Galvanic Coupled Cyber-Physical Body Sensor Network

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• **Research Motivation:** Implanted wireless sensors promise the next generation of health-care by in-situ testing of abnormal physiological conditions, personalized medicine and proactive drug delivery to ensure continued well being. However, these sensors must communicate with an external control, which raises questions on how to ensure energy efficient data delivery through the body tissues. This research proposal addresses this issue by using weak electric currents instead of radio frequency waves, resulting in two orders of energy savings. However, in this scarcely explored paradigm, there are several interesting challenges that must be overcome. These include (i) modeling the human body propagation channel, (ii) identifying the best placements of implants and other auxiliary data forwarding nodes, and (iii) devising scientific methods to characterize and improve channel capacity.

We envisage the creation of a new type of 'wireless network' composed of sensors and actuators embedded within the human body and external data processing and computational centers, which we call as a *cyber-physical body network* (CP-BN). Our initial investigations in this area have focused on *galvanically coupling* a low power signal to the human tissues using a pair of electrodes, while taking advantage of its conducting property. As shown in Figure 1, pair of transmitted electrodes can be placed at any point within the human body (though only the on-skin case is depicted). While the majority of the induced current flows through the two transmitter electrodes, weak secondary electrical currents are set up in the longitudinal direction that can carry the same information to a distant pair of receiver electrodes. These signals suffer losses as they pass through the human tissue, as well as result in components along other radial directions that cross multiple tissue layers. Thus, modeling the propagation of these galvanic coupled signals, building the physical layer, and then the operation of the other higher networking layers for the specialized CP-BN will bring a novel coupled approach spanning the cyber (communication, processing, networking) and physical domains (human body channel, tissue safety limits).

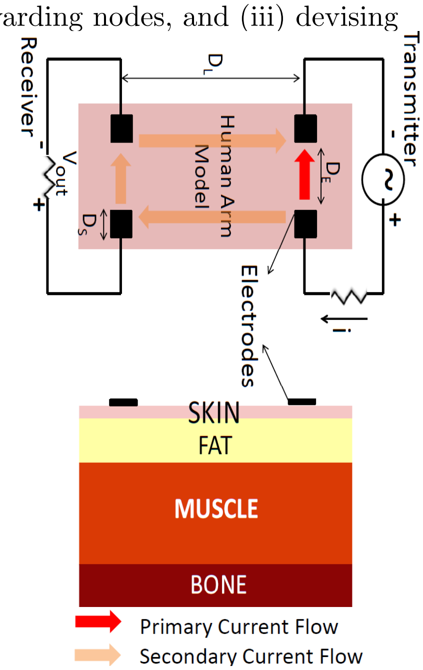

Figure 1: Realizing CP-BN through galvanic coupling

In our efforts to realize the vision of CP-BNs, our early results pertain to estimating the channel gain within the human tissue using electrical signal transmissions through galvanic coupling. We constructed a 2-port equivalent circuit model and an ANSYS HFSS finite element method-based simulation suite of the human arm using known electrical conduction properties of tissues, which is under review in [1]. Results showed a good match between our theoretical and simulation channel models with prior experimental studies for on-skin propagation. We also studied the properties of skin-muscle and intra-muscle propagation, and how specific choices of modulation and noise levels affect the signal strength.

• **Proposed Research** To realize the full potential of CP-BN, we will tackle the following research challenges ahead.

1. *Interference Estimation and Capacity Calculation:* From [1], we identified the ideal range of operating frequencies for CP-BN to be between 100 KHz- 1 MHz. Below this range, are the naturally occurring electrical signal frequencies. Above this range, the energy in the signal escapes out of the body. We will build models of channel capacity that gives the maximum attainable upper bound for this feasible frequency range. We will study the best modulation schemes individually suited to the different tissue layers that provide the best results, close to the upper bound.

2. *Toplogy design:* Depending upon the required bit rates, we will incorporate relay nodes that will establish connections with individual implants, and then transfer the data through a multihop forwarding mechanism. Thus, multiple implants spread throughout the body can be connected with the help of relays to a central querying point. The relay mechanism offers interesting high data rate capabilities (for e.g., the relay nodes can be placed on the skin, with direct RF transmitters). However, their relative position with respect to the implanted sensors will need to be carefully decided. We will take into account two modes of interference, between the links connecting the implants to the relays, and then between the relays themselves, through an optimization approach to jointly identify the topology of the sensors and relays. We will also explore how additional network-assisted features, such as synchronization among implants, link quality analysis, and self healing may be affected through the relays.
3. *Scalability:* We will investigate multiple access issues when the external relay communicates with multiple sensors. As the number of implants increases, each active link introduces a finite amount of energy into the body tissues. The overall aggregate energy incident at each point within the tissue needs to be within the legally defined safety limits [2]. Thus, we shall study the trade-off between power, bandwidth, and tissue energy, especially with regards to typical implant applications using real-world test-cases.
4. *Protocol Requirements:* In this task, we will study the operation at the higher layers of the protocol stack. For instance, a sudden change in heart rate and lactate sensor reading is an alarming situation and needs a high duty cycle and enhanced reliability. However, if these sensor fluctuations are accompanied by a sudden increase in human activity levels, then the situation is not critical and the reporting requirements may be relaxed correspondingly. This brings in a unique aspect of CP-BNs in the sense that human activities influence the operation of the software protocols.

• **Potential Impact to CPS** The objective of CP-BN is to build a reliable platform for real-time communication that is adaptable to application demands of wearable and implant sensors, prevailing health conditions, and the actions of the monitored human subjects. This area is in a nascent stage, and very little work has been done in the area of CPS for implanted sensors. The proposed research will tackle difficult challenges through a holistic approach that includes analytical modeling, systems design, algorithm development and protocol implementation to realize the promise of CP-BN.

Once this area of research matures, CP-BNs will potentially revolutionize health-care. We envisage diverse applications that will benefit sportsmen and women, military personnel and other professionals who operate in dangerous conditions without comprehensive and ready medical facilities, infants and at-risk elderly population. The ability to sense physiological changes within the body and take proactive monitoring steps will increase longevity of human life, and reduce costly operations that are only possible for affluent sections of society. We believe the future of health-care lies in controlling drug delivery and sensing via medical implants, and CP-BNs will take the first steps towards making this vision a reality.

References

[1] M Swaminathan, FS Cabrera, G Schirner, and K R Chowdhury, *Characterization and Signal Propagation Studies for Wireless Galvanic Coupled Body Sensors*, IEEE Journal on Selected Areas in Communications, under review.
[2] ICNIRP (International Commission on Non-Ionizing Radiation Protection), Guidelines for limiting exposure to time-varying electric, magnetic, & electromagnetic fields (up to 300 GHz), Health Phys, 1998.

About the Author

Meenupriya Swaminathan is a second year PhD student at Northeastern University. Her research focuses on designing, implementing and optimizing Body Sensor Networks. She currently holds a masters degree in computer engineering. She is an active member of Society of Women Engineers (SWE) and was a holder of Early Faculty Induction Fellowship from All India Council of Technical Education (AICTE).