Waveform Design for Optimal Wireless Power Transfer Using Evolutionary Algorithms

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***Abstract*—One of the possible ways to increase the end-to-end power transfer efficiency in a radiative Wireless Power Transfer (WPT) system is by transmitting multi-tone signals optimized according to the receiver rectenna's nonlinear behavior and the Channel State Information (CSI). This optimization problem is a non-convex problem that has been tackled in the past with Sequential Convex Programming (SCP) algorithms. Since SCP algorithms do not guarantee to track the globally optimal solutions, there is interest in applying some other optimization methods to this problem. Here we apply various Evolutionary Algorithms (EAs) with different characteristics. The performance of the designed waveforms is evaluated in Matlab, using a simplified Single Input Single Output (SISO) system model. EAs are successfully applied to waveform design for WPT and seem to track the optimal solutions in the tested cases. Moreover, the effectiveness of the SCP-QCLP method is verified.**

***Index Terms*—Wireless Power Transfer, Waveform Design, Evolutionary Algorithms, Channel State Information**

I. Introduction

Radio Frequency (RF) Wireless Power Transfer (WPT) is a technology that can be used for powering up low-power devices, with many applications in the concept of the Internet of Things (IoT) [1]. In a traditional radiative WPT system, a continuous wave RF carrier is transmitted and after propagating through the medium it is received and rectified by a receiver rectenna.

The transmission of multi-tone pulsed wave signals, optimized according to an objective function that incorporates both the Channel State Information (CSI) and the rectifier's nonlinear behavior, was proposed in [2]. These optimized waveforms proved to increase the end to end power transfer efficiency in a WPT system. An improved objective function was introduced in [3] for the same optimization problem. However, in both of these publications, it was stated that the solutions tracked by the proposed Sequential Convex Programming (SCP) optimization methods are not guaranteed to be the globally optimal solutions due to the non-convex nature of the problem.

Evolutionary Algorithms (EA) are metaheuristic algorithms inspired by Darwin's theory of evolution of species and designed for solving challenging global optimization problems. EAs are not guaranteed to track the globally optimal solutions due to their stochastic direct-search nature. Hence, it is a common practice to test various EAs with different characteristics in a specific optimization problem in order to examine which one yields the best solutions. One of the most popular EAs is the Differential Evolution (DE) algorithm [4]. The performance of DE relies heavily on the values of its control parameters and thus tuning is required before application. More sophisticated algorithms that are adaptive and require no tuning have been proposed based on DE. Some of these algorithms are Composite DE (CoDE) [5] and Success History based Adaptive DE with Linear population size reduction (L-SHADE) [6]. Finally, an algorithm that stands out for its simplicity as it does not have any algorithm-specific control parameters is Jaya [7].

The purpose of this study is to apply DE, CoDE, L-SHADE and Jaya algorithms in the waveform design for WPT problem and examine if they can introduce any improvement compared to the SCP-QCLP (Quadratically Constrained Linear Programming) method used in [3].

II. Model Description

The system model represents a Single Input Single Output (SISO) WPT system. It consists of a transmitter, a multipath propagation channel and a receiver rectenna (Fig. 1). The transmitted RF signal propagates through the medium and then is received and rectified by the rectenna (Fig. 2) in order to supply a load.

A. Transmitted and received waveforms

The transmitted signals incorporate multiple carriers and are structured in a way that has already been proposed in the literature. The main characteristic is that the sub-carriers are

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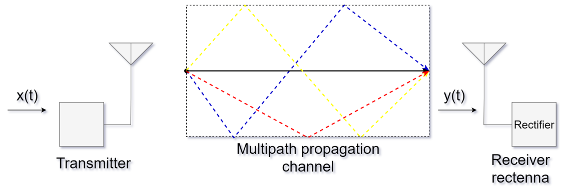

Fig. 1. The system model in Wireless Power Transfer technique.

evenly spaced in the frequency domain. These waveforms are periodic pulsed signals which can be expressed by:

$$x(t) = \Re\Big\{\sum_{n=1}^{N} s_n e^{j\phi_n} e^{j2\pi f_n t}\Big\} = \sum_{n=1}^{N} s_n cos(2\pi f_n t + \phi_n) \quad (1)$$

where n is a positive integer, $N \geq 1$ is the total number of sub-carriers, and s_n, ϕ_n, f_n are the amplitude in Volts, phase in radians, and frequency in Hz, of the n^{th} sub-carrier respectively. The s_n, ϕ_n, f_n values can be organized in vectors:

$$\boldsymbol{S} = [s_1, s_2, \cdots, s_N] \\ \boldsymbol{\Phi} = [\phi_1, \phi_2, \cdots, \phi_N] \\ \boldsymbol{F} = [f_1, f_2, \cdots, f_N] \quad (2)$$

The total number of sub-carriers and the associated f_n frequencies that form the transmitted signal are defined by the choice of the signal's central frequency (f_c), bandwidth (B) and pulse period (T_o). The minimum and maximum frequencies allowed in the signal's frequency spectrum are $f_{min} = f_c - \frac{B}{2}$ and $f_{max} = f_c + \frac{B}{2}$ respectively. Then, the frequencies f_n coincide with the multiples of $1/T_o$ included in the interval $[f_{min}, f_{max}]$.

The propagation channel is characterized by its frequency response at f_n:

$$H_n = A_n e^{j\psi_n} \quad (3)$$

where A_n is the amplitude and ψ_n is the phase. These values can be also organized in vectors $\boldsymbol{A}$ and $\boldsymbol{\Psi}$ respectively.

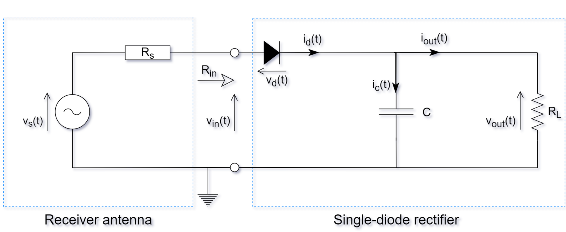

Fig. 2. Rectenna circuit model [3].

Assuming that the propagation channel is linear time-invariant, the incident wave upon the rectenna $y(t)$ is expressed by:

$$y(t) = \Re\Big\{\sum_{n=1}^{N} s_n A_n e^{j\phi_n} e^{j\psi_n} e^{j2\pi f_n t}\Big\} = \sum_{n=1}^{N} s_n A_n cos(2\pi f_n t + \phi_n + \psi_n) \quad (4)$$

B. Propagation channels

For the sake of realism, the propagation channels were devised in a laboratory environment. Their frequency response was obtained by Vector Network Analyzer (VNA) measurements in the interval [600 MHz, 1200 MHz], using a step of 1 MHz. In order to create a complex multipath propagation channel, we placed a rectangular box with highly reflective surfaces and various metal obstacles between the transmitter and the receiver. We conducted VNA measurements for four different propagation channels by placing the receiver antenna in four different positions respectively (Fig. 3). From the measurement data, we can calculate $\boldsymbol{A}$ and $\boldsymbol{\Psi}$ depending on the waveform characteristics.

C. Rectenna model

In this paper we used the rectenna model of Fig. 2 has been adopted in [2], [3]. It consists of an antenna followed by a single diode rectifier and a load. The receiver antenna is modeled by a voltage source $v_s(t)$ and a series impedance ($R_s = 50\ \Omega$), whereas the rectifier's input impedance and input voltage are denoted by R_{in} and $v_{in}(t)$ respectively. This model is deliberately simple and relies on several assumptions. The antenna is assumed to be lossless and the matching with the rectifier perfect ($R_s = R_{in} = 50\ \Omega$). Also, the antenna noise term is omitted and the diode's series resistance is neglected since it is considered to be ideal. All the values

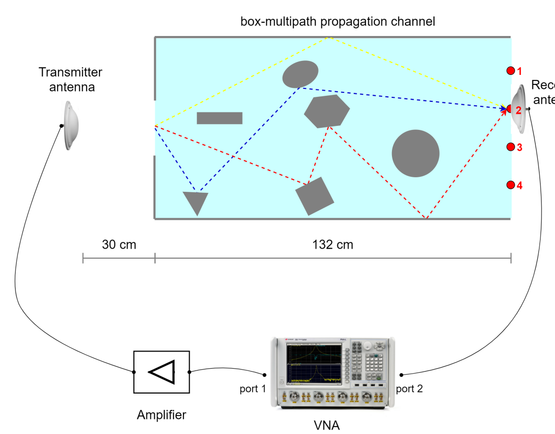

Fig. 3. Schematic view of the setup used for the VNA measurements of four multipath propagation channels. The top view of the three dimensional box interposed between the transmitter and the receiver is depicted.The box contains highly reflective metal objects placed randomly inside,while tinfoil is adhered to its inner walls.The position of the receiver antenna for each one of the four different channels is marked with red color and a corresponding number.

TABLE I
OPTIMAL F, CR VALUES OF DE ALGORITHM AND TERMINATION CRITERIA FOR WAVEFORMS WITH $B = 100$ MHZ BANDWIDTH.

T_o (ns)	N	FE_{max}	(F & CR)
20	2	500	(1 & 0.9)
40	4	5000	(0.4 & 0.8)
80	8	20000	(0.3 & 0.7)
160	16	50000	(0.3 & 0.9)
320	32	200000	(0.1 & 0.7)

associated with the components of this circuit are chosen to be same as in [3].

D. Objective function

The objective function used in this study was proposed in [3] and is derived by applying Kirchhoff's circuit laws to the rectenna's circuit model (Fig. 2), followed by some simple manipulation. According to the analysis in [3], the maximization of the DC power delivered to the load is equivalent to the maximization of the following objective function:

$$\beta(\boldsymbol{S}, \boldsymbol{\Phi}) = \frac{1}{T_o} \int_0^{T_o} e^{\frac{\sqrt{R_s} y(t)}{\eta V_t}} dt \tag{5}$$

Subject to the constraints:

$$s_n \geq 0 \quad and \quad \sum_{n=1}^{N} \frac{s_n^2}{2} \leq P_t \tag{6}$$

In (5), η is the ideality factor of the diode ($\eta = 1.05$) and V_t is the thermal voltage ($V_t = 25.86 \ mV$). In (6), P_t is the transmit power constraint in Watts.

The phases ϕ_n of the transmitted signal can be chosen optimally as $\phi_n = -\psi_n$, according to [2], [3]. Consequently, for a particular propagation channel and specified values of f_c, B and T_o, the optimization problem reduces to tracking the $\boldsymbol{S}$ that maximizes (5). It should be noted that the calculation of (5) requires the numerical computation of the integral and the method used in this study is the 2-point Newton-Cotes formula as in [3].

III. RESULTS

A. Application of algorithms

In this section, we apply DE, CoDE, L-SHADE, Jaya and SCP-QCLP algorithms in the waveform design for WPT problem. For this test we set $f_c = 910$ MHz, $B = 100$ MHz, and T_o = 20, 40, 80, 160, 320 ns. The propagation channels tested are the four channels described in II-B. Consequently, the total number of tested cases is 20. The transmit power constraint is set to P_t = -30 dBm. This choice leads to a $y(t)$ with average power that varies roughly from -13 dBm to -21 dBm, depending on the channel and the waveform. Each EA is executed 50 times per case. For each obtained solution $\boldsymbol{S}$, we calculate the rectified DC power using the appropriate expressions derived by the rectenna model of Fig. 2 and a bisection method as described in [3]. From this data, we calculate the average rectified DC power over 50 runs for each algorithm.

In the optimization problem of waveform design for WPT, the population vectors of any EA coincide with the vector of amplitudes $\boldsymbol{S}$, while the dimensionality (D) of the problem is equal to the waveform's total number of sub-carriers (N). The only necessary modification to the tested algorithms was the addition of a very simple mechanism for the substitution of the vectors that violate the boundary constraints of the specific problem.

As for the control parameter settings of the algorithms and the termination criteria (maximum number of function evaluations FE_{max}), we give out all the details in the following lines. Table I lists the termination criteria used in each case as well as the optimal control parameter values for DE. These values were obtained by conducting a parametric study for the 5 cases of the second propagation channel. The population size (NP) in the DE algorithm was set to $NP = 10D$. For CoDE the population size was set equal to D, but in the cases where $D < 6$ the population size was set to $NP = 6$. This is because the minimum required number of population vectors in CoDE is 6. In L-SHADE we set the mutation scheme parameter to $p = 0.11$, the size of the external archive to $A = 1.4NP$, the size of the historical memory to $H = 5$, the initial population size to $NP^{init} = 18D$, and the final population size to $NP^{min} = 4$. Finally, in Jaya, we set the population size to $NP = 10D$.

B. Performance comparison

The average rectified DC power for the waveforms designed by different algorithms is given in Table II. We observe that all WPT modes yield very similar average values of rectified DC power. In DE mode, a maximum percentage decrease of 2.96% compared to SCP-QCLP mode is observed in channel 1 for T_o = 320 ns. This is a mild performance degradation that could be addressed to the fact that F and CR were tuned based only on the second channel's cases. However, judging by the general outcome, these F and CR values seem to be quite suitable for all the tested channels. CoDE, L-SHADE and Jaya modes demonstrate a performance that can be considered equivalent to that of SCP-QCLP. Jaya's performance is just slightly degraded for $N = 32$, as we observe a maximum percentage decrease of 0.66% in channel 4. CoDE and L-SHADE generally display very small values of percentage increase in the rectified DC power compared to SCP-QCLP, with a maximum of around 0.06% in channel 4 for $T_o = 40$ ns. However, this increase is negligible and it is probably due to the value of the termination criterion used in SCP-QCLP mode (it was set to $\in = 10^{-3}$ as in [3]).

Despite the fact that we used EAs with different characteristics and suitable for different types of problems, they all converged practically to the same solutions. The best and worst values of rectified DC power given by each algorithm in each case were very similar. This is an indication that these solutions are possibly the globally optimal ones and that the tested algorithms can easily track them.

We should note that EAs didn't detect any solution in any of the cases to demonstrate more than 0.06% increase in the rec-

TABLE II
AVERAGE RECTIFIED DC POWER IN WATTS FOR DE, CODE, L-SHADE, JAYA AND SCP-QCLP WPT MODES. THE VALUES OF THE TABLE WERE CALCULATED OVER 50 RUNS OF EACH ALGORITHM. FOUR DIFFERENT PROPAGATION CHANNELS WERE TESTED AND MULTI-TONE WAVEFORMS WITH $B = 100$ MHz AND $T_o = 20, 40, 80, 160$ OR 320 ns. THE TRANSMITTED POWER WAS SET TO $P_t =$ -30 dBm.

Ch. No.	T_o (ns)	N	DE	CODE	L-SHADE	Jaya	SCP-QCLP
1	20	2	2,0784E-09	2,0784E-09	2,0784E-09	2,0784E-09	2,0784E-09
1	40	4	1,1236E-08	1,1221E-08	1,1239E-08	1,1239E-08	1,1236E-08
1	80	8	1,2948E-08	1,2966E-08	1,2966E-08	1,2966E-08	1,2961E-08
1	160	16	2,2155E-08	2,2156E-08	2,2156E-08	2,2154E-08	2,2152E-08
1	320	32	6,4281E-08	6,6245E-08	6,6245E-08	6,6031E-08	6,6243E-08
2	20	2	1,2062E-08	1,2062E-08	1,2062E-08	1,2062E-08	1,2062E-08
2	40	4	1,3837E-08	1,3836E-08	1,3837E-08	1,3837E-08	1,3829E-08
2	80	8	1,9669E-08	1,9669E-08	1,9669E-08	1,9669E-08	1,9666E-08
2	160	16	4,2089E-08	4,2089E-08	4,2089E-08	4,2081E-08	4,2088E-08
2	320	32	1,7623E-07	1,7630E-07	1,7630E-07	1,7568E-07	1,7630E-07
3	20	2	3,2990E-08	3,2990E-08	3,2990E-08	3,2990E-08	3,2990E-08
3	40	4	3,9686E-08	3,9686E-08	3,9686E-08	3,9686E-08	3,9685E-08
3	80	8	7,2231E-08	7,2379E-08	7,2379E-08	7,2379E-08	7,2357E-08
3	160	16	2,3419E-07	2,3419E-07	2,3419E-07	2,3412E-07	2,3419E-07
3	320	32	1,2162E-06	1,2180E-06	1,2180E-06	1,2125E-06	1,2180E-06
4	20	2	2,1149E-08	2,1149E-08	2,1149E-08	2,1149E-08	2,1149E-08
4	40	4	3,0328E-08	3,0326E-08	3,0328E-08	3,0328E-08	3,0308E-08
4	80	8	8,1711E-08	8,1841E-08	8,1841E-08	8,1841E-08	8,1822E-08
4	160	16	2,3133E-07	2,3133E-07	2,3133E-07	2,3123E-07	2,3133E-07
4	320	32	1,1046E-06	1,1074E-06	1,1074E-06	1,1001E-06	1,1074E-06

tified DC power compared to the SCP-QCLP solution. Also, we should remark that all EA methods have a disadvantage compared to SCP-QCLP, which is the longer execution time due to their stochastic nature. EAs are far more complicated algorithms and able to solve challenging objective functions, but this feature is not an advantage in this particular problem.

IV. CONCLUSION

In this paper, we investigated the application of EAs in the waveform design for WPT problem. More specifically, we applied DE, CoDE, L-SHADE and Jaya algorithms for the optimization of the transmitted multi-tone waveforms in a SISO WPT system in the presence of a multipath propagation channel. EAs seem to successfully track the optimal solutions to this non-convex problem since all four tested algorithms converge to very similar results. However, EAs were not able to track any significantly better solutions compared to the SCP-QCLP algorithm. This is an indication that the objective function's landscape for the tested propagation channels is not very complicated and the increased complexity of the EAs cannot provide any benefit compared to the SCP-QCLP algorithm.

The advantage of using EAs is that they are very flexible and can be used in conjunction with any objective function. To this end, a more realistic model of the rectifier, designed in some simulation software, could be integrated in the objective function. Also, EAs could be used for investigating the optimization of both the amplitudes and the phases of the transmitted signal. This could be interesting in a scenario were there is an additional Peak to Average Power Ratio constraint.

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