Energy Efficient Body Area Networking Based on Off-the-shelf Wireless Sensors

Sema Dumanli
Telecommunications Research Lab
Toshiba Research Europe Ltd
32 Queen Square, BS14ND
Bristol-UK
sema.dumanli@toshiba-trel.com

Sedat Gormus
Telecommunications Research Lab
Toshiba Research Europe Ltd
32 Queen Square, BS14ND
Bristol-UK
sedat.gormus@toshiba-trel.com

Ian J. Craddock
Telecommunications Research Lab
Toshiba Research Europe Ltd
32 Queen Square, BS14ND
Bristol-UK
ian.craddock@toshiba-trel.com

ABSTRACT

Body area networks (BAN) require careful hardware and software design which will enable the battery powered sensor devices to operate effectively and reliably over long periods of time. On body sensor design is a challenging task due to the body being in the near-field of the radio and the complex interaction between the two.

Off-the-shelf wireless sensors can be optimized to realize an efficient BAN by combining an enhanced shorted patch antenna design with a cross layer energy aware protocol. Here, we demonstrate a system design approach where the performance of WBANs is greatly enhanced.

Keywords

BAN, Shorted Patch Antenna, Omni-directional Radiation, Cooperative Communication, Sensor Networks

1. INTRODUCTION

It is estimated that in the twenty first century, the population of the world is going to age more rapidly than the previous century [1]. The people aged over 80 formed 0.5% of the whole population in 1950, 1.1% in 2000 and is expected to form 4.1% by 2050. Dependency ratio increases in parallel with the ageing and so the demand for medical services. Current medical techniques will not be able to meet that demand in the future while the existing healthcare system is already suffering from the increasing number of old patients. Wireless sensor networks can be of great help in order to tackle this challenge. Many projects have been developed for wireless health monitoring over the past couple of years [2] [3]. Limited battery life of the sensors and the communication taking place on a very lossy medium are among the most important problems awaiting to be addressed. Here we are proposing an efficient wireless sensor network for mobile health monitoring using off-the-shelf wireless sensors with a focus on the engagement of an on-body antenna design and an efficient protocol.

A shorted rectangular patch antenna operating in omni-directional mode for on-body usage is designed and design guidelines are given in Section 2. Performance analysis have been reported in isolation and in the intended usage scenario of connection to a TelosB module [4]. On-body propagation is investigated through simulations and measurements in Section 3. Section 4 outlines an energy efficient cross layer protocol design. In Section 5 the proposed antenna and the protocol is engaged in a realistic scenario where five on-body sensors are located on a male subject and performance results on the efficiency improvements are presented. The paper concludes in Section 6.

BODYNETS 2013, September 30-October 02, Boston, United States

DOI 10.4108/icst.bodynets.2013.253638

2. ANTENNA DESIGN

Placing the antenna close proximity to human body typically distorts the radiation pattern, reduces the radiation efficiency due to absorption by the lossy tissue, shifts the resonant frequency and changes the matching [5]. Different types of antennas have been proposed to tackle aforementioned problems. Shorted ring patch antennas are good candidates for BAN when operated at omni-directional mode which generates omni-directional radiation patterns in horizontal plane although they have not attracted much attention over the past years. Higher mode microstrip square patch antennas have been proposed in [5] and the performance of the antenna is compared with a conventional patch and a monopole antenna near body surface and shown to be having monopole like characteristics with $4mm$ antenna body separation. The simulated radiation efficiency was measured to be lower than 50% although low loss expensive dielectric material was used. Similarly, a circular shorted ring patch antenna, however operating at its TM_{01} mode, is proposed to be used for bed side monitoring applications in [8]. Although a detailed explanation has not been provided for the antenna design, the antenna has been proven to be suitable for on-body to off-body links.

Shorted ring patch antennas are good candidates for BAN when operated at omni-directional mode which generates omni-directional radiation patterns in horizontal plane although they have not attracted much attention over the past years. This omni-directional mode which is suitable for many applications can be generated by forming a magnetic current loop as discussed in [9][10] with both circular and rectangular shaped shorted patches. Low profile higher mode microstrip square patch antennas have been proposed in [5] with two shorting pins and the performance of the antenna is compared with a conventional patch and a monopole antenna near body surface and shown to be having monopole like characteristics with $4mm$ antenna body separation. The simulated radiation efficiency was measured to be lower than 50% although low loss expensive dielectric material was used. Here a square patch antenna comprising 4 shorting pins electrically connecting the radiating patch to the ground plane at symmetrical points and a coaxial feed is proposed as seen in Figure 1. By using a layered structure, the efficiency of the antenna is boosted up to 95% although the antenna is built on low cost, high loss FR4 substrate as opposed to the antenna proposed in [5]. With this arrangement, all the edges of the patch is excited generating a magnetic current loop in the horizontal plane. Therefore the antenna radiates horizontally and equally in all directions among the body when positioned on the body surface. The overall size is 0.052λ x 0.37λ x 0.37λ at $2.45GHz$.

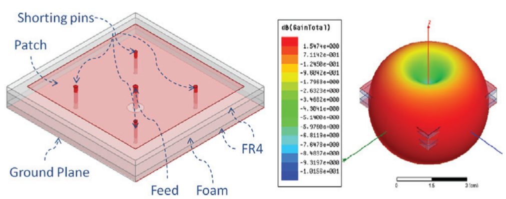

Figure 1: Diagram of the shorted patch antenna (on the left) and Simulated radiation pattern of the shorted patch antenna in isolation (on the right)

For ease of prototyping, the patch and the ground plane are modelled on FR4 to be manufactured with standard PCB technology. The antenna is centrally fed with a coaxial connector.

2.1 Performance Analysis in Isolation

Described structure generates an omni-directional pattern as seen in Figure 1 with vertical polarization which is ideal for the on-body applications [6]. Maximum gain of $1.5dB$ is observed at $\theta = \pm 90$ with 95% simulated radiation efficiency. There is minimal radiation in the vertical direction minimizing the performance degradation due to the lossy tissue.

The operating frequency is chosen to be an unlicensed ISM band $2.45GHz$. TelosB sensor motes which are used to evaluate realistic scenarios also operate at the same frequency band. The simulated $10dB$ band of this particular antenna is from $2.38GHz$ to $2.53GHz$ which is in-line with the measurements. Using the PCB technology, five antennas are prototyped. Good repeatability is achieved as seen in Figure 2.

2.2 Performance On The Body

The frequency response of the antenna in isolation is compared to the antenna located on a three layered planar phantom [11] [12] representing the superficial layers of the human chest with $2cm$ and $5mm$ antenna body separations as seen in Figure 2. $5mm$ separation is chosen in accordance with the realistic scenario where minimum separation is restricted with the thickness of the sensor mote. $2cm$ is considered to be a large distance and used as a bench mark. The electrical properties of the tissues used are listed in Table 1. The detuning effect of the antenna body interaction has been observed on the frequency response however no further optimization is performed due to the complicated nature of the sensor mote and the human body. The return loss is assumed to be considerably insensitive to lossy materials in the antenna's near-field. The simulated efficiency of the antenna is 74% for the worst case scenario. The maximum local Specific Absorption Rate (SAR) averaged over $1gr$ of tissue is calculated to be $0.028W/kg$ for $5mm$ antenna body separation assuming $1.125g/cm^3$ density for the tissue with $10dBm$ incident power (incident to the antenna). This is much below the SAR limits for mobile devices determined by Federal Communications Commission (FCC). Moreover the sensors output power, namely the antenna's input power is set to $-25dBm$ for the measurements.

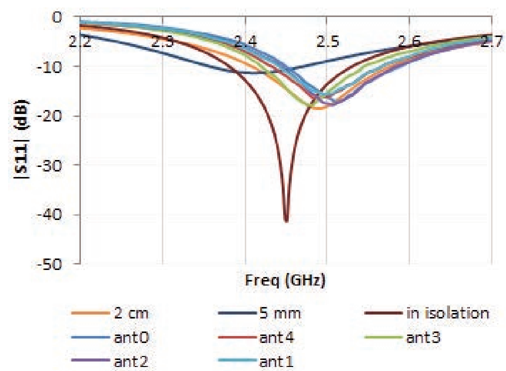

Figure 2: Simulated frequency response of the antenna on a three layered planar phantom connected to the TelosB mote for $5mm$ and $2cm$ antenna body separations and Measured frequency responses of the rectangular shorted patch antenna demonstrating the repeatability of the structure

Table 1: Electrical properties of the human tissues at the operating frequency of $2.45GHz$

Tissue	Conductivity (S/m)	Relative Permittivity	Loss Tangent
Skin	1.6	42.8	0.27
Fat	0.11	5.3	0.14
Muscle	1.74	52.7	0.24

3. ON-BODY PROPAGATION

The shorted rectangular patch antenna has been shown to be suitable for on-body usage in Section 2. In this section, the propagation on the body is analysed. Back to back transmission measurements are taken on 3 male Subjects with different body compositions with a pair of identical transmit and receive antenna connected to the TelosB mote for the following transmission scenarios:

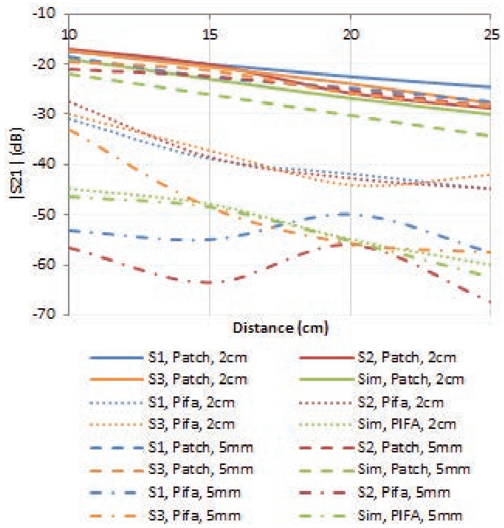

Figure 3: ALB Propagation: Back to back transmission versus path length for $5mm$ and $2cm$ antenna-body separations for the Patch antenna and the internal PIFA of the TelosB mote, where "S1, S2 and S3" are the subjects and "Sim" stands for HFSS simulations

1. Along the Body (ALB) propagation where two sensors are positioned on the chest of the subjects with antenna body separations of $5mm$ and $2cm$, path lengths of $10, 15, 20, 25cm$.

2. Around the Body (ARB) propagation where two sensors are positioned around the abdomen of the subjects with antenna body separations of $5mm$ and $2cm$, path lengths of $15, 20, 25, 30cm$.

The shorted patch antenna and the internal PIFA of the TelosB mote are tested for the 1^{st} scenario. 150 samples are taken on each subject performing their daily activities such as sitting and walking in an office environment and the received powers are averaged over time. As seen in Figure 3, at $2cm$ antenna-body separation, averaged received power levels of the shorted patch antenna pair were $18.1dB$, $15.6dB$ and $15.9dB$ higher than the internal PIFA pair for S1, S2 and S3 respectively. The improvement achieved by the shorted patch antenna on the received power levels of the sensor pair is considerably higher when the sensors are positioned closer to the human body. The improvements averaged over distance are 30.42, 36.5 and $24.9dB$ for S1, S2 and S3. The shorted patch antenna does not only outperform the internal PIFA but also shows resistance to the degradation caused by the lossy tissues nearby while the antenna-body separation is decreased. The reduction in the maximum received power levels of the sensors moving from $2cm$ antenna-body separation to $5mm$ antenna-body separation are $3dB$, $4.1dB$ and $2.1dB$ for the worst cases of each subject, which is less than the predicted degradation of $4.2dB$. On the other hand, sensors operating with the internal PIFA face up to $28.9dB$ degradation when moved closer to the body surface.

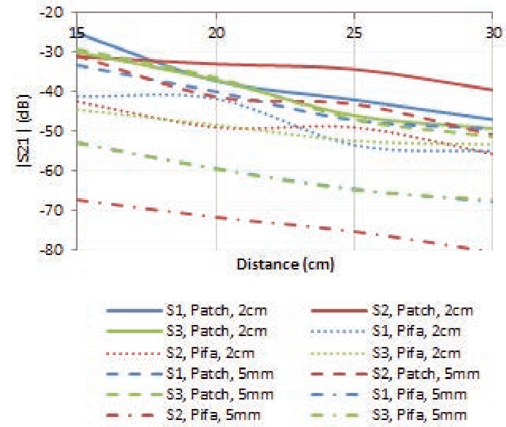

Figure 4: ARB Propagation: Back to back transmission versus path length for $5mm$ and $2cm$ antenna-body separations for the Patch antenna and the internal PIFA of the TelosB mote, where "S1, S2 and S3" are the subjects

Comparisons for the ARB scenario is plotted in Figure 4. Considering the $5mm$ antenna-body separation with the shorted patch antenna connected to the sensors, transmission coefficient is approximately 15 dB less than that of the ALB scenario. The proposed patch antenna outperforms the internal PIFA on average by $11.2dB$ and $23.7dB$ for $2cm$ and $5mm$ antenna-body separations respectively. However the maximum received power levels of the sensors are observed to be changing more in the ARB scenario when the sensors are moved closer to the body.

4. PROTOCOL DESIGN

Sensor nodes in a WBAN setup are expected to function long periods of time with limited energy. This requirement dictates an energy efficient design approach to WBANs. From the discussions in the previous sections, we know that the radiation efficiency can be improved significantly via an application specific antenna design approach. But, this will not be sufficient on its own to enable a long network lifetime. Improving efficiency of the protocol stack is also crucial from the network lifetime perspective.

In most of the modern sensor devices, the radio transceiver consumes a significant portion of the power used in the sensor node. In [13], it is highlighted that an 802.15.4 based sensor node requires around 10 times more power for radio operations as compared to the active mode of the CPU and memory operations. To overcome this problem, an efficient radio duty cycling (RDC) protocol is proposed which cycles the radio on and off at predefined intervals for transmitting and receiving in order to extend the sensor lifetime. This method requires the nodes with data to probe their next hop nodes in order to establish connectivity and introduces some performance penalty. But, it is proven that significant sensor lifetime increase is achievable by taking advantage of such a technology.

The shorted patch antenna proposed in this paper can enable the use of very low transmit power levels. In this case, it may be possible that such a WBAN can suffer from packet drops in high mobility scenarios due to channel variations in the propagation environment. In this case, the efficiency of the RDC based medium access mechanisms can be negatively affected due to multiple retries at MAC layer. In this case, a cooperative routing approach can significantly reduce the number of MAC retries by taking advantage of diversity created by multiple routes to the destination node. In our earlier work [14], we have shown that a light-weight cooperative communication protocol (called ORPL) can significantly reduce the number of MAC layer retries in a wireless sensor network. Here, we demonstrate the real life performance of this protocol using PIFA and the proposed shorted patch antenna.

ORPL makes use of the RPL routing protocol's parent structure as described in RFC [15] that stores at least one candidate parent (when possible) to be kept at each client node alongside with the default parent. In ORPL, the same packet is sent to the both default parent and backup parent to create an alternative route to the sink node. If the default parent receives the data packet, it forwards the packet to the sink node. When the default parent fails to acknowledge the packet, the backup parent is responsible for forwarding the packet. The coordination of the parents is achieved through acknowledgement frames which introduces no extra overhead as highlighted in our earlier work [14].

5. PROPOSED SYSTEM PERFORMANCE

Performance of the proposed system is analysed in a realistic scenario where 5 sensors are placed on a male subject as seen in Figure 5. The subject has carried on his daily activities in an office environment wearing the TelosB sensor modules running Contiki OS. The radios of the TelosB sensor are configured to use lowest transmit power available in the CC2420 module [16]. Each experiment has lasted until 600 samples are collected from the sensors with a reporting interval of 5 seconds. Each sensor transmits a 60 bytes data payload which contains statistical information about the node (default parent, backup parent, next hop RSSI, etc). The packets are transmitted via UDP protocol using Contiki OS IPv6 stack. Experiments are run using two different software stacks utilising standard RPL implementation of Contiki OS and ORPL protocol respectively.

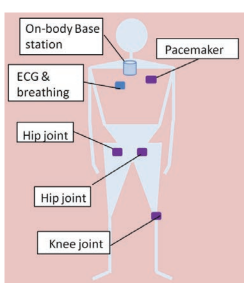

Figure 5: Realistic Scenario

Figure 6 shows the total number of MAC layer retransmissions observed in the WBAN and the average next hop SNR levels observed by the sensor nodes during the experiments. According to the average SNR results, the sensor nodes with PIFA have a relatively small SNR margin (around $18dB$) to reliably transmit data to their intended next hop. The next hop SNR levels vary significantly when the subject changes his position (e.g. standing up, sitting down, and walking). Hence, the MAC layer of the sensor has to retry several times to get the data packets to its next hop node. For RPL, the MAC layer retries are twice as many as compared to ORPL protocol when using PIFA.

On the other hand, when the proposed patch antenna is utilised, the average one hop SNR is found to be around $31dB$. This larger SNR margin enables the sensor nodes to communicate realibly with each other. Furthermore, the retry performance of the network improves significantly leading to 5 to 10 fold reductions for RPL and ORPL protocols respectively. This confirms our initial observation on the potential benefits of using a high efficiency system design approach for on body communication.

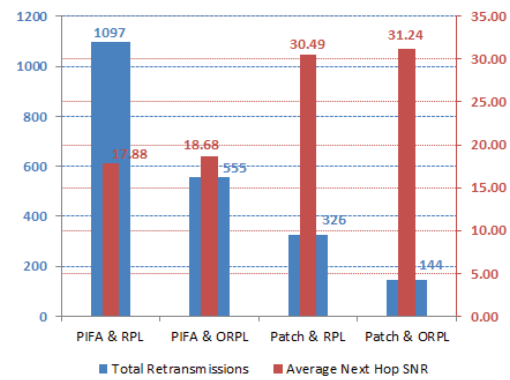

Figure 6: Performance of proposed system

6. CONCLUSION

A health monitoring sensor network has been built with off-the-shelf wireless sensors. The battery life time of the network is improved focusing on two critical aspects of the system. Firstly the radiation performance is enhanced by means of a purposefully designed on-body antenna of which radiation is directed along the body for optimum communication with the rest of the on-body sensors. Secondly an Opportunistic RPL protocol is utilized significantly reducing the number of MAC layer retransmissions. In combination, total retransmissions have been reduced to $1/10^{th}$ of its value.

7. ACKNOWLEDGMENTS

The author would like to thank to Dr Filippo Tosato, Dr Zubeir Bocus and Dr Siva Subramani for their contribution to the work.

8. REFERENCES

[1] United Nations Department of Economic and Social Affairs Population Division, "World Population Ageing: 1950-2050", http://www.un.org/esa/population/publications/worldageing19502050/ , [accessed] June 2013.

[2] CodeBlue: Wireless Sensors for Medical Care, http://fiji.eecs.harvard.edu/CodeBlue ,[accessed] June 2013.

[3] The Human ++ Project, http://www.imec.be/ScientificReport/SR2007/html/1384156.html , [accessed] June 2013.

[4] "TELOSB Mote Platform," http://bullseye.xbow.com:81/Products/productdetails.aspx?sid=252, Jun 2013.

[5] G. A. Conway, W. G. Scanlon, "Antennas for over-body-surface communication at 2.45 GHz", IEEE Transactions on Antennas and Propagation, vol. 57, no. 4, April 2009.

[6] Y. I. Nechayev, P. S. Hall, I. Khan, and C. C. Constantinou, "Wireless channels and antennas for Body-Area-Networks", The Seventh International Conference on Wireless On-demand Network Systems and Services IEEE/IFIP WONS 2010, pp. 137- 144, 2010.

[7] T. Alves, B. Poussot, and J. M. Laheurte, "Analytical propagation modeling of BAN channels based on the creeping-wave theory", IEEE Transactions on Antennas and Propagation, vol. 59, no. 4, pp. 1269 - 1274, 2011

[8] T. Kikuzuki, A. S. Andrenko, M. G. S. Hossain, I. Ida, K. Kasai, Y. Ohashi, "A simple path loss model for body area network in the bed side monitoring applications", Asia-Pacific Microwave Conference Proceedings (APMC), pp.765-768, Dec 2011.

[9] N. Merce, P. Tejedor, J. Vassal'lo, "The TM01 mode of microstrip radiators and some of its applications", Ninth International Conference on Antennas and Propagation, (Conf. Publ. No. 407), vol. 1, pp.33-36, Apr 1995

[10] C. Martin-Pascual, I. Seoane, "On the generation and applications of the monopolar ("zeroth" like) mode in noncircular patches", ICECom 17th International Conference on Applied Electromagnetics and Communications, pp.160-163, Oct 2003.

[11] S. Dumanli and C. J. Railton, "On-Body Transmission at 5.2 GHz: Simulations Using FDTD With a Time Domain Huygens' Technique", IEEE Transactions on Antennas and Propagation, vol. 59, no. 10, pp. 3910-3917, Oct 2011 .

[12] S. Dumanli, S. Gormus, I. J. Craddock, "Energy efficient body area networking for mHealth applications," 6th International Symposium on Medical Information and Communication Technology (ISMICT), pp.1-4, March 2012.

[13] N. Tsiftes and A. Dunkels, "A Database in every sensor", SenSys 2011, 1-4, Nov 2011, Seattle, Washington.

[14] S. Gormus, Z. Fan, Z. Bocus, and P. Kulkarni, "Opportunistic Communications to Improve Reliability of AMI Mesh Networks," in *IEEE Innovative Smart Grid Technologies Europe (ISGT EU) conference, Manchester, UK*, 2011.

[15] T. Winter, P. Thubert, and et. al., "RPL: IPv6 Routing Protocol for Low Power and Lossy Networks, RFC 6550," IETF ROLL WG, Tech. Rep., March 2012.

[16] "TI CC2420 Radio,"http://www.ti.com/product/cc2420, Jun 2013.