Energy Efficient Body Area Networking for mHealth Applications

Sema Dumanli, Sedat Gormus, and Ian James Craddock

***Abstract*—Propelled by the need to reduce the cost of caring for the ageing population, we observe an impetus towards enabling remote patient monitoring (mHealth) via low power medical sensor networks. A practical mHealth network consisting of several sensor modules located on the patients body needs to operate over long periods of time without any intervention. This requires efficient hardware and software design which will enable the battery powered sensor devices to operate efficiently and reliably with minimal energy consumption.**

This paper combines efficient antenna design with a cross layer energy efficient protocol to realize wireless body area networks (WBANs) where the main aim is to maximise network life time. Towards this goal, we demonstrate a high efficiency system design approach where the performance of WBANs are greatly enhanced.

***Index Terms*—WBAN, antennas, cooperative communication, sensor networks.**

I. Introduction

LINKS IN a WBAN can be classified into three categories: off-body, on-body and in-body links [1]. On-body links are the links in between the antennas on the body which might be used for medical applications. Possible medical applications include monitoring heart rate, blood pressure, temperature and respiration. Different sensors can be positioned on a patient's body in order to collect continuous data or provide real-time feedback. This healthcare practice, supported by electronic processes and wireless communications is called mHealth [2]. mHealth provides much greater mobility to the patient and decrease the cost of health care practices.

There are several challenges to overcome in hardware and software aspects of mHealth systems. One of the main obstacle in mHealth applications is the battery life time of the sensors used. Here a sophisticated antenna design is engaged with an efficient cross layer protocol to tackle this. The internal PIFA antenna and proposed BAN antenna will be examined in Section II-A. Their performances on the body will be demonstrated in Section II-B. A transmission scenario on a human chest phantom will be analysed for realistic comparisons in Section II-C. An energy efficient cross layer protocol design is outlined in Section III. Section III-C gives some initial performance results on the energy efficiency figures of the proposed protocol. Paper concludes with Section IV

II. On-body Antenna Design

On body antenna design is a challenging task due to the body being in the near-field of the antenna and the complex interaction between the two. Channel models for Line of Sight (LOS) situations have been studied in [3] and [4]. Both studies focused on the properties of the channel while using commercial Ultra Wide Band (UWB) antennas which are not dedicated to WBAN scenarios. The impact of the antenna height on the path loss has also been investigated [5] and concluded a significant impact while considering basic dipole antennas. However this impact strongly depends on the antenna type and the direction of radiation.

More efficient systems can be formed by dedicated antennas which are less sensitive to near field effects of the body and have more application oriented gain patterns. For the case of on-body, the antenna radiation should be directed along the body since diffraction is the most effective propagation mechanism especially for Non-line of Sight (NLOS) WBAN scenarios. The internal PCB antenna of TelosB [7] module is not suitable for this application therefore a novel BAN antenna to be connected to the module is proposed here.

All authors are with the Telecommunications Research Laboratory, Toshiba Research Europe Ltd., Bristol, BS1 4ND, UK. e-mail: ({sema.dumanli, sedat.gormus, ian.craddock}@toshiba-trel.com).

A. Internal Antenna and BAN Antenna in Isolation

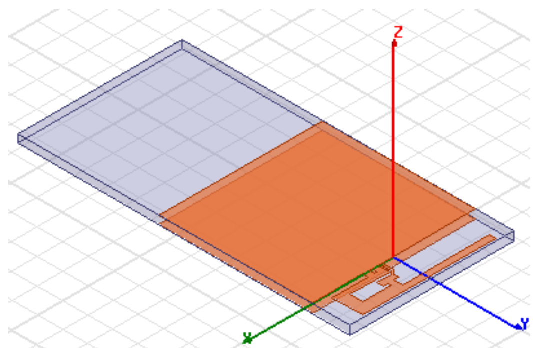


Fig. 1. Internal PIFA modelled in HFSS

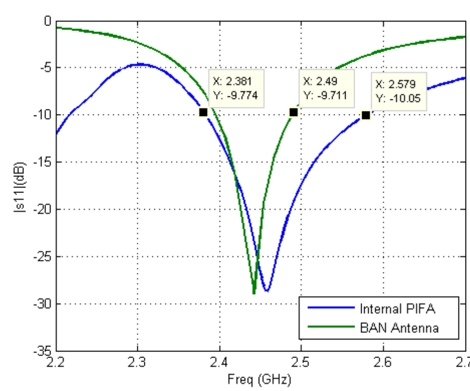
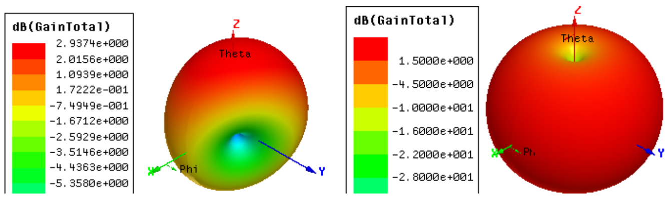


Fig. 2. Comparison of s11 for internal PIFA and BAN antenna

The internal PIFA embedded on the the sensor is modelled in HFSS as seen in Figure 1. 1.6 mm thick FR4 substrate is used and 30 by 32 mm ground planes which are assumed to be solid conductors are introduced on both sides of the sensor. The overall module dimensions are provided in [7]. The BAN antenna is a patch antenna modelled on 3 mm thick 5 cm x 5 cm metallized foam.

In Figure 2, return loss of the internal PIFA is compared to the proposed BAN antenna. It can be seen that the simulated results for the internal PIFA matches well with the measured results provided in [7]. Proposed BAN antenna has similar performance over 2.4



(a) Internal PIFA (b) BAN Antenna

Fig. 3. 3D Radiation pattern of the antennas in Isolation

GHz ISM frequency band. However the radiation patterns of the two antenna are drastically different as seen in Figure 3. Here the total gain is plotted in dB and PIFA is horizontally polarized while the BAN antenna is vertically polarized. Note that vertical polarization is favoured over horizontal polarization for on-body communications due to the excitation of the surface wave. In addition, BAN antenna is radiating along the body which makes it more suitable for this application. The pattern is omnidirectional in the axis of the sensor with 1.5 dB maximum gain at the angle of $\theta = 90^o$ which achieves equal transmission towards all the nodes on the body while the internal antenna is radiating distally with a maximum gain of 2.9 at $\theta = 0^o$ and not radiating along the body.

B. Internal Antenna and BAN Antenna on the Body

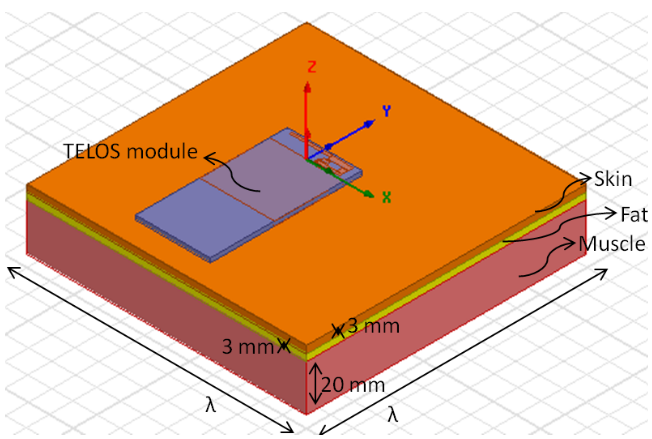
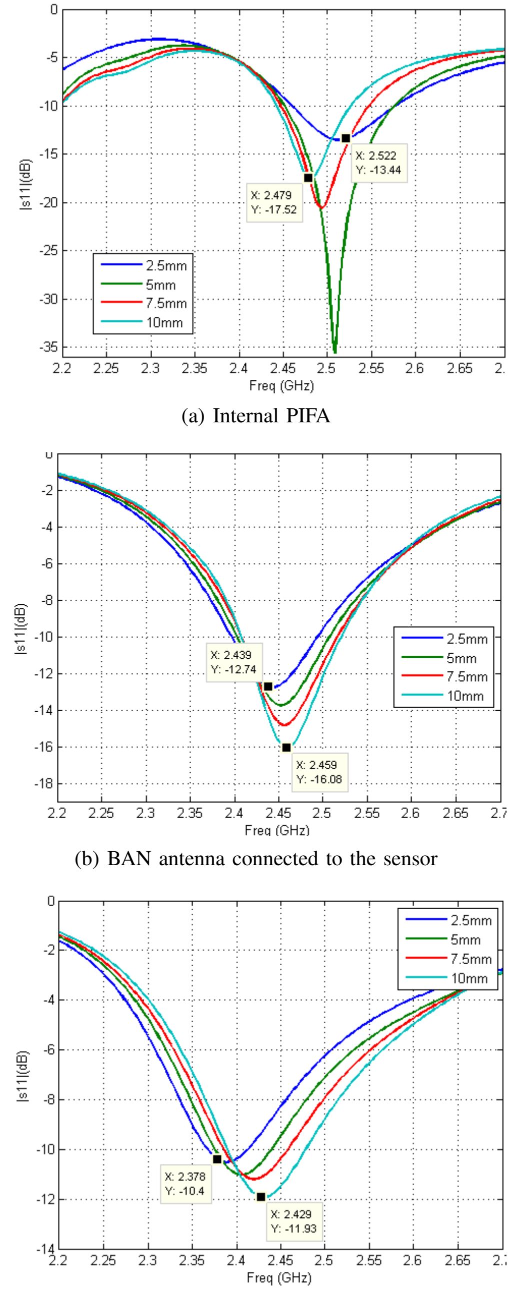


Fig. 4. Numerical layered planar phantom for human chest

The proposed BAN antenna is not only suitable to be used on TelosB modules but also in other WBAN scenarios. In order to demonstrate that the BAN antenna is investigated under two cases. First it is located on the body, then it is connected to the sensor via an SMA connector and the sensor is located on the body. The effect of the body on the internal PIFA and on the BAN antenna in these two cases are investigated. A layered planar chest phantom is designed in HFSS with the dimensions given in Figure 4 [6]. The electrical properties of the tissues are listed in Table I. The distance between the antennas and the skin is varied between 2.5 mm to 10 mm and the change in reflection coefficient of each antenna is demonstrated in Figure 5. It can be seen that the centre frequency of the internal PIFA increases as the antenna-body separation is decreased. However the antenna is still performing well at the operating frequency of 2.45 GHz for all cases but 2.5 mm separation. For the case of BAN antenna connected to the sensor, centre frequency moves from 2.459 GHz to 2.439 GHz as the separation is changed from 10 mm to 2.5 mm. In all cases, the antenna is performing well at the operating frequency. However in this case, the actual separation between the



(a) Internal PIFA

(b) BAN antenna connected to the sensor

(c) BAN antenna

Fig. 5. The effect of the body on the reflection coefficient of the antennas for antenna-body separations of 2.5, 5, 7.5 and 10 mm

body and the antenna is higher than the internal PIFA since the BAN antenna is connected on top of the sensor with a perpendicular SMA connector. The performance of the BAN antenna without the sensor is not acceptable for 2.5 mm antenna-body separation while following similar trend as the BAN antenna on the sensor in the change of centre frequency. Effect of antenna-body separation on the radiation efficiency can be seen in Figure 6. BAN antenna has more than 80% radiation efficiency in all cases while the internal PIFA has less than 20% efficiency. This is due to the fact that PIFA's radiation pattern is not optimized for BAN applications.
From these analysis, it can be seen that the proposed BAN antenna is quite suitable for on body communications. The analysis are extended to a transmission scenario in the following Section.

TABLE I
ELECTRICAL PROPERTIES OF THE HUMAN TISSUES ARE THE OPERATING FREQUENCY OF 2.45 GHZ

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

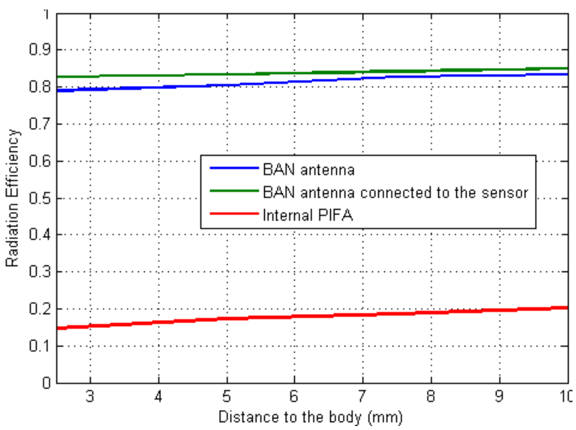


Fig. 6. Effect of antenna body separation on the radiation efficiency

C. Back-to-back Transmission on the Body

A pair of identical transmit and receive antennas with 5 mm antenna-body separation are located on the chest and the distance between the two has been changed from 10 cm to 25 cm in order to compare the performances of the internal PIFA and the BAN antenna. As in the previous section, BAN antenna is investigated for the previously mentioned two cases: on the sensor and stand alone. Received signal power at the operating frequency is plotted for each case for different transmitter receiver separations as seen in Figure 7. More than 23 dB increase is observed in the received power level when the BAN antenna is used instead of the internal antenna for each separation. There is less than 5 dB difference between the two cases of the BAN antenna.

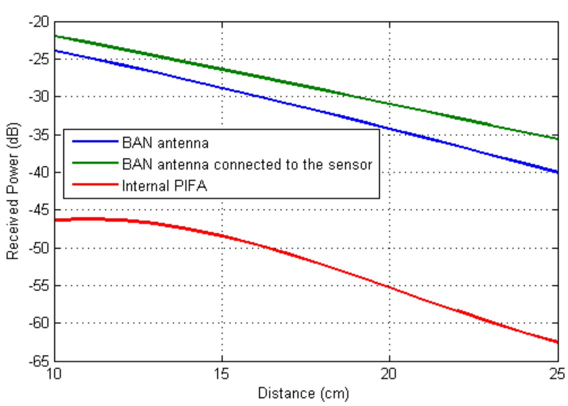


Fig. 7. Received power at 2.35 GHz vs different transmitter receiver separations

As seen from the analysis, the antenna design is critical for on-body systems and with an appropriate design, the performance of the system can be improved drastically.

III. EFFICIENT PROTOCOL DESIGN USING COOPERATIVE COMMUNICATION

A sensor node in a WBAN is expected to operate without requiring a battery replacement over long periods. This requirement is one of the most important driving forces behind energy efficient design for WBANs. Although it is possible to significantly improve the radiation efficiency through smart antenna design process, this will not be enough on its own to guarantee a long network lifetime. An energy aware network stack is needed to reduce the power consumption of a sensor node to a level which will enable the node to operate over long periods of time.

The radio chip is responsible for a significant portion of the power usage of a wireless sensor node. In [11], authors show that a sensor node consumes the most amount of energy while transmitting data and listening to the wireless channel. Therefore, they propose an efficient radio duty cycling (RDC) protocol which turns on/off the radio at predefined intervals for transmitting/receiving data packets in order to save energy. Even though, this method introduces some performance penalty, it has been shown that it is possible to drastically increase the battery life of a sensor node taking advantage of such technology.

Low levels of transmit power used in WBANs may result in many packet dropped due to channel variations in the propagation environment. In this case, performance of the RDC based protocols will be negatively affected due to multiple MAC layer retransmissions. To overcome this, cooperative communication protocols can be employed in order to further improve energy efficiency of WBANs. In our previous work [12], we have shown that a light-weight cooperative communication protocol (called ORPL) can significantly reduce number of MAC layer retransmission in a wireless sensor network. In this section, we analyse the energy efficiency aspects of ORPL in WBANs.

A. Brief Overview of ORPL

The proposal described in the RPL draft [10] creates a Directed Acyclic Graph (DAG) rooted at a sink node to maintain network state information. A path from a sensor node orienting towards and terminating at the sink node consists of the edges in the DAG. After the DAG is constructed, each client node will be able to forward any upward traffic (destined to the sink) to its parent as the next hop node.

ORPL takes advantage of the existing parent structure of the RPL protocol which requires at least one candidate parent (where possible) to be kept at each client node alongside with a default parent. In ORPL, the same frame is sent to the both default parent and backup parent. If the default parent receives the frame, it forwards the frame to the next hop and the candidate parent(s) discards the copy of the forwarded frame upon overhearing the default parent's transmission. When the default parent does not receive the frame, the node closest to the sink in the receiving parent set is responsible for forwarding the frame to its parent. This enables a more robust point-to-point link as compared to an RPL link.

B. Evaluation Scenarios

For the purpose evaluating the energy efficiency of ORPL protocol, we used TelosB [7] devices with Contiki operating system as the development platform. Contiki [9] is an open source operating system specifically designed for low power sensor devices. Furthermore, it has a well maintained RPL version which implements a large subset of the IETF RPL draft [10] which we used as a baseline for comparing performance with that of the ORPL protocol. In addition to providing support for running on target hardware, Contiki also provides an emulator called Cooja which facilitates development, testing and debugging of the code before running it on the target platform.

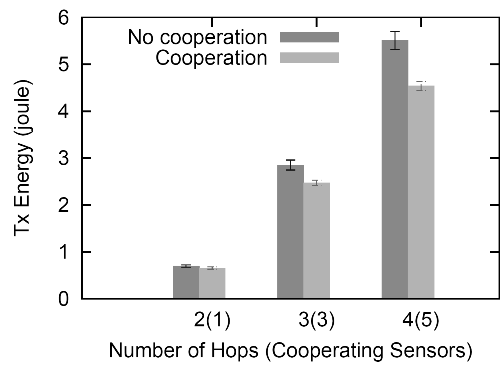
Here, we evaluate a WBAN scenario using Cooja where 3 networks; with 3, 5 and 7 client nodes with a sink node; are configured to have 2, 3 and 4 hops respectively. In each set-up there are two nodes at middle hops that cooperatively forward the frames of the client nodes. For example, in the 3 client network, the client node, that is two hop away from the sink node, forwards its traffic to both of its two parents. In this case, there is only one client node that can take advantage of cooperative transmission.

We configure the client nodes to send 108 bytes packets with 4 seconds periods to the sink node. The intermediate nodes are responsible for forwarding their own data as well as the data belonging to the client nodes connected to them. For each scenario, 10 simulations are run with different random seeds and the results are averaged.

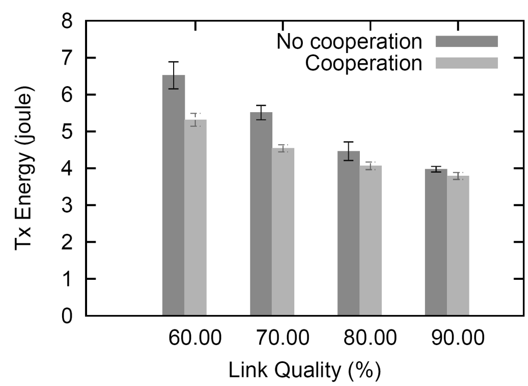
C. Performance Results

Figure 8(a) shows the transmit energy consumption for RPL and ORPL protocols in a scenario with a fixed link success probability where a 70% success probability was used to demonstrate the efficiency of ORPL protocol. The link success probability depends on the distance as given by the free-space path loss formula [8]. The aggregate transmission energy results in the figure belong to the client nodes that can take advantage of cooperative communication when ORPL protocol is utilised. Hence in the base (2 hop) scenario, there is only one sensor which can take advantage of cooperative communication. The results in Figure 8 (a) show an interesting trend where as the number of hops increase in the network, the energy efficiency of ORPL protocol becomes more pronounced. This is due to the fact that the intermediate cooperative nodes forward their own traffic as well as the traffic originating from the clients in the deeper hops. An efficiency improvement of 25% is achievable with a 4 hops network with 5 cooperative clients. This efficiency is expected to improve with increasing number of clients that take advantage of cooperative communication.

Figure 8(b) shows the transmission energy consumption RPL and ORPL protocols for increasing link success probabilities. The advantage of using ORPL diminishes as compared to standard RPL protocol with the improving link quality. This is logical since the number of MAC layer retransmissions gets lower when the links are reliable. But, this is not expected to be the case in a real deployment scenario where the nodes experience severe path losses in a WBAN.



(a) Energy usage for increasing number of hops



(b) Energy usage for different link quality metrics

Fig. 8. Transmit energy requirements of standard routing as opposed to cooperative routing

IV. CONCLUSIONS

Self organising wireless mesh networks are low cost and low power and therefore attractive for realising practical WBANs. In this paper, we proposed a solution that takes advantage of efficient antenna and protocol designs with the aim of reducing the power consumption of the sensor nodes in a WBAN. The results show significant performance improvements achieved by our approaches. As future work, we aim to validate the efficiency of the proposed mechanisms in real life scenarios using a hardware based test bed.

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