Optimization of Near-Field Wireless Power Transfer Using Evolutionary Strategies

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***Abstract*—The parameter space for power transfer by near-field, magnetically coupled, half wavelength coil resonators was explored by evolving the coil shape using an evolutionary strategy and method of moments antenna analysis. The starting coil shapes were solenoid, which were evolved to enhance the power transfer between multiple coils. Through the use of an appropriate fitness function and tuned search space boundaries, the shape of a set of solenoid coils was evolved to improve the power transfer over a wider operating range when compared to the non-evolved case.**

***Index Terms*—near-field antenna, wireless power transfer, genetic algorithm, optimization algorithm, evolutionary strategies, wide-band**

I. Introduction

Ever since Nikola Tesla displayed the first wireless power transfer (WPT) experiment using electromagnetic induction in 1891, significant efforts have been put into realising an efficient form of wireless power transfer. Over the years, this search has only intensified to satisfy the desire for more convenient, cordless ways of supplying power to the ever increasing number of electronic devices.

Wireless power transfer can be achieved through the use of either near or far-field electromagnetic (EM) waves. Far field wireless power transfer systems simply use high power antennas to transmit and the radiation is usually in the RF or microwave range. However, near-field wireless power transfer systems utilise electric and/or magnetic coupling to share energy through the near-field, which is usually done in a resonant mode.

In general, applications using far-field EM waves offer good range but are sensitive to directionality and are limited to a direct line of sight between emitter and receiver. By contrast, the near-field wireless system can be less sensitive to directionality, is not limited to a direct line of sight between emitter and receiver (because non resonant objects within the field will tend to have a negligible effect on the power transfer) but is limited by range. In addition, near-field wireless power transfer systems using magnetic coupling (such as coils) are safer for humans than other systems, which create large electric field energy densities in space, and have therefore spurred recent research in this area.

Kurs *et al* demonstrated a 60W power transfer at 40% efficiency with magnetically coupled solenoid coils over a distance that was approximately 4 times the diameter of the solenoid [1] and the transmission of power to multiple devices [2]. Subsequent work centred on magnetically coupled resonator coils and the effects of frequency tuning [3], of multiple transmitters [4], of multiple receivers [5] and of the improvement of power transfer utilising meta-materials [6][7]. Optimising the power transfer between systems of magnetically coupled coils is a relatively simple task of maximising the magnetic coupling, $k = M/\sqrt{L_1 L_2}$ and choosing the correct operating frequency. Maximising k can be done via making a large inductance, L (using many turns or a large radius) or through increasing the mutual inductance, M,

$$M = \frac{\mu}{4\pi} \oint \oint \frac{dl_1 dl_2}{R_{12}} \quad (1)$$

, where the subscripts 1 and 2 refer to coils 1 and 2, dl are the elements of the coils length, R_{12} is the distance between elements in coils 1 and 2 and μ is the magnetic permeability of the medium. To maximize equation 1, one must simply make the distance between the coils small (small R). However, in general this applies to a lumped element analysis, which has been the predominant method in the work cited above. In many real life applications the operating frequency may need to be changed continually as the position between strongly coupled coils changes or wide band applications are needed for information transfer. In this work we alter the shape of a solenoid coil to maintain high power transfer efficiency while operating over an improved bandwidth.As the individual and coupled resonant frequencies (hence bandwidth), coupled and self impedances are all functions of the shape of the coils and therefore mutually dependent, the task to optimize these simultaneously is a multi-objective problem. To solve this optimization problem we use an evolutionary algorithm, which are known to be highly suitable for these problems [8], to evolve the shape of a normal solenoid coil to optimize certain parameters, described by a fitness function, F. Optimising the shape of magnetically coupled coils has not previously been considered for near-field wireless power transfer, neither has a evolutionary algorithm been used to optimize them. In general, an evolutionary algorithm works on the principle of biological evolution, where individuals (coils of different shapes in our case) are chosen for their fitness (power transfer and or wide band capability in our case) to bread a new generation of individuals, where the process is reiterated until a individual with the best fitness is found. We used the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) [9] which is ideal

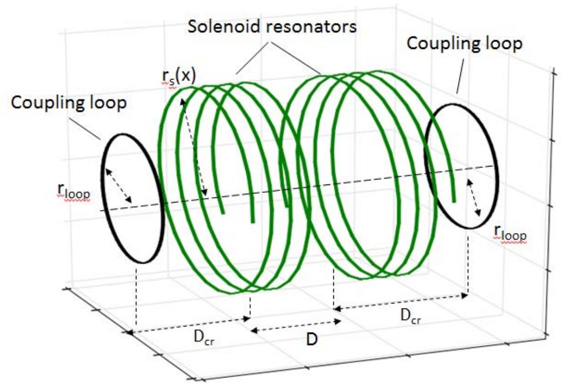

Fig. 1. Basic geometry description of the antenna configuration

for a complex solution space with multiple minima and non-linear relation between parameters.

To determine the power transfer between sets of coils we used a finite element method partially based on the electromagnetic tool contained in [10] which uses the Method of Moments (MoM) with the R.W.G basis functions and the Electric Field Integral Equation (EFIE) [11] to compute the radiation and scattering patterns of arbitrary antennas for far field applications. This tool was modified for our purposes to solve only the impedance matrix of the coupled coils from which the power transfer was calculated, and to be congruent with the CMA-ES algorithm.

II. Method

The power transfer between four coils shown in figure 1 was optimized by evolving the shape of the solenoid coils while the loops were kept static. The independent variables that parametrize the shape of the solenoid are the wire thickness (W), wire length (L), number of turns (N), variation in z-axis position and the space between turns. These were altered in a random way by the CMA-ES algorithm to generate a population of individuals.

The R.W.G analysis method [11] was then used to determine the power transfer between the loaded input and output loops shown in fig 1, which was then passed to the CMA-ES algorithm in order to calculate the appropriate fitness. Based on the fitness, the individual (altered solenoid coil) would then be discarded or used to generate the next generation. The CMA-ES algorithm also adds some mutation to each generation by randomly changing some of the variables which determine the shape of the coil. The solenoid resonators have predominantly magnetic coupling and are open-ended. They resonate in the fundamental half wavelength TEM mode.

A. Electromagnetic model

After the random shape of the solenoid was created, the impedance matrix of the coupled structure was calculated and used to find the input and output port impedances (two elements on each of the coupling loops). The input and output impedances were used to load the coupling loops with lumped elements such that the structure were always matched. This was done to avoid the CMA-ES algorithm evolving shapes to impedance match rather than optimising power transfer. Once the structure is matched, the power transfer is recalculated as

$$\frac{P_{load}}{P_{input}} = \frac{Real\left[V_{load} \cdot I^*_{load}\right]}{Real\left[V_{input} \cdot I^*_{input}\right]} = \eta \tag{2}$$

B. CMA-ES & Fitness Criteria

The fitness criteria used in the CMA-ES algorithm is given by,

$$F = \sum_n \left(1 - \alpha_n \left(\frac{P_r(n)}{P_t}\right)^2\right) \tag{3}$$

Here, P_r and P_t are the received and transmitted power respectively. By evaluating the transfer function at different input frequencies (f_n), the fitness function F is a function of both the power transfer and bandwidth which is subsequently passed to the CMA-ES algorithm. In the cases presented here, all frequencies are equally weighted ($\alpha_n = 1$). Multiple instances of optimization are run and compared afterwards to establish whether a global minimum was reached.

III. Results

Starting with a standard solenoid antenna (figure 1), the CMA-ES algorithm was used to optimize the power transfer around a set frequency of 56 Mhz over an inter-coil distance of $D = 1.0 - 2H_a$. Here, H_a is the maximum height of the antenna above/below the transmitter/receiver loop. The value of H_a is one of the input parameters of the GA, but restricted to a maximum value of 0.15m. The results for the evolved solenoid are shown in figure 6 with a close-up of the resonator in figure 2. The power transfer efficiency (η) obtained was 0.82. Notice that the amplitude of the current density is maximized at the midway point of the antenna due to the use of the half wavelength mode. The radius at this

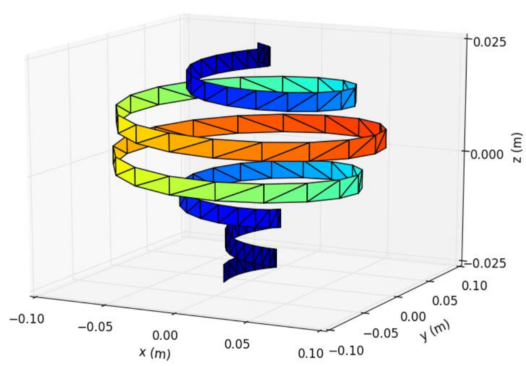

Fig. 2. Example of a GA-evolved solenoid antenna

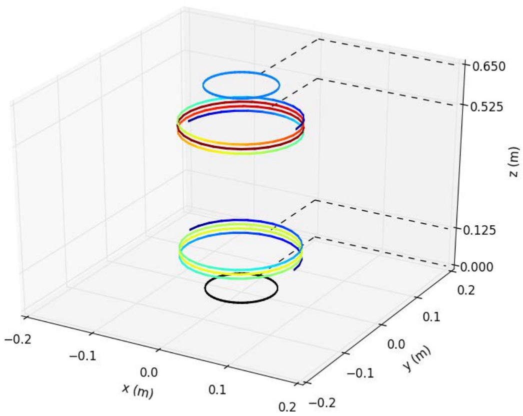

Fig. 3. Non-evolved solenoid antenna with $r_a = 8.0$cm at $f = 58.82$MHz coupling over an inter-solenoid distance of $D = 0.4$m

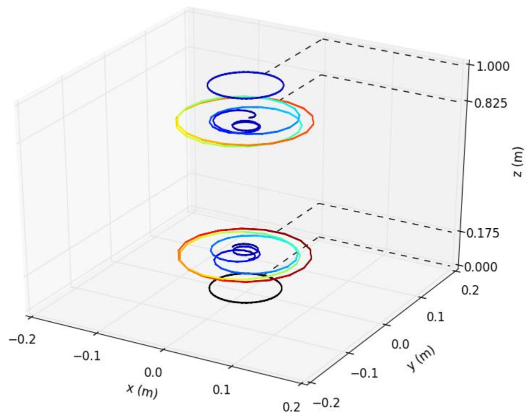

Fig. 6. Evolved solenoid antenna with $r_a = 8.5$cm at $f = 56.03$MHz coupling over an inter-solenoid distance of $D = 0.65$m

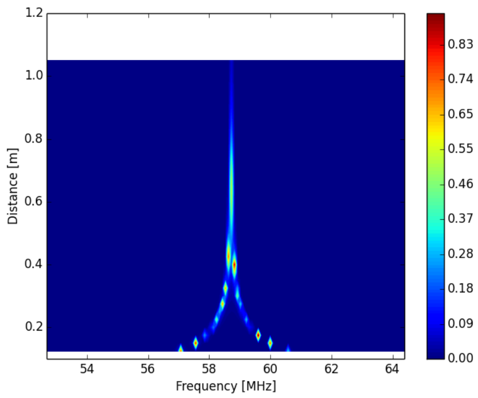

Fig. 4. Surface plot of $|S_{12}|$ for the non-evolved solenoid of figure 3

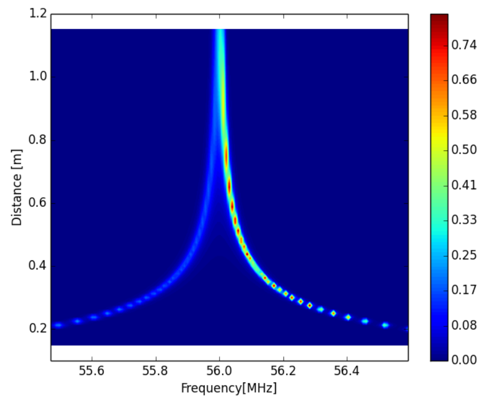

Fig. 7. Surface plot of $|S_{12}|$ for the evolved solenoid of figure 6

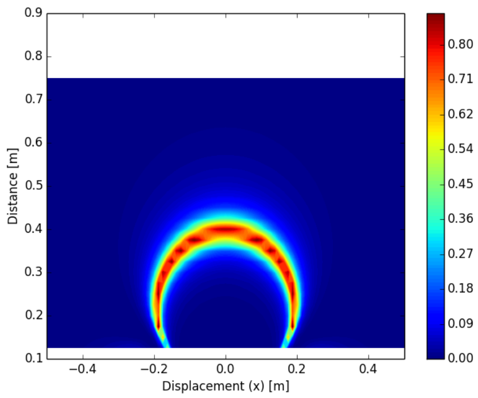

Fig. 5. 2D transfer efficiency for the evolved solenoid antenna of figure 3

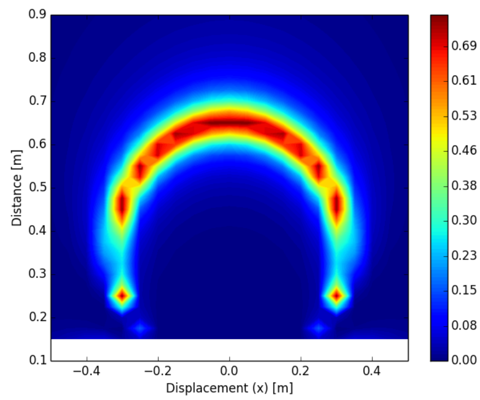

Fig. 8. 2D transfer efficiency for the evolved solenoid antenna of figure 6

point (r_a) is 8.5cm. The minimal loop-solenoid (proportional to coupling coefficient k) distance was 15.35cm.

For comparison, the performance of non-evolved solenoid was determined considering an average radius of 8.0cm (see figure 3. For this case a power coupling of 0.85 was obtained at 58.82MHz at $D = 0.65 - 2 * 0.125 = 0.4$m. The minimal loop-solenoid distance in this case was 10.40cm.

The surface plots of the transfer efficiency ($|S_{12}|$) for the evolved antenna is shown in figure 7 as function of transfer distance and frequency. The splitting of the resonant frequency

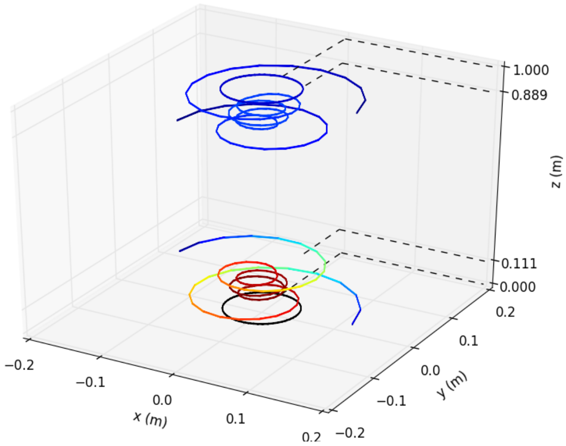

Fig. 9. Evolved solenoid antenna with $r_a = 5.1$cm at $f = 86.57 \pm 1\%$MHz coupling over an inter-solenoid distance of $D = 0.78$m

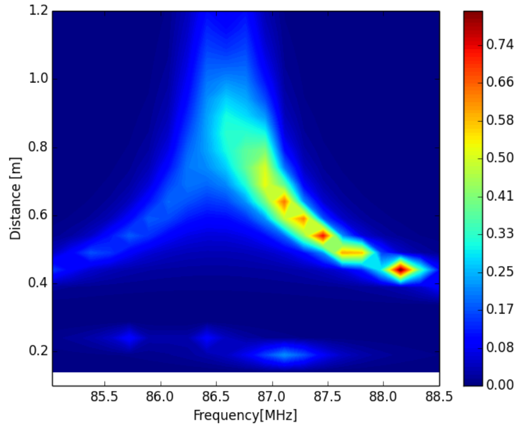

Fig. 10. Surface plot of $|S_{12}|$ for the evolved solenoid of figure 9

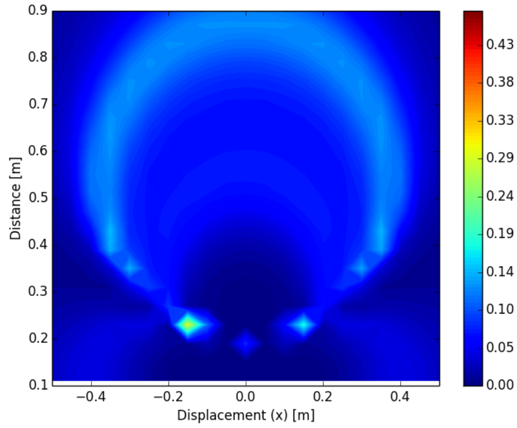

Fig. 11. 2D transfer efficiency for the evolved solenoid antenna of figure 9

towards shorter inter-solenoid distance is clearly visible. Also, notice the higher efficiency at the high frequency splitting. Note that the discrete curve is caused by the numerical evaluation with a fixed step size.

For the same antenna, the 2D efficiency diagram is shown as a function of lateral displacement and distance in figure 8. The efficient forward transfer cone is clearly visible, optimized for a magnetic coupling over 0.65m. Due to the splitting of the coupling frequency at close separation between the coils, a slight lateral displacement can partly compensate the frequency shift thereby restoring (part of) the coupling.

A. *Broadband frequency Optimization*

Following this initial optimization around a single frequency, the broadband characteristics were explored by optimising using a discrete number of frequencies around the central frequency ($f_5 = [0, \pm 0.5\%, \pm 1\%]$). The shape of the broadband optimized antenna is shown in figure 9. The minimal loop-solenoid distance in this case was 4.97cm. For this case a power coupling of $[0.28, 0.18, 0.09, 0.22, 0.13]$ was obtained at $D = 0.78$m. Figure 10 shows the surface plot as a function of transfer distance and frequency. In an attempt to match the multiple frequency fitness function, the evolved solenoid indeed enhanced the broadband characteristics. However, this slight broadening around the central frequency could only be achieved at the cost of a lower power transfer efficiency, as can be seen in figure 11 which shows the transfer efficiency for this antenna as function of distance and lateral displacement.

IV. Conclusions & Discussion

Using an evolutionary strategy algorithm, the shape of sets of solenoid coils have been evolved. The results show an improved near-field power transfer capability in the evolved cases when compared with the non-evolved antenna with similar radial dimensions. A single frequency power transfer of 82% could be achieved over a distance of 0.65m in the evolved case, compared to 85% for the non-evolved solenoid over a distance of 0.38m. When attempting to evolve towards a broadband characteristic, conflicting requirements between coupling distance and broadband characteristics resulted in a trade-off at a lower average coupling efficiency. Because the antenna coil is optimized towards a specific target parameter, the transfer characteristics of two different sets of antenna are not easily compared. For future work therefore, a multi-objective optimization approach will be beneficial in order to decouple the input parameters in the optimization. Furthermore, the final coil shape depends strongly on the chosen form of both the fitness criteria and the formulation of the coil geometry. We expect that further adaptations can therefore improve the bandwidth and/or power transfer characteristics.

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