On the Use of Ultrasonic Waves as a Communications Medium 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.**

***Index Terms*—Biosensor networks, body area networks, channel model, implanted sensors, ultrasonic communications.**

I. Introduction

The SCIENTIFIC field of wireless biosensor 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 RF communications are dominating [6]. For biosensor networks, research on RF communications focuses 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 to 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 signal power that can be emitted. In addition to this, 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].

In this paper, 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 fit 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 implanted 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 II, we provide a review on the principles of ultrasonic waves. Section III describes simple propagation models that are used to evaluate ultrasonic waves as a communications medium. In Section IV, we discuss the impact of the use of ultrasound on the system design, followed by the conclusions of our paper in Section V.

II. Principles of Ultrasonic Waves

The first use of ultrasound for biomedical applications was reported in the 1940s [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 this way, the transducers used must be always in contact with nongaseous surfaces in order to be able to produce effective ultrasonic pulses. Fortunately, this disadvantage does not affect scenarios where implanted sensors need to communicate with each other, since the human body consists mainly of nongaseous media. On the other hand, human tissue is considered to be a lossy medium through which ultrasound is dissipated in the form of heat. In the case of medical ultrasound used for diagnostics, where the system is rarely used, this heat is so small that no damage is caused to the tissues [8]. But more importantly, in all cases, ultrasonic wave heat dissipation is minimal compared to the amount of heat produced through propagation of electromagnetic RF waves, as explained in [10]. This fact derives from

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the different interaction between the human body and the two corresponding propagation waves (ultrasound and RF), which we consider. Since human tissue is vulnerable to heat absorption, ultrasound waves are therefore advantageous as communication medium against RF waves for biomedical applications. However, in the case of using ultrasound for biosensor networks, 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 in [23]. 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 on the surface of the medium. In this sense, wave theory is also applicable to sound waves.

Acoustic waves in brief have the following characteristics.

1) Pressure and particle velocity are in phase.
2) 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.
3) 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

$$a = \alpha f^{\beta} (\text{in decibels/centimeter/megahertz}) \quad (1)$$

where f is the carrier frequency and α and 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:

$$c = \frac{1}{\sqrt{\rho_0 K}}. \quad (2)$$

Different human tissues have different values for density, speed of sound, attenuation, 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 [11] and [12].

B. *Sonic Wave Reflection and Scattering*

Sound in any medium travels in a straight line. When the wavefront reaches an interface between media with different characteristic impedances, then the wave undergoes reflection and refraction. Snell's law [11] applies to this case; therefore, we define the reflectivity R of the wave that describes the percentage

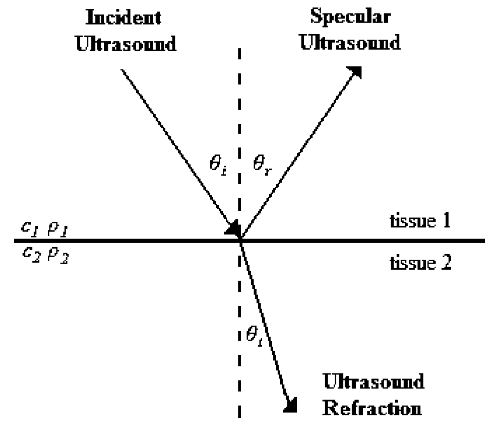

Fig. 1. Transmitted beam is refracted according to Snell's law to an angle θ_r to the normal.

of the incident wave, which is reflected as

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

where the subscripts i, r, and t, respectively, correspond to the incident, reflected, and transmitted wave; θ indicates angle, and Z_1 and Z_2 are the characteristic impedances of the two media, where $Z_i = \rho_i c$. In Fig. 1, the physical phenomenon of reflection and refraction is depicted when the incident ultrasound beam reaches a discontinuity between two tissues with diverse acoustic characteristics.

Equation (3) 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 [11]. In the case where the acoustic wave meets an object, which is relatively 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 [11].

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. On the basis of 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 popular geometric models, as the ones used in indoor RF communications [13], [14] adjusted to the physics of ultrasonic wave propagation.

III. Simple Ultrasonic Propagation Models

A. *Elliptical Model*

By using the ultrasound theory of the previous section, a simple 2-D statistical model for the propagation of ultrasound in human tissue has been defined, as shown in Fig. 2. This is a standard way of representing wireless environments where the total distance traveled by the signal is limited by channel attenuation and receiver sensitivity. We chose to simulate the implanted sensors environment as a statistical geometric model, so as to

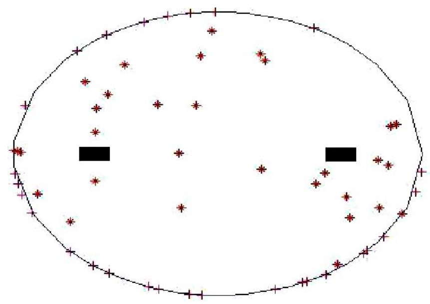

Fig. 2. Propagation model of human tissue channel. Asterisks in ellipse area are scatterers while crosses on ellipse perimeter are reflectors. Dark rectangles are transmitter and receiver locations.

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 to the model used, an omnidirectional transducer and an omnidirectional receiver are located on the long axis of an ellipse. The inside of the ellipse is considered to have the acoustic attributes of one certain human tissue, so that the attenuation coefficient can be calculated according to the tissue's acoustic characteristics and the frequency of the acoustic signal. In our simulations, the inside of the ellipse is assumed to be human fat. 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.

The reflectors are considered to have the acoustic attributes of human kidney tissue, so that reflectivity can be derived according to the characteristic impedances of kidney and fat tissues 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. Because of nonuniform acoustic characteristics of the human body, no line-of-sight (LOS) signal was considered.

In this model, scatterers simulate the role of small and nonuniform surfaces encountered in the signal propagation path that could correspond to various organs of human body or even weakly reflective heterogeneous media. Therefore, scatterers are not modeled according to Snell's law, but rather as reflecting surfaces with a Rayleigh-distributed random reflection coefficient.

Taking into account that characteristic acoustic values of different human tissue types do not change drastically, but in a range of $\pm 5\%$ [9], with this model, we can derive general conclusions about the propagation of ultrasound in the human body, with the exception of certain particular cases. These cases involve the inclusion of mediums such as bone 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), while the incident angle is computed considering the perimeter of the ellipse as the boundary between the diverse tissues.

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 narrow band, the received signal model is derived as

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

where N is the total number of multipath components.

By implementing this 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 different transmitter–receiver distances. In order to calculate the rms delay spread and received signal attenuation, we model the impulse response of the multipath channel.

The propagation model defined earlier was used to simulate wave propagation in the presence of 20 reflections and 20 scatterers. The specific channel has been evaluated for carrier frequencies ranging from 1 to 10 MHz. For each carrier frequency, distances from 1 to 100 cm 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 decibels as well as rms delay spread for each case.

To evaluate the amount of losses of ultrasonic waves against the corresponding losses of RF waves inside the human body, our proposed ultrasonic communication model is compared to the propagation loss model (PMBA) of RF waves inside homogeneous human tissue, as this is presented in [15]. This comparison is demonstrated in Fig. 3. We may observe that ultrasonic carrier frequencies up to 2 MHz are not drastically attenuated within the environment of the human body, thus 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, as shown in Fig. 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 respect to the distance traveled, and therefore,

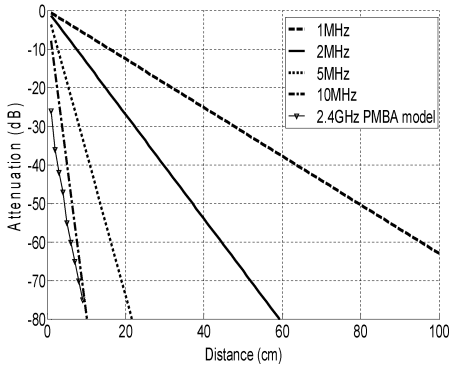

Fig. 3. Attenuation of ultrasonic signal propagating through human fat tissue, for various ultrasonic frequencies, compared to the RF propagation model (PMBA) for homogeneous human tissue.

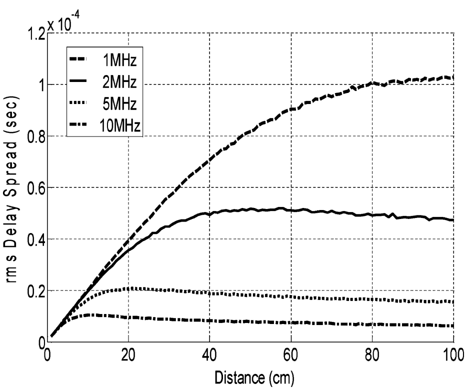

Fig. 4. rms delay spread of the elliptical channel model, with 20 scatterers and 20 reflectors.

multipath components with large excess delays have significant amplitudes. For example, if a carrier frequency of 1 MHz would be used, this would result in a maximum rms delay spread [16] of 1.0×10^{-4} s and a minimum 50% coherence bandwidth of 1.9 kHz. The corresponding coherence bandwidth for 2 and 5 MHz is 4.2 and 12.9 kHz, respectively.

B. Gaussian Model

A generalized model simulating the propagation of ultrasound waves inside the human body is also considered in order to come up with safe conclusions concerning the use of these waves as a communications medium. We chose the Gaussian geometric model for this purpose, since it provides the means to model a number of diverse environments with different tissue characteristics that would be encountered in biosensor communications. The assumptions made for ultrasonic propagation through this geometric model are the same as previously presented in the elliptical model. According to this, omnidirectional transducers are used. The transmitter is located at the center of the 2-D plane, while the receiver's position varies from 5 to 105 cm away from the transducer for different sets of executions. The Gaussian model treats the human organs inside the body as clusters of scatterers in the 2-D space, following the Gaussian distribution. Each cluster represents a different medium—human organ—and is considered to have specific attributes (speed of sound,

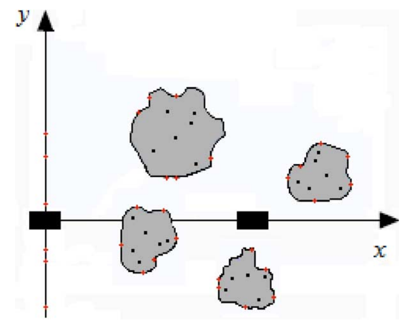

Fig 5. Gaussian propagation model. Dots in the clusters are scatterers while crosses on the surface of the clusters are reflectors. Dark rectangles are transmitter and receiver locations.

attenuation coefficient, average density, acoustic impendence, reflection coefficient). On the borders between the clusters and the medium that fills in the space, reflectors are located to simulate the effect of reflection. In the simulated model, we used six clusters of scatterers, each one representing the pancreas**,** the spleen**,** the lungs**,** the kidney, and also bones and air cavities. The medium between the clusters is assumed to be human whole blood [17]. The characteristic acoustic attributes of the aforementioned mediums can be found in [11], [12], and [18]. Similar to Section III-A, the multipath components are considered to undergo either one scattering or one reflection before reaching the receiver, while no LOS signal is considered.

The Gaussian model we propose is considered to be generalized compared to the elliptical, since it includes air cavities and bones whose acoustic attributes have large deviations from the mean human tissue. In the area behind the transducer, additional reflectors are located to simulate the skin. This assumption is based on the hypothesis that in biosensor environments, one node (main node) is used as base station collecting all the data from the rest nodes in order to transmit them outside the body through RF. According to this, the main node should have a stable position (probably implanted in human skin), while the receiver's position varies according to the monitoring application.

The proposed Gaussian model is shown in Fig. 5. It includes six different clusters of six scatterers and six reflectors, each representing diverse tissues in the vicinity of the transducers, plus six reflectors behind the transmitter that represent the human skin tissues. In total, there are 36 scatters and 42 reflectors. The carrier frequencies of the ultrasonic waves range from 1 to 10 MHz. In this model, each execution contains 1500 realizations (500 more than the elliptical model) since the variations are greater. Mean values of each execution have been considered to calculate the signal attenuation and the rms delay spread. Results on the mean attenuation of ultrasonic signals, compared to typical RF attenuation in equivalent environments [15], are shown in Fig. 6 when the medium of propagation between clusters is assumed to be human whole blood.

Comparing the ultrasound attenuation results of the two models (Figs. 3 and 6), we observe that in the case of the Gaussian model, the waves are less attenuated, giving better results than the Elliptical one. This fact is independent of the geometry of the channel and also of the reflectors–scatterers that are used in each model. Attenuation is directly connected to the

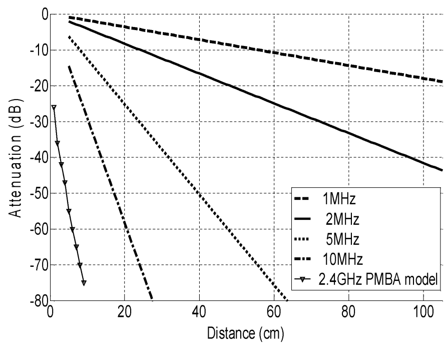

Fig. 6. Ultrasonic signal attenuation using as propagation medium human whole blood, compared to the RF propagation model (PMBA).

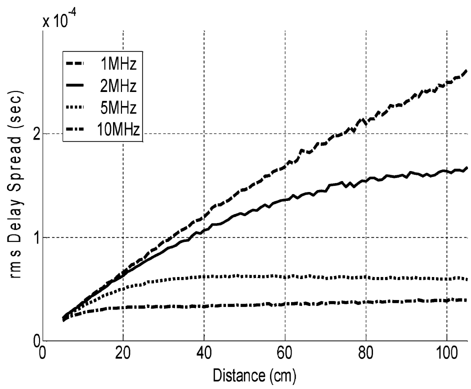

Fig. 7. rms delay spread of the Gaussian model using 36 scatterers and 42 reflectors, and omnidirectional transmitter/receiver.

propagation medium that is assumed to exist between the human organs/clusters of scatterers. Fig. 6 shows that ultrasonic frequencies of 1 and 2 MHz have the best attenuation characteristics, while waves of 5 MHz are not rigorously attenuated by the human body and can also be used as a carrier for ultrasound communication.

In order to come up with safe conclusions concerning the carrier frequency that can be used for this model, the rms delay spread metric is also evaluated, as shown in Fig. 7. We may observe that the frequencies of 1 and 2 MHz have rms delay spread values, which are significantly high as a result of the low attenuation inside the human body. Since these frequencies are not rapidly attenuated as the distance increases, the multipath components that reach the receiver with large excess delay have considerable amplitudes. As we move to higher frequencies, the behavior of the rms delay spread slope converges to 16.0×10^{-5} and 6.0×10^{-5} s for the 2 and 5 MHz frequency, respectively, resulting in a minimum 50% coherence bandwidth of 1.2 and 3.3 kHz The corresponding coherence bandwidth for 1 MHz is 0.8 kHz.

To further expand on the evaluation of the Gaussian model, simulation results were held out for the case of directional transmission–reception, since this is the case for ultrasonic transducers (e.g., [19]). To achieve this, an ultrasonic transmitter emitting waves in beams of 60° beamwidth and a similar ultrasonic receiver, both having radiation patterns pointing generally in the same direction, replace the omnidirectional transducers of the previous simulations. The effect of directional transducers

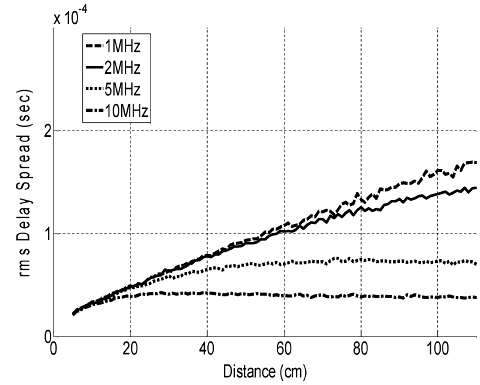

Fig. 8. rms delay spread of the Gaussian model using 60° directional transmitter–receiver.

is that only the reflected and scattered beams that lay within the transmitter–receiver beams are taken into consideration.

The results are shown in Fig. 8. The rms delay spread slope converges to 14.0×10^{-5} and 7.3×10^{-5} s for the 2 and 5 MHz frequency, respectively, resulting in a minimum 50% coherence bandwidth of 1.4 and 2.7 kHz. The corresponding coherence bandwidth for 1 MHz is 1.1 kHz.

Comparing the results for the two cases (omnidirectional and directional), one can observe that the 2 and 5 MHz carrier frequency results are similar for both cases. As for the 1 MHz frequency, the rms delay spread result of the directional case is significantly improved, thereby approaching the corresponding result of the 2 MHZ carrier frequency of both cases.

C. Evaluation of Simulation Results

From the aforementioned results, we can observe the following. Lower frequencies introduce less attenuation, but higher rms delay spreads, while higher frequencies support higher coherence bandwidths, but introduce more attenuation to the signal. For the elliptical model, which would be more appropriate for modeling intra-organ communications, a good compromise between these properties of the signal would seem to be the use of ultrasonic waves of 2 MHz, where the absorption from human tissues is quite small, while the rms delay spread for the distances considered allows for reasonable communication rates. For the Gaussian model, which would more effectively model interorgan and biosensor to base station communication, a good compromise between attenuation and rms delay spread seems to be the use of frequencies around 5 MHz.

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 transceivers. 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 paper, we envision future biosensor networks that contain the following parts.

1) 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 gastrointestinal system.
2) 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 among 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 and acts as a bridge between the biosensor network and the outside world.

The setup described before 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.

1) *Limited power resources:* Due to the size and the location of wireless sensors, their power resources are limited.
2) *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.
3) *Low computational capability:* The aforementioned limitations in combination with the tasks of sensing and communicating also restrict the computational capabilities of the nodes.
4) *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 before 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 reevaluating 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

Because of 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 (OFDM), frequency-hopping spread spectrum (FHSS) modulation, or we could simply increase the modulation order with bandwidth-limited modulation schemes, since the attenuation characteristics of the channel ensure high SNRs at the receiver. According to results obtained by the aforementioned models, we can deduce that bit rates in the order of 10–40 kb/s can be supported using simple linear modulation schemes [16]. However, much higher rates can be supported in the order of few 100 kb/s if we use advanced signal-processing techniques, i.e., OFDM, adaptive modulation and coding, etc.

We should also note that the use of ultrasonic frequencies does not require licensing, and the amount of external and adjacent channel interference is negligible, as opposed to the use of license-free industrial-scientific-medical (ISM) RF bands.

B. Node Architecture

Because of 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 2 MHz 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.

However, the implementation of ultrasonic transducers has become cost effective with the introduction of microelectromechanical (MEMS) systems [20]. Moreover, the total area of an ultrasonic transducer could be less that 12 mm^2 [21], hence 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 on the design of the network in order to avoid network partitioning and failure. Studies made in WSN applications on the use of directional transmissions [22] 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. What is demonstrated by the implementation of a simple propagation model in human tissue is the feasibility to achieve operational bit rates in relatively low ultrasonic frequencies (less than 5 MHz) at distances up to 100 cm, without using any advanced signal-processing techniques. 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 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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