical component L2 part of the antenna is present at 180 degrees, which leads to more radiation and gain.

The antenna was installed in the case to check the performance change, as shown in Figure 8, according to the presence or absence of the case cover. The fabricated prototype of the IFA antenna shown in Figure 10a was built on a 30-millimeter thick RF IS-680 board with relative dielectric constant equals to 3.2. The SMA connector has been used for the measurement of S11. The length of L2 was shortened from 30 to 0 mm, while S11 has been measured as shown in Figure 8. The best results around −19 dB at 2.45 GHz have been obtained when L2 was 5 mm.
An inverted F type antenna (IFA) for ZigBee communication of a sensor RF module has been designed. The antenna was fabricated and measured as shown in Figure 8. The best results around 1.6 dBi in the z-axis were obtained when L2 was 5 mm. The antenna is designed on the x-y plane, and Figure 9a shows the 3D antenna radiation pattern matched to antenna coordinates. The maximum gain is about 1.5 dBi, and the gain at 0 degrees is about 1.3 dBi. The reason why the gain of the proposed antenna can be applied to an RF module and sensor module, which can be applied to detect the behavior of livestock in general as well as cattle.

The antenna was installed in the case to check the performance change, as shown in Figure 10b. The length of L2, the vertical length of the antenna, has been tuned to detect the behavior of livestock in general as well as cattle. The simulated antenna radiation 3D patterns with antenna design and coordinates of the IFA antenna are shown in Figure 9a, and radiation patterns of x-z and x-z planes are shown in Figure 9b,c obtained when L2 was 5 mm.

The optimized and tuned IFA antenna has been installed on the RF module, and the optimum length of L2 from the simulation was 5 mm and 5 mm also with the measurement of $|S_{11}|$. The length of L2 was shortened from 30 to 0 mm, while $|S_{11}|$ has been maximized when the received signal strength at the main receiver is at its maximum. The optimum length of L2 was 4 mm, as shown in Figure 10c.

After verifying the antenna performance of the designed IFA antenna with an Agilent PNA network analyzer, the IFA antenna has been built on the RF module as shown in Figures 2 and 4, and the RF module with the IFA antenna is installed on the mainboard shown in Figure 10b. The length of L2, the vertical length of the antenna, has been tuned with the received signal intensity (RSI) of communication between the main receiver board and the sensor module in the case as in Figure 10b. The length of L2, the vertical length of the antenna, has been tuned to detect the behavior of livestock in general as well as cattle.

Comparing the signal strength measurement with the chip antenna and the proposed IFA antenna, 20 dB RSI can be enhanced on the communication system. The proposed IFA antenna can replace the chip antenna on the module, and 20 dB RSI can be enhanced on the communication system. The RSI has been measured at the same setup and distance and compared with the RSI of the chip antenna, as shown in Figure 2. The 14 dB patch antenna has been used for the receiver antenna, and the RSI has been measured for the two different cases.

**Figure 9.** Simulated antenna radiation patterns of the IFA antenna.

**Figure 10.** Fabricated and tested IFA antenna with RF board and RF module and optimum length of L2.
and the sensor module in the case as in Figure 10b. The L2 is shortened from 30 to 0 mm every 1 mm and measured the RSI of the system. The length of L2 has been optimized when the received signal strength at the main receiver is at its maximum. The optimum length of L2 from the simulation was 5 mm and 5 mm also with the measurement with a PNA network analyzer. When the antenna was installed on the physical RF module and tested with RSI, the optimum length of L2 is 4 mm, as shown in Figure 10c.

The optimized and tuned IFA antenna has been installed on the RF module, and the RSI has been measured at the same setup and distance and compared with the RSI of the RF board with the original chip antenna, as shown in Figure 2. The 14 dB patch antenna has been used for the receiver antenna, and the RSI has been measured for the two different cases.

Table 1 compares the RSI of two different antennas on the RF module: the original chip antenna and the proposed IFA antenna. The 256 RSI has been sampled per second and averaged since the RSI is so jumpy, even though transceivers are not moving. The steady RSI has been used and compared. The RSI of the chip antenna was −50 dBm while the proposed IFA antenna was −30 dBm with the same receiver antenna. There is 20 dB enhancement with the proposed IFA antenna.

Table 1. Comparison of signal strength measurement with chip antenna and proposed IFA antenna.

| Rx/Tx Antenna | Chip Antenna | Designed IFA Antenna |
|---------------|--------------|----------------------|
| 14 dB Receiver Antenna | −51 dBm | −30 dBm |

4. Conclusions

An inverted F type antenna (IFA) for ZigBee communication of a sensor RF module has been designed and fabricated. The optimized IFA antenna has been measured and installed on the RF TRx module of the sensor board worn by livestock. The performance of the IFA antenna has been analyzed with and without the cover of the board and optimized. The designed IFA antenna has a return loss of −19 dB and a gain of 1.6 dB at 2.45 GHz. The signal strengths of RSIs with a chip antenna and the proposed IFA antenna have been compared. It is about 20 dB enhancement with the IFA antenna compared to the chip antenna on the module. The proposed IFA antenna can replace the chip antenna on the RF module, and 20 dB RSI can be enhanced on the communication system. This proposed antenna can be applied to an RF module and sensor module, which can be applied to detect the behavior of livestock in general as well as cattle.

Funding: This research was supported by Daegu University Research Grant.

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: “MDPI Research Data Policies” at https://www.mdpi.com/ethics.

Conflicts of Interest: The author declares no conflict of interest.

References
1. Balanis, C. Antenna Theory: Analysis and Design, 4th ed.; Wiley: Hoboken, NJ, USA, 2016.
2. Stutzman, W.L.; Thiele, G.A. Antenna Theory and Design, 3rd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2012.
3. Yu, J.; Park, B. 1.9GHz Small IFA Design and Fabrication. J. Korean Electromagn. Eng. Soc. 2004, 8, 183–187.
4. Chae, K.; Cho, Y.; Yim, J. 2.4/5GHz Wireless LAN Inverted-F Antenna. J. Korean Electromagn. Eng. Soc. 2004, 15, 183–187.
5. Yu, J.; Ban, Y.-L.; Zhang, L.-W.; Sim, C. Very low profile Inverted-F antenna with 2.4/5.8GHz WiFi for metal-cover table computer. In Proceedings of the 2017 IEEE ICCEM Conference, Kumamoto, Japan, 8–10 March 2017. [CrossRef]
6. Liu, Z.; Hall, P.; Wake, D. Dual-frequency planar inverted-F antenna. IEEE Trans. Antenna Propag. 1997, 45, 1451–1458.
7. Yang, C.; Yeum, I.; Jung, C. Compact & Contact Quad-Band(DVB-H UHF/L, WLAN 11 a/b) Antenna for PMP Applications. J. Korean Inst. Electromagn. Sci. 2010, 3, 146–149. [CrossRef]
8. Rhee, E. Miniaturized PIFA for 5G communication networks. Appl. Sci. 2020, 10, 1326. [CrossRef]
9. Choi, J.; Yun, J. Low-Profile Planar Inverted-F Antenna for Ultra wideband Applications. *J. Korean Inst. Electromagn. Sci.* **2016**, *4*, 235–240. [CrossRef]

10. Yousaf, J.; Jung, H.; Kim, K.; Nah, W. Design, Analysis, and Equivalent Circuit Modeling of Dual Band PIFA Using a Stub for Performance Enhancement. *J. Korean Inst. Electromagn. Sci.* **2016**, *3*, 169–181. [CrossRef]

11. Available online: [www.antenna-design](http://www.antenna-design) (accessed on 29 December 2020).