A Cooperative Transmission Technique for Telehealth

(Invited Paper)

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***Abstract*— A form of Telehealth is remote patient monitoring. We propose a generic topology for such a monitoring system and apply to it a physical layer cooperative transmission (CT) technique. The generic topology is as follows. We consider "on-body" sensors, and a hub device (such as a phone, PDA, or wireless LAN access point) that is away from the body, which can function as a central fusion node and connect to the Internet. Using CT will reduce the total power required for sensor transmission by exploiting the spatial diversity of multiple single-antenna terminals. This will increase the longevity of battery-driven on-body sensors. 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 applications. In this paper, we provide a first treatment of communication using OLA for on-body sensors in the Ultra-wideband (UWB) range and investigate the potential diversity gains that can be achieved.**

***Keywords*— Body Area Networks, Sensor Networks, Opportunistic Large Arrays, Wireless Cooperative Communications**

I. INTRODUCTION

"Telehealth, defined as the use of advanced telecommunication technology to exchange health information and provide health care services across geographic, time, social, and cultural barriers, is a fast growing trend worldwide" [1]. Telehealth offers empowerment and better quality of life for patients and reduced cost of care for people with chronic disease, such as cardiovascular disease, diabetes, chronic respiratory diseases, and cancer. One form of Telehealth is remote patient monitoring, which today typically involves a patient going each morning to a fixed terminal in their home, and performing various measurements, such as blood pressure and heart rate [2]. The measurements are uploaded to the hospital or nurse center database via the wired telephone lines. While such systems have demonstrated positive outcomes, e.g. in terms of reduced number of trips to the emergency room [3], wireless monitoring promises further improvements by providing continuous monitoring and patient mobility. Such monitoring is one application for the very active research topic of body area networks (BANs) [4]. However, a challenge for wireless monitoring is reliability in getting the signals from the BAN to the internet, and low energy consumption to extend battery life in the BAN transmitters. This paper investigates the potential of an energy efficient cooperative transmission scheme called the Opportunistic Large Array (OLA) [5], to get signals off the body.

One can envision a typical wireless platform to consist of low-power sensors (skin patches) placed on the human body, and a sink node or hub (i.e. access point such as a cell phone) away from the body, where data is collected. The conventional protocols of direct transmission, minimum transmission energy Medium Access Control (MAC)-based multi-hop routing [6], and static clustering [7]–[8] may not be optimal for BANs. Cooperative communications have a big advantage in terms reliability, and energy efficiency compared to communication without any cooperation [9].

In this paper, we consider how a simple two-hop cooperative transmission method might enable communication between the sensors on the body and the sink node. The method uses a form of cooperative transmission called the Opportunistic Large Array (OLA). Using OLA, all or some of the sensors on the body 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. 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.

II. MODELING ASSUMPTIONS

For this analysis, we have tried to use practical values for variables such as transmitter power, body attenuation, and receiver noise, to show the relative gains of OLA two-hop transmission relative to single-hop transmission. Sections II-A, II-B, and II-C explain the choice of the wireless technology, the basic network architecture, and a channel model for communication between the on-body sensors (skin patches). 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

The sensor has an extremely tight power budget, whereas the sink/access point has a slightly more relaxed power budget. Today's low power radios such as Bluetooth [12] and Zigbee cannot meet this stringent requirement [13]. The Federal Communications Commission (FCC) has recently legalized a spectral mask between 3.1–10.6 GHz specifically for UWB communication. Further, this frequency range in the spectrum has attracted a lot of attention from the research community to characterize the wireless channel for BANs [13], [19]–[24]. In, [13], a design for an UWB impulse transmitter for the frequency range of 3–6 GHz was proposed. Impulse UWB systems (duration of the transmitted pulses is of the order of nanoseconds) have the advantage of operating with a low duty cycle. The IEEE 802.15.4a committee is in the process of developing an UWB standard for ultra low power communication and has included BANs for medical and sport monitoring among their relevant application scenarios [17], [18].

B. Network Model

We evaluate a sensor network where each sensor node is a skin patch on the human body, and the sensors are uniformly distributed over a disk as shown in Fig.1. The objective is for the message from an "on-body" sensor in the center of the disk to reach the sink that is some distance away from the disk ("off-body"), but on the same plane as the disk. We acknowledge that a disk is not a realistic model of the human body, however, for an initial study, we want to use a very simple model.

Half-duplex nodes are assumed to be distributed uniformly and randomly over a disk of radius R_c. The source node is assumed to be in the middle of the disk. The access point (i.e. the sink) is a distance d away from the source. The "deterministic model" [10] is assumed, which means that the power received at the sink is the sum of the powers from each of the relay transmissions. This model implies the transmissions from each sensor are orthogonal to each other and can be recovered separately by the sink node. We

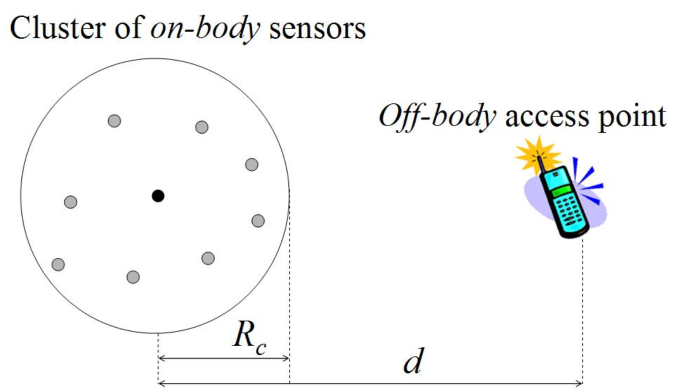

Fig. 1. The planar network architecture. The source is indicated by the darkened (black) sensor at the center of the cluster.

expect that in a realistic scenario, a desired number of orthogonal dimensions can be created by relays appropriately offsetting their transmissions, for example, in delay [11]. Every wireless channel between a single transmitter and a single receiver is assumed to suffer free-space path loss and log-normal shadowing; this includes the links from the source to other sensors and from the sensors to the sink. Multi-path fading is ignored.

The cooperative routing protocol for the proposed network architecture involves two hops to reach the destination (access point) from an on-body "source" sensor. The first hop is the transmission from the source to the other on-body sensors in the vicinity. In other words, with the first hop, on-body sensors are "recruited to form an OLA". The second hop is from the OLA to the access point that is away from the body.

C. Channel Model

Two kinds of channel models are required, one kind for each hop.

Because of the extreme close range and the fact that the antennas are worn on the body, the BAN channel model has different path loss, amplitude distribution, clustering, and inter-arrival time characteristics compared with the other non-BAN application scenarios within the 802.15.4a context for ultra-wideband (UWB) communications [17],[18]. Therefore, the generic channel model representing typical indoor and outdoor environments, associated with IEEE 802.15.4a standard, is not applicable for BANs [17].

Recently, there has been a lot of activity in the research community to characterize the wireless channel for the first hop. While some previous efforts [19] used the Finite Difference Time Domain (FDTD) simulations for narrowband systems, the work by [20]–[22] address the influence of arm motions, and provide information about the impact of ground reflections and other nearby scatterers. The body area channel characterization in [20]–[22] was done by measuring the electromagnetic wave propagation around the torso to develop a simple pathloss law and comparing it with previous results in the literature. The BAN channel characterization efforts [20]–[23] focus predominantly on communication between sensors on the body.

In contrast, characterization of the wireless channel for the second hop hasn't received a lot of attention. To the best knowledge of the authors, there are just two works that address a similar topology. In [24], the distances between the body-worn sensors and the access point is very small (order of centimeters). On the other hand, [25] considers a far away access point and implanted sensors in the Industrial Scientific Medical (ISM) band. So these models are not directly applicable.

For both hops, we use the basic empirical pathloss model given by

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

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 $d_0 = 0.1m$). γ is the path-loss exponent and we denote the pathloss exponent of the i-th hop as γ_i. σ is the lognormal shadowing standard deviation and we denote the shadowing parameter of the i-th hop as σ_i.

Tab. 1. Parameters for the Two hops

Parameter	Value
Reference distance, d_0	0.1m
Pathloss at the reference distance, L_{d_0}	50.5 dB
Pathloss exponent for first hop (γ_1)	6
Pathloss exponent for second hop (γ_2)	2
Lognormal shadowing (σ)	4 dB
Receiver Sensitivity	-91 dBm
RF frequency band	3–6 GHz
Transmit Power (from skin patch)	-5 dBm
Gain of antenna on the skin patch	0 dBi
Gain of antenna on the access point	2 dBi
Number Monte Carlo trials	10,000

The different parameters assumed for our simulations are listed in Table 1. The channel parameters for the first hop, $\gamma_1 = 6$ and $\sigma_1 = 4dB$, have been taken from [20]-[22] and are valid for the 3–6 GHz band. Because of the existing limited literature, our choice for the parameters for the second hop are a bit more subjective. We choose $\gamma_2 = 2$ (same as the free space path loss), and $\sigma_2 = \sigma_1 = \sigma = 4dB$. We think this is a conservative estimate. The authors in [24] recommend a slow fading margin of 15 dB to account for signal losses due to change in antenna positions. Further, the 4 dB shadowing standard deviation is also based on the recommended margins in [25] of between 7 and 14 dB to account for body size and orientation and arm movement. Another point to note is that we have not modeled the path loss for the sensors that are very close to the source (say, less than 0.1 m) as they would be automatically recruited for cooperative transmission.

III. Analysis Approach

Our general analysis approach was the following:

- Monte Carlo techniques were used to generate the on-body sensor field. The sensor field was assumed to be a circular disc of radius R_c, and number of on-body sensors was assumed to be N_s.
- The first hop was from the source sensor (located at the center of the circular disc) to the on-body sensors and entailed recruiting sensors to form an OLA. The skin patch transmit power was -5 dBm. Using link budget analysis, the selected sensors had received power greater than the receiver (RX) sensitivity (chosen to be -91 dBm, which is consistent with [17], [18]).
- The second hop was from the OLA to the access point.
- For a given transmit power, and the number of sensors in the OLA, the range d that achieved approximately $X\%$ outage to the access point for the two-hop cooperative transmission method using Monte Carlo techniques was found.
- The total transmit power of the cooperative transmission network for that range was computed by adding the powers of the source and all the relays.
- To realize the power gains from cooperative transmission technique, the total transmit power required to achieve the same X% outage for direct transmission (single-hop transmission) to the hub was calculated. The pathloss without any

shadowing assumption was calculated and used to compute the mean transmit power ($\overline{P_t}$) from the source. Note that the $\overline{P_t}$ is a function of the RX sensitivity and the same value as the sensors was assumed. Next, assuming lognormal shadowing, the required transmit power for direct transmission was computed.

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 decoding sensors and the SNR received at the access point are correlated.

IV. Simulation Results

For our simulation results, we assumed a sensor field where there are 10 sensors uniformly distributed on a circular disk of radius 0.4 m. The distance of the access point from the body was varied from 4 to 6 m in steps of 0.5. The number of Monte Carlo simulations to generate the results were 10,000.

In Fig. 2, a scatter plot of the received power at the remote access point and the number of sensor nodes participating in the relay is presented. One can observe that not all on-body sensors participate in the OLA transmission all the time. From Fig. 2 one can infer that as the number of decoding sensors increases, the power received at the access point also increases.

Figs. 3 shows the cumulative distribution functions (CDFs) for the total transmit power of the cooperative transmission approach. We observe in Fig. 3 that the highest total power in the distribution is only under 6 dBm; this is much less than the 28.6 dBm required for the direct transmission case (calculated as described in Section III). This shows that the cooperative transmission approach requires less energy compared to the direct transmission.

The aggregate receiver power (at the access point) using the cooperative and non-cooperative approaches is shown in Fig. 4. We can see that for a reliability of around 90%, there is a diversity + array gain of about 14 dBm per antenna for the cooperative transmission technique for a range of 4m. This power gain of 14 dBm could be alternatively used to achieve range extension.

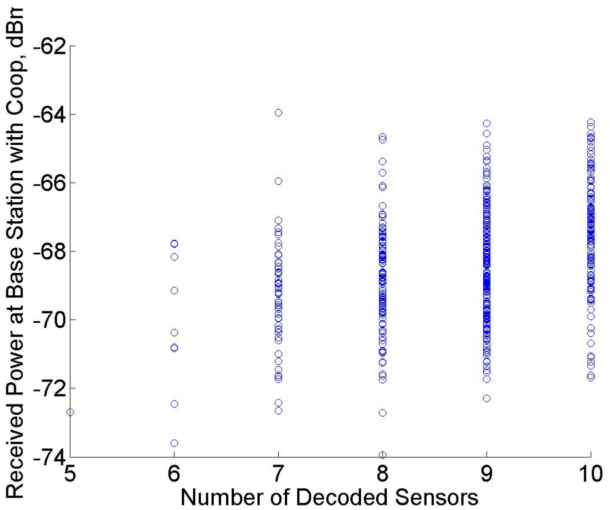

Fig. 2. Scatter plot of received power at the access point vs. the number of relays (4m).

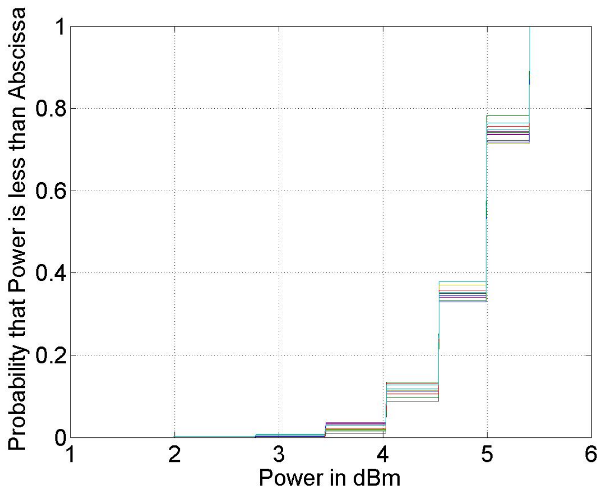

Fig. 3. CDF of the total transmit power for cooperative transmission for the range that achieves 97% reliability (4m).

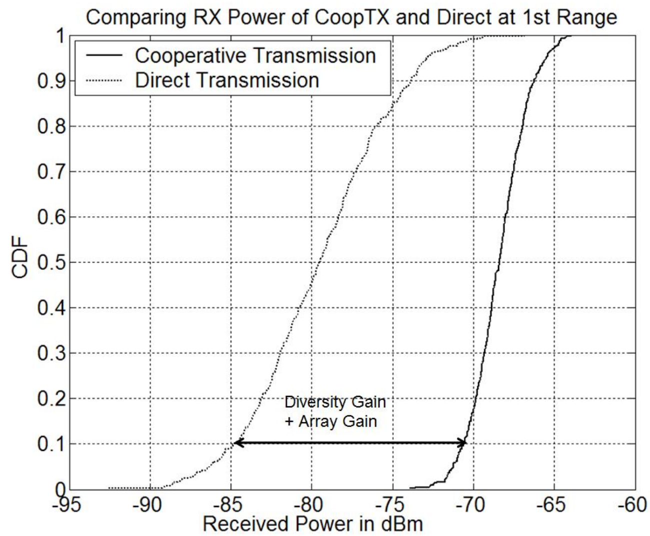

Fig. 4. Received Power for Coop TX Relative to the 1st Antenna

V. Conclusions

Using sensors to monitor health information around the body is a promising new wireless application. Furthermore, emerging UWB technologies provide a potential air interface for low data rate short range communication scenarios matching the requirements of bio-medical sensor devices. This paper outlines the basic gains possible by using cooperative transmission techniques for BANs. The results from this paper indicate that two-hop OLA cooperative transmission shows promise for enabling long-range transmission directly from on-body skin patches without requiring high skin patch 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. Future work involves incorporating more practical modeling aspects of multipath fading and limited number of orthogonal receive channels.

Acknowledgements

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