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Modelling and Characterisation of a Compact Sensor Antenna for Healthcare Applications

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***Abstract*— The paper presents a planar compact antenna structure used in sensors aimed at healthcare applications. Antenna performance is numerically investigated with regards to impedance matching, radiation patterns, gain and efficiency. The compact size of the sensor causes the antenna to be susceptible to variable changes caused by the presence of lumped components. The study illustrated the importance of including full sensor details in determining and analysing the antenna performance. The body-worn sensor performance is also demonstrated and effects on antenna parameters are analysed, specifically radiated power, efficiency and front to back ratio of radiated energy. Radio propagation characterisation of the sensor operation in stand alone and on-body scenarios are introduced. Improvements are necessary in antenna design, matching circuitry and also sensor layout for better coverage and for obtaining maximum achievable communication range to produce efficient and reliable medical telemetry and monitoring systems.**

***Index Terms*— Healthcare sensor, compact antenna, wearable device, numerical modelling, efficiency.**

I. Introduction

Wireless body area networks (WBAN) provide promising applications in medical sensor systems and personal entertainment technologies [1]-[2]. They present the apparent option for efficient, flexible systems with constant availability, reconfigurability, unobtrusiveness and true extension of a human's mind. The idea of a body area network was initiated for medical purposes in order to keep continuous record of patient's health at all times. Sensors are placed on the human body to measure specified parameters and signals in the body, e.g. blood pressure, heart signals, sugar level, temperature, etc.

Antennas are essential part of WBAN and their complexity depends on the radio transceiver requirements and also on the propagation characteristics of the surrounding environments. For the conventional long to short wave radio communication, conventional antennas have proved to be more than sufficient to provide desired performance minimising the restrains on cost and production time. On the other hand, for todays and tomorrows communication devices, the antenna is required to perform more than one task or in other words the antenna needs to operate at different frequencies to account for the increasing new technologies and services available to the user, e.g. systems on pills [5] and miniaturised sensors [6]. For wireless sensor applications, antennas need to be efficient and immuned from frequency and polarisation detuning. Understanding the antenna radiation pattern for wireless sensors, specifically when applied for body-worn applications, is vital in determining the sensor performance. It is also important to specify how coupling into the propagation mode which may be a surface wave or free space wave or a combination of both occurs.

This paper presents sensor designs and modules developed by the group Healthcare Devices and Instrumentation, Philips Research, for operation in the unlicensed ISM band (2.4 GHz). Maximum achievable coverage range is to be delivered by the sensor with respect to the transceiver sensitivity levels. Modelling and characterisation of the antenna deployed in the full sensor are discussed and investigated with regards to surrounding components and data connectors (full sensor details are included). Antenna enhancement techniques are demonstrated to improve impedance matching and hence antenna efficiency. Radio channel characterisation of propagation from a wearable sensor is also presented and cross-referenced with numerical simulation results for validation.

II. Antenna Requirements

The sensor antenna design is restricted by many factors including the sensor size, chips placement, lumped element locations and flexibility of the sensor structure to be shuffled with minimum cost and changes to antenna performance. Figure 1 shows photographs of the sensor transceiver layer and the prototype module fabricated. A schematic design of the modelled sensor antenna and also an exploded diagram of the proposed sensor is illustrated in Fig. 2.

The current antenna deployed in the sensor design is a printed quarter wavelength monopole, etched on the edge of the circular PCB board. Hence the antenna is designed with the printed wire wrapping the transceiver chip and other components. The antenna is derived from the circumference monopole, which is derived from the bent and inverted L antenna [7]. The sensor antenna performance is sensitive to lumped components, pins and copper routings presence. The surrounding and adjacent components are modelled as a perfect conductor block around which the antenna is printed. The PCB board includes ground plane and supply voltage copper sheets.

When a monopole is placed or printed on a dielectric material with permittivity other than 1, the antenna dimensions have to be modified in order to achieve performance at the frequency of interest. This leads to redefinition of antenna impedance by the approximation,

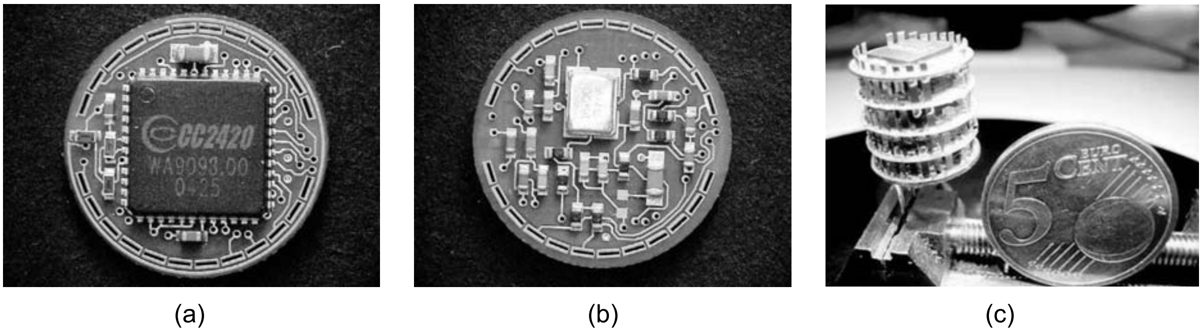

Fig. 1. Photographs of (a) top view of the transceiver layer, (b) bottom view of the transceiver layer and (c) the manufactured prototype sensor

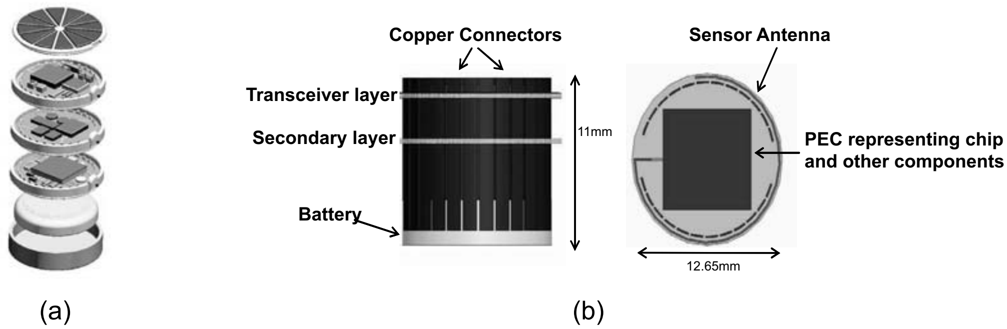

Fig. 2. (a) Exploded diagram of the proposed healthcare sensor and (b) dimensions and detailed structure of the modelled sensor including the antenna.

$$Z(\omega, \epsilon_{eff}) = \frac{1}{\sqrt{\epsilon_{eff}}} Z\left(\sqrt{\epsilon_{eff}}\omega, \epsilon_0\right) \quad (1)$$

where ϵ_{eff} is the effective permittivity and ϵ_0 is the vacuum permittivity. This leads to the antenna length being shortened by a factor of $1/\sqrt{\epsilon_r}$ to ensure the resonance is at the desired frequency. The metal pins and copper lines provide an extension to the antenna which increases the impedance value expected, however, due to the capacitive coupling between the antenna and surrounding components the antenna impedance tends to decrease comparing to the general monopole impedance of 36 Ω. Therefore, the radiation characteristics of the antenna are directly affected; hence changes in antenna gain and efficiency are expected.

III. Numerical Analysis of Antenna Performance

A. Initial Design

The antenna design deployed in the proposed sensor is numerically analysed using the Finite Element Method (FEM) utilised in the High Frequency Structure Simulator (HFSS), Ansoft$^{\text{TM}}$. The printed circular monopole antenna is modelled on FR4 substrate (ϵ_r=4.6 and thickness of 0.3mm). The printed antenna thickness is $35\mu m$ and the width of the line is $150\mu m$. The ground and supply voltage layers added have a diameter of 5.5mm, thickness of $17.5\mu m$ each and separation between the layers of $80\mu m$. The actual antenna length is 31.5mm (approximately quarter wavelength of the required frequency, 2.4GHz). The complex impedance at the RF transceiver differential output is 115+j180 , therefore a matching circuit is applied in order to match the output to the single-ended monopole (matching to 50Ω) [10].

Figure 3 presents the return loss of the sensor antenna when only one layer is modelled in comparison to full sensor modelling. The one layer model includes the printed antenna, the transceiver chip and PCB board. The figure illustrates the significance of considering full structure modelling in characterising small antenna designs integrated with radio systems. The return loss of the antenna demonstrates the effect of the connectors on reducing the resonance frequency due to increase in electric length of the antenna caused by connectors current distribution. The calculated antenna gain is -1.2 dB with radiation efficiency of 48%.

B. Performance Enhancement

Investigating the impedance of the current sensor antenna, the real part of the antenna impedance is calculated as 11Ω. In general monopole antennas have impedance of 36Ω; however, this impedance is dependent on shape and size of the antenna. The bend shown in current antenna design causes the inductive reacting part to increase in comparison to capacitive reactance and reduces the real impedance part. Therefore, one solution is to modify the current matching circuit to match complex transceiver impedance $115 + j180\Omega$ to 11Ω. Figure 3 shows the return loss of one layer and full sensor antenna models when a modified matching circuit is applied and the improved impedance matching is apparent for both cases at

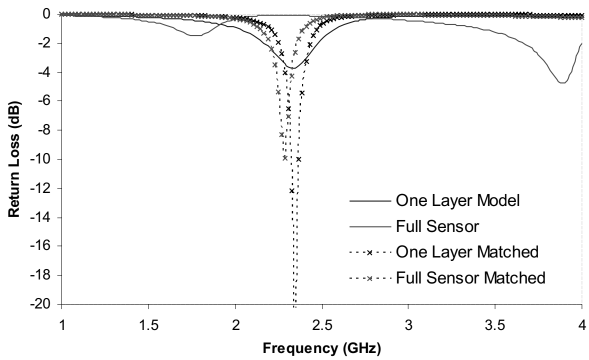

Fig. 3. Comparison of sensor antenna return loss for one layer and full sensor models. Comparison between original antenna matching and modified matching circuits.

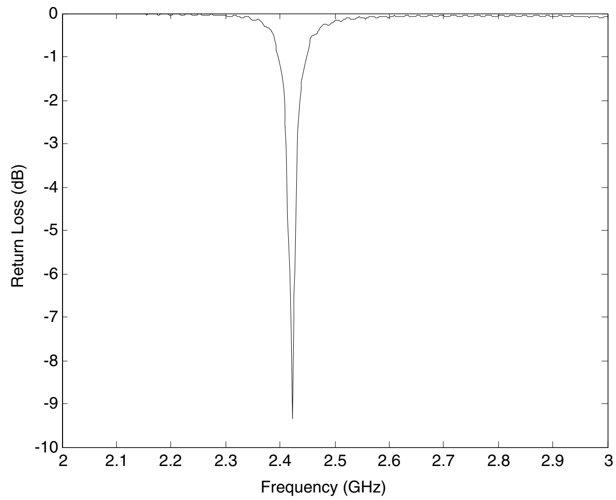

Fig. 4. Simulated return loss of sensor antenna in free space with resonance around the desired frequency.

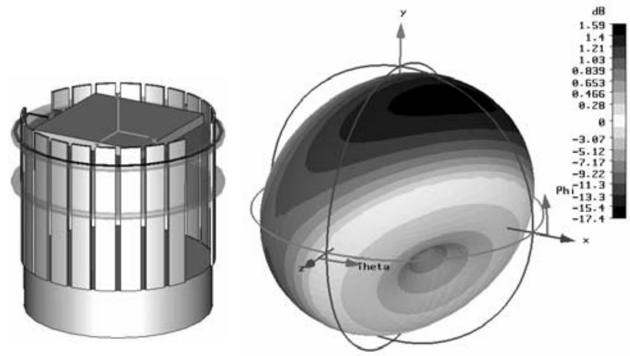

Fig. 5. Sensor antenna radiation pattern numerically calculated at 2.4GHz.

the frequency of interest.

Initial analysis of the monopole impedance at 2.4GHz demonstrated the effect of adjacent components on antenna performance and hence antenna impedance. The antenna has a calculated complex impedance of $35 + j320\Omega$ at 2.4GHz. Another solution of the impedance matching problem is to introduce A 0.2pF capacitor at the antenna input to match the antenna to the 50Ω impedance seen at the current matching circuit output (recommended by transceiver data sheet [10]). Figure 4 presents the sensor antenna return loss and the resulting narrowband response caused by capacitor addition. The 3D antenna radiation pattern at 2.4GHz is shown in Fig. 5. The pattern is different from that of a conventional vertical monopole due to introduced bend and also the effect of surrounding elements. The antenna gain calculated numerically is around 1.6dB with efficiency of 77% which demonstrates improvements in both impedance matching and antenna radiation and hence total antenna efficiency in comparison to the unmatched antenna design discussed above. This illustartes the potential extended coverage area served by the sensor with simple and reliable performance enhancement techniques. The modelled sensor structure includes two layers of modules in comparison to four illustrated in the prototype photograph in Fig. 1. Two layers proved to be sufficient enough for obtaining reliable data.

IV. Body-Worn Sensor Modelling

Body-worn sensor antenna performance is numerically investigated using the finite integral technique (FIT) utilised in CST Microwave Studio$^{\text{TM}}$. The sensor is placed on the human chest, as shown in Fig. 6, with the antenna radiating element normal to the body. The used model is the commonly available detailed multi-layer human model, namely the visible male model developed by the US air force (http://www.brooks.af.mil/AFRL/HED/hedr/). The simulated return loss of the sensor shows the slight detuning due to presence of lossy tissues with sensor placed 2mm away from the body, Fig. 7. Although the detuning effect is minimum, the narrowband nature of the antenna (with capacitor used for matching) signifies such changes and its direct influence on radiated energy.

The antenna gain when placed on the body is increased to 2.4dB caused by reflections from the human body, which at this high frequency is considered as a large reflector due to high losses and also very small penetration depth. The azimuth plane radiation patterns shown in Fig. 8 illustrate the effect of human body on the antenna performance and the reduced radiated power in the backward direction with front to back ration of around 25-30 dB. This is clearly demonstrated in Fig. 9, which presents the electric field distribution around the human body at 2.4 GHz in both vertical and horizontal planes. The field distribution defines clearly the creeping waves created by diffraction of propagating waves around the body curvature and also the power absorption with regards to front to back power ratio.

V. Radio Propagation Characteristics of the Sensor Antenna

The spatial performance of the sensor antenna is anaylsed experimentally in free space (anechoic chamber measurement).

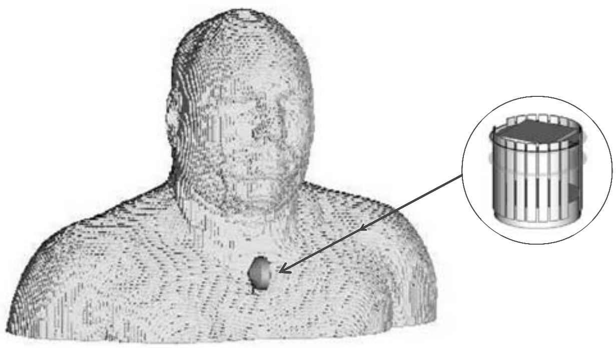

Fig. 6. Sensor placed on the male model provided by the visible US human project.

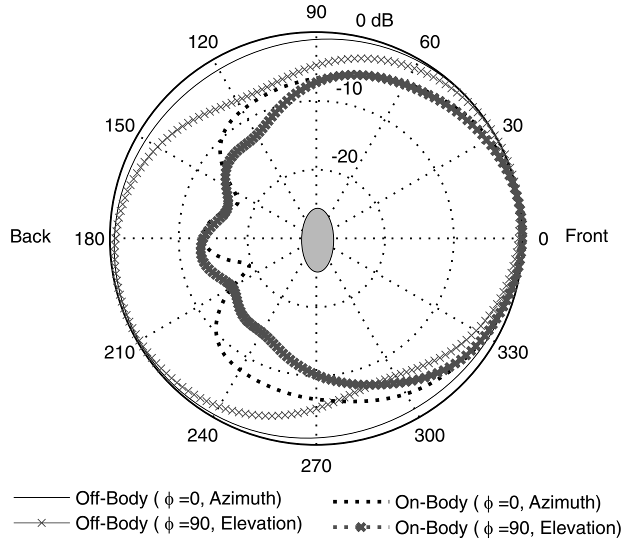

Fig. 8. Radiation pattern of sensor antenna when placed in free space and on the body in both aziuth and elevation planes (Fig. 5).

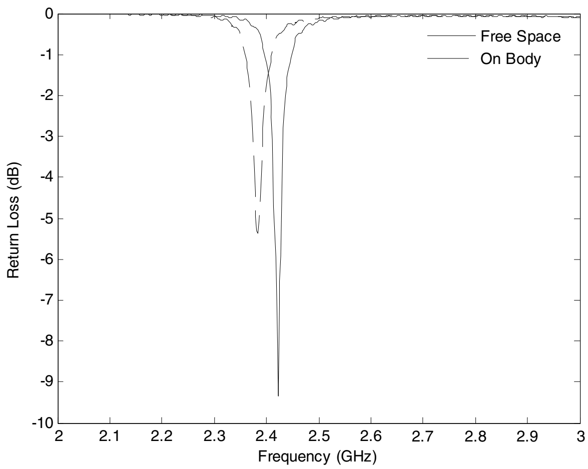

Fig. 7. Return loss for capacitor matched sensor antenna with resonance at 2.4 GHz when place in free space and on the body.

The sensor is placed on a turn-table with angular variations of 0^0 to 360^0. The sensor is used as transmitting unit and a microstrip patch antenna connected to a spectrum analyser acts as a receiving node. The patch antenna is placed 88 cm away from the transmitting sensor. The sensor is placed on the turn-table in horizontal and vertical orientations to investigate polarisation effect on propagation channel. Similar setting is repeated when the sensor is worn by the user (similar position presented in Fig. 6). The spectrum analyser received spectrum demonstrated a picked signal at 2.405GHz, which is covered by both sensor and patch antennas.

Figure 10 shows measured co-polar and cross-polar patterns of the sensor antenna radiation performance in free space and also when placed on the body with the antenna normal to

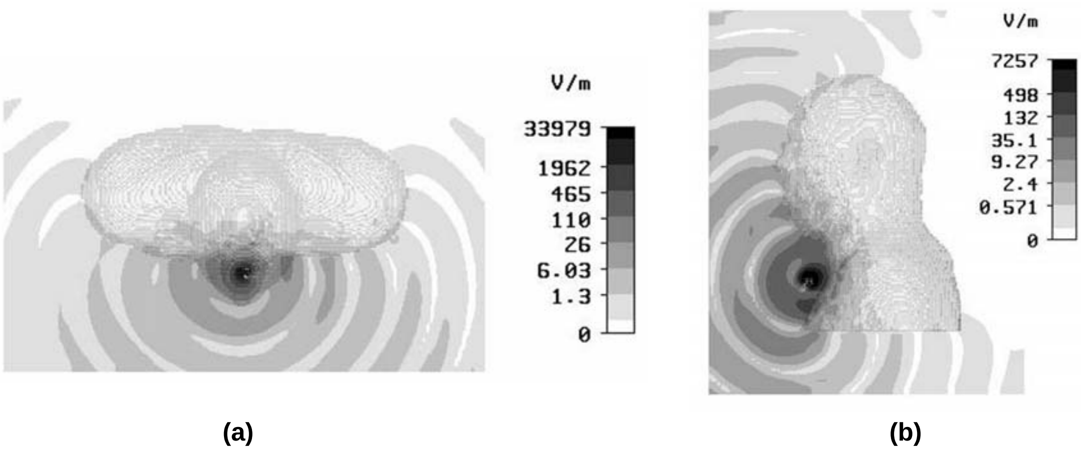

Fig. 9. Electric field distribution around the human body induced by the sensor antenna in (a) Horizontal (top view) and (b) Vertical (side view).

the body. When the body shadows the communication link between Tx-Rx nodes, at around 180^0 the loss due to the body shadowing is around 30dB, which agrees with results aforementioned from numerical analysis. The angular patterns in Fig. 9 present reasonable omni-directional behaviour of the sensor antenna with maximum variation of 8-10dB for free space cases (off-body).

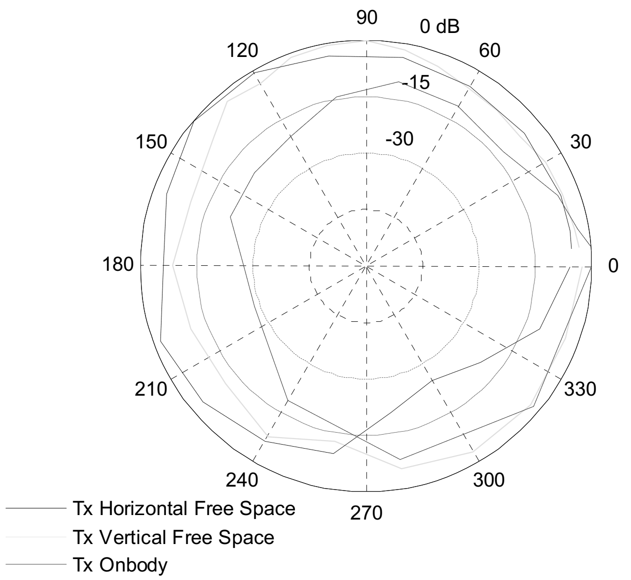

Fig. 10. Received power pattern when Tx (Sensor) is placed 88cm from a receiving patch antenna for horizontal and vertical sensor placements.

Following the set-up described above, path loss analysis of the radio channel between the transmitting sensor and the patch for cases where the sensor is placed in free space and on the body in the anechoic chamber and in indoor environment is performed. Figure 11 demonstrates the path loss measured in indoor environment. As predicted from Frii's path loss formula, the exponent is lower than that of free space with a value of 1.3 when the sensor is placed on the body due to multipath components from the different scatterers. For similar distances the loss is higher for NLOS cases. The directivity of the antenna increases when the antenna is placed on the body due to high losses at 2.4GHz of the human tissues which leads to an increase in the received power for the same distances applied in the stand alone sensor scenario.

VI. Conclusion

A study of a compact antenna used in sensors aimed at healthcare applications in the ISM band (2.4 GHz) was presented. The antenna performance was investigated numerically considering the effect of full sensor structure in comparison to antenna printed on PCB board model. The investigation demonstrated the significance of considering the detailed sensor design in analysing the antenna and radio propagation performance due to the compact size of the proposed sensor. The compact size of the sensor and the careful placement of components surrounding the antenna

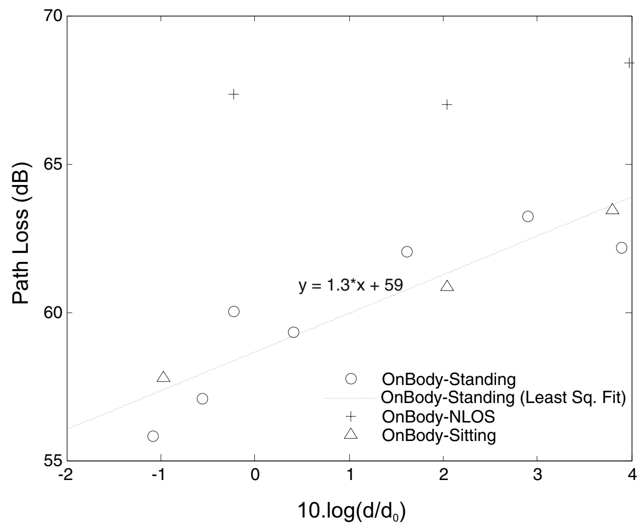

Fig. 11. Indoor measured path loss when sensor placed off and on body with modelled path loss using the least fit square technique (line related body standing skip off body).

introduced many challenges in determining and improving the antenna performance with regards to impedance matching, gain, efficiency and front to back ratio of radiated energy. The antenna performance evaluation and radio propagation characterisation provided promising indications of potential optimum performance sensor designs.

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