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Wireless Power Transfer for Wearable and Implantable Devices: a Review Focusing on the WPT4WID Research Project of National Relevance

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Abstract

In future health-care systems, wearable/implantable devices are foreseen as strong breakthroughs to allow patients home monitoring, enabling better life and more sustainable health care systems. Although electronics for implantable sensors are relatively mature, ensuring the energy to reliably operate with these devices is still missing. The Research Project of National Relevance (PRIN) WPT4WID (Wireless Power Transfer for Wearable and Implantable Devices) is focused on the development of innovative solutions for wireless power transfer applications. The research has specific concerns to the trustworthiness and medical compliance of the implementations, searching for the best trade-off among miniaturization, energy transfer efficiency, and safety. This main goal is achieved through a multidisciplinary approach able to efficiently model and characterize the devices and the wireless channel as a whole, for both near-field resonant and far-field radiative coupling mechanisms.

1 Introduction

Remote health control by means of small wearable or implantable devices is foreseen as one of the most urgent technology developments for the next incoming years, with a significant social and economic impact. It is expected to transform the health-care system worldwide, allowing patients, especially those with chronic diseases, to be continuously monitored and/or assisted at home, thus significantly enhancing the quality of their life and at the same time the sustainability of the whole healthcare system. Even though the electronic technologies for implantable devices and for “lab-on-a-chip” solutions are relatively mature and several demonstrative prototypes are available , a stable, secure, and safe approach to ensure the energy needed to operate the devices is not yet available. This project aims at developing innovative solutions to fill this gap, by studying, designing, implementing, and testing various physical-level configurations for transferring wirelessly on demand the electromagnetic (EM) energy sufficient to remotely sustain the wearable or implanted devices. This ambitious goal will be pursued by integrating all partners’ expertise in the field of wireless power transfer (WPT), EM characterization, dosimetry of human tissues and non-homogeneous radio channel modelling. Complementary coupling mechanisms for WPT will be considered, as described in Fig. 1, namely the near-field reactive (inductive) one, in the low-MHz frequency band, and the far-field radiative one in the millimeter (mm)-wave range. The latter has not been intensively studied so far for WPT applications, due to the inherent path losses, but it is currently under vast investigation as the future EM spectrum for the development of 5G communications .

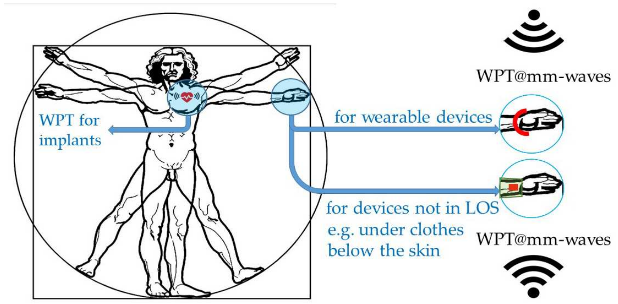

Figure 1. Different WPT mechanisms for energizing wearable and implantable devices: near-field coupling in the low MHz range for deep implants, and far-field radiative coupling for wearable or superficial implants in the microwave/mm-wave range.

The concurrent goal is to establish the best trade-off between system miniaturization and energy transfer efficiency. Differently from other application scenarios, an effective exploitation of WPT for wearable and implantable devices necessarily needs to include realistic EM characterization of the surrounding environment. In particular, the frequency-dispersive human tissues, having variable, non-homogeneous, and possibly anisotropic EM characteristics need to be included.

The research covers the design of the concurrent transmitter (TX) and receiver (RX) sides: at the TX side, conformal and reconfigurable coils and antennas are designed to optimize the focusing of the transmitted energy for various reference distances from the receiver. While in this case specifications on miniaturization are relaxed, the RX side is always designed as the best compromise between efficiency, orientation-independent operation, and miniaturization. An exhaustive contextualization of the proposed design needs to be carried out when dealing with wearable devices to account for the body (in particular the skin), and the presence of clothes or small objects. : This looks necessary not only for proper evaluation of link transfer efficiency but also to favorably exploit the channel for the transmitted power waveform in the scenario under test. To this aim, we investigate here the feasibility of WPT applications to effectively feed wearable and implantable devices in real scenarios. The outcomes will provide the assessment of the best frequency-power-dimension combinations of the specific WPT link, accounting for all the media involved.

2 Near-Field Resonant, Non-Resonant, and Far-Field Intentional WPT

In many WPT applications of reactive near-field (NF), the power is transferred by inductive (resonant or non-resonant) coupling between two or more coils [1]. Many factors affect the coil design: frequency, power, size, distance between TX and RX coils, electric and magnetic field (EMF) safety and EM compatibility (EMC) regulations. WPT systems can be used to recharge the battery of an active implantable medical device (AIMD), which is often characterized by a reduced lifetime: e.g., pacemakers require a surgery intervention to replace the battery on a 5+ year basis. To solve this problem, the inductive coupling is attractive to feed a deep implant because the biological tissues are highly penetrable by low frequency magnetic fields [2]. However, no commercial applications are available, mainly due to limitations on size and weight for the RX coil and difficult compatibility with pacemaker/relevant magnetic fields. One of the critical aspects, not yet defined, is a system approach to define the WPT frequency, especially for deep implants. Lower frequencies improve the magnetic field penetration in the human body but with non-optimal WPT performance, while higher frequencies could generate various issues, such as eddy currents, heating, etc. Several unlicensed frequencies are tested depending on power to be transferred, coils dimensions, implant depth and position. Goals are maximum PTE, defined as the ratio between the received power and the tissue absorption, or maximum inductive coupling. Main constraints are the ICNIRP basic restrictions (internal electric field for $f < 10$ MHz, SAR for $f > 100$ kHz).

Far-field (FF) WPT systems have been exploited for indoor or wearable applications [3], and their focus on biomedical implantable devices is recently increasing [4]. WPT in the FF allows longer transmission distances and a miniaturization of the RX antenna, due to the fact that the operating frequency in FF applications is usually higher than that used for reactive NF applications. Losses due to tissue absorption can lead to low power transmission efficiency (PTE), but several implants, as pacemakers, require low power [5]. Moreover, the miniaturization of the implantable antenna is a worthwhile compromise, ensuring the output power to be consistent with the safety guideline (< 2 W). RF-to-DC efficiencies of 40-50% are feasible for off-body applications with low RF power (-20 dBm). As for the rectifying section, the use of simple topologies is better for low-power applications [6], [7].

Systems operating at mm-waves allow for high data-rates as well as high cell-densification . In this respect, antennas showing excellent figures of directivity-bandwidth product per unit area or showing radiating features that adaptively reconfigure themselves according to the environment needs, represent a technological breakthrough. Moreover, radiators capable of energy focusing at mm-waves represent a future challenge. This project aims to realize wideband and reconfigurable mm-wave TX antennas in the FF and focusing systems in the radiative NF for WPT applications.

The design and realization of novel mm-wave TX devices, exploiting different radiation mechanisms (FF WPT or radiative NF WPT) is carried out to demonstrate agile pattern reconfigurability and NF focusing capabilities. EM Band-Gap (EBG) resonant cavity antennas (RCAs) are tested since they are cost-effective while providing moderate performance, but they only guarantee fixed-beam (non-reconfigurable) radiation [8].

In order to overcome this limitation, the flexibility of leaky-wave antennas (LWAs) is exploited for designing either reconfigurable radiators operating in conventional FF context [9] or efficient focusing devices operating in NF environment . In particular, pattern reconfigurability in the FF is achieved through tunable materials, while the focusing capability in the NF is achieved by generating diffraction-free beams through leaky waves.

The innovative features of the proposed systems lay on the possibility to continuously transmit power to different devices, even if they move: this is due to the reconfigurable properties of LWAs and the communication of the mobile RX positions to the fixed TX, the design of cost-effective TX antennas exploiting the advantages of EBG technology, and the possibility to focus energy in the radiative NF at mm-waves by means of diffraction-free beams.

3 Channel Models Integrable in the WPT Link Including the Presence of the Human Body and Phantom Developments of Human Tissues

Available ray-tracing (RT) models are currently used to predict propagation losses and wideband channel parameters as delay/angular spreads, including EM propagation effects, i.e., diffraction, transmission, scattering, etc.. In particular, diffuse scattering can be implemented adopting the Effective Roughness model [10], or other RT models available in the literature, tuned and parametrized for mm-waves. With reference to WPT systems for wearable antennas, possible unwanted targets would be small objects (e.g., buttons, buckles) that may introduce significant absorption of the WPT radiation. Therefore, an evaluation of the scattering has to be included into the prediction model. A possible solution for propagation modelling may be represented by the combination of traditional RT approaches with the full-wave scattering [11] from small objects close to the line-of-sight (LOS) path.

The propagation can be modeled with a hybrid model, where the link budget is evaluated through an RT approach, including the LOS path and multipath from the walls of the room, and through the scattering contribution by unwanted targets close to the LOS path, evaluated with a full-wave technique [11], [12]. Another solution may be represented by a full 3D RT tool, which embeds the diffuse scattering contribution from objects [10].

Possible targets are classified in terms of size, shape, physical properties, and TX/RX distance. Then, specific models based on full-wave techniques are developed to predict the scattering from the target, according to its shape. Analytical models are employed in the case of canonical targets, thus achieving high accuracy at low computational cost, whereas numerical techniques will be employed for targets with non-regular geometry.

When the target is in the NF of the TX and RX, scattering will be evaluated with a general RT approach. When the target is in the FF, the full-wave model can be used to evaluate the scattering properties of the selected objects to be embedded into the full 3D RT tool.

The modeling of the interaction of mm-waves with the anthropomorphic models will permit to evaluate the impact of the human body both in visibility and no-visibility conditions with the antenna. Moreover, such an approach will enable a dosimetric evaluation to verify compliance with protection guidelines. This will also drive the frequency selection and the concurrent design of the TX and RX sides for optimizing the penetration depth (for implantable devices) or the field distribution (for wearable devices), while complying with the safety standards.

Mm-wave frequencies are promising candidates for the future 5G networks and indoor communications. However, the absorbing properties of the human body due to the EM frequency dispersion of biological tissues have always prevented their use. Within this project, we plan to investigate this spectrum with a multi-phyiscs approach. This will be based on a three steps study: i)an extensive measurement campaign of the body tissues EM characteristics up to 50 GHz, ii) synthesis of their frequency-dispersive models; iii) use of such models in dosimetric simulations for the design of wearable or subcutaneous antennas: e.g., investigating scenarios where the antenna is under one or more layers of clothes, or even implanted below the skin

The research relies on literature data [13], [14], and on experimental data taken during recent measurement campaigns, where ~400 ex-vivo samples of human tissues were characterized up to 50 GHz. These results serve for the realization of phantoms: ex-vivo samples under controlled conditions in terms of humidity are adopted [15] to have a realistic approximation of the impact of the human body on the WPT system. Two complementary approaches are used: the development of in-house materials suitable for the 3D printing of complex geometries [16] and in-house mixtures suitable for the realization of simpler, less expensive geometries [17].

4 Conclusion

The outcomes of the presented project can be a breakthrough for the crucial role of implantable medical devices. Indeed, while the microelectronic technology is mature for providing real-time vital monitoring systems continuously operating, there are still no mature results to ensure sufficient energy to operate. The final outcome of the project is described by Fig. 2, i.e., to derive a set of rules to be followed for future WPT applications for wearable and implantable devices.

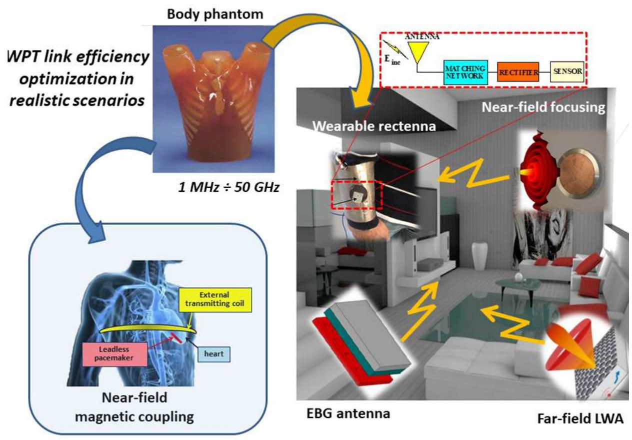

Figure 2. Envisioned scenario for the final outcomes of the WPT4WID project.

The link efficiency maximization is the main target for both the NF and the FF WPT links. This goal will be faced by means of a multidisciplinary approach consisting of simultaneously designing the TX and RX sides embedded in the actual harsh radio channel. In other words, the technology is not yet free from the energy storage system. Indeed, thanks to the low-power operation, electromagnetic energy, wirelessly transferred on demand, is foreseen as the most promising solution. The integrated approach proposed by the project is based on the design and test of different EM systems, using realistic environment models comprising indoor ambient, obstacles and human tissues. It is expected to provide accurate prediction of the energy transfer mechanism to to fill the gap of this technology . While inductively coupled systems have been developed, a general procedure based on the relationship among operating distance, frequency power and the channel involved is not available yet. Furthermore, the use of completely different approach based on the exploitation of the emerging mm-waves is a big technological challenge with few solutions yet available but is a very promising one due to the inherent miniaturization while preserving the efficiency of the wireless system. Furthermore, the selection of the most adequate technology for any target, from mm-waves to low frequency inductive coupling, taking always into account the presence of the human body which can significantly alter WPT and the always possible health effects.

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