Interfacing Biological and Wireless Systems

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Over the last decade, wireless communication networks have achieved many major successes and emerged as the key technology for enabling ubiquitous access to information. However, several challenges remain, energy-efficiency being one of the most notable. At the same time, biological systems are well known to be extremely energy efficient. From the brain that performs outstandingly complex tasks with only few tens of watts, to the ear that can carry the equivalent of a billion floating-point operations per second, biological systems are many orders of magnitude more efficient than our state of the art wireless systems. A natural, although clearly challenging, question is if we can build biologically- enabled wireless networks. This quantum leap in efficiency would be analogous to the improvements from Pascal's mechanical calculators to electronic digital computers. We argue that recent advances in bio-engineering technology, and synthetic-biology will dramatically expand the frontier of wireless communication research. An example of system that can benefit from such research is a wireless sensor network. Most wireless sensor nodes rely on a periodic wakeup to be paged for requests. This results in significant energy consumption and increased delay. A Bio-enabled Sensor Network composed of a nano-power sensing device that can go in a full sleep mode but can still be woken up using a fairly long-range RF signal could solve this problem. The idea is to transduce a weak Electro- Magnetic (EM) signal into biological signals and use a biological device to demodulate the information embedded in the original EM signal.

Nanoscale resonators exhibit resonance behavior involving the mechanical vibration of system elements. The natural frequencies of such resonances will, generally, be in the radio frequency range. Some of these systems will be coupled to the electromagnetic field by the charge distributions or by their magnetic moment they carry. In addition to communications networks and environmental sensors, applications to healthcare are medicine can be important as well.

Magnetic coupling in contrast to electric coupling, is not affected by strong attenuation, thus can penetrate deep in biological media and manipulate the targeted magnetic molecules inaccessible to electric signals with the same original energy. Due to many attractive characteristics, Magnetic nanoparticles (MNP), among various classes of magnetic materials, make an strong candidate for use in bio-devices. Small size in addition to the fact that they can easily be encapsulated in different protein coatings allow them to attach to virtually all receptors on the cell membrane without undesired consequences on receptors' functionality and cell's health. Most importantly, MNP can easily be manipulated by alternating EM fields (e.g. wireless signals) via thermal and mechanical effects. While thermal effects of EM exposure on MNPs are well understood and being used in medical procedures such as hyperthermia, details and validity of controlled mechanical interactions of EM fields and MNPs are yet to be fully understood. Mechanical manipulation of MNTs can be classified based on the use of magnetic Force or Torque. Since the dimensions of the MNP are often much smaller than wavelength of the EM signal, the gradient of the magnetic field along the body of the particle is negligible. Therefore, the torque mechanisms, which depend on the amplitude of the field instead of its gradient, are preferable.

New paradigms for solar energy conversion inspired by photosynthesis in leaves use non-radiative dipole- dipole coupling for direct transfer of energy also called Forster resonance energy transfer (FRET). Jean-Baptiste Perrin showed that energy could be transferred from an excited donor molecule to its neighbors through direct electrodynamic interactions. These near-field interactions would allow the donor to transfer of excitation energy without the emission of a real photon. Perrins model, however, was based on dye molecules with precisely defined oscillator frequencies, and it incorrectly predicted that energy transfer could occur over distances of up to the visible spectrum wavelength (~ 500 nm). In contrast to the earlier assumptions made by the Perrin, Forster observed that because the resonance between the oscillating dipoles is not perfect, the energy range of the energy transfer estimated by Perrin must be reduced by a factor of 100. This result is good agreement with experimental FRET observations with standard dyes. As a matter of fact a similar principle applied to the radio waves provides efficient wireless non-radiative energy transfer. WiTricity, based on resonant inducting coupling, demonstrates the transfer of high amount of energy (~ 60 W) over a distance of 2m at remarkably high efficiency (~ 40%). Although the size of the implemented system (coils of radius 40 cm) is a great deal larger than MNP dimensions, the theoretical analysis supports the possibility of similar resonant coupling in nano-scale. It is possible to couple an external resonator to an engineered nanocoil attached to a targeted receptor creating an exclusive and efficient channel of energy from outside to the biological system.

In conclusion, we argued that advances in biophysics and synthetic biology are opening a new frontier for wireless communication and molecular computation. These fields have been revolutionized with significant discoveries over the last few years. Remote control of cells and bio-organisms and the engineering of synthetic digital bio-devices are already a reality. Furthermore, networks of cells can be interconnected through AM/FM controlled waves of calcium ions. However, a comprehensive scientific framework for designing, and reasoning about wireless to bio/bio-synthetic links and networks is still lacking. Significant challenges have to be overcome to allow propagation, interfacing, robustness, and safety of bio- enabled wireless communication networks.