Ultra-miniature bluetooth tag with antenna on package for red palm weevil tracking

Rana Muhammad Bilal, Zulma Lopez Reyes, and Atif Shamim
Department of Electrical and Computer Engineering, CEMSE Division
King Abdullah University of Science and Technology (KAUST)
Thuwal, Saudi Arabia
ranamuhammad.bilal@kaust.edu.sa

Abstract— Ultra-small tracking devices are necessary for monitoring small insects or pests such as Red Palm Weevil (RPW). Understanding movement and behavior of such pests is important because they create huge economic impact by destroying expensive crops. However, designing RF system and antenna mountable on such small insects is very challenging. Previously reported works in literature either have insufficient tracking range of few cm only; or are bulky (greater than 4cm); or are only capable of tracking one insect at a time. This paper reports a Bluetooth enabled ultra-miniature tracking tag which is detectable at a range of 78m and can be used to track multiple insects simultaneously. Presented tag uses a modified patch antenna-on-package design, and measures 6mm x 6mm x 3.5mm only.

Keywords— *insect tracking, RPW tracking, BLE tracking tag, antenna on package, modified patch antenna.*

I. INTRODUCTION

Red Palm Weevil (RPW) is a destructive pest for palm trees. Entire lifespan of its larvae is spent in palm tree's trunk, hollowing it out and resulting in tree's death. Over past few decades, Red Palm Weevil has spread to major part of Middle East, where date palms form a significant portion of exports and revenue. This has fueled interest in understanding RPW behavior to formulate counter strategies and control policies. For instance, understanding average and maximum commute distance of RPW adults helps to establish quarantine radius i.e. how much potentially infected area to cordon off if one date palm is found infected in a date farm. However, designing an RF system and antenna within such small size and weight limitations (so as to be suitable for attaching to RPW) is challenging.

RPW adults typically have body length of 35mm to 40mm. For tracking such insects, most suitable place to attach a tag is "thorax", as indicated in Fig. 1 below. Attaching tag to thorax does not blocks any moving part such as wings or leg; or critical sensory organ such as eyes or antennae; and thus does not hinders natural movement/behavior of the insect. On thorax of an adult red palm weevil an approximate 8mm by 8mm is available, where a tracking tag might be attached. This area is marked in yellow in Fig. 1.

As discussed in [1], device attachment to insects should weigh less than 10 percent of body weight of the insect. Typical RPW adult weight is 1g approximately [2]. Thus, a tracking tag suitable for monitoring RPWs should be maximum 8mm x 8mm in size and not weigh more than 100mg. Further, in order to provide meaningful monitoring information, tag must have adequate detection range (at least few tens of meter).

Fig. 1. Typical adult red palm weevil, area suitable for tracking tag mounting indicated by yellow box

Certain previous works in research literature have reported systems or approaches for tracking of such small insects. For instance [3] is a passive Radio Frequency Identification (RFID) tag for tracking/monitoring of honey bees. This tag although small in size and weight, has a very small tracking range of few cm only and thus is only suitable for very specific application of honey bee tracking, where an RFID reader can be fitted on nest's entrance. Reference [4] has reported millimeter wave harmonic sensor and radar system for tracking of Australian plague locusts. However, harmonic sensors do not contain identification information and thus cannot be used to track multiple insects simultaneously. Reference [5] has reported a very high frequency (VHF) active RFID tag for insects tracking. However, the reported tag requires a 10cm long thin wire whip antenna, which makes it unsuitable for mounting on small insects such as RPWs. Finally, [6] has used Bluetooth Low Energy protocol combined with Antenna on package design to present a 6mm x 6mm x 5mm tracking tag for monitoring of RPWs, with identification information as well as a read range of 300m. Whilst the tag presented in [6] is decently small, it misses on certain Bluetooth low energy protocol aspects that can be exploited to relax bandwidth requirements on Antenna design and thereby further reduce size of the Tag. Also, reported range of 300m is in free space and doesn't takes into account ground reflection or multipath effect.

This paper presents design of a Bluetooth enabled ultra-miniaturized tracking tag for RPW insects, with a modified patch antenna on package. Presented tag exploits Bluetooth low energy protocol to relax bandwidth requirement of antenna design from 83.5MHz to 2MHz, measures 6mm x 6mm x 3.5mm and has a detection range of 78m (including consideration for multipath). Body effect of mounting on RPW is also discussed.

II. TAG DESIGN

Bluetooth based tracking tag presented in this paper, consists of an embedded BLE printed circuit board (PCB), a modified patch antenna on package and a silver oxide coin cell to power the tag. Tag is programmed with an identification number, which is meant to be unique for each tag. Each tag broadcasts its unique identification number at a programmed broadcast interval of 100ms. Thus, a BLE scanning device can scan for these advertisement packets and identify vicinity of multiple RPW insects simultaneously, each distinguished by its unique identification number.

A. Bluetooth low energy (BLE) PCB

Embedded PCB for the tracking tag uses NRF52832, which is a Bluetooth system-on-chip (SOC) in a wafer level chip scale package (WLSCP). Footprint for this SOC measures 3mm x 3.2mm only. A 2 layer printed circuit board containing requisite passives i.e. a 32MHz crystal oscillator to generate clock pulse for the circuit, decoupling capacitors and programming pads is designed as shown in Fig. 2 below.

Fig. 2. Top and Bottom copper layers of Embedded PCB

Fabricated PCB measures 5mm x 5mm and weighs 57.7mg only. Fig. 3 shows fabricated PCB of tracking tag, its size comparison to a human finger nail and an RPW insect fitted with the fabricated PCB using super glue.

Fig. 3. Fabricated PCB of tracking device, size comparison to a human finger nail, an RPW mounted with fabricated PCB

B. BLE protocol exploit for antenna bandwidth reduction

BLE protocol specifies spectrum from 2400MHz to 2483.5MHz. Covering this entire bandwidth can make antenna design (in a constrained space of less than 8mm x 8mm) quite challenging. Interestingly however, BLE spectrum is sub-divided into 37 data and 3 advertisement channels. As per BLE specifications, a peripheral device may advertise in non-connectable mode. Thus, such a device only utilizes the 2MHz advertisement channels and is discoverable/detectable on nearby BLE scanning devices. Tag

presented in this paper is configured via embedded programming to advertise in non-connectable peripheral mode at 39th BLE channel. Thus, the associated bandwidth requirement for antenna design relaxes to 2MHz (from 2479MHz to 2781MHz)

C. Modified Patch Antenna-on-Package

Two techniques are implemented to achieve the high level of miniaturization that this application demands: dielectric loading and shaping. First, the antenna is designed on a high dielectric constant material, so the wave propagation slows down [7]. Subsequently, four slots are introduced to force the current to travel a longer path, and vertical sections of conductor are added to extend the size of the patch [8]. Fig. 4 displays the development of the geometry and table 1 summarizes the performance at each stage.

Fig. 4. Antenna design stages.

The antenna is a 5 x 5 mm² patch antenna on a 1 mm thick ceramic dielectric with relative permittivity of 37, and loss tangent of 0.001, and a 6 x 6 mm² ground plane at the bottom. The patch is fed on the edge to ensure high impedance. At the first stage, the antenna operates at 4.8 GHz, so the patch is to be modified to lower the frequency.

In the second stage, four straight slots are introduced, and the effect of their width S_w and length S_l are studied. As shown in Fig. 5, the frequency shifts down as the width or length increases because the current path is lengthen. However, the antenna does not reach the desired frequency range yet.

In the third stage, three vertical sections are added to enlarge the radiating structure. Similarly to the previous case, the frequency shifts down as the height of the vertical section p_z increases, reaching 2.6 GHz when p_z becomes 0.9 mm.

Fig. 5. Return loss of the parametric simulations. (Dimensions are in mm)

In order to achieve further miniaturization the slots are bended and lengthen, and a 2.7 nH inductor is inserted to match the antenna to 50 Ω . The practical losses of the inductor are considered in the simulation as a series resistor of 0.13 Ω . Up to this stage, the antenna resonates at 2445 MHz and its maximum gain is -14.8 dB.

TABLE I. ANTENNA PERFORMANCE AT EACH STAGE OF MINIATURIZATION

Stage	Frequency (MHz)	Gain (dB)	ka
Patch on ceramic	4775	-2.41	0.38
Straight slots	3250	-13.1	0.30
Vertical conductor sections	2600	-14.4	0.23
Bended slots and inductor	2445	-14.8	0.22
Tag on RPW	2480	-14.6	0.22

III. PERFORMANCE SIMULATIONS AND RESULTS

Finally, the effect of the system-on-package (SoP) is addressed. The package, battery, BLE PCB and RPW body are included in the simulation, as shown in Fig. 6. The package is modeled as a cover with relative permittivity of 4.4 and loss tangent of 0.02, while the RPW body is modeled as a 25 x 15 x 10 mm³ box with relative permittivity of 7 and loss tangent of 0.27 [9].

Fig. 6. System-on-package and simulation on modeled RPW. (Dimensions are in mm)

Fig. 7 displays the return loss and radiation pattern of the SoP on the RPW. The maximum gain is -14.6 dB. The frequency shifts up because of the dielectric loading effect of

the package, while RPW body causes a gain attenuation of 1.7 dB at the bottom of the radiation pattern. As expected for a small antenna design, the radiation pattern exhibits a nearly omnidirectional shape. The antenna operates at 2.48 GHz with a 10 dB bandwidth of 11 MHz, which is sufficient to cover the 39th advertisement channel at 2.48 GHz as well as three data channels.

Fig. 7. Tag performance: return loss and radiation pattern.

Two ray ground reflection model [10] is used to estimate the detection range of the presented Bluetooth tag. On the receiver side, the chip sensitivity is -96 dBm, and the typical gain of a Bluetooth antenna is -2 dB. On the transmitter side, the antenna gain is -14.6 dB and the output power of the Bluetooth chip is 4 dBm. This translates to an estimated detection range of 78m.

IV. CONCLUSION

An ultra-miniature Bluetooth enabled tracking tag for red palm weevil monitoring has been developed. Tag uses a modified patch antenna-on-package with a gain of -14.6db and is detectable at a range of 78m using Two-Ray ground reflection model. Size of the designed tag is smaller than similar tags previously reported in literature and detection range is suitable for red palm weevil monitoring.

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