On the Use of Ultrasonic Communications in Biosensor Networks

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***Abstract*—In this paper the problem of wireless communications in human tissue is addressed for biosensor network applications. Today's offered solutions involve the usage of RF communication systems, which have shown to provide adequate performance to ensure proper network functionality. Yet, they do not ensure that human tissue is not harmfully affected. In order to overcome this issue, we propose the use of ultrasonic waves for wireless communications in biosensor networks, motivated by the fact that, in contrast to electromagnetic waves, ultrasound has been used for almost a century now for medical purposes without any reported side-effects. A simple propagation model is used to evaluate ultrasonic waves as a communication medium, study the feasibility of our proposal, the effective bit rates that may be achieved, the power efficiency of the scheme, as well as other system issues.**

I. Introduction

The scientific field of wireless bio-sensor networks has been developing extensively in the last few years, promising a significant upgrade in the quality of healthcare services provided to users. The vision for future biosensory systems includes the development of networks of devices implanted in the human body, which will be used for real-time health monitoring, diagnostics, or as prosthetic devices (i.e. [1]-[5]). The challenges involved in meeting this vision are still a great many, including the development of implantable material, sensing devices, algorithms and protocols for communication. In the field of sensor communications in particular there has been a large amount of technology transfer from the ad-hoc and sensor networks fields of research, where radio-frequency (RF) communications are dominating over the last decades [6]. For biosensor networks, research on RF communications is focusing on the challenges involved with the way that the human body behaves as a communication medium as well as how RF waves affect the health of human tissues. This research has not been conducted solely for biosensor network applications but for the general case of electromagnetic emissions from any device that resides in the vicinity of the human body. The human tissue is very vulnerable in heat absorption. If this is done over a specific limit, then the tissue can either be damaged or infected by bacteria that otherwise could not grow in population due to lack of heat [4]. This fact further limits both the energy that a biosensor can consume as well as the communication rate that can be used. In addition to that, it is widely known from wireless communications that heat absorption from human tissue increases as wave frequency increases [6]. For this purpose, wireless communication in, or close, to the human body is carefully designed and used as sparsely as possible [7].

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In this work we propose to by-pass these problems by using a communication medium other than RF: ultrasonic waves. We are motivated by the fact that, in contrast to electromagnetic waves, ultrasound has been used for almost a century now for medical purposes without any reported side-effects. Therefore it would be fitting to use ultrasound as a communication medium for implanted or even wearable biosensor communications.

In this paper we present a study on how the ultrasonic waves would behave as a transmission medium in a human body environment, and discuss how the medium would affect the communication ranges, the achievable rates, and the overall design of the system. Our goal is to provide an alternative means of creating networks of implantable sensing devices, without being limited by the hazardous implications of the use of RF waves.

The rest of the paper is organized as follows. In section 2 we provide a review on the principles of ultrasonic waves. Section 3 describes a simple propagation model that is used to evaluate ultrasonic waves as a communication medium. In section 4 we discuss the impact of the use of ultrasound on the system design, and finally we conclude our paper in section 5.

II. Principles of Ultrasonic Waves

The first use of ultrasound for biomedical applications has been reported in the 1940's [8]. Thereafter, many ultrasonic systems have been developed for health monitoring and diagnostics, using frequencies in the range from 2 to 100 MHz [9].

Ultrasound follows the laws of reflectivity and refraction, and can be transmitted in directional beams. However, ultrasonic waves propagate very poorly through gaseous media [8]. In that way, the transducers used must have always contact with non-gaseous surfaces in order to be able to produce effective ultrasonic pulses. Fortunately, this disadvantage does not affect scenarios where implantable sensors need to communicate with each other, since the human body consists mainly of non-gaseous media. On the other hand, human tissue is considered to be a lossy medium and ultrasound is quickly dissipated in the form of heat. This heat in the case of medical ultrasound used for diagnostics, where the system is rarely used, is so small that no damage is caused to the tissues [8]. In the case of using ultrasound for biosensor networks however, we need to evaluate the amount of losses of ultrasonic waves in the human body, against the corresponding losses of RF waves. Propagation models for ultrasonic pulses used in diagnostics have already been presented [9]. In the next paragraphs, a review of the physics of ultrasound when used as a constant-wave carrier is presented, in order to try and establish a simple propagation model based on the specific theory.

A. Physics of Ultrasonic Waves

Ultrasound consists of acoustic waves with frequency over 20,000 cycles per second. In general acoustic waves are vibrations of the molecules or atoms of the medium in which sound propagates. These vibrations are organized in a sinusoidal fashion. The areas of compression and refraction are created by periodic pressure applied to the surface of the medium. In that sense, wave theory is applicable also to sound waves.

Acoustic waves in brief have the following characteristics:

- Pressure and particle velocity are in phase.
- Particles in the medium oscillate with equal excursion in the positive and negative directions. Therefore, there is no net movement of material; the molecules simply vibrate back and forth with frequency ω.
- Wave phase fronts progress with velocity c equal to the speed of sound and particles oscillate with velocity u.

Attenuation of acoustic waves is caused mainly by absorption of the pressure energy by the medium. Attenuation in human tissue is a variable of the tissue acoustic properties and the frequency of the constant wave. It has been shown [9] that attenuation can be modeled as,

$$a = \alpha f^{\beta} \, (dB / cm / MHz) \tag{1}$$

where f is the carrier frequency and α,β are constants that depend on the acoustic characteristics of the tissue. The speed of sound c is a variable of the average tissue density ρ_0 and compressibility K. The relationship is the following:

$$c = \frac{1}{\sqrt{\rho_0 K}} \tag{2}$$

Different human tissues have different values for density, speed of sound, attenuation at the same frequency etc. A very thorough measurement of human and animal tissue characteristics have been made throughout the years. Typical values of acoustic attributes for a selection of tissue types can be found in [9].

B. Sonic Wave Reflection and Scattering

Sound in any medium travels in a straight line. When the wave front reaches an interface between media with different characteristic impedances, then the wave undergoes reflection and refraction. Snell's law applies to this case and therefore we can define the reflectivity R of the wave that describes what percentage of the incident wave is reflected:

$$R = \frac{p_r}{p_i} = \frac{Z_2 \cos\theta_i - Z_1 \cos\theta_t}{Z_2 \cos\theta_i + Z_1 \cos\theta_t} \tag{3}$$

where the subscripts i, r and t correspond to the incident, reflected and transmitted wave respectively, θ is angle and Z_1, Z_2 are the characteristic impedances of the two media, where $Z_i = \rho_i c$.

The above equation is valid only for reflections that occur when the traveling wave meets relatively large and uniform reflective surfaces. This type of reflection is called specular. In the case where the acoustic wave meets an object that is small relative to the wavelength, it has irregular shape and is weakly reflective, as is the case with ultrasonic waves traveling within the human body, the occurring phenomenon is called scattered reflection and cannot be modeled by applying Snell's law. The Rayleigh probability density function must be used in order to model such refractions.

Therefore the ultrasound propagates within the human body in the same way that RF waves would in an indoor environment with a large amount of scatterers and a bounded propagation delay. Based on this observation, we can evaluate the performance of a communication system based on ultrasonic waves, and estimate the amount of energy losses that could cause damage to the tissues, using an elliptical geometric model, as the one used in indoor RF communications [11], adjusted to the physics of ultrasonic wave propagation.

III. A Simple Ultrasonic Propagation Model

By using the ultrasound theory of the previous section a simple two dimensional statistical model for the propagation of ultrasound in human tissue has been defined, as shown in figure 1. This is a standard way of representing wireless environments were the total distance traveled by the signal is limited by channel attenuation and receiver sensitivity. We chose to simulate the implanted sensors environment as such a statistical geometric model, in order to be able to estimate signal behavior regardless of the specific locations of transmitters and receivers, and provide generalized results on the use of ultrasonic waves for biosensor communications. According the model used, an omni directional transducer and an omni directional receiver are located on the long axis of an ellipse. The inside of the ellipse is considered to have the acoustic attributes of the tissue of a human muscle, so that the attenuation coefficient can be calculated according to muscle tissue acoustic characteristics and the frequency of the acoustic signal. A number of scatterers are uniformly distributed into the ellipse and a number of reflectors are also uniformly distributed on the perimeter of the ellipse.

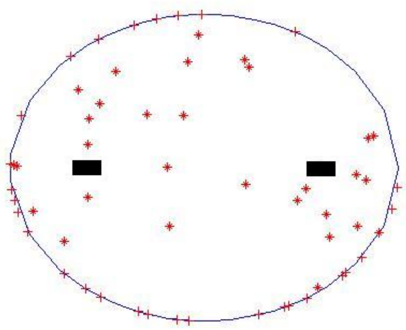

Fig. 1. Propagation Model of Human Tissue Channel. Asterisks in ellipse area are scatterers while crosses on ellipse perimeter are reflectors. Dark rectangles are transmitter and receiver locations.

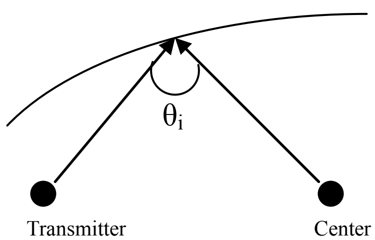

Fig. 2. Ultrasonic Reflection Angle.

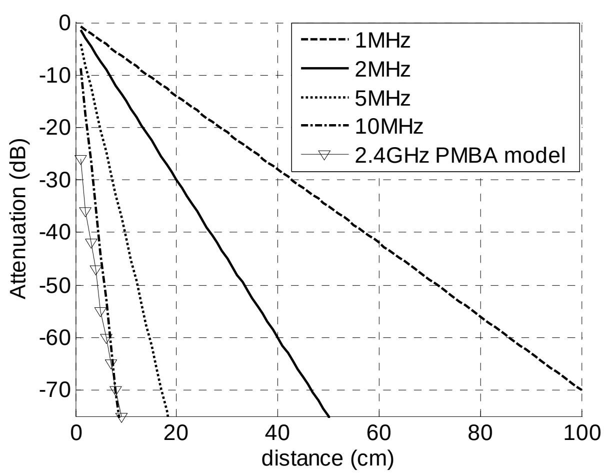

Fig. 3. Signal attenuation in channel with 20 scatterers and 20 reflectors.

The reflectors are considered to have the acoustic attributes of human fat, so that reflectivity can be derived according to the characteristic impedances of kidney and fat tissue and the angle of incidence of the ultrasonic wave. The multipath components are considered to undergo either one scattering effect or one reflection before they reach the receiver. Due to non-uniform acoustic characteristics of the human body, no line-of-sight (LOS) signal was considered.

Taking into account that characteristic acoustic values of different human tissue types do not change drastically but in a range of ±5% [9], with this model we can derive general conclusions about the propagation of ultrasound in the human body, except for some specific cases. These specific cases involve the inclusion of media like bone, muscle and air cavities in the propagation channel whose acoustic characteristics have large deviations from the mean human tissue and generally introduce high attenuation to sonic waves. These cases could be considered separately. However, since no LOS signal is considered in our model, the aforementioned media can be considered as additional reflectors or scatterers in the communication environment.

In order to compute the large scale model attenuation for each component, the total path length is computed and the amplitude attenuation is calculated according to (1), multiplied by the total path length. The time of arrival of each multipath component is computed according to (2).

Regarding the effects of reflectors, reflectivity is computed according to (3). The incidence angle of the wave is considered to be the angle formed by the incident wave and the axis that crosses the center of the ellipse, as shown in figure 2. Regarding the effects of scatterers, a random number is added to the path attenuation, having uniformly distributed random phase shift and Raleigh distributed random amplitude. At the end, all the multipath components are added together to form the total attenuation losses of the signal according to wireless communications theory. The uniformly distributed delays when added follow the Rayleigh distribution which is suitable for describing the scattering phenomena, as it was stated in the previous paragraph. Assuming that the transmitted signal $u(t)$ is narrowband, the received signal model will be,

$$r(t) = \Re\left\{ u(t) \left[\sum_{n=0}^{N(t)} a_n(t) e^{j\phi_{nc} t} \right] \right\} \tag{4}$$

where N is the total number of multipath components.

By implementing the specific model we are interested in finding the total attenuation imposed on the transmitted signal, as well as the rms delay spread caused by the multiple signal paths. In this way we can characterize the defined channel accordingly and measure its capabilities for different signal frequencies and for different transmitter-receiver distances. In order to calculate rms delay spread and received signal attenuation, we model the impulse response of the multipath channel.

The propagation model defined above was used to simulate propagation in the presence of 20 reflections and 20 scatterers. The specific channel has been tested for carrier frequencies ranging from 1 to 10 MHz. For each carrier frequency, distances from 1 to 100 centimeters have been simulated that correspond to typical biosensor applications. As the specific model is statistical, each case was executed

1000 times and mean values have been considered in order to calculate amplitude attenuation in dB as well as rms delay spread for each case.

In figure 3 the mean attenuation of the proposed medium is compared to a typical RF medium presented in [12]. We may observe that carrier frequencies up to 2MHz are not severely attenuated within the environment of the human body, presenting very low absorption by the human tissues in the form of heat. In other words, by using ultrasonic frequencies, the risks involved with the use of ultrasonic waves to communicate between implanted sensors will be quite low, compared with the use of RF waves.

Since there is multipath propagation in the medium, there will be fading effects in the received signal amplitude. The severity of these effects can be evaluated using the rms delay spread metric of the channel, shown in figure 4. We may observe that the use of lower carrier frequencies increases the rms delay spread of the channel. This can be explained by the fact that low frequencies are not severely attenuated with distance traveled, and therefore multipath components with large excess delays have significant amplitudes. For example, if a carrier frequency of 1MHz would be used, this would result in a maximum rms delay spread [13] of $7x10^{-5}$ sec, and a 50% coherence bandwidth of 11.4 KHz. The corresponding coherence bandwidth for 2 and 5MHz is 24.5 and 68KHz respectively.

From the above results the following conclusions can be made: Lower frequencies introduce less attenuation but higher rms delay spreads, while higher frequencies support higher coherence bandwidths but introduce more attenuation to the signal. A good compromise between these properties of the signal would seem to be the use of ultrasonic waves around 2MHz, where the absorption from human tissues are quite small, while the rms delay spread for the distances considered allow for reasonable communication rates.

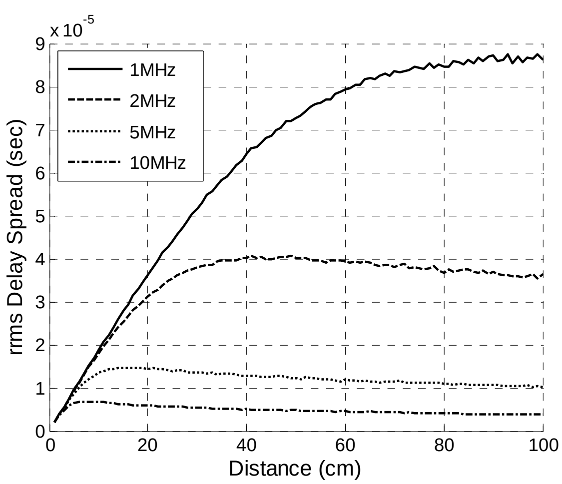

Fig. 4. RMS delay spread of channel with 20 scatterers and 20 reflectors.

IV. Discussion

In the previous section we have shown that it is feasible to use ultrasonic waves as a communication medium in implanted biosensor networks. In this section we discuss issues that are related to the system architecture of a body resident network of implanted biosensors. Such a network has not been considered hitherto due to the use of RF transducers in biosensor networks. In fact, most of the applications proposed or implemented so far concern either the use of one sensor that stays in the human organism for a limited amount of time, or more sensors that do not reside in the human body but are located near it or on the skin in order to collect data [1-5]. In this work we envision future biosensor networks that contain the following parts:

- A number of biosensors implanted in a limited area of the body for monitoring reasons. This area could be the perimeter of a human organ like the kidney or a wider one including the gastro intestinal system.
- An external device (node) located on the human body acting as a base station for the implanted biosensors.

The biosensors must be able to communicate amongst themselves in order to exchange information or perform data aggregation from one part of the network to the other, and they could also be able to communicate with the base station in order to provide the user with any valuable information that they collect, or reply to any possibly submitted query. The base station in this case is considered to be a node that resides on the body skin or possibly implanted near the skin surface.

The setup described above could be a model for any wireless sensor network (WSN) application, and so the limitations posed on the specific system are the limitations that apply to the general case of any WSN. These include the following:

- Limited Power Resources: Due to the size and the location of wireless sensors, their power resources are limited.
- Limited Memory: The size of the sensors as well as the limited power resource pose great limitations to the amount of available memory of the sensor.
- Low Computational Capability: The above limitations in combination with the tasks of sensing and communicating restrict also the computational capabilities of the nodes.
- Low Communication Rate: Communication in wireless sensors is the most energy consuming activity. For this reason, it must be kept to a minimum in order to prolong the sensor's lifetime.

For biosensor networks, the limitations listed above are amplified due to the fact that the sensors reside in a very sensitive environment, where human tissue is vulnerable to heat absorption. Therefore, the use of ultrasonic waves seems to be the most attractive choice for this reason. This choice would lead to re-evaluating a number of issues involved with the design of a complete communication system. Some of these issues are identified and discussed in the following paragraphs.

A. Communications

Due to the low attenuation of ultrasonic waves, there is a significant effect of multipath components in the received signal. In order to mitigate these effects, we have to choose among the use of equalizers, orthogonal frequency division modulation, frequency hopping spread spectrum modulation, or to reduce the transmission rates. For implanted sensors that have quite limited processing capabilities, it seems that the best path to follow is to reduce the bit rates of transmitted data. Using the aforementioned model we can deduce that bit rates in the order of 10-70Kbps can be supported without introducing inter-symbol interference [13]. We could also reside to the use of frequency shift keying modulation schemes that are quite common in acoustic communication systems due to their inherent immunity to multipath effects.

We should also note that the use of ultrasonic frequencies does not require licensing, as RF waves do, and the amount of external and adjacent channel interference is negligible.

B. Node architecture

Due to the low attenuation of carrier waves with frequencies below 2 MHz, the receiver specifications can be quite relaxed in terms of receiver sensitivity and dynamic range. Moreover, the power efficiency of the proposed communication medium is large, since very small transmission powers may be used to reach the distances identified in this paper. Finally, the complexity cost and power efficiency of transceivers working in the range of 2MHz is much lower than corresponding transceivers working at 2.4 GHz.

C. Transducer Implementation

The use of RF waves in communications requires the implementation of antennas that are at least a quarter of a wavelength large. For example, in order to use the industrial-scientific-medical band around 2.4 GHz, the length of the antennas should be at least 3 cm. These dimensions are prohibitive for implanted devices. One could overcome this problem by increasing the carrier frequencies of the RF waves, but in this case the propagation characteristics of the resulting waves would be far worse than those of ultrasonic waves, resulting in more complicated and costly node implementations.

On the other hand, the implementation of ultrasonic transducers has become cost effective with the introduction of micro-electro-mechanical (MEMS) systems [14]. Moreover, the total area of an ultrasonic transducer could be less that 1mm2 [15], therefore being compatible with most envisioned future applications of biosensor networks.

D. Networking

Transmissions from ultrasonic transducers are in general directional. This would have an impact in the design of the network in order to avoid network partitioning and failure. Studies made in WSN applications on the use of directional transmissions [16] would be most helpful in carefully planning the network functionality.

E. Security

As opposed to RF waves that propagate poorly in the human body while being transmitted quite well in the air, ultrasonic waves emitted by implanted sensors will propagate poorly outside the human body. Therefore it will be quite hard for unauthorized eavesdroppers to acquire sensitive information directly from patients that use the system.

V. Conclusion

In this paper the problem of wireless communications in human tissue has been addressed for biosensor network applications. Today's offered solutions involve the usage of RF communication systems for biosensor networks. These systems are tested and they provide performance that ensures proper network functionality. Yet, they do not ensure that human tissue is not harmfully affected.

In order to overcome this issue, the use of ultrasound for wireless communication in biosensor networks is suggested. By the implementation of a simple propagation model in human tissue, it is shown that is feasible to achieve operational bit rates (10 to 20 Kbps) in relatively low ultrasonic frequencies (less than 5 MHz) at distances up to 100 centimeters. At these frequencies the amount of heat absorbed by human tissues is much less than that absorbed when RF waves are used. Of course the specific propagation model is simplified and more realistic channel models may be studied in the future, corresponding to specific locations in the human body and to experimental results. For example, it could be proven that the arms and legs of a patient would behave more like waveguides, reducing the attenuation as well as the rms delay spread of the received signal.

Finally, we have considered several system issues involved with the use of ultrasonic waves for body-resident biosensor networks showing that their use would have several benefits in the total system architecture.

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