European Contributions for Wireless Power Transfer Technology

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I. INTRODUCTION

In this paper recent European-based contributions for Wireless power transmission (WPT) are presented. The themes discussed within the paper are related to several applications spanning from future IoT and 5G systems, to high power electrical vehicles charging. The contributors to this paper are all members of a European Consortium on WPT, called COST IC1301.

Wireless power transmission is the driving technology that will enable the next batch of consumer electronics revolution, including battery-free sensors, passive RF identification (RFID), passive wireless sensors, Internet of Things (IoT), and machine-to-machine (M2M) solutions.

These new devices can be powered by harvesting energy from the surroundings, including electromagnetic energy, or by designing specially tailored beamed wireless energy to power them. In this respect, we can further separate the WPT beam in near field and in far field, where the near field implies normally inductive or capacitive coupling, and the far field implies radio frequency transmission. In Europe, a group of Universities, Research Institutes and Companies, has joined efforts to achieve advancements in this area. This consortium is called WiPE (Wireless Power Transmission for Sustainable Electronics) or COST Action IC1301, a European Union framework for break-through science and technology.

This paper is a summary of the most recent developments in the research by some of the members of this group. The paper is subdivided into three major groups of technology discussions: far-field (WPT) developments, near field developments and WPT applications.

Within the far field approaches, issues such as waveform analysis and modelling of RF-DC converters, propagation modelling and antennas specially tailored for WPT schemes are discussed.
For near field approaches, issues such as optimized design of WPT inductive links, modelling of these schemes, usage of electrical resonance for transferring power across non-negligible distances, and underwater WPT will be a topic of discussion.

Finally, several applications will be discussed, from integration of WPT in buildings, to the use of such systems in wireless sensor networks, embedding WPT schemes in car textiles and using RFID schemes for improved efficiency.

II. FAR FIELD DEPLOYMENTS

A. Waveform design for maximizing RF-DC conversion efficiency

The power transfer efficiency of wireless power transfer systems is one of the most important parameters for the practical application of the technology. The total efficiency of a WPT system can be defined as

$$\eta_T = \eta_{RF} \eta_L \eta_E$$  \hspace{1cm} (1)

where $\eta_{RF}$ is the DC-RF efficiency of the transmitter, $\eta_L$ is the wireless link efficiency, and $\eta_E$ is the RF-DC conversion efficiency of the receiver. The various contributions to the overall efficiency can be presented in more detail by considering the individual efficiencies corresponding to specific system blocks such as separating the receiver efficiency into receive antenna efficiency, rectifier efficiency and DC-DC converter circuitry efficiency contributions [1].

In an attempt to maximize the obtained efficiency, recent literature has investigated the effect of the transmitted signal waveforms on the RF-DC conversion efficiency of rectifier circuits [2], [3]. Initial results have shown that signals with peak-to-average-power (PAPR) ratio greater than 3 dB, which corresponds to the PAPR of a pure sine wave, may lead to a higher RF-DC conversion efficiency compared to continuous wave (CW) signals. The effect of different signals with a time-varying envelope on the RF-DC conversion efficiency has been investigated, such as chaotic waveforms [4] as well as various digitally modulated signals and white noise [5-8]. The results show that it is possible to obtain a better RF-DC conversion efficiency compared to CW signals using signals with a high PAPR. This can happen under certain average input signal power levels and under certain output load conditions [9]. Additionally, the complementary cumulative distribution function (CCDF) of a signal reveals detailed information about the number and frequency of occurrence of signal peaks relative to its average value, and signals with the same PAPR can lead to a different RF-DC conversion efficiency [9]. Depending on the application requirements which define a target input average power and output load, one may synthesize a signal waveform which maximizes the RF-DC conversion efficiency, such as the so called multisine signals [10]. These signals are composed of a sum of sinuswaves equally spaced in frequency by $\Delta f$ and usually $\Delta f \ll f_c$. It can be shown that if all the subcarriers are added in phase, the resultant time domain signal exhibits a high PAPR value that depends on the number of subcarriers and their spectral weight distribution. Another important aspect is that the envelope is a periodic signal with its period being inversely proportional to the frequency spacing ($\Delta f$). A small value for this $\Delta f$ is desired in order to increase the number of subcarriers in a limited bandwidth; however a small $\Delta f$ leads to a very long envelope period, decreasing the frequency at which the output filtering capacitor is refreshed. Thus, multisine signals should be carefully designed and must take into account receiver characteristics such as the low-pass filter time constant.

In order to increase the output filtering capacitor refresh rate, the work reported in [13-15] proposes a new type of multisine signal. By using subcarriers that are harmonically related ($\Delta f = f_0$), the envelope’s peak frequency will be as high as the first subcarrier frequency, reducing the constraints about the output low-pass filter time constant. Moreover, if the subcarriers are equally weighted and in phase, the time domain waveform is asymmetric with high positive peaks and low negative peaks. This asymmetric characteristic will boost the efficiency not only in low power environments due to its high PAPR, such as conventional multisines, but also in high power, when the diode is operating near its breakdown (Asymmetry reduces the peak-to-peak swing). Because of the harmonic relation between carriers, several intermodulation products generated by the rectifying process will contribute to a DC increase.

Another type of high PAPR waveform suitable for wireless power transmission is proposed in [14]. Following radar fundamentals, a linear frequency modulated signal known as chirp signal is considered. If an up-chirp is correlated with a down-chirp (Pulse Compression Technique), a pulse will be created and its high PAPR and occurrence can be controlled with the basic chirp bandwidth and frequency sweep time. The occurrence of the pulse should be carefully controlled to avoid a large ripple in the output, which in turn reduces the output DC voltage. Due to its very high PAPR nature, this kind of signal will drive the rectifying element into its breakdown zone for lower input power when compared with other excitations.

Fig. 1, presents some of these improvements when comparing several different waveforms.

![Figure 1 – Comparison of RF-DC conversion efficiency with different waveforms.](image)

Finally, we should emphasize that the absolute value of the RF-DC conversion efficiency strongly depends on the nonlinear device and circuit architecture characteristics of the rectifier, and it is possible to improve the obtained efficiency by combining wireless power transfer with other energy harvesting technologies such as mechanical [11] or thermal [12].


B. Modelling aspects of RF-DC conversion

After realizing the advantage of multi-sine excitation for wireless power transfer, it becomes necessary to understand the impact of various design parameters such as bandwidth or the number of tones. In [16] the multi-sine signal is represented as an AM modulated signal as (4), with bandwidth \( B \) (5),

\[
x(t) = A_m \cos(2\pi f_c t), \quad (4)
\]

\[
B = N_t \cdot \Delta f. \quad (5)
\]

Here \( f_c \) is the carrier frequency, \( A_m \) is the envelope of the signal, \( N_t \) represents the number of tones and \( \Delta f \) their frequency spacing.

Given this signal representation, the analytical radio frequency (RF) power conversion efficiency \( (PCE = \frac{v_{DC}}{R_{L}p_{in}}) \) is calculated by relating the bandwidth and envelope amplitudes to the output DC voltage \( V_{DC} \) for different signals by applying the following equation

\[
V_{DC} = \int_{0}^{N_t \cdot \Delta f} v_{out}(A_m) \cdot Pd f(A_m) \cdot dt \quad (6)
\]

\( Pd f(A_m) \) is the probability distribution function of the envelope amplitude as triggered by the multi-sines. \( V_{DC} \) as described in (6) is the average function of instantaneous output voltage \( v_{out} \) depending on different \( A_m \) reflecting the input power dependent performance of rectifiers.

The input signal to the rectifier \( x(t) \) is the multi-sine signal \( x(t) \) where parts of the signal are reflected due to circuit mismatches, which depend on the \( B \) of the input signal \( x(t) \). As a result, \( B \) and circuit mismatches also change \( Pd f(A_m) \). By studying the reflection coefficient \( S_{11} \) of the given rectifier, we can select the optimal bandwidth of the signal.

For the circuit used in this analysis, the optimal \( B \) is 2 MHz as shown in Fig. 2

Knowing that the number of tones \( N_t \) influences both the \( B \) and amplitude shape \( Pd f(A_m, t) \) of \( x(t) \), the optimal \( N_t \) can be determined using the mathematical model described above.

The analytical results are confirmed by measurements. The measurement configuration is shown in Fig. 3. Depending on the rectifier used in this experiment, the \( PCE \) of the multi-sine based wireless power transfer (WPT) system can be improved 25.1 \% compared to a continuous wave excitation WPT for -5 dBm input power in Fig. 4.

C. Link modelling and integrated antenna design strategies for ultra-wideband wireless power transfer

The Internet of Things (IoT) vision requires the deployment of vast amounts of wireless nodes that are invisibly integrated into their environment. Important challenges when designing such nodes include ensuring sufficient autonomy to guarantee reliable wireless communication over sustained periods of time, while avoiding interference with other devices. For compactness and eco-friendliness, the use of large batteries should be avoided and small energy buffers, such as supercapacitors, should be preferred. Therefore, the device should be able to continuously harvest energy from multiple sources available in its environment. Intentional wireless power transmission may supplement the powering process, or it may act as the only power supply in cases where all energy sources are scarce.

Interference issues and health risks associated with the transmission of RF power beams may be avoided by lowering the power spectral density. This is achieved by spreading out the radiated power over a large frequency band. Such a technique is already applied in ultra-wideband (UWB) communication, which is allowed by the US FCC in the 3.1–10.3 GHz frequency band, provided that the power spectral density remains smaller than \(-41.3 \text{ dBm/MHz} \) [17]. Similarly,
the European Commission has issued an EC decision allowing UWB devices to use the [3.4-4.8] GHz and the [6.0-8.5] GHz band with the same maximum power spectral density, provided that signals in the lower frequency band meet a low duty cycle restriction [18]. An important challenge to implement such UWB-WPT in an IoT setting is that wireless nodes will operate in a diverse range of deployment scenarios. In most of them, many objects will be present in close proximity of the receive antenna, causing potential antenna detuning and reduction in radiation efficiency. Moreover the WPT wireless channel will differ significantly from free space, as important shadowing and multipath fading effects may occur. Therefore, we have developed robust high-performance UWB antennas and a dedicated block model that describes all antenna and multipath propagation characteristics playing a role in the complete wireless power link. Both components enable the development and optimization of stable UWB WPT links, operating in all kinds of adverse deployment conditions. They enable optimal exploitation of the large bandwidth by designing suitable waveforms, and maximize wireless power transfer while still respecting the safety and health regulations.

Designing UWB antennas for the IoT paradigm is highly complex. Deployment conditions require antennas featuring a high antenna/environment isolation for stable radiation. A low profile, compact and adaptable geometry, which conforms to the environment, is needed for invisible integration. Such antenna topologies typically exhibit narrowband radiation characteristics. Recently, the implementation of substrate integrated waveguide (SIW) technology in novel antenna materials such as textile fabrics [19], paper and cork [20], has resulted in novel designs that reconcile all the above requirements. By confining the electromagnetic fields by rows of vias, components operate in isolation from their environment, yielding a performance almost as stable as in waveguide components [21]. For cavity-backed SIW slot antennas, such as the antenna array shown in Fig. 3, only the slot radiates, enabling the deployment of active circuitry directly underneath and energy harvesters on top of the cavity [22]. The complete antenna area may thus be reused, apart from the radiating slot. Ultra-wideband operation is implemented by exciting multiple cavity modes at carefully selected frequencies within the operational bandwidth. Moreover, the antenna may be miniaturized by exploiting half-mode and quarter-mode principles.

Besides using a suitably designed antenna, the optimization of the wireless power transfer channel requires that the wireless channel characteristics and the deployment characteristics of the antennas are fully taken into account. Indeed, multipath propagation will affect the power transfer, causing fading and shadowing effects as experienced in conventional communication channels. Furthermore, objects in direct proximity, being in the reactive near field, of the transmit and/or receive antennas will modify the channel’s power transfer characteristics. Therefore, they should also be included in a global WPT model applied to optimize the power transfer. As a computer-aided-engineering tool for UWB-WPT system designers, we have developed a modelling framework [23] for wireless power transmission over ultra-wideband links in multipath propagation environments. Although the concatenated black-box model is specifically implemented for WPT in the vicinity of the human body, the framework may also be successfully applied to other typical IoT configurations. The modularity of the model makes it easy to replace the measured or simulated black-box descriptions of the antennas and the channel by those that are pertinent to the setup at hand. Proximity effects caused by objects in the reactive near-field of the antenna may easily be accounted for by incorporating the embedded active element antenna pattern and the detuned antenna impedance in the black-box description of the antenna under study. For the application of this model to body-centric WPT, we refer to [24]. By relying on a fast-multipole-based expansion of the channel [24], the Friis-based path loss black box may be extended such that the channel model also applies to the radiative near field.

![Ultra-wideband substrate-integrated waveguide textile antenna array for wireless power transfer](image)

**Figure 5 – Ultra-wideband substrate-integrated waveguide textile antenna array for wireless power transfer**

**D. Miniature, efficient rectennas with integrated power-management for battery replacement**

Using a small rectenna and thus a small receiving antenna will result in a small DC output voltage. Therefore a circuit is needed for boosting this voltage up to the desired voltage. This circuit needs to be powered by the low-voltage, low-power DC signal available. For our prototype we have chosen to use the Texas Instruments TI BQ25570 Ultra Low Power Harvester Power Management IC [25]. The converter can cold start from 0.33 V DC and after this cold start can continue on 0.10 V DC. The output DC voltage can be chosen between 1.3 V and 4.0 V, using the internal buck converter.

The circuit has been tested by connecting a voltage doubling rectifier [26] to a signal generator, using a lumped-element LC impedance matching network in between the two. The output of the power management IC is dynamically loaded, using an array of load resistors. These load resistors are connected to switch-operating FETs. These switches are (time-) controlled using an Arduino Mega Board [27] with Atmega2560 Atmel micro-controller. The test-system is shown in Fig. 6.
Figure 6 – Rectenna test circuit. The antenna is replaced by a signal generator. Energy is stored in capacitor $C_{\text{STOR}}$. The circuit is designed for and tested at 868 MHz.

In Fig. 6, $\eta_r$ is the RF-to-DC Power Conversion Efficiency (PCE) of the rectifier circuit with matching network, $\eta_b$ is the overall efficiency, $\eta_{b1}$ is the RF-to-DC PCE of the rectifier with matching circuit combined with the boost converter and is given in [28]. The boost converter PCE $\eta_b$ and buck converter PCE $\eta_{b2}$ can be found from the earlier defined PCE’s [28].

For a constant on-time $t_{\text{on}}$ and a constant load resistance, the maximum values of $\eta_r$, $\eta_b$, $\eta_{b1}$, $\eta_b$ and $\eta_{b2}$ are obtained at 868 MHz for different RF input power levels by varying the off-time $t_{\text{off}}$, see Fig. 2. The results are shown in Fig. 7.

Figure 7 – Time diagram of drawing DC power from the circuit shown in Fig. 1. $T$ is the period. During $t_{\text{on}}$, a DC power $P_{\text{out}}$ is drawn. During $t_{\text{off}}$ no power is drawn.

Figure 8 – Maximum Power Conversion Efficiencies as a function of RF input power level for the setup shown in Fig. 6.

Using the Friis equation, an assumed 3W EIRP at 868 MHz and the results shown in Fig. 8, the average obtained DC power has been calculated as a function of distance for two receive antennas (1 and 6.1 dBi gain). The results are shown in Fig. 9.

Figure 9 – Average obtained DC power vs. free line of sight distance for two antennas. The solid lines represent the results for the circuit described in this paper. The dashed lines represent the results for a commercially available radiative WPT system tested for the same EIRP but for a frequency of 915 MHz.

From Fig. 7 and Fig. 9 we can conclude that with a 6.1dBi receive antenna we can get 30µW continuous DC power up to 10 m distance or 60 mW during 40 ms every 2 minutes up to the same distance.

For a prototype, a 2dBi miniaturized 915 MHz antenna [29], complex conjugately matched to the rectifier has been combined with the TI BQ22570 IC, resulting in a 10cm x 6cm wireless battery as shown in Fig. 10.

E. Compact microwave rectenna for satellite health monitoring

In order to provide reliable and high bit rate broadcasting links, high gain microwave antennas are used on broadcasting satellites. These antennas are located on panels positioned on the external surfaces of the satellite and are subject to spill-over losses. In some areas of the antenna panels, the electric field generated by the spill-over losses of microwave antennas may reach the following maximum levels (effective values) [30]: 40 V/m in C-band, 49.5 V/m in X-band, 106 V/m in Ku-band and 127 V/m in K-band. These E-field levels are unusual for
terrestrial applications, but they can occur on satellites when data links are functional. These (residual) electromagnetic fields can be harvested in order to power autonomous wireless sensors for structural health monitoring of the satellite. The radiated power of microwave antennas is almost constant and consequently the DC power regulatory circuits should be minimal for such harvesting systems. In order to demonstrate the proof-of-concept and the feasibility of such harvesters, several rectennas were developed by the research group at CNRS-LAAS Toulouse [31] in the framework of research grants funded by CNES (French Space Agency). The goal was to develop high-efficiency and compact rectennas providing DC power in the range of the mW. Based on innovative antenna topologies (CDA: Cross Dipole Antenna and CDAA: Cross Dipole Antenna Array) we recently proposed compact coplanar stripline-supported rectennas. Fig. 11 shows the CDA rectenna topology while the CDAA rectenna is given in Fig. 12. CDA rectennas use only the top side of the PCB. In the case of CDAA the antenna and the diode are located on the top side of the PCB while the shorting RF capacitor and the load are located on the bottom side. The conjugate matching condition (between antenna and the rectifier) is achieved without the use of a dedicated matching circuit but by properly controlling the input impedance of the antenna (CDA or CDAA) and the input impedance of the rectifier. A reflector plane, positioned below the rectennas at approximately quarter wavelength distance is used to increase the antenna gain and consequently to improve the overall performances of the CDA and CDAA rectennas.

![Figure 11 – Top view of the CDA rectenna and a photo of the manufactured prototype (inset).](image1)

The efficiency $\eta$ (in %) of the rectenna can be computed by using the following definition [32]:

$$\eta_1 = \frac{P_{DC}}{S \cdot A_G} \cdot 100$$

(7)

$$\eta_2 = \frac{P_{DC}}{S \cdot A_{eff}} \cdot 100 = \frac{4 \pi P_{DC}}{S \cdot G_R \cdot \lambda^2} \cdot 100$$

(8)

where $P_{DC}$ is the harvested DC power, $S$ is the incident electromagnetic power density, $A_G$ denotes the area of the radiating surface, $A_{eff}$ is the antenna effective area, $G_R$ is the gain of the antenna and $\lambda$ is the wavelength of the illuminating electromagnetic wave. The efficiency $\eta_1$ can be viewed as a ‘worst-case’ definition because $A_{eff} \leq A_G$ for passive antennas.

Experimental results [33] show that 1.15 mW of DC power can be harvested in Ku-band (14.7 GHz) by using a compact CDA rectenna illuminated by an electric field of 60 V/m ($S \sim 955 \, \mu\text{W/cm}^2$). This ultra-compact Ku-band CDA rectenna (2.5 cm$^2$ or 0.6 square wavelength) exhibits a conversion efficiency of $\eta_1 = 48\%$ ($\eta_2 = 66\%$). A low-cost silicon Schottky diode (SMS201 from Aeroflex/Metelics) in a molded plastic (DFN) package was used for this design. A manufactured K-band (18.8 GHz) CDA rectenna (using an AsGa Schottky diode MZBD-9161 from Aeroflex/Metelics) [30] demonstrated that a DC power of 1.28 mW can be harvested when an electric field of 91 V/m ($S \sim 2.2 \, \text{mW/cm}^2$) illuminates the rectenna. The efficiency of this CDA rectenna is $\eta_1 = 48\%$. We note that CDA and CDAA rectenna topologies can be easily adapted for other operating frequencies. The experimental results obtained with these rectennas demonstrate that implementing autonomous wireless sensor can be a feasible solution for the structural health monitoring of satellite antenna panels.

F. Design and optimization of phased arrays for long-range WPT

The design of phased array antennas is a key issue in order to guarantee high efficiency, reliable, and cost-effective deployments for long-range WPT systems [34]. Unlike in communications and radar applications, the goal of a WPT system is the maximization of the end-to-end power transfer efficiency. Therefore, unconventional constraints, and consequently design methodologies, need to be taken into account. As for long-range WPT systems, this means that the transmitting array is required to focus the power within a narrow angular sector towards the receiving station/s. On the other hand, the receiving (i.e., rectenna) array must be able to convert the largest amount of radio-frequency impinging power. In this framework, several researches have been carried out over the last few years thanks to the growing importance of this area boosted by the diffusion of electrical autonomous systems (e.g., drones, cars, high altitude platforms) and the renewed interest towards the very challenging and fascinating application of the Space-Based Solar Power (SBSP) aimed at guaranteeing a continuous feeding of the Earth with renewable...
and clean energy [35]. Novel methodologies for the design of arrays for long-range WPT and the optimization of their degrees of freedom (DoFs) have been introduced aimed at:

(i) defining the best array configurations (e.g., positions and excitation weights of the array elements) such to maximize the beam collection efficiency (BCE), namely the ratio between the power transmitted towards the receiving/target area and the total radiated power, in case of transmitting arrays or the efficiency of the microwave power collection for rectenna arrays.

(ii) synthesizing simplified array architectures for reducing the antenna complexity and costs as well as simplifying the HW/SW implementation.

As for the optimal design of transmitting planar phased arrays, a strategy for synthesizing the optimal tapering of the amplitude weights guaranteeing the maximum BCE performance in case of arbitrary transmitting planar apertures and target areas has been proposed in [36]. The approach, based on the solution of a generalized eigenvalue problem by means of a deterministic method, has allowed study of the theoretical limits of the power transmission efficiency of WPT planar phased arrays. Useful guidelines on the design of the transmitting array configuration have been reported in order to achieve high values of BCE close to 100%, whatever the shape of the transmitter and/or the receiving area. As a representative example, Fig. 13(a) shows the power pattern generated by a planar array of 20x20 elements whose excitation amplitudes have been synthesized by means of the method described in [36] and achieving a BCE performance of 99.96%.

![Power pattern and distribution of amplitude weighting coefficients](image)

Figure 13 – Power pattern (a) and distribution of the amplitude weighting coefficients (b) of an optimal Slepian planar array.

The activities on receiving antennas for long-range WPT have been focused on the study and definition of innovative rectenna arrays for SBSP systems to be used in the ground station. Starting from the key observation that the DC currents at the output of the rectifying circuitry used for each individual element or cluster of elements have no phase term and consequently their coherent sum is not needed, the position of the elements have been properly optimized in order to avoid super-positions and shadowing effects that would reduce the end-to-end WPT efficiency [37]. Moreover, because a portion of the microwave power arriving on the rectenna array is unavoidably backscattered, the DoFs of the element positions have been defined such that the re-radiated field is focused towards a mirror which can re-direct the power towards the rectenna array [37].

Innovative array architectures for reducing the complexity and weight of the transmitting arrays have been studied as well. Two strategies have been investigated, namely the clustering of the elements into sub-arrays in order to reduce the number of amplifiers and phase shifters/delay units, and the use of irregular (e.g. sparse) array layouts in order to minimize the number of radiating elements [38]. The optimization of the DoFs of the arrays has been carried out by means of ad-hoc design methodologies. As for clustered arrays, an excitation matching approach based on the Contiguous Partition Method (CPM) [39] has been exploited in order to define the clustering configuration and the sub-array excitations so as to obtain a pattern as close as possible to the one having optimal BCE [36]. The availability of the optimal excitations has enabled, through the CPM, the effective synthesis of very large phased arrays, unfeasible when using classical design methods. The design of sparse planar arrays matching a desired reference pattern has been addressed by means of an innovative synthesis method based on the Bayesian Compressive Sensing (BCS) [40]. The key advantage of the BCS methodology is that it allows light transmitting arrays with a minimum number of elements. The preliminary results have shown that BCS-designed array configurations with a 35% reduction of the total number of elements guarantee to afford a BCE-optimal power pattern by considering the same antenna aperture. Further studies in this area of research will consider the design of arrays with more complex geometries (e.g., conformal) as well as the use of simpler feeding networks characterized for example by isophoric (i.e., uniform) amplitude weights.

G. Far-field Channel Modeling for WPT Systems

It is frequently the case that well-designed, efficient WPT systems fail in the application field, because of undesired effects, caused by the propagation-channel. The power-limitations of WPTS, imposed by the turn-on voltage of the front-end diodes, require careful field-installations and good prediction of the channel, so that most of the available RF power will be harvested. Far-field WPTS are found at frequencies starting from 100MHz up to several GHz, with the most common application-field, being passive UHF RFID technology around 900MHz.

The necessary minimum input power (~ -20dBm) for the operation of battery-less devices, imposes specific limitations in the associated propagation channel. Unobstructed Line-Of-
Sight (LOS) conditions between the transmitter and the passive device must exist. The transmitted electromagnetic signal reaches the receiver from other paths after interacting with the environment (scattering, reflections, diffractions, etc.) and interacts with the strong LOS contribution constructively or destructively depending on the phase of each multipath component. This process creates fading, which varies in time depending on the variability of the propagation environment. Careful modeling of the environment, and the transmit-receive system is necessary, including the radiation patterns and polarizations of the antennas, the geometrical and electromagnetic characteristics of the surrounding environment. Simplified path-loss models, not accounting for fading, should be avoided. Suitable candidates for WPT channel modeling are i) analytical ray-tracing models, ii) computational electromagnetic models and iii) probabilistic models.

In [41], [42], an analytical ray-tracing model is developed, in order to analyze the fading patterns in typical indoor WPT application-areas. Methods to improve the performance of passive UHF RFID systems are proposed. For instance, it is shown that by deploying two transmit-antennas illuminating the same region and connecting a 180° phase-shifter in one of them, one can eliminate “holes” (destructive interference patterns) inside the area of interest by changing the phase of one of the antenna in a sequential manner, boosting the performance of WPT systems. Furthermore, multi-antenna configurations are analyzed and could be used when minima of the field are desired in specific locations, e.g. above the bed of a patient.

Ray-tracing propagation modeling delivers accurate predictions, provided that the actual environment is exactly as modeled. However, this is not possible for the majority of applications, where walls and furniture are incorrectly modeled (geometrically or/and electromagnetically). Furthermore, such models output a static screenshot of the field, with maxima and minima at fixed locations, implying that the field-pattern will remain unchanged, and do not accommodate the reality of the fast changing environment. Finally, even though they are much faster than computational electromagnetic models (CEMs), ray-tracing are still very-slow to handle problems of automated planning (deployment) of WPT networks. Clearly, CEMs suffer from all the aforementioned disadvantages plus they require vast amounts of memory and time. Nevertheless, CEMs provide the most accurate estimations for problems with known geometry in well-defined spaces, e.g. the field of a shelf-antenna inside a library [43].

To overcome, these limitations a fast site-specific probabilistic model was developed exploiting the particularities of WPTs, due to the power constraints of the system, while carefully considering all significant propagation factors that affect the accuracy of the estimations [44]. The probability that the power is above a specified threshold is derived for any antenna and for any polarization axis. The model overcomes the limitation of delivering an unrealistic stationary output field. In fact, it cannot predict the location of a minimum or a maximum. However, it can evaluate the probability that such an event might happen.

The model exploits the existence of a strong power component in WPT systems and models the reception level by a Rician probability density function:

$$f(x|\nu, \sigma) = \frac{x}{\sigma^2} e^{-\frac{(x^2+\nu^2)}{2\sigma^2}} I_0\left(\frac{x\nu}{\sigma^2}\right),$$

where $\nu^2$ is the power of the LOS strong component and $2\sigma^2$ is the mean power of the other contributions. Therefore, by calculating the above two parameters at each location inside the area of interest, one can estimate the probability that the reception magnitude $x$ is greater than a given threshold $\gamma$, e.g. see Fig. 14. Furthermore, in [44], all multiply reflected rays initially bouncing on the same obstacles are clustered in a single “super-ray”. Then the contribution of this super-ray is approximated by a closed form equation; the key to derive the equation is to treat the phases of each ray within the cluster as random variables, identically and uniformly distributed over [0-2\pi]. The success of the model is that the output probability carefully considers the radiation patterns, the polarization of the involved antennas and the geometry and electromagnetic properties of the surrounding environment, similarly to an analytical ray-tracing model. The key assumptions of the model are validated against ray-tracing and measurements in [45]. The probabilistic model is compared to a FDTD model in [46] and with additional measurements. A realistic model of the environment is inserted in the CEM model (Fig. 15), including all furniture and measurements were conducted in the same area. Both models demonstrated similar performance in terms of accuracy; in fact the probabilistic model was slightly better (1.7% RMS error vs. 3.6% of the CEM model) (Fig. 16). The simulation-time was 135h for the CEM model in an advanced workstation and less than a minute for the probabilistic model running on a laptop. Finally, the proposed model is exploited in a deployment problem in a large area and is combined with a Particle Swarm Optimization method to deliver a deployment-solution satisfying specific constraints [47].
III. NEAR FIELD DEPLOYMENTS

A. Simultaneous wireless power transfer and Near-field communication

1) Theoretical and Numerical Contributions

To realize mid-range magnetic resonant Wireless Power Transfer (MRWPT) systems, the efficiency of the system was optimized by numerical electromagnetic modeling [48]-[50]. In [48], a MRWPT system consisting of electrically and magnetically coupled spiral resonators and loop inductances was presented. In [48] and [49], the experiment reported in [50] has been reproduced by using a full-wave simulation. An approach considering the WPT link as a two-port network has been used. In [49], a theoretical investigation has been performed in order to find, for a given WPT link, the load values that maximize either efficiency or the power on the load. In [51], a unified approach has been proposed for energy harvesting and WPT. In [52], we presented the rigorous network modeling of several concepts for realizing efficient magnetic-resonant wireless power transfer (MRWPT). We implemented the ideally required 1:n transformer by using immittance inverters. We derived series and parallel matching topologies for maximum wireless power transfer [53].

2) Inductive Power Transfer for Electrical Vehicles (EVs)

The possibility of using inductive power transfer for EVs has been considered in [54]-[57]. This moving field inductive power transfer (MFIPT) system for supplying power to electric vehicles while driving along the route uses primary coils arranged below the pavement for transmitting the energy via an alternating magnetic field to a secondary coil located at the vehicle below its floor (see Fig. 17). To minimize losses only the primary coils located below the secondary coil of a vehicle are excited. The operation principle of MFIPT system is based on a resonantly operated switched DC to DC converter converting the DC power supplied by the stationary power line to DC power delivered to the moving electric vehicle.

Contactless power supply of EVs on highways allows low battery capacities since the batteries are required only in local traffic and on side roads where no moving field inductive power transfer system would be installed.

3) Inductive Power Transfer for Implantable Medical Devices (IMDs)

The use of a wireless resonant energy link for energizing modern IMDS has been suggested in [58]-[61]. In more detail, a WPT link for powering pacemakers has been presented in [59]. The proposed system consists of two inductively coupled planar resonators, and has been optimized for operation in the MedRadio Service core band centered at 403 MHz. The implantable receiver is a compact square split ring resonator (see in Fig. 18a), while the transmitter is a spiral loop loaded by a lumped capacitor (see the inset of Fig. 18b). The performance of the WPT link was experimentally investigated by using the setup illustrated in Fig. 18b; a minced pork was used to simulate the presence of human tissues. The measured 2-port scattering parameters are illustrated in Fig. 18c; from experimental tests, a power transfer efficiency of 5.24 % is demonstrated at a distance of 10 mm.

4) Frequency Agile Systems for Near Field Deployments

Near field WPT can be operated either at a fixed frequency, as considered in [49] (and in this case the optimal load value is dependent on the coupling) or with an agile frequency. In fact, when the coupling is changed, by appropriately changing the operating frequency, we can obtain higher power values on the load. The latter operating principle has been considered in [62], [63] where a Royer oscillator has been used.
B. Design of non-standard inductive wireless power configurations and the potential applications

Recent advances in battery and super capacitor technology, and the further miniaturization of embedded hardware have enabled the integration of inductive wireless power transfer in contemporary smart electronic devices [64]. At the same time, a number of industrial standardization actions and regulations have been established: the Qi-standard of the wireless power consortium is defined [65], while the Power Matters Alliance merged with the Alliance for Wireless Power [66]. The name of this new alliance will be published later this year. The current state-of-the-art for consumer electronics is oriented towards low power transfer (i.e., up to 15 W) and a well-defined alignment of the receiving structure with regard to the transmitting coil for a certain amount of time in inductive coupled systems.

Due to the nature of the principle of wireless inductive power transfer, it is possible to realize configurations with on-the-fly energizing moving receivers and situations with random separations and orientations between the receiver and transmitter. However, these require further research towards an optimal design. As a representative example for moving receivers, the research group DraMCo of the KU Leuven (Belgium) has investigated the inductive charging of a wireless mouse [67] of type M705 from Logitech [68], which is normally powered by two AA batteries. The available amount of space for the receiver circuitry, receiver coil, and super capacitors, was created by removing the two AA batteries. Careful design led to a solution that functions autonomously for more than 15 minutes, while the full charging takes only 10 seconds. The required time to activate the transmitter to the high power mode is only 50 ms. Strategic placement of the transmitting structure led to an autonomous system, where the regular replacement of batteries is not needed anymore.

Another example is the realization of a through-display wireless charging solution for a medical wristband [69], shown in Fig. 19. This device was developed for use by medical staff in maternity hospitals. It performs measurements of the body temperature, bilirubin levels and oxygen saturation of newborn babies in only 1.25 seconds by means of self-designed measurement techniques. Ease of use was a key factor in the design, resulting in a device without controls. It relies on a super capacitor energy buffer, which can be charged wirelessly in less than 5 seconds by touching a transmitting unit. Through-display powering was realized by placing the receiver coil behind the display. Also an energy study was carried out, revealing that a full buffer provides enough energy for 38 parameter measurements or more than 3 days of standby time. After each measurement, the device automatically transmits the data wirelessly to a computer. The miniaturized device consists of 7 PCB’s and contains solely Texas Instruments (TI) ICs (17 pieces). It is equipped with a Qi receiver, a super capacitor charger, 3 power supplies, and a state-of-the-art ferroelectric random access memory (FRAM) microcontroller that controls the sensors, the display, the wireless transmitter and even its own power supplies. This solution of KU Leuven was the winner of the Texas Instruments Analog Design Contest Europe 2014, among 299 submitted projects. Fig. 19 shows the developed device.

Other currently running research projects include wireless power transfer for the IoT for animals, more specifically for the energy provision of wireless sensor networks to monitor the health of dairy cows. KU Leuven and Ghent University recently started a project on the construction of a wireless sensor network to have real-time information on the health status of each individual cow as a member of a large stock, both in- and outdoor. The contemporary solutions for this kind of configuration consist of on-board battery powered hardware [70]. Regular replacement of the battery hinders the widespread application of this wireless solution. The goal of the project is to make use of specific and regular time slots (e.g., drinking of the animal) to wirelessly charge a super capacitor that is integrated in a small collar attached box. This will thus lead to a maintenance-free technology. The stored energy on the super capacitors can then be used for longer haul wireless communications and the powering of the wireless body sensor network of the animal. Aspects such as the distance between the drinking troughs, the time the animal typically needs to drink, and the energy consumption during autonomous operation determine the design space for this inductive wireless power solution. This work is supported by the iMinds-MoniCow project, co-funded by iMinds, a research institute founded by...
the Flemish Government in 2004, and the involved companies and institutions.

C. Implantable Inductively Powered UHF RFID Tag

This work is focused on development of a system for a human body implant with an UHF RFID tag powered by inductive wireless power transfer (IWPT). This section provides a short overview of the system design. More details about the design can be found in [71a].

A classical RFID tag is usually passive and its operation is enabled by power received from an RFID reader during communication [71]. However, in the case of the implantable tag, the power emitted by the reader at 866 MHz the UHF frequency band is dissipated in the human body tissue. This leads to decrease of sensitivity of the tag for communication with increasing thickness of tissue between the reader and the tag due to insufficient level of power for tag operation. The problem can be overcome with the help of a tag using a semi-active chip. Powering of this kind of chip can be assured not only by the reader but also by an additional source. The additional source delivering power by IWPT [72] at 6.78 MHz in the ISM frequency band is considered in this case.

Fig. 20. (a) and (b) show mutual arrangement and scheme of the side of the reader and the side of the tag respectively. Elements for RFID communication and powering through IWPT on the side of the reader are designed as a center-excised Archimedes spiral antenna and a circular loop respectively, see Fig. 21. (a). These elements on the side of the tag are represented by a folded dipole antenna and a rectangular loop, see Fig. 21. (b). Additional circuits are connected between powering pins of the RFID chip of the tag and the rectangular loop, or to the circular loop in order to assure efficient powering.

The structure of the reader side is designed to be placed on the surface of the human body. The structure of the tag side is compact and suitable for implantation into the human body. Communication sensitivity of the tag is increased by 21 dB with the help of IWPT.

D. WPT Underwater

The employment of sensors within underwater environments is today a standard practice in several fields of activity, namely environmental monitoring, aimed at collecting data on water or seabed parameters as well as for the inspection of permanent subsea infrastructures. These sensors may be located in fixed or mobile structures. Sensors deployed on permanent subsea structures or on the seabed generally lack cabled connections, and therefore rely on batteries. Approaching these sensors with Autonomous Underwater Vehicles (AUVs) for replenishing their batteries and recovering measurement data is very appealing. However, presently, the most common solution involves the operation of remotely operated vehicles (ROVs), which is very expensive since a support vessel is required, and therefore can only be considered for small-scale operations. On the other hand, sensors may be carried by mobile underwater vehicles such as ROVs or AUVs for underwater sensing in
specific missions. In fact, the employment of AUVs is an emerging practice, potentially suitable for large-scale autonomous operation [72][80]. Fig. 22 below shows the MARES AUV, which is a highly flexible small-scale AUV developed at INESC TEC, that can operate at a maximum depth of 100 m and can be configured to carry specific prototypes and logging systems for experimental evaluation [73].

Figure 22 – Picture of the MARES AUV, developed at INESC TEC.

The use of AUVs is limited by the duration of their energy source charge. Therefore, there is a need for an energy solution that can support the operation of a number of AUVs within underwater environments for long periods of time. Currently available AUV recharging solutions are very complex, typically requiring “wet mate” connectors [74], which are prone to failure and require frequent maintenance and/or too complex docking mechanisms. As such, these solutions are not appropriate for scaling-up due to the high costs, and therefore their usage has been limited. The research on techniques for underwater wireless power transfer has been increasing in the past few years, targeting not only the battery charging of AUVs but also wireless powering of underwater sensors.

Witricity released a white paper in 2013 [75] demonstrating the possibility of using resonant magnetic coupling (RMC) through salt water. The authors transferred power across a plastic container filled with water and used a halogen lamp as a load. The authors conclude that a significant power level (up to several kW) may be transferred across a gap of 15 cm with a wireless transfer efficiency in the order of 80%. Inductive coupling is currently the alternative to wet-mate connectors most often seen in the literature. For instance, in [76] the authors describe an underwater wireless power transfer system based on inductive coupling. The efficiency and power transfer capability reported are very good, 90% and 400 W, respectively. However, the operating distance is extremely small, 2 mm. This means that there is no margin for error in terms of alignment in the AUV charging scenario. This is also the reason why in these cases some kind of mechanical stabilization is usually required. For instance, in [77] the charging station is outfitted with cones. In [78] an underwater WPT system is reported with wireless transfer efficiency of 60% across a gap of 10 cm, using an antenna with a size of 25 cm x 25 cm. The authors state that the energy flow in seawater is guided by eddy currents caused by the magnetic field, although the power level is not mentioned. A novel WPT technique that considers the coupling through the electric field rather than from the magnetic field is resonant electric coupling (REC), which was independently proposed by [79] and [80] in 2014. However, the employment of REC for underwater WPT has not been reported yet.

In the following we present results from an underwater WPT system evaluation using 3D electromagnetic simulation. As shown in Fig. 23, we consider two different architectures, namely a coil- and a spiral-based copper inductor setup, both having a maximum diameter of 16 cm, and 3 mm of copper thickness. In both cases, a parallel capacitor was included to achieve anti-resonance at around 100 kHz, where the system operates optimally using 50-ohm impedance at both transmitter and load sides.

Seawater was considered as the transfer medium (permittivity of 81 and conductivity of 4 S/m), while the Tx/Rx where kept within a box filled with distilled water to avoid resonance losses. A third configuration based on parallel plates was evaluated to assess the viability of the REC principle for underwater WPT. However, the conductivity of the transfer medium was observed to reduce dramatically the efficiency of the method, rendering it useless even at very short range.

Figure 23 – Underwater WPT simulation models considering (a) Coil based inductor and (b) Spiral based inductor.

The simulated efficiency as a function of the seawater gap is presented in Fig. 23. It can be seen that the efficiency remains approximately constant in the over-coupled region, up to 8 cm and 13 cm, for the coil and spiral based inductors, respectively. Efficiency falls rapidly after that point, corresponding to the under-coupled region. Depending on the requirements of the problem at hand, any of the solutions may be attractive. In conclusion underwater WPT using magnetic resonance appears to be a promising solution to transfer power to underwater equipment.

Figure 24 – Efficiency versus seawater gap for both configurations
E. Usage of resonant electrical coupling in WPT

The wireless transfer of power based on electrical resonance briefly mentioned in the previous sub-section is based on the circuit model shown in figure 25. In this circuit, power is wirelessly transferred from the source (on the left) to the load (on the right), through the capacitances C3 and C4. The resonances at the transmitter and the receiver are defined by L1 and C1, and by L2 and C2, respectively. As shown in [81], a very reasonable efficiency can be achieved with very low values of C3 and C4, as long as the losses, represented by R1 and R2, are kept low. This is similar to resonant magnetic coupling in the sense that very reasonable efficiencies can also be achieved with very low magnetic coupling coefficients, if the losses are kept low. Low values of C3 and C4 and low magnetic coupling coefficients are extremely important to the increase of spatial freedom. Spatial freedom is currently one of the most desirable properties in WPT.

An implementation of the previously mentioned circuit, consisting of two identical devices, is shown in figure 26. Each device measures approximately 16 cm by 16 cm by 3.6 cm and is composed by a coil and two conductive plates of identical areas. The capacitances C1 and C2 are implemented by the close proximity of the conductive plates in each device. Figure 27 shows the voltage measured at the terminals of a 680 Ohm load connected to the output of an RF-to-DC converter. As shown in figure 26, the RF-to-DC converter is connected to one of the devices, with the other device connected to a signal generator. At this point, experimental peak efficiencies of 61% and 38% can be obtained at distances of 12 cm and 30 cm, respectively.

Figure 27 - Measured voltage as a function of frequency for distances equal to 12 (curve 1), 16, 20, 24 and 30 cm (curve 5), considering a transmitted power of 16 dBm.

It is also possible to observe a relatively low variation of peak voltage in the case of a rotational misalignment, in particular when the receiver is perpendicular to the transmitter, as shown in figure 28. However, it is important to mention that this behavior is most likely caused by the constructive combination of resonant electrical coupling and resonant magnetic coupling addressed in [82], rather than resonant electrical coupling alone.

Figure 28 - Measured voltage as a function of frequency for angles equal to -90 (curve 1), 40, 0 (same as in figure 27), 40 and 90º (curve 5), considering a transmitted power of 16 dBm.

IV. WPT APPLICATIONS

A. WPT Integration in Buildings

The physical layer is crucial for the effective integration of the electronics with any hosting object. Mechanical flexibility, high shape customization, recyclability and low fabrication processes and materials costs, are needed in order to enable the IoT. For these reasons, particular attention has to be given by the scientific community to the demonstration of substrate independent processes which make possible the application of the devices on many materials, especially those not normally
used in electronics [85]. Common substrate independent processes which fit these requirements are: inkjet printing [7], 3D printing, gravure printing, screen printing and metal adhesive laminate [86, 87].

As a case-of-study we consider the so called “energy evaporation”, a system where localization capabilities in conjunction with long- and short-range WPT functionalities are combined together and embedded into floors, [88]. This example is a significant one since it shows the need for integration between Large Area Electronics (LAE) devices and the environment.

Figure 29(a) shows the scheme of a distributed matrix of unit-cells composed of a 5.8 GHz patch antenna surrounded by a HF coil at 13.56 MHz. The patch is responsible for long range WPT while the coil has the dual role of short distance WPT source and localization through the connection with NFC tags. In Fig. 29(b) the performance of the unit-cell fabricated on top of a cork substrate demonstrates its feasibility by adopting a non-conventional material for electronics (but common in indoor environments). The fabrication is performed using a metal adhesive method [87].

![Figure 29 - “Energy evaporation”](image)

The importance of the result in Fig. 29 demonstrates that, with proper design, RFID tag and RFID sensors could be integrated in tiles and similar construction materials, thus enabling a variety of novel, energy autonomous, IoT and WPT applications.

B. Algorithmic WPT applications in wireless ad hoc networks

Wireless power transfer technologies offer new possibilities for managing the available energy and lead the way towards a new paradigm for wireless ad hoc networking [89]. Wireless power transfer enabled networks consist of nodes that may be either stationary or mobile, as well as a few mobile nodes with high energy supplies [90]. The latter, by using wireless power transfer technologies, are capable of fast recharging the network nodes. This way, the highly constrained resource of energy can be managed in great detail and more efficiently. Another important aspect is the fact that energy management can be performed passively from the perspective of nodes and without the computational and communicational overhead introduced by complex energy management algorithms. Finally, energy management can be studied and designed independently of the underlying routing mechanism used for data propagation.

There are considerable challenges in making such wireless power enabled ad hoc networks work. First of all, the control of (stationary or mobile) wireless chargers is not trivial. Assuming a finite initial energy, those devices have a limited lifetime and their available energy supplies should be injected in the network wisely. Secondly, the wireless power transfer process itself consists of a challenging task. For example, the extent to which a network node should be charged, in order that the global network lifetime is prolonged, is not obvious. Finally, other issues such as the amount of energy given to the chargers, the trajectory that they should follow inside the network, their behavior with respect to the communication pattern and energy dissipation inside the network, further complicate the design and implementation of a wireless ad hoc network of this kind. An example layout of a proof-of-concept setting for wireless power transfer in wireless ad hoc networks is shown in Figure 30.

The impact of the charging process to the network lifetime for selected routing protocols is studied in [91]. A mobile charging protocol that locally adapts the circular trajectory of the mobile charger to the energy dissipation rate of each sub region of the network is proposed and compared against several other trajectories following a detailed experimental evaluation. The derived findings demonstrate significant performance gains in uniform network deployments.

Three alternative protocols for efficient recharging are proposed in [92], addressing key issues which are identified as: (i) to what extent each sensor should be recharged (ii) what is the best split of the total energy between the charger and the sensors and (iii) what are good trajectories the MC should follow. One of the protocols (LRP) performs some distributed, limited sampling of the network status, while another one (RTP) reactively adapts to energy shortage alerts judiciously spread in the network. As detailed simulations demonstrate, both protocols significantly outperform known state of the art methods, while their performance gets quite close to the performance of the global knowledge method (GKP) that is also provided, especially in heterogeneous network deployments.

The case of employing multiple mobile chargers in a network
is investigated in [93]. Four new protocols for efficient recharging are proposed, addressing new key issues: (i) what are good coordination procedures for the Mobile Chargers and (ii) what are good trajectories for the Mobile Chargers. Two of the protocols (DC, DCLK) perform distributed, limited network knowledge coordination and charging, while two others (CC, CCGK) perform centralized, global network knowledge coordination and charging. As detailed simulations demonstrate, one of the distributed protocols outperforms a known state of the art method [93a], while its performance gets quite close to the performance of the powerful centralized global knowledge method.

The collaborative charging feature is enhanced in [94] by forming a hierarchical structure. The chargers are distinguished in two groups, the hierarchically lower Mobile Chargers (MCs) which charge sensor nodes and the hierarchically higher Special Chargers (SCs) which charge MCs. Four new collaborative charging protocols are designed and implemented in order to achieve efficient charging and improve important network properties. The protocols are either centralized or distributed, and assume different levels of network knowledge. Extensive simulation findings demonstrate significant performance gains with respect to non-collaborative state of the art charging methods. In particular, the protocols improve several network properties and metrics such as the network lifetime, routing robustness, coverage and connectivity. A useful feature of those methods is that they can be suitably added on top of non-collaborative protocols to further enhance their performance.

A new approach in studying the problem of efficiently charging a set of rechargeable nodes using a set of wireless energy chargers, under safety constraints on the electromagnetic radiation incurred, is followed in [95]. A new charging model is defined, which greatly differs from existing models in that it takes into account real technology restrictions of the chargers and nodes of the system, mainly regarding energy limitations. The model also introduces non-linear constraints (in the time domain), that radically change the nature of the computational problems which are considered. In this charging model, the Low Radiation Efficient Charging Problem (LREC) is presented and studied, in which the amount of “useful” energy transferred from chargers to nodes (under constraints on the maximum level of imposed radiation) is optimized. Several fundamental properties of this problem are presented and indications of its hardness is shown. Finally, an iterative local improvement heuristic for LREC is proposed, which runs in polynomial time and its performance is evaluated via simulation. The algorithm decouples the computation of the objective function from the computation of the maximum radiation and also does not depend on the exact formula used for the computation of the electromagnetic radiation in each point of the network, achieving good trade-offs between charging efficiency and radiation control. The algorithm also exhibits good energy balance properties. Extensive simulation results supporting the claims and theoretical results are provided [95].

In [96], wireless power transmitters that charge the battery of the network nodes in mobile ad hoc networks are employed and two new, alternative protocols that configure the activity of the chargers are proposed. One protocol performs wireless charging focused on the charging efficiency, while the other aims at proper balance of the transmitters’ residual energy. Towards a more realistic validation, an evaluation is performed, not in a simulation environment, but through an experimental setting of real devices. Figure 30 shows the layout of the experimental setting in which 4 wireless power transmitters and 3 wireless sensor motes were used.

![Figure 30 – Layout of an experimental setting for wireless power transfer in wireless ad hoc networks.](image)

**C. Solution of WPT for spatial distributed nodes of WSN.**

Wireless Sensor Networks (WSNs), based on the ZigBee protocol for example, are low power and low throughput networks commonly used for distributed low-range sensing and control. In some cases, spatially distributed ZigBee nodes cannot be powered up using batteries or cables. In these cases, a RF-based Wireless Power Transfer system can be considered as potential solution. Because demand on power for each WSN node can vary over time, the charging system must constantly monitor the state of each node and send an adequate amount of energy to allow constant operation. Examples of other WPT for WSNs can be found in [96] and [97].

This work presents a concept and physical realization of a 2.45 GHz WPT system for charging Wireless Sensor Network nodes spatially distributed. The system utilizes a 4x1 patch array transmitter with switched radiation beam in order to ensure large spatial coverage. The beam switching is realized using a 4x4 Butler matrix, whose inputs are connected to a SP4T – 4-way high isolation RF switch. After connecting the switch to the high power signal generator (here WSN node generating a single tone 2.45 GHz signal and 1 Watt amplifier for each Butler matrix input for increasing the power level), a directional transmitter was obtained. On the receiving side, the RF power was collected using a highly directional planar Yagi-Uda antenna. The antenna was connected to a rectifier including 5-stage voltage multiplier and a matching circuit for high DC output level. The output of the rectifier was connected to the 0.47 F supercapacitor gathering energy for powering one WSN node. In total 4 receivers were used in the proposed system,
each placed in the maximum gain direction of each transmitter radiation pattern. The schematic drawing of the system is shown in Fig. 31.

![Figure 31 – Schematic of the presented WPT system](image)

During operation of a WSN node, measurements of certain physical quantities can be completed and send to the data sink (WSN receiver in Fig. 31). Apart from that, each WSN node can measure and send the voltage level of the supercapacitor to which it is connected. The voltage levels can be collected periodically from each WSN node to the data sink located at the transmitter. Based on WSN node responses, the transmitter radiation pattern can be autonomously switched in time in order to cover current energy demand of each WSN node and thus allow the network to remain operational for a long time.

Using received voltage levels, the transmitter can switch radiation patterns according to the following algorithm:

1) Receive voltage levels from all nodes. 2) Calculate difference and offset from the limit voltage value for each node. 3) Calculate illumination duration for each node (weighted sum of factors from point 2). 4) Start counter and switch radiation patterns in calculated moments. 5) Go to point 1).

In Fig. 32, the WPT system for automated charging of WSN nodes can be seen.

![Figure 32 – Autonomous WPT system realized for supplying the power to WSN nodes distributed in space.](image)

To verify performance of the WPT system, a charging experiment has been performed. In the experiment, all WSN nodes were measuring and sending the data to the sink while being charged according to the algorithm. Voltage levels measured by all WSN nodes versus time are presented in Fig. 33.

![Figure 33 – Result of the charging experiment.](image)

It can be seen that the node with the lowest voltage level obtains the highest amount of energy from the transmitter. Other nodes are discharging slowly, but in case of high energy loss (sudden voltage drop in Fig. 33), the system would direct the energy flow to the nodes most in need of energy.

The presented 2.45 GHz WPT system allows wireless charging of multiple WPT nodes by switching of the transmitter’s radiation pattern. The implemented algorithm allows full automation of the charging process and also equalization of voltage levels for all WSN nodes, independent of the node’s measurement frequency and initial voltage level.

D. Exploitation of 3D textile materials for wireless feeding of in-car sensor networks

3D textile material consists of two firm layers at a constant distance. The distance in between the layers is kept constant by fine fibers which are perpendicular to the firm layers. Hence, the 3D fabric can be understood as a dielectric waveguide. This 3D fabric can be used as upholstery in cars, buses or airplanes, and such upholstery can play the role of a feeder or a communication channel.

![Figure 34 – 3D textile material.](image)

The idea of the exploitation of a 3D textile material for a wireless power transmission was tested in a car with a metallic roof (Fig. 35). The transmit antenna TX and the received antenna RX were attached to a 3D textile upholstery. Using this technique the electromagnetic energy was efficiently guided by the textile material along the car roof.
The idea was verified by measurements in a real car. In Fig. 36, the transmission between antennas in free space (black) is compared with the transmission between antennas placed on the roof upholstery of an empty car (blue) and a fully occupied car (red).

Efficiency of the described wireless power transmission is demonstrated by Fig. 37 comparing transmission between the transmit antenna and the receive antenna placed in free space (black), on conventional upholstery (blue), on 3D textile (green) and in 3D textile (red).

In order to minimize attenuation of the channel, the transmitted electromagnetic wave has to be polarized perpendicularly to the metallic surface of the roof. Therefore, an open ended rectangular waveguide and a planar horn antenna integrated to the substrate were used in the experiments (Figure 38).

For experiments in a car, the planar horn antenna integrated to the substrate showed better behavior thanks to its narrower radiation pattern (Fig. 39). For measurements in the laboratory, the open ended rectangular waveguide was exploited due to a simpler calibration.

E. Harmonic Tags

In the field of passive UHF RFID, the nonlinear behavior of the harvesting section of the RFID chip can be exploited to develop augmented tags. Three categories of applications can be envisaged by exploiting: (1) the impedance power dependency [101]-[102], (2) harmonic generation [103]-[105], and (3) efficient waveform design [106]-[108].

To enable such applications, the nonlinear characteristics of RFID chip must be determined. Fig. 40 shows the normalized Power Spectral Density (PSD) of a passive RFID chip response measured using a similar method to the one reported in [104]. The setup considers the chip activation threshold power, the reader harmonics suppression and the chip impedance matching at the fundamental frequency as in common tags. The harmonic frequencies level (i.e. at 1.736 GHz and notably at 2.604 GHz) at the chip activation threshold is significant compared to the fundamental frequency level. The energy contained in the 3rd harmonic generated by the RFID chip can be exploited to set a second RF link tag-to-reader at that harmonic frequency.
**Harmonic Tag design:** A proper design of the tag antenna enables the transmission of the modulated 3rd harmonic signal from tag to reader [102]. The obtained channel diversity can be exploited as a redundant communication channel, for instance, in order to increase the robustness of the RF uplink. Additionally, the pattern direction of the antenna can be designed to be different than the one for the fundamental signal, for instance in order to develop an application for localization. It can also be used to enable some specific applications by receiving the signal at the third harmonic.

**Measurement:** Fig. 41 shows an example of harmonic tag using a dual band LF inverted antenna. Fig. 42 shows the 3rd order harmonic response levels of two prototypes based on the harmonic tag with different chip in each one (chip 1 [108] and chip 2 [109]), and one commercial tag. Results of an experimental parametric analysis are summarized in Table 1.

![Fig. 40 – Example of normalized power spectral density of a tag response measured at the activation threshold of the chip under test.](image)

**TABLE I**  
**PARAMETRIC ANALYSIS RESULTS**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Power of the response at 3f</th>
<th>*Read range at 3rd harmonic.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabrication sensitivity</td>
<td>12 MHz detuning</td>
<td>-82 dBm</td>
</tr>
<tr>
<td>Kind of chip</td>
<td>Greater bandwidth with chip 1</td>
<td>Quasi-similar for both chips</td>
</tr>
<tr>
<td>Commercial tag</td>
<td>Slightly wider bandwidth for commercial tag</td>
<td>-90 dBm</td>
</tr>
</tbody>
</table>

* The read range at 3f0 considers -90 dBm of reader sensitivity.

As it can be seen in Table 1, the read range at the third harmonic is a few meters, which is comparable to that at fundamental frequency in this design. However, the design of the antenna at the 3rd harmonic could be quite different in order to enable new applications. Localization, energy harvesting, sensing and authentication are among the possible options.

**F. UHF RFID Library Management System**

A passive UHF RFID Library Management System (LMS) was designed and built in order to serve the purpose of a university library [112]. The prototype was actually built and tested in a laboratory setting with very good evaluation results. The main objectives of the project were to: a) provide stock management including inventory monitoring, identification of missing or lost library items and locating books on shelves; b) implement item security measures against possible thefts often incurred in libraries; c) eliminate time-consuming processes when checking items out of the library or returning items to the library.

A block diagram of the RFID-enabled LMS is shown in Fig. 43. It consists of several sub-systems including smart shelves, user self-service desk, database server, portal security system and mobile cart unit. The database server is the backbone for the whole system. It is the place where all the relevant information such as book titles, user accounts, checked-out books, and stock-taking reports are kept.

Using the self-service desk (see Fig. 44(b-c)), which consists of a PC, an RFID reader and a near-field antenna, the library users can perform all functions that typically take place in a...
library environment, namely search for a book by title, author, publisher or ISBN number. In addition, they are allowed to review their own activity record, to self-checkout books, and to return to the library previously checked-out books. A user-friendly Graphical User Interface (GUI) was developed in order to provide to the users enhanced functionality and transparency. Through this User Interface (UI), the librarian has additional privileges compared to the average user including modification of system settings, editing user accounts and book entries (e.g. add new books), stock-tacking and monitoring the RFID entrance security system (shown in Fig. 43).

The smart shelves of the LMS, depicted in Fig. 45, are specially designed to serve the tasks of the university library. Each cabinet is equipped with an RFID reader with multiple ports, which is connected through cables to each one of its shelves. Although these shelves look like common shelves, they are in fact specially designed RFID antennas, such as the one illustrated in Fig. 46, through which the reader can receive the unique identification numbers (Electronic Product Code – EPC) of the books that are placed on top of them. This enables the automatic stock taking with the push of a button, as well as locating and identifying missing and misplaced books on library shelves in record time. RF multiplexers (as shown in Fig. 47) are also used at intermediate points between the reader and the shelf antennas in order to reduce the total number of readers required to cover the overall needs of the library. The multiplexers are software-controlled (using Arduinos) and they are already implemented in the in-house developed software application. Each RFID reader can be connected and service up to 32 antennas.

A security portal at the entrance of the library, as shown in Fig. 43, consists of a stationary RFID reader and a high-gain antenna or array of antennas. This system is connected to the network in order to provide access to the software application developed for this purpose. Alert information is passed to a dedicated software application that runs on the circulation desktop which is controlled by the library administrator. The system is programmed to activate an alarm every time a non-authorized attempt is made to remove library items (e.g. books and magazines) from the library entrance.

A mobile cart unit, shown in Fig. 44(a), enables book identification and localization on the library shelves. The mobile cart system is equipped with an RFID reader, an antenna, a laptop/tablet with touch screen and a UPS that provides power to the reader and laptop. The system uses the Wi-Fi connection to access the database server and provide valuable information to the user. The mobile cart can be pushed around the library while scanning the books on individual shelves.
The ability of the system to effectively read and correctly identify the books residing on top of the shelf antenna depends on the electromagnetic coverage, the uniformity and strength of the field in the volume of the shelf, and the interference to nearby shelves. It was identified experimentally that tag readability requires a minimum field level of approximately 20 dBV/m [113]. The wooden cabinet that was built and tested in the laboratory was also modeled on SEMCAD-X using a FDTD algorithm [114]. Our goal was to identify problematic regions either due to reduced EM coverage or strong interference in neighboring shelves.

In Fig. 48, the areas where the E-field values are above 20 dBV/m are shown in yellow color for two antenna designs: a straight line and a meander line. Figs. 48(a) and (b) represent the field magnitude for the straight line whereas Figs. 48(c) and (d) represent the corresponding field for the meander line. The straight line was excited with a power source set to 20 dBm whereas the meander line was excited with a power source at 15 dBm. It is clear that both antennas result in reduced electromagnetic interference (EMI) for nearby shelves. However, the meander line with a lower input power level seems to provide a better EM coverage and even lower EMI.

In addition to EM coverage and interference at nearby shelves, the distribution of the peak spatial specific absorption rate, averaged over 10g of tissue mass (psSAR_{10g}), was assessed for a human model (phantom) [115] in close proximity to shelf antennas with and without the presence of books on the shelf. The dielectric properties of the human tissues were calculated according to the parametric model proposed by Gabriel et al. [114]. In the worst case scenario, all shelf antennas in the cabinet were active. All values were normalized to 1W of power radiated by each antenna.

In the case of the wooden cabinet and straight-line antennas, higher psSAR_{10g} values were calculated when the model was placed at the smallest distance to the shelf but in the absence of books. SAR values were in all cases reduced by a factor of 10 as compared to those obtained for a metallic cabinet. Specifically, at 5mm distance, the maximum SAR values are 0.076W/kg for Thelonious (see Fig. 49), 0.059W/kg for Ella and 0.041W/kg for Duke, these are all human models [114]. When the human models were placed 10cm away from the cabinet, the corresponding SAR values were reduced to 0.022W/kg, 0.015W/kg and 0.012W/kg, for Thelonious, Ella and Duke, respectively.

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G. Wireless power transmission for batteryless biomedical and implantable microsystems

Wireless power transfer is desperately needed in wearable biomedical sensors [116], implants [117], individually addressable neurostimulators [118], retinal and other prostheses [119], and in biomedical applications such as interventional magnetic resonance imaging (MRI) [120]. In each of these critical applications, there is an important size constraint on a system, which makes the use of batteries impractical since this puts a limit to overall size and shortens lifetime. Certain applications such as MRI, have high power internal electromagnetic fields prohibiting use of long metallic wires due to induced heating. Therefore, power and data transmission must be done wirelessly to the systems in these applications and they must be miniaturized.

These microsystems should also be able to receive data in order to be programmed or awoken in addition to transmission of data. Typically, long operation distance, higher bandwidth and lower power densities are desired. However, meeting these in a small batteryless system is still a big design challenge, realization of which would open a world of widely used wireless health monitoring systems.

Wireless power transfer to batteryless microsystems can be achieved using inductive or capacitive coupling in the near field. Inductive coupling with the reception of modulated backscattered data is a frequently employed technology in implants, which is also used commonly in passive RFID tags. This technology results in small sizes. However, it has a disadvantage of shorter operation distance of around 0.5 to 20 cm [121]. CardioMEMS has a passive telemetry based implanted wireless blood pressure sensor system working over a distance of 20 cm and size of 5x30 mm$^2$ [122]. Low MHz region such as 3 or 30 MHz is found to be a good compromise between tissue absorption and bandwidth [123]. However, research still continues to find the optimal frequency for wireless power transmission into tissue [124].

Several other biomedical implants have been proposed using this type of telemetry. However, many of them require large sized antennas because of frequency ranges in the MHz being used. Antenna sizes are on the order of one to tens of centimetres when the GHz frequency range is used [125] and become greater as frequency declines. Miniaturized wirelessly powered passive RFID tags operating at 60 GHz are shown to become greater as frequency decreases, but at the cost of increased path losses, design complexity and power density [127]. A biomedical implant has been proposed using 1 GHz power for a 2x2 cm$^2$ square loop transmit antenna and a 2x2 mm$^2$ square loop receive antenna through 15 mm of layered bovine muscle tissue with a measured link gain of -33.2 dB [128]. Active microsystems can obtain better operation distance using smaller antennas or coils of around 0.5 mm, unfortunately, this means they have batteries [129].

Optical power transmission for wireless sensors and microsystems

In the context of system miniaturization and wireless power and data transmission, optoelectronic systems have the potential to be smaller than the RF powering WPT solutions. They offer higher power densities, which can be delivered simply by lasers or other light sources. Laser beam powering of RF tags with on-chip silicon photodiodes helped to miniaturize them to 500x500 µm$^2$ sizes [130]. This miniaturization proved valuable in studying ant behavior by tagging individual ants [131]. However, in these small RF tags, communication is established by RF signals using small on-chip antennas, which limits the working distance to around 5 mm.

A 1.5 mm$^3$ energy autonomous wireless intraocular pressure monitoring system is implemented using an integrated 0.07 mm$^2$ solar cell that can harvest a maximum power of 80 nW under a light irradiance of 100 mW/cm$^2$ (AM 1.5 sun condition) to recharge a 1 mm$^2$ thin-film battery to power the system. It also includes a 4.7 nJ/bit FSK radio that achieves 10 cm of transmission range, which is also used to receive wake-up signals [132]. Another version of this microsystem is also implemented by employing an integrated optical receiver to load program data and request data instead of the RF receiver, keeping optical powering and RF data transmission. The system generates 456 nW under 10 kilolux light to enable energy autonomous system operation [133]. Another solution has been demonstrated for this problem with a microsystem aligned to the tip of an optical fiber, where an on-chip photovoltaic cell is used for optical powering and a separate laser diode for communication [134, 135].

Despite being very attractive solutions for wireless power transfer, on-chip photovoltaic cells made of silicon can supply open-circuit voltage of around 0.6 V, which is not enough for integrated circuits (IC) and sensors. Series connection of multiple photodiodes in silicon-on-insulator (SOI) wafers have been demonstrated as a solution [136], however SOI technology is more expensive and less available compared to standard CMOS processes. An external light emitting diode (LED) used as a photovoltaic cell can be more beneficial.

A LED can supply higher open circuit voltage (1.3 V for near infrared, 1.6 V for red, 1.7 V for green, etc.) than silicon photodiodes. Circuitry can be run directly from this higher voltage without the need for voltage elevation which consumes valuable power. Since the microsystem needs an external optoelectronic element to transmit data optically (silicon, being an indirect semiconductor, cannot generate photons of any sufficient quantity), the LED can also work as data transceiver. Placing the photodiode outside of the IC die saves expensive on-chip area. With the photovoltaic cell placed out of the die, the die can be covered in optically opaque material since the powering light can induce latch-up and noise and can increase leakage currents. Photon absorption is more efficient in direct bandgap materials of LEDs (e.g. AlGaAs) in contrast to indirect bandgap materials (e.g. silicon) [137]. Record level efficiency improvements in GaAs solar cells have been achieved in this way, stressing commonalities between efficient photovoltaic cell and LED designs [138]. An LED is also an efficient photovoltaic cell for a limited range of its wavelengths that are about 20-30 nm shorter than peak emission wavelength.

With the added benefits of LEDs, an improvement in wireless and batteryless optoelectronic microsystem has been made by using it for both wireless powering and data transmission as depicted in Fig. 50. The use of a single LED with a die size of 350x350 µm$^2$ with the help of an IC (230x210 µm$^2$) and a
storage capacitor (0.5x1 mm²) resulted in a 1 mm³ wireless and batteryless microsystem [139].

![Figure 50 – Conceptual representation of the optically powered and optically transmitting microsystem using a single light emitting diode.](image)

For transcutaneous implants, optical powering can be done using light with wavelengths between 600 and 900 nm, called the near-infrared (NIR) window, where hemoglobin absorbs weakly and penetration of light can reach a maximum depth of around 5 cm [140]. Experimental results show that the laser power level of 1 W/cm² drops to 1 mW/cm² (30 dB power loss) through 3.4 cm thick bovine tissue when 808 nm wavelength is used [141].

H. Design of battery-less CMOS sensors for RF-powered Wireless Sensor Networks

The wireless Sensor Network (WSN) is a group of spatially dispersed sensors (nodes) for collecting physical or environmental information and to cooperatively pass their information through the network to a central location. A WSN has several applications, for example building monitoring and automation, health care monitoring, air pollution monitoring, forest fire detection and water quality monitoring. Normally, each network node comprises a radio transceiver, a microcontroller, sensors and an energy source, usually a battery. The lifetime of most sensors is mainly limited by the autonomy of their batteries. There are several solutions for extending the life of batteries among which we can include the harvesting of electromagnetic energy available in the environment. As semiconductors technologies evolve over time not only the size of MOS transistors decreases towards nanometric scales but also the circuits, power consumption is considerably reduced. This trend favours the integration of several complex functions in a SoC (System-on-Chip). It is thus possible to integrate complete ultra-low power autonomous sensors for RF-powered WSNs.

UMONS Microelectronics Laboratory is engaged in designing a wireless RF-powered temperature sensor.

The architecture of the temperature sensor is depicted in Fig. 51. RF energy is harvested with an Rx antenna, which is adapted to a rectifier/multiplier through a LC matching network in order to maximize energy transfer. The output of the rectifier charges an external capacitor that supplies the rest of the circuits on the chip. A power management unit checks and regulates the minimum voltage level required across the external capacitor. It also controls the sensor working cycle by enabling/disabling properly each block in view of minimal power consumption. The temperature is measured with an ultra-low power temperature sensor that delivers a digital word to a modulator which yields the transmission frame. The output of the modulator controls a voltage controlled oscillator (VCO) through a digital-to-analog converter (DAC) in order to generate the 4-FSK signal which is transmitted by a Tx antenna.

A 100 kHz master clock generator provides the time reference for all digital circuits of the sensor. For a 15.6 ms long transmission frame at 50kb/s the BER (bit error rate) results in 10⁻⁹. The system can operate at 0.5V while consuming 84µW in on-mode and 28.6nW in idle-mode. The achieved input sensitivity is -26dBm.

![Figure 51 – Wireless and battery-less temperature sensor architecture](image)

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REFERENCES


[64] Detailed information at http://www.wirelesspowerconsortium.com


[67] Technical specifications can be found at http://www.logitech.com/en-us/product/marathon-mouse-m705


[69] Representative example found at http://www.bellaag.com


[82] Fernandes, R.D.; Matos, J.N.; Carvalho, N.B., “Constructive combination of resonant magnetic coupling and resonant electrical...


