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Antenna Tuning for Wearable Wireless Sensors

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***Abstract*—When miniaturized wireless sensors are placed on or close to the human body, they can experience a significant loss in performance due to antenna detuning, resulting in degradation of wireless performance as well as decreased battery lifetime. Several antenna tuning technologies have been proposed for mobile wireless devices but devices suitable for widespread integration have yet to emerge. This paper highlights the possible advantages of antenna tuning for wearable wireless sensors and presents the design and characterization of a prototype 433MHz tuner module..**

I. INTRODUCTION

Wearable wireless technology is seeing a rapid emergence in recent times in areas such as healthcare and activity monitoring, driven by the need for small and reliable monitoring devices. This technology can be used in applications such as out-patient monitoring and providing in-home lifelines for the elderly [1-2]. Wireless sensor motes [3] are an ideal platform for these types of applications. However, conventional battery powered wireless sensors with an integrated antenna, when placed on or close to the human body, can experience a significant loss in performance due to antenna detuning. The issues associated with antenna detuning were investigated in detail in [4] for a 433MHz ISM (Industrial Scientific and Medical) band wearable sensor using a small 50Ω commercial planar shown in Fig .1.

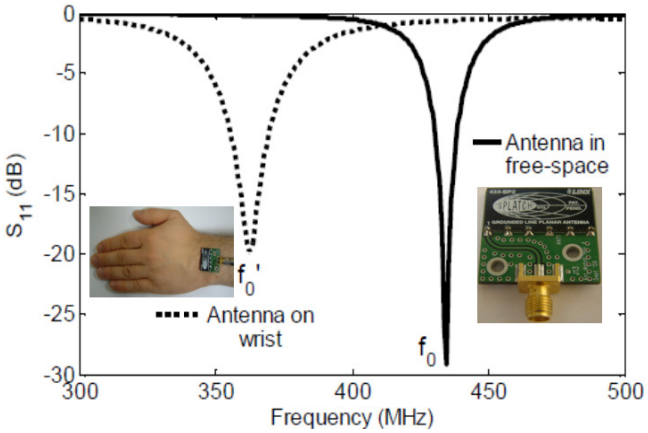


Figure 1. Comparison of measured return loss for a 433MHz antenna test assembly when placed in free-space and then placed on a human wrist [4].

It can be seen that when the antenna return loss is measured in a free-space condition, the antenna is correctly tuned to the nominal frequency f_0 of 433MHz with a corresponding return loss of close to 30dB. This represents a very good impedance match with close to 100% power transfer to antenna. However, when the antenna is now placed on the human wrist, the antenna impedance is affected significantly. The resonant frequency decreases to a value of 363MHz and the return loss (at f_0) drops substantially to less than 1dB representing approximately 20% power transfer to the antenna or 80% power loss. In this case, the lack of adaptive impedance matching for a wearable sensor placed on the body will greatly degrade wireless performance. Wireless sensor devices operating at UHF frequencies employ fixed antenna matching circuits to match the antenna to the radio transceiver. However, fixed matching circuits are designed to operate with a constant antenna impedance (typically 50Ω) and are incapable of adapting to changes in antenna impedance caused by re-orientation or movement that are inevitable in mobile or wearable deployments. One solution to the above problem is the use of an impedance matching system that adaptively corrects for any changes in antenna impedance. Antenna tuning solutions, particularly automated solutions are therefore extremely desirable, especially for mobile and cellular wireless applications. To address the above issues, adaptive antenna tuning networks have been investigated by researchers in recent times. These antenna tuning circuits have been designed using different technologies to create variable reactive elements that allow the networks to be tuned. Adaptive tuners have been demonstrated using technologies including varactor diode devices [6], barium strontium titanate (BST) technology [7], CMOS technology [8] and increasingly micro-electro-mechanical systems (MEMS) solutions [9]. The main concern is the trade-off between improved performance and losses and challenges towards implementation include component losses, tuning ratio, linearity and integration issues [10].

II. EFFECTS OF ANTENNA TUNING ON RECEIVED POWER AND POWER CONSUMPTION FOR A WIRELESS SENSOR

The Tyndall 25mm wireless sensor platform was the focus of this work [3]. Each wireless sensor is made from a number of sensor, power and communication layers. The 433MHz

radio transceiver layer was utilized due to its suitability for wearable sensor applications and is based on Nordic's NRF905 radio transceiver. In order to investigate the merits of antenna tuning and its effect on power consumption, the test setup shown in Fig. 2 was used for two test cases.

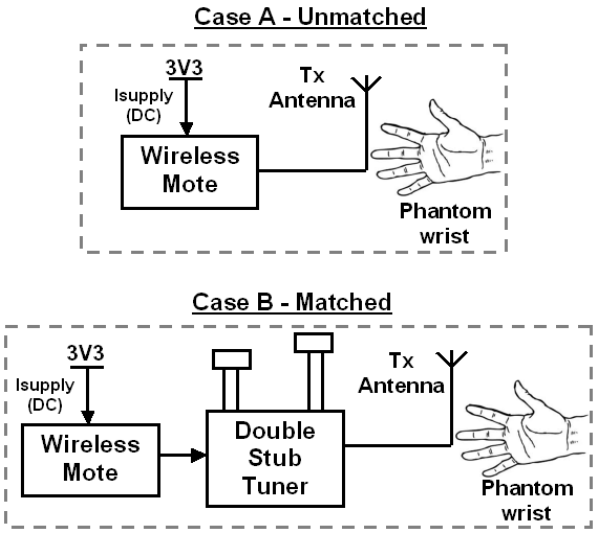


Figure 2. Block diagram of measurement setup.

In Case A, a transmitting wireless mote was first connected directly to the transmitting antenna mounted on a phantom wrist via a 50Ω coaxial cable. The phantom wrist was developed to mimic the RF properties of human tissue [4]. The received power at a frequency of 433MHz at a distance of approximately 2.5metres from the transmitting antenna was then measured with a spectrum analyzer as shown in Fig. 3. In a laboratory environment, is a difficult to perform repeatable RF measurements of this type. The receive power was therefore measured a total of 10 times in order to provide a larger sample of measured values.

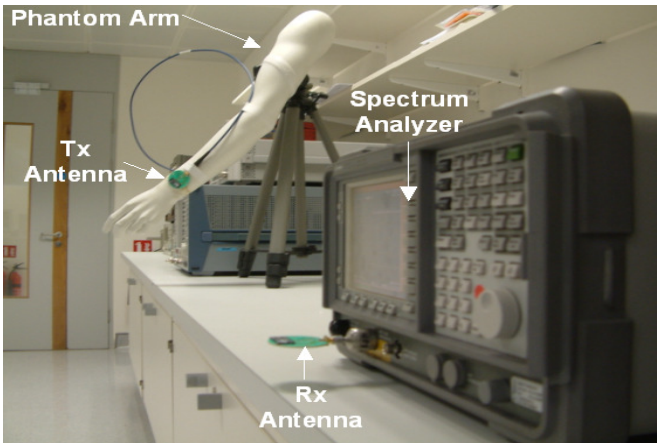


Figure 3. Photograph of measurement setup.

In Case B, the only difference was that on this occasion, a double stub tuner [5] was inserted between the transmitting wireless mote and antenna. The tuner was then pre-adjusted to match the antenna using a vector network analyzer and the receive power measured in the same manner as previously. Fig. 4 summarizes the measured results. It can be seen that when the detuned wireless sensor transmit antenna is manually matched using a stub tuner, a significant improvement (4-5dB) in received power is measured for the same transmit power. Without antenna impedance matching, the transmit power would need to be increased by 4-5dB to maintain a specified level of received power but at the expense of increased supply current for the wireless sensor.

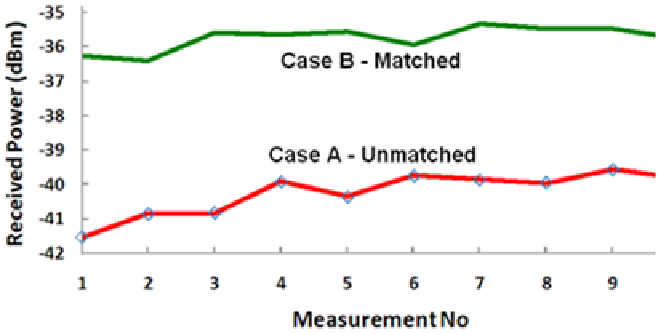


Figure 4. Measured received power before and after antenna tuning

This is clearly not desirable for low power wireless applications where battery lifetime is a critical issue. In order to obtain a quantitative measure of the effect of increasing the transmit power of this wireless sensor by an amount of 4dB, the supply current was monitored for varying transmit power and the results are plotted in Fig. 5.

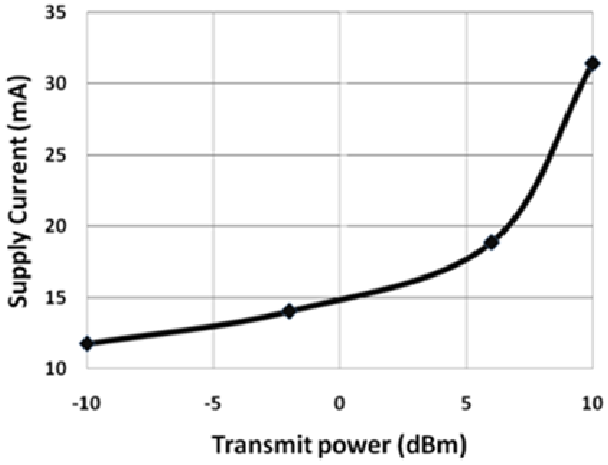


Figure 5. Relationship between wireless sensor current consumprion and transmit power under a 50Ω load condition.

It can be seen that there is a substantial cost in terms of wireless sensor supply current in increasing transmit power at the highest output power levels for this radio transceiver in comparison to lower transmit powers. In practice, many wireless sensor applications operate the radio at maximum transmit power in order to maximize range and throughput and reduce packet loss. It can be seen from Fig. 5 that without matching, in order to increase the transmit power by 4dB from 6dBm to 10dBm, requires an additional 12.54mA of supply current which is substantial. In contrast, with low loss matching between radio and antenna, a 4-5dB increase in received power can be measured at the receive antenna with no increase in current consumption. It is therefore apparent that there is a significant benefit in matching the antenna and

radio impedances rather than increasing radio transmit power of the wireless sensor.

III. Adaptive Antenna Matching Circuit

Due to the lack of a commercial antenna tuning solution, the objective of this work was to investigate the design of a functional prototype antenna tuning system, specifically for low power, wearable wireless sensors that could be implemented using off-the-shelf components. As part of this work, a dedicated hardware test platform was previously developed to allow automatic, real-time measurement of antenna return loss [4]. It also provides a flexible means of controlling and evaluating different types of adaptive antenna tuning circuits and tuning algorithms for use in wireless sensor applications. A block diagram of this platform is shown in Fig. 6. In an environment where the antenna impedance is changing such as a wearable/mobile application, a closed-loop system monitors the reflection coefficient of the antenna in real time. It then constantly adjusts the matching network (shown in dotted area) to minimize the reflected power from the antenna.

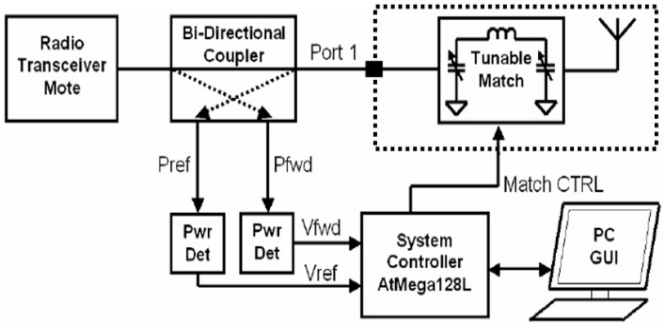


Figure 6. Wireless mote tuning system.

In terms of implementation, narrowband antenna tuners can be designed using well known matching topologies such as L-type, T-type and Π-type networks or combinations of these. A widely used impedance matching network topology is the low-pass Π-type shown in Fig. 7.

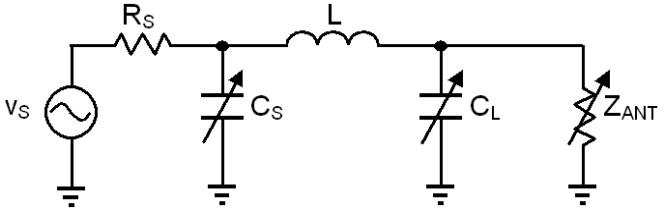


Figure 7. Π-type matching network.

Its suitability stems from the fact that the overall quality factor of the network is higher than for the L-type [12] and the Π-type also has harmonic rejection capability with a wider matchable impedance range compared to other types. The Π-type matching network for this application, is composed of three reactive elements L, C_S and C_L. Also shown are the source voltage V_S and the source impedance R_S which is typically 50Ω. The variable antenna impedance is denoted by Z_{ANT} and represents a range of antenna impedance values. It can be seen that the inductor has not been made variable. In practice, variable inductors are difficult to implement and in this application, the inductor has been made fixed and only C_S and C_L are made variable. The chosen implementation of the variable capacitor for both C_S and C_L is shown in Fig. 7. A four-bit array of binary weighted capacitors is digitally switched during tuning using low loss RF switches. This provides a range of 2^4=16 individual capacitance values for C_S and C_L or 256 different tuning combinations in total.

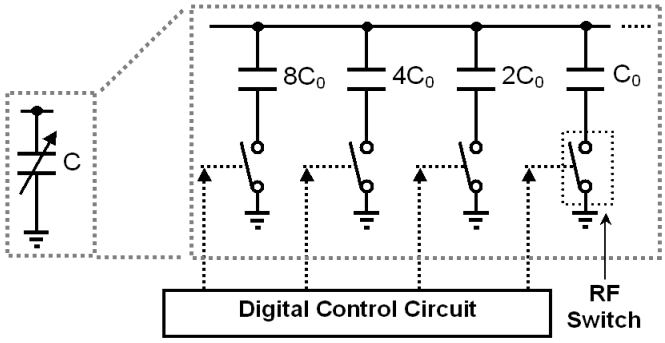


Figure 8. Variable capacitor Implementation

The RF switches that were used for this application are CMOS SPDT based discrete types that operate from DC to 3GHz [13]. These components were chosen primarily due to their low insertion loss, high isolation and low power consumption. In addition, they were attractive in terms of power consumption, requiring a DC supply current of less than 1uA which was an important consideration when used in a low power wireless sensor application. In terms of choosing capacitance values for the circuit, a simple 1-switch design was first simulated using measured s-parameter data for the RF switch. This was necessary in order to determine 2 key parameters for the design: the on-resistance of the switch R_{ON} and the off-capacitance of the switch C_{OFF}. Simulation revealed values of C_{OFF} = 1.9pF and R_{ON} = 4.4Ω, both measured at 433MHz. The value of C_{OFF} sets an important lower limit of $4C_{OFF}$ = 7.6pF for the minimum achievable capacitance using these switches. In addition, the on-resistance of the switch is a critical factor in determining both the insertion loss of the matching network as well as the range of antenna impedances that can be matched. A more comprehensive simulation model was next developed that also included the parasitics of the capacitors and inductor as well PCB properties and traces. Antenna impedance data [4] was also measured for use in the simulation model. This model was then run in order to calculate the optimum values for the two variable capacitances to match a range of antenna load impedances ranging from the antenna in free-space (best case) to touching the skin (worst case) and the optimized matching network with component values is shown in Fig. 9.

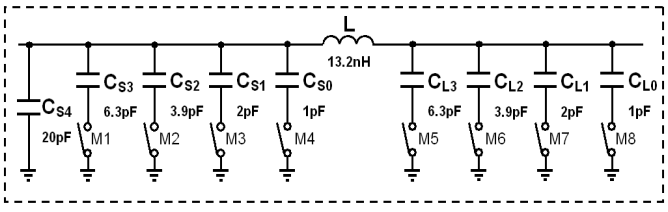


Figure 9. Final component values for tuning network

The fabricated matching circuit is shown in Fig. 10 and is inserted between the antenna and wireless mote as shown in Fig 6. The SMA connector on the left connects to the wireless mote side and the SMA on the right connects to the antenna. The RF switches were carefully placed on the PCB to minimize parasitics. Four switches were placed on each side of the PCB as close as possible to the high-Q matching inductor shown in the center. The digital interface to control the switches is made via the ribbon cable shown.

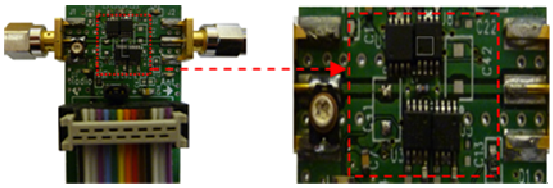


Figure 10. Fabricated tuner module (left), Zoomed view (right)

IV. MEASUREMENTS

Fig. 11 shows the measured de-embedded capacitance of C_L. It can be seen that the capacitance rises linearly across the range except for a small deviation from state 7 to 8. This is not an issue as the most-significant capacitor C_{L3} in Fig.8 can be fine tuned to correct this. C_L has a minimum measured capacitance of 7.65pF and a maximum of 27.59pF in 1.7pF steps.

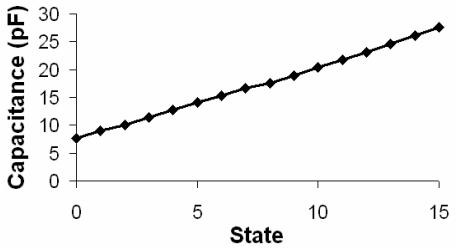


Figure 11. Measured capacitance of C_L after fabrication (at 433MHz).

The fabricated circuit was then connected to the system controller [4] to test the performance in matching an un-tuned antenna. The system controller implements a tuning algorithm that upon request, sequentially searches for values of matching capacitor values C_S and C_L that minimize the return loss of the antenna. Once the optimum values of capacitance are found, they are written to C_S and C_L and stored in memory until the next tune is initiated. The process takes approximately 0.3s to complete the tuning operation. Fig. 12 shows the measured return loss before and after tuning.

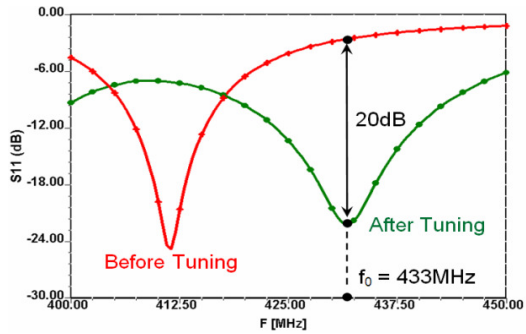


Figure 12. Measured antenna return loss before and after tuning

It can be seen that there is a significant improvement of approximately 20dB in the measured return loss of the antenna after tuning.

V. CONCLUSIONS

This paper has highlighted potential advantages of antenna tuning for wireless sensors. A functional prototype 433MHz closed-loop antenna tuner module was developed using commercial RF switch components and a 20dB improvement in measured return loss has been demonstrated. Future work will investigate in detail the losses of the system and the development of an automated tuner suitable for on-chip integration for applications in wearable wireless sensor applications.

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