Research Letters

Powering In-Body Nanosensors With Ultrasounds

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Abstract—Embedded nanosensors will be a key feature of emerging medical monitoring systems. Power for these sensors could be harvested from ultrasonic vibrations generated by portable miniature sources and converted to electrical energy by piezoelectric nanowires. This letter analyzes the frequency and intensity of ultrasounds required to power an embedded nanosensor subject to medical safety limits, absorption by human tissue and reflection from interfaces. We calculate input and output power at different levels of energy conversion efficiency. Our analysis suggests that ultrasounds can be a viable source for energy harvesting of in-body nanosensors.

Index Terms—Nanosensors, energy harvesting, ultrasound.

I. INTRODUCTION

THE internet of bio-nano things [1] aims to interconnect heterogeneous molecular communication networks within the human body to the outside world through a bio-cyber interface. However there are major challenges to overcome in the deployment of networks of nano-devices within a living biological environment. On the one hand the miniature size of the devices and the medium in which they are deployed can change their material properties. On the other hand the very high frequencies that nano-devices need for communication show limited penetration through biological tissue. Moreover, network components must have sufficient power for data collection, computation and transmission [2]. One method of power provision is energy harvesting from external sources (electromagnetic (EM), vibrational, or thermal). In this letter we propose the use of energy

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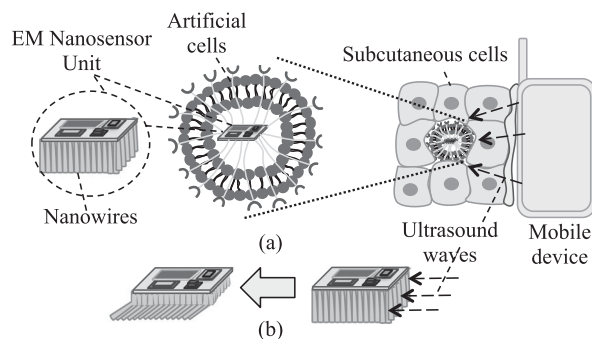
Fig. 1. Scenario of Ultrasounds (a) propagating from an external device through skin and fat cells to embedded EM-based nanosensor, and (b) bending piezoelectric nanowires.

harvesting *EM nanosensors* (which we refer to as nanosensors) operating in the Terahertz, infra-red or optical wavebands to enable communications. Our proposed scenario is illustrated in Fig. 1, where a nanosensor is encapsulated in a bio-compatible artificial cell and is embedded into human tissue. Ultrasounds from a portable external source then induce vibrations in piezoelectric nanowires in the nanosensor to harness energy for the device. The powering of sensors embedded in human tissue by ultrasounds was investigated by Ozeri and Schmilovitz [3] but this was at a macro (cm^2) and not at the nano scale. Wang *et al.* used ultrasounds to power a 2 mm^2 nanogenerator immersed in water [4] and biofluid [5]. The ultrasound excitation at 41 kHz produced measurable voltage and current but the intensity of the ultrasound and the energy conversion efficiency were not stated. The balancing of energy production and energy requirements of a 1000 μm^2 ac nanogenerator was examined by Jornet and Akyildiz [6]. A cyclic vibrational force of 50 Hz was applied in the model and the harvested energy per cycle was stored in a nanocapacitor with a maximum capacity of 800 pJ. The model showed how this level of energy could be used for basic data transmission.

This letter models the novel use of a miniature external ultrasound source to power an embedded nanosensor. We calculate the energy available for harvesting at the nanosensor and compute the potential power output. Energy-harvesting principles using ultrasounds are outlined in Section II. Our modelling of harvested energy is discussed in Section III, the power output is analysed in Section IV and our conclusions and future work are presented in Section V.

II. Nanosensor Energy Harvesting

An energy harvesting nanosensor will include a nanogenerator with nanowires that convert induced vibrations from an external ultrasound source to electrical energy (see Fig. 1).

A. Ultrasounds as an Energy Source

Ultrasounds are generated when an electric field is applied to an array of piezoelectric crystals located on a transducer surface. Electrical stimulation causes mechanical distortion of the crystals resulting in vibration and production of sound waves. In our study we consider ultrasound frequencies in the range from 50 kHz to 1 MHz. We use a maximum ultrasound intensity of 720 mW/cm^2 in line with medical recommendations [7]. We model a miniature portable ultrasound source as emitting a narrow beam (mm^2) into human tissue with no spreading. The ultrasound intensity arriving at the nanosensor depends on the power output of the ultrasound source, the distance from the nanosensor and the attenuation of the beam by any medium in the path. The attenuation is caused by 1) the absorption of energy by the tissue (through molecular vibrations and relaxation) and 2) the reflection of energy at tissue interfaces. We do not include in this model other factors that can contribute to attenuation. These include cases where the nanosensor maybe tilted with respect to the beam or where the nanosensor is deformed and displaced by tissue movements.

For our proposed approach, three different power intensities need to be modelled: 1) the initial intensity emanating from the ultrasound source; 2) the ultrasound intensity entering the nanogenerator following penetration through tissue layers; and 3) the piezoelectric power intensity emerging from the nanogenerator.

B. Ultrasound Absorption in Human Tissue

The parameters we use for ultrasound transmission in the human body are based on those of medical imaging [7]. First we consider energy absorption in the tissue layer. If the initial intensity is I_o then the intensity I_d for a beam of frequency f MHz at a depth of d cm is represented as:

$$I_d = I_o 10^{-(\alpha f d/10)} \quad (1)$$

where the absorption coefficient α, expresses the power loss and has a value of 0.6 dB/cm/MHz for skin/fat. The reduction in intensity at different frequencies and skin/fat depths up to 10 cm is shown in Fig. 2. Higher frequencies are more strongly absorbed than lower frequencies and the graph shows that a 1 MHz beam has lost half of its intensity (3 dB) at a skin/fat depth of 5 cm.

Acoustic reflections at tissue interfaces (e.g., between fat and muscle) are caused by differences in *acoustic impedance* (the density multiplied by the speed of sound). The unit of acoustic impedance is the Rayl (kg·s^{-1}·m^{-2}). If two materials have acoustic impedances Z_1 and Z_2 then the ratio between incident intensity I_o and reflected intensity I_r is represented as [7]:

$$\frac{I_r}{I_o} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2} \quad (2)$$
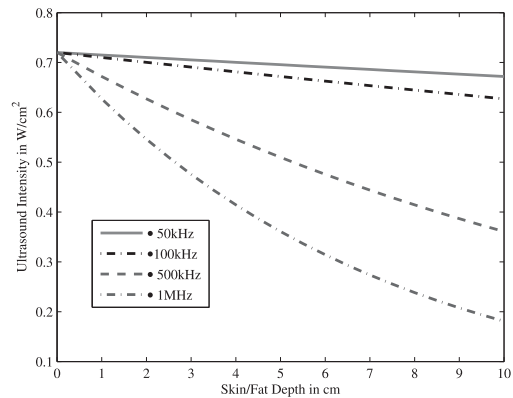

Fig. 2.   Plot of Ultrasound Intensity versus Skin/Fat Depth. Initial intensity is 720 mW/cm^2.

The acoustic impedance of air is 429 Rayl while that of skin/fat is 1.4 MRayl. Therefore, the reflection at an air/human tissue interface would result in up to 99% of the ultrasound being reflected because of the large difference in the acoustic impedance [7]. Consequently, there should be no air gap between an ultrasound transducer and human tissue. In our model we assume only one type of tissue (skin/fat) between the source and nanosensor with no air gap. For maximum power transfer, the absorption and the acoustic impedance of the artificial cell membrane and substrate should match the characteristics of body tissue as closely as possible (e.g., using polymer-based materials).

III. Modelling Ultrasound Energy Harvesting

The nanogenerator must convert incident ultrasounds into mechanical vibrations and then into piezoelectric energy. The use of *Zinc Oxide* (*ZnO*) nanowires for energy harvesting was proposed by Wang and Song [8]. The nanowires in this type of dc nanogenerator are fixed at one end to a substrate while the other end is free and can bend. Systematically bending the nanowires produces current and voltage amounts that are collected by an electrode. The maximum potential at the nanowires surface is directly proportional to the bending and inversely proportional to the length-to-diameter aspect ratio. In [8] the bending is performed by an atomic force microscope (*AFM*) tip. In our model the nanowire bending is driven by ultrasound. The nanogenerator power harvesting depends on: 1) the amount of bending the nanowires are subjected to; 2) the bending events per second (frequency); and 3) the nanowires per unit area (density). The energy per cycle of the ultrasounds will determine the amount of bending, while the frequency of the ultrasounds will determine the quantity of bends per second.

A. Bending a Nanowire

The following analysis of the energy needed to bend a nanowire is based on work by Wang and Song [8] for a *ZnO* nanowire dc nanogenerator. A nanowire can be modelled as a thin cylindrical rod with a specific modulus of elasticity

TABLE I
FORCE, DISPLACEMENT AND WORK FOR BENDING A NANOWIRE

Force (nN)	Displacement (nm)	Work (fJ)
60	109	3.274
80	146	5.821
90	164	7.36
100	182	9.09

(a)

(b)

Fig. 3. Energy per cycle at 50 kHz (a) and 1 MHz (b) against skin/fat depth and varying nanogenerator area.

(Young's modulus). Bending a nanowire requires the application of a force and this is countered by the elasticity of the nanowire. If a constant force F is applied until a maximum bending before discharge, denoted y_m, is achieved, then the balance of forces is represented as:

$$F = \frac{3YIy_m}{L^3}, \qquad (3)$$

where Y is the elastic modulus of a nanowire, I is the area moment of inertia and L is the length. This equation can be used to calculate the maximum bending that corresponds to a specific applied force. The energy (work), denoted ΔE, required to bend the nanowire by an amount y_m is represented as:

$$\Delta E = \frac{3YIy_m^2}{2L^3}. \qquad (4)$$

Examples of calculated values for force, displacement and work for bending a nanowire that is 50 nm in diameter and 600 nm long using an AFM tip are shown in Table I. The work required for bending is of the order of femtojoules and the magnitude of bending is sufficient to deliver a piezoelectric energy output.

B. Ultrasound Cycle Energy

We need to compare the work levels for bending a nanowire in Table I with the energy that can be delivered to a nanowire by ultrasounds. A plot of delivered energy per vibrational cycle at 50 kHz and 1 MHz for a range of nanogenerator areas and different skin/fat depths is shown in Fig. 3. The nanowire density is set at 20 per μm^2, the initial input intensity is fixed at 720 mW/cm^2, and the intensity at different depths is calculated using (1). At a fixed density, the energy per nanowire per cycle is independent of the area of the nanogenerator. At 50 kHz the energy level is from 7.1 to 6.7 fJ at 1 cm and 10 cm depth, respectively. The energy per cycle per nanowire at 1 MHz is initially over 20 times lower than at 50 kHz (0.03 fJ) and decreases more rapidly with depth. A second plot of energy per cycle per nanowire for a fixed area (1000 μm^2), but with varying nanowire densities and skin/fat depths is shown in Fig. 4. Higher nanowire densities will reduce the energy absorbed per nanowire for a fixed area. At 50 kHz the energy per nanowire per cycle drops below 6 fJ at these values (see Fig. 4: Density 20, Skin/Fat depth 10 cm). At 1 MHz the energy per nanowire is lower than 1 fJ at all densities and depths. Both plots show that for a fixed input intensity, an ultrasound frequency of 50 kHz will deliver more than 6 fJ 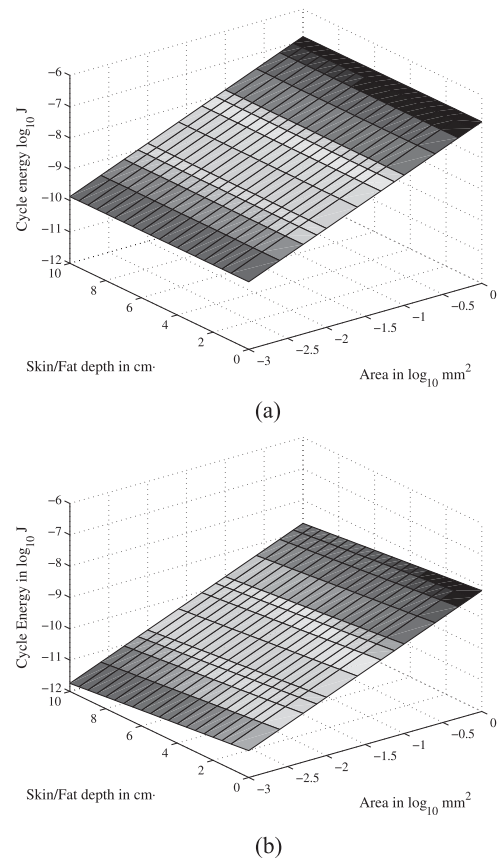per cycle to a nanowire provided the density is equal to or lower than 20 nanowires per μm^2. This means that the magnitude of 50 kHz ultrasound cycle energies per nanowire are comparable to the bending energies shown in Table I, but the 1 MHz cycle energies are too low to provide sufficient bending.

IV. POWER OUTPUT ANALYSIS

The total output energy of a nanogenerator depends on factors such as area, piezoelectric efficiency of the nanowires, absorption or reflection of ultrasound within the nanosensor and the fraction of nanowires that contribute to the electrical output. The dc *ZnO* nanogenerator in [8] had an output energy per nanowire of approximately 0.05 fJ but this did not use ultrasound. Comparing this output to an input level of between 5.82 fJ (force of 80 nN) and 9.09 fJ (force of 100 nN) per nanowire in Table I suggests a conversion efficiency of between 0.55% and 0.8%. Therefore a 1000 μm^2 ultrasound harvesting nanogenerator with 20 nanowires per μm^2 and a work per nanowire of 7 fJ could have a power output of 38.5 nW when a conversion factor of 0.55% is used. Proposed pulse-based modulation techniques (as described by Jornet and Akyildiz [9]) require average power levels of 1 to 10 μW. Spreading the pulses in time by a factor of 100 to 1000 brings the average power back to the nW level.
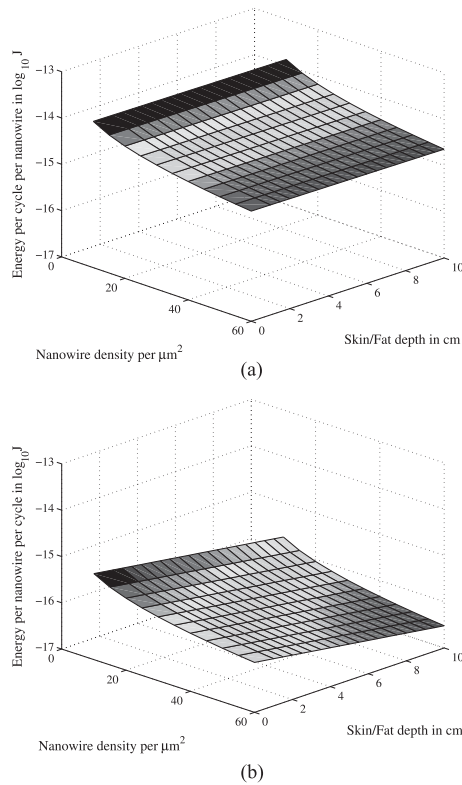
Fig. 4.   Energy per cycle at 50 kHz (a) and 1 MHz (b) against skin/fat depth and varying nanowire density.

V. Conclusion and Future Work

We have shown that an external ultrasound source can theoretically supply vibrational energy to an embedded nanosensor that uses the bending of *ZnO* nanowires to produce power. The intensity of the ultrasounds must remain within safe medical limits and there must be no air gap between the source and the human skin. In this letter we have analysed the amount of force and work required to bend the nanowires and the quantity of ultrasound energy delivered over varying nanogenerator areas and densities of nanowire with respect to the skin/fat depth. Our proposed approach can lead to new energy harvesting techniques for the *Bio-cyber* interface of the Internet of Bio-Nano Things. Based on our analysis the nanosensor unit can provide higher μW power levels by: 1) engineering the nanowire density and dimensions for maximum efficiency; 2) optimising the collection area of the nanogenerator; and 3) cascading nanogenerators to produce more power. However, a frequency of 50 kHz

delivering nanowatts of power may provide enough energy over a number of seconds for the direct operation of the nanosensor without the need for intermediate battery or capacitor storage.

As part of our future work we will model a portable (or on-body) ultrasound transducer device. The overall efficiency of a portable battery-operated device and energy harvesting system will depend on factors such as: 1) dc to ac conversion in the unit (typically 80% efficiency); 2) ac electric to ultrasound conversion (typically 90%); 3) attenuation in the tissue; 4) movement of the the nanosensor; 5) piezoelectric nanowire conversion process (less than 1%); and 6) the electrical demand of the nanosensor for processing and transmission of data.

Clearly, the greatest proportional reduction will be within the energy harvesting system. An overall efficiency can be computed in the case where the actual function of the nanosensor and its electrical requirement is known.

While we analysed a single nanosensor here, we also intend to study clusters of nanosensors embedded in the body. A cluster can provide greater data collection capability while mitigating the effects of slight movements or changes in orientation of individual nanosensors. The total power supplied to any cluster would still have to fit within safe medical limits. Clusters will improve overall efficiency by ensuring that a greater fraction of the ultrasound power is intercepted and used for harvesting.

References

[1] I. Akyildiz, M. Pierobon, S. Balasubramaniam, and Y. Koucheryavy, "The internet of bio-nano things," *IEEE Commun. Mag.*, vol. 53, no. 3, pp. 32–40, Mar. 2015.

[2] M. Kocaoglu and O. Akan, "Minimum energy channel codes for nanoscale wireless communications," *IEEE Trans. Wireless Commun.*, vol. 12, no. 4, pp. 1492–1500, Apr. 2013.

[3] S. Ozeri and D. Shmilovitz, "Ultrasonic transcutaneous energy transfer for powering implanted devices," *Ultrasonics*, vol. 50, no. 6, pp. 556–566, 2010.

[4] X. Wang, J. Song, J. Liu, and Z. L. Wang, "Direct-current nanogenerator driven by ultrasonic waves," *Science*, vol. 316, no. 5821, pp. 102–105, 2007.

[5] X. Wang, J. Liu, J. Song, and Z. L. Wang, "Integrated nanogenerators in biofluid," *Nano Lett.*, vol. 7, no. 8, pp. 2475–2479, 2007.

[6] J. Jornet and I. Akyildiz, "Joint energy harvesting and communication analysis for perpetual wireless nanosensor networks in the terahertz band," *IEEE Trans. Nanotechnol.*, vol. 11, no. 3, pp. 570–580, May 2012.

[7] W. R. Hendee and E. R. Ritenour, *Ultrasound Waves*. New York, NY, USA: Wiley, 2003, pp. 303–316.

[8] Z. L. Wang and J. Song, "Piezoelectric nanogenerators based on zinc oxide nanowire arrays," *Science*, vol. 312, no. 5771, pp. 242–246, 2006.

[9] J. Jornet and I. Akyildiz, "Femtosecond-long pulse-based modulation for terahertz band communication in nanonetworks," *IEEE Trans. Commun.*, vol. 62, no. 5, pp. 1742–1754, May 2014.