The 11th International Symposium on Wireless Personal Multimedia Communications (WPMC'08)

OPPORTUNISTIC LARGE ARRAY-BASED COOPERATIVE TRANSMISSION TECHNIQUES FOR LONG-TERM BODY IMPLANTS

Aravind Kailas
Georgia Institute of Technology
Atlanta, USA

Mary Ann Ingram
Georgia Institute of Technology
Atlanta, USA

ABSTRACT

Today's aging population is driving wide-scale demand for more-advanced healthcare treatments, including wireless implanted devices that can deliver ongoing and cost-effective monitoring of a patient's condition. Wireless sensor networks (WSNs) have been considered for body area networks (BANs) and implanted WSNs. For most BANs, the generic topology involves "on-body" sensors or Implanted Medical Devices (IMDs), and a hub device (such as a phone, PDA, or wireless LAN access point) that is on or away from the body, which can function as a central fusion node and connect to the Internet. This paper applies to IMDs a new physical layer cooperative transmission (CT) technique. CT can reduce the total power required for sensor transmission by exploiting the spatial diversity of multiple single-antenna terminals. This means that the implanted sensor batteries can last longer. The opportunistic large array (OLA) is a simple CT approach that saves energy relative to conventional multi-hop routing by allowing all nodes that can decode to relay the message. OLA avoids the overhead of assigning clusters and cluster leaders. To date, OLA has not been considered for human body implants. In this paper, we provide a first treatment of communication using OLA for implanted sensors for the Medical Implant Communication Services (MICS) standard and investigate the potential power reductions that can be achieved. In this paper, we consider the ICD application where the implanted sensors are connected by wire, but the OLA technique is still useful for relay to an off-body destination. We compare the total transmit power expended by the cooperative transmission network compared to the power that would be required for a single hop (i.e. directly from the source to the sink) to have the same reliability.

I. INTRODUCTION

The delivery of health-related services and medical information via Telecommunications technologies such as wireless sensor networks is a growing new interdisciplinary field. A concept known as "ubiquitous medical environment" is one where advanced wireless technologies are applied to ensure the timely and accurate delivery of medical data [9]. In this paper, we investigate the prospects of a Cooperative Transmission (CT) technique called "Opportunistic Large Array" (OLA)[16] for such a medical environment. We consider OLA for reliable wireless communication between the implanted sensors in the human body and a hub (sink node) located away from the body. A typical hub could be a mobile phone to Personal Digital Assistant (PDA).

For chronically ill patients requiring frequent updates of health parameters, implanted wireless biosensors would provide freedom and mobility, and from a medical viewpoint, provide more precise measurements and continuous patient compliance [17]. Potential applications for multiple, long-term implanted physical (e.g. temperature, pressure) sensors [10], include pacemakers [8] and implanted cardioverter defibrillators (ICDs), control of chronic pain, epilepsy [15], and Parkinson's Disease. Implanted biosensors could form a Wireless Sensor Network (WSN) similar to worn sensor networks commonly referred to as Body Area Networks (BANs) [13]. The conventional protocols of direct transmission, minimum transmission energy Medium Access Control (MAC)-based static clustering [11], [24], and multi-hop routing [23] may not be optimal for BANs. Using OLA, all or some of the implanted sensors help by relaying the signal transmitted by one sensor. The sensors operate without any mutual coordination, but naturally fire together in response to energy received from the source (the originating sensor). In this way, the transmit power in each sensor is kept very low, but the collective signal is strong enough and has enough diversity to enable its reception at a relatively long distance away by the sink node.

In this paper, we focus on the ICD application because it is one of the few current implanted sensor applications that involves multiple sensors. Because surgeons want to limit risk of infection and other complications, they want to make only a single incision when inserting an ICD [4]. The current practice is to insert the main part of the ICD under the clavical. This part has multiple wires attached that are allowed to lie in the vein leading to the heart, as shown in Fig. 1. The wires have sensors on them and are directed to different areas of the heart. Since the sensors are connected by wire, there is no need for inter-sensor wireless communication. The sensors are separated by several centimeters, and therefore the sensors have different shadowing and multipath fading in their wireless connection to the hub device. Furthermore, the shadowing and fading will change with time as the hub position changes relative to the body. This separation provides an opportunity for diversity transmission. The OLA is proposed as a low-overhead way to acheive diversity (for both shadowing and fading), which thereby extends the range to the hub by allowing each sensor to reduce its fade margin.

We use the deterministic model in [18], where the power received at the sink is the sum of the powers from each sensor. This is consistent, for example, with direct sequence spread spectrum, wherein each sensor transmits with one or more (intentional) chip delays relative to each other, and the hub device employs a RAKE receiver [19].

II. MODELING ASSUMPTIONS

For this analysis, we have tried to use practical values for variables such as transmitter power, body and typical implant antenna gains, and receiver noise, to show the relative gains of OLA transmission relative to direct transmission. In Sections A., B., and C. the wireless technology, the basic network architecture, and a channel model for communication from the implanted sensors are briefed. The subsequent sub-sections round off the other modeling assumptions that have been made to investigate this promising new application of wireless sensors.

A. Air Interface

Implant transmission is characterized by extremely low peak power and low duty cycle, so the body can safely dissipate the heat generated by the transmission. The transmissions must also be reliable and not cause excessive interference to other applications in the same band. The several standards already in use or being considered for use in implants are listed in Table 1.

In this paper, we use the Medical Implant Communications Service (MICS) standard and assume the sensors to operate in the 402–405 MHz band. According to the Federal Communications Commission (FCC), MICS is an ultra-low power, unlicensed, mobile radio service for transmitting data in support of diagnostic or therapeutic functions associated with implanted medical devices [1]. The MICS permits individuals and medical practitioners to utilize ultra-low power medical implant devices, such as cardiac pacemakers and defibrillators, without causing interference to other users of the electromagnetic radio spectrum. The FCC requires no licensing for the band of operation, but mandates that MICS equipment must only be operated by a duly authorized health care professional.

B. Network Model

We propose a network of wireless transceivers implanted in a human and connected to the internet via phone or wireless LAN access point, for medical biosensing. Fig.1 illustrates the ICD application. The implanted sensors are connected by a wire inside the body and are represented by the "white" points in Fig.1 and are assumed to be half-duplex nodes. The objective is for the message from the implanted sensors to reach the sink that is some distance away from the body. We assume all the implanted sensors and the access point are on the same plane. We acknowledge this setup is not a realistic model of the human body, however, for an initial study, we want to use a very simple model. The network architecture detailing the placement of the sensors (on the wire strip) and the access point is shown in Fig. 2.

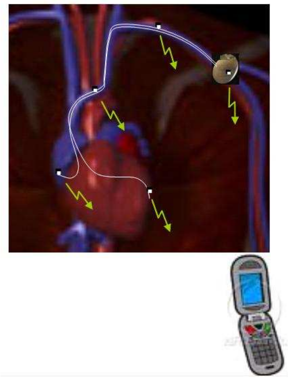

Figure 1: Implanted cardioverter-defibrillator Application. The implanted sensors "fire" together (depicted by the green arrows) to the "off-body" sink (depicted by a cell phone).

The cooperative routing protocol for the proposed network architecture involves two hops to reach the destination (access point) from an "in-body source" sensor. The first hop is the transmission from the source to the other in-body sensors in the vicinity, which form an "in-body OLA". The second hop then, is from the OLA to the access point that is away from the body. To the best knowledge of the authors, there are two recent works that address a similar network topology. The influence of a patient's body shape and position on the radiation pattern at a "far away" point from an implanted radio transmitter was simulated and studied in [12], while in [14], a similar study was done with body-worn sensors and a "close-by" access point (worn on the wrist with a distance of separation on the order of centimeters). While the implanted sensor operated in the the Industrial Scientific Medical (ISM) band in [12], the body-worn sensors operated in the 2.4 GHz range in [14].

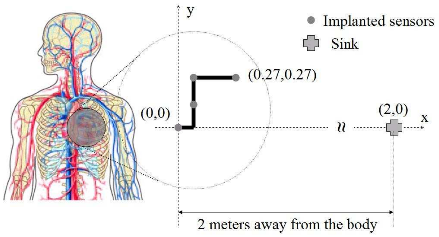

Figure 2: The proposed network architecture. The "grey" circles represent the implanted sensors connected by a wire, and the grey "+" symbol denotes the sink node that is 2 m away from the human body.

However, in this paper, since the in-body sensors are "wired", the first-hop is wired and error-free. So, we only consider the second- hop for our analysis. We assume that the in-body OLA has been formed and evaluate the power gains possible with CT in the second hop.

C. Channel Model

We present the wireless channel model for the hop from the in-body OLA to the external access point. Our model is based on the current available literature in this area. We will refer to this model as the "in-out" channel model.

We assume that the transmissions from each sensor are orthogonal to each other and can be recovered separately by the sink node. We expect that in a realistic scenario, a desired number of orthogonal dimensions can be created by relays ap-

Table 1: Current Standards for Sensor Implants in the Human Body

Standard	PHY Layer	Band of Operation	Cited in
MICS[1]	4-FSK/2-FSK	402–405 MHz	[12]
IEEE 802.15.4 [3]	DSSS, BPSK/DSSS, O-QPSK/CSS	868(Europe)/915(US)/2.4 GHz	[20]
IEEE 802.15.4a UWB [5]	BPM-BPSK with spreading	250–750 KHz/3.1–5 GHz/6–10.6 GHz	[6]
UWB [2]	PPM	3.1–10.6 GHz	[7]

propriately offsetting their transmissions, for example, in delay [21]. Every wireless channel between a single transmitter and a single receiver is assumed to suffer free-space path loss and shadow fading. Multi-path fading is ignored. This is because there are currently no validated models for multi-path. We note that inclusion of multi-path would only enhance the diversity gain of OLA. Therefore our analysis represents a lower bound on its performance.

For the hop from the OLA to the access point, we use the basic pathloss and shadowing model given by

$$L_d = L_{d_0} + \gamma 10 \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma, \tag{1}$$

where L_d is the pathloss in Decibels (dB) at an arbitrary distance d, L_{d_0} is the pathloss at the reference distance, d_0, in dB (here $d_0 = 0.1m$), X_σ is the deviation because of shadowing, and γ is the path-loss exponent. The channel parameter $\gamma = 2$ and is consistent with the assumptions made in [12]. Two papers [12] and [14] discuss shadow fading for this channel. The authors in [14] recommend a slow fading margin of 15 dB to account for signal losses due to change in antenna positions, while the author in [12] gives a fade margin between 7 and 14 dB to account for body size, orientation, and arm movements. This justifies the inclusion of the fading term in our wireless channel model.

Due to the non-availability of a correlated fading wireless channel model in the existing literature, we use the following approach to model the "in-out" wireless channel for our analysis. The channel model is based on the measurements in [12]. In Fig. 3, the measurements in [12] have been digitized and re-plotted. This figure shows the distribution of the gains for a male phantom [1] as a function of plane and angle. The gain sequences resulting from different planes (XY, YZ and XZ) were sampled every 4.43 ° and then concatenated to estimate the autocorrelation sequence labeled "concatenated gain sequence" shown in Fig. 4. While concatenating the gain sequences, the only important consideration was to minimize the amplitude of the discontinuities. Fig. 5 represents the autocorrelation of the fading coefficients in terms of "lag" samples, for all the four sequences. Correlated fades were created by using an offset window of values (such as 4) from the gain curves, where the offset is the lag that produces the desired correlation. A list of all the other different parameters assumed for our simulations have been provided in Table 2.

Table 2: Parameters for the hop from "in-body OLA" to the access point

Parameter	Value
Reference distance, d_0	1m
Pathloss at the reference distance, L_{d_0}	25 dB
Pathloss exponent (γ)	2
Receiver Sensitivity	-89 dBm
RF frequency band	402–405 MHz
Transmit Power (from implanted sensor)	-2 dBm
Body Gain	-33 dBi
Gain of antenna on the access point	2 dBi

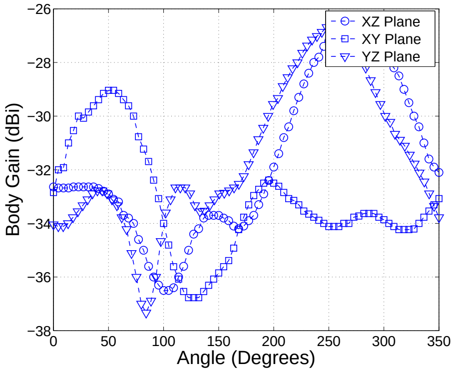

Figure 3: Gains for a male phantom as a function of radiation plane and angle.

III. RESULTS AND DISCUSSION

For our simulation results, we assumed a sensor field described in Section B.. There are two basic types of gains achieved with antenna arrays (multiple antennas at the transmitter or receiver) – array gain and diversity gain. The array gain is the increased average output SNR with these multiple antennas that would be obtained in a non-faded environment or a perfectly correlated fading environment. Hence, if there are M_t transmitting antennas, the combined signals are added in phase, while the noise is added incoherently, producing a gain of M_t with M_t antennas. Diversity gain is the decreased required receive SNR for a

---

[1] The MICS standard defines a phantom to be used in order to measure compliance with the limit of -16 dBm. The MICS phantom consists of a cylinder with a diameter of 30 cm that is filled to a height of 76 cm with a tissue simulating liquid. The liquid has the same electromagnetic properties as muscle, at the frequency band of interest.

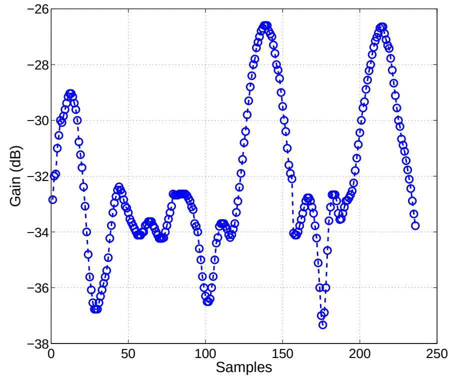

Figure 4: Concatenated gain sequence.

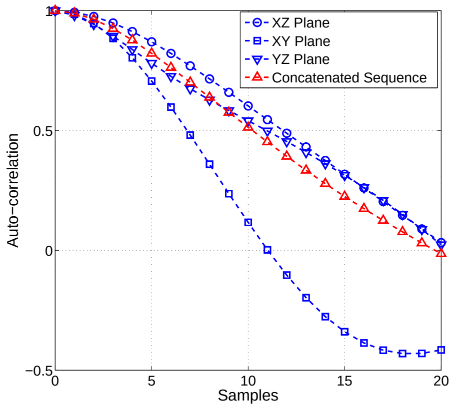

Figure 5: Correlated shadow-fading sequence for implanted sensors in the MICS band.

specified bit error rate (BER) averaged over the fading. In other words, this is the reduction in fade margin that’s obtained by reducing the fading with the antenna array. This gain depends on the BER and has a maximum limit of the fading margin, regardless of how many antennas are used. Using the example from [22], for a binary phase-shift-keyed (BPSK) system at a 1% BER, the fade margin needed is 9.5 dB with one antenna. This margin is reduced to 4.3 dB (a diversity gain of 5.2 dB) with two antennas, and to 1.9 dB (7.6 dB diversity gain) with four antennas. Thus, the diversity gain can be larger than the array gain for a small number of antennas, but the array gain dominates for a larger number of antennas as the array gain grows linearly with the number of antennas. But the diversity gain saturates at the fading margin.

The OLA cooperative transmission approaches produce array gain and “macro”-diversity gain. The array gain comes from the simple addition of powers from each of the relays, and therefore depends on how many sensors relay. The macro-diversity gain comes from the multiplicity of independently shadowed links in the second hop. Therefore, it is natural to expect that the number of cooperating transmitters and the SNR received at the access point are correlated.

Fig. 6 shows the cumulative distribution functions (CDFs) of the implant transmit power using CT approach for different autocorrelation indices. We observe that as the correlation index increases for a given reliability level, the implant transmit power required is lower.

Figs. 7 show the cumulative distribution functions (CDFs) of the total power diversity gain for different values of correlation indices. The total power gain is just the sum of the array gain (proportional to the number of sensors participating in the relay, 4 in this case). As one would expect, the total power gain using CT is higher for lower values of correlation indices. As the correlation index becomes higher, the number of independently fading paths decreases and the power gain decreases.

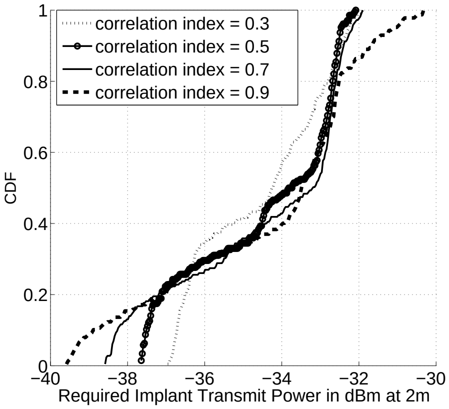

Figure 6: CDF of the implant transmit power required (2m).

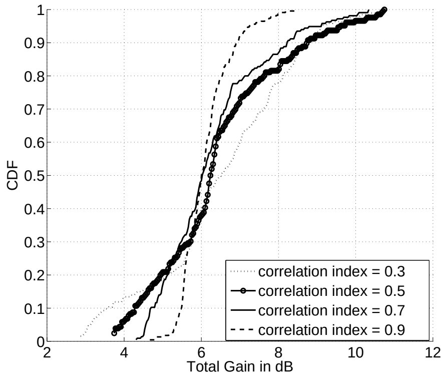

Figure 7: CDF of the total (array + diversity) gain for CT relative to the 3rd antenna (2m).

IV. CONCLUSIONS

Using sensors to monitor health information around the body is a promising new wireless application. This paper outlines the basic gains possible by using cooperative transmission techniques for implanted sensors. The results from this paper indicate that a OLA cooperative transmission shows promise for enabling long-range transmission directly from implanted sensors without requiring high sensor transmission powers or requiring that the hub is worn on the body. While it is true that each sensor transmits more often with with the OLA approach than with single hop, the net power is lower and the OLA approach should be safe for the human body as long as the rate of transmissions is low enough for any heat generated to be dissipated. Suggestions for future work include measuring the spatial correlations of channel gains for both the "in-in" and "in-out" channels.

REFERENCES

[1] Etsi en 301 839-1 v1.2.1. Technical report, ETSI.

[2] Uwb emission limits. Technical report, FCC, Washington DC, USA, 2002.

[3] Ieee 802.15.4, wireless medium access control (mac) and physical layer (phy) specifications for low-rate wireless personal area networks (lr-wpans). Technical report, IEEE, October 2003.

[4] Personal Communication with Dr. Egon Toft, Professor and Practicing Surgeon, Aalborg University, DK, 2007.

[5] Ieee p802.15.4a/d7, part 15.4:wireless medium access control (mac) and physical layer (phy) specifications for low-rate wireless personal area networks (lr-wpans): Amendment to add alternate phy. Technical report, IEEE, January 2007.

[6] Medical, health care drive wireless innovations. Technical report, Nikkei Electronics Asia, July 2007.

[7] F. Chin, W. Zhi, and C.-C. Ko. System performance of ieee 802.15.4 low rate wireless pan using uwb as alternate-phy layer. In *Proceedings of 4th Annual IEEE Pervasive Computing and Communications Workshops*, 2003.

[8] B. Dai, A. Urbas, and R. A. Lodder. Prospects for implantable sensors powered by near infrared rechargable batteries. *NIR*, 17(1):14–15, 2006.

[9] J. Donoghue and J. Herbert. Profile based sensor data acquisition in a ubiquitous medical environment. In *Proceedings of 4th Annual IEEE Pervasive Computing and Communications Workshops*, 2006.

[10] S. Furman, D. Hayes, and D. Holmes. *Batteries for Implantable Biomedical Applications*. Futura, New York, 1993.

[11] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan. Energy-efficient communication protocols for wireless microsensor networks. In *Proceedings of the Hawaian Int'l Conf. on Systems Science*, 2000.

[12] A. J. Johansson. *Wireless Communication with Medical Implants: Antennas and Propagation*. PhD thesis, Lund University, Sweden, 2004.

[13] E. Jovanov. Wireless technology and system integration in body area networks for m-health applications. In *Proceedings of the IEEE Engineering in Medicine and Biology 27th Annual Conference*, 2005.

[14] I. Z. Kovacs, G. F. Pedersen, P. C. F. Eggers, and K. Olesen. Ultra wideband radio propagation in body area network scenarios. In *Proceedings of the ISSSTA*, 2004.

[15] V. Piccone, J. Piccone, L. Piccone, R. LeVeen, and E. Veen. Implantable epilepsy monitor apparatus. United States Patent 4566464, 1986.

[16] A. Scaglione and Y. Hong. Opportunistic large arrays: Cooperative transmission in wireless multihop ad hoc networks to reach far distances. *IEEE Transactions on Signal Processing*, 15(5):2082–92, August 2003.

[17] L. Schwiebert, S. Gupta, P. Auner, G. Abrams, R. Lezzi, and P. McAllister. A biomedical smart sensor for visually impaired. *IEEE Sensors*, June 2002.

[18] B. Sirkeci-Mergen, A. Scaglione, and G. Mergen. Asymptotic analysis of multi-stage cooperative broadcast in wireless networks. *Joint special issue of the IEEE Transactions on Information Theory and IEEE/ACM Trans On Networking*, 6(52):2531–50, JUne 2006.

[19] L. Thanayankizil and M. A. Ingram. Opportunistic large array concentric routing algorithm (olacra) over wireless fading channels. In *Proceedings of Wireless Sensors Workshop, IEEE GLOBECOM*, 2007.

[20] N. Timmons and W. Scanlon. Analysis of the performance of ieee 802.15.4 for medical sensor body area networking. In *Proceedings of the First Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks (SECON)*, 2004.

[21] S. Wei, D. Goeckel, and M. Valenti. Asynchronous cooperative diversity. In *Proceedings of the CISS*, 2004.

[22] J. Winters. Understanding mimo: Part i. http://www.commsdesign.com, articleID=161601515, 2005.

[23] W. Ye, J. Heidemann, and D. Estrin. An energy-efficient mac protocol for wireless sensor networks. In *Proceedings of the IEEE INFOCOM*, 2002.

[24] M. Younis, M. Youssef, and K. Arisha. Energy-aware routing in cluster-based sensor networks. In *Proceedings of the 10th IEEE/ACM International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS)*, 2002.