Differential Chaos Shift Keying-based Wireless Power Transfer

Priyadarshi Mukherjee, Constantinos Psomas, and Ioannis Krikidis
Department of Electrical and Computer Engineering, University of Cyprus
{mukherjee.priyadarshi,psomas,krikidis}@ucy.ac.cy

IRIDA Research Centre for Communication Technologies

University of Cyprus

1 Introduction

- Wireless traffic expected to increase more than five times between 2019 and 2025 [1]
- For applications where large number of devices are deployed, powering or charging becomes critical as well as costly
- Wireless power transfer (WPT) charges devices by harvesting energy from ambient/dedicated radio-frequency (RF) signals [2]
- Efficient WPT architectures rely on accurate models of the energy harvesting (EH) circuit
- Experimental studies [3] demonstrate that nonlinear rectification process at the EH circuit enables high PAPR signals like multitone signals and chaotic waveforms to provide higher DC output power

2 Motivation & Contribution

- Differential chaos shift keying (DCSK): widely studied chaotic signal-based communication system
- Majority of DCSK related works focus on error performance of such systems for various scenarios
- Few works [4],[7] investigate DCSK-based WPT, but they are unaware of the EH circuit characteristics or the design of excitation waveforms
- Motivated by this, we present a DCSK-based WPT architecture by taking into account the nonlinearities of the EH process. Specifically,
  1. Propose a novel WPT architecture, where an analog correlator is employed at the receiver to boost EH performance
  2. Demonstrate flexibility of the proposed architecture, as the correlator can control the PAPR of the received signal at the harvester
  3. Derive analytical expressions of PAPR and the harvested DC for both cases, i.e. with and without the correlator

  The analytical framework provides a convenient methodology for obtaining nontrivial insights into how key parameters affect the performance.

3 A Chaotic Signal-based WPT System Architecture

3.1 System Model

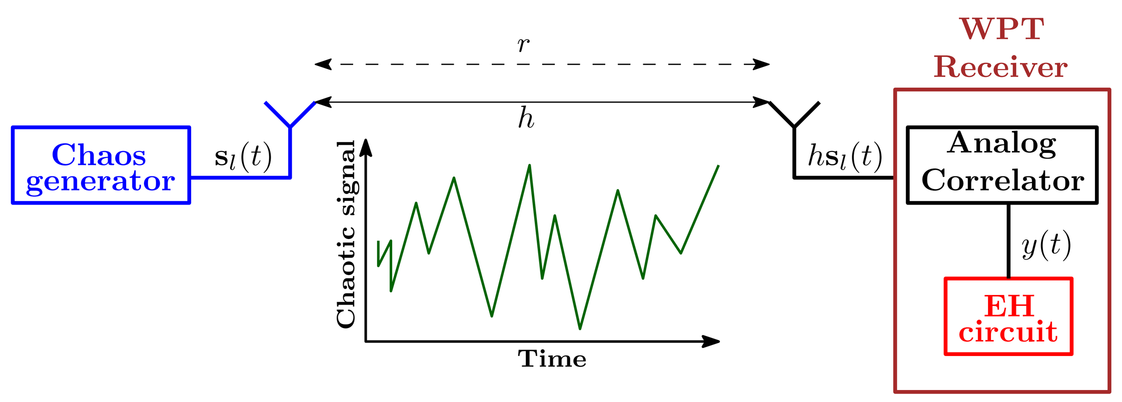

Figure 1: Proposed architecture for DCSK-based WPT.

- Point-to-point WPT set-up, where
  - Tx employs DCSK signal generator
  - Rx consists of an analog correlator, followed by an EH circuit
- Channel model
  - Small-scale fading: Rayleigh fading
  - Large-scale path loss: $r^{-\alpha}$, where $\alpha > 2$ is path loss exponent
- Considering nonlinear EH model, output DC current [2]

$$z_{\mathrm{DC}} = k_2 R_{ant}\mathbb{E}\{|y(t)|^2\} + k_4 R_{ant}^2 \mathbb{E}\{|y(t)|^4\}, \tag{1}$$

where k_2, k_4, R_{ant} are circuit parameters

3.2 Chaotic signals

- Each DCSK symbol represented by two consecutive chaotic signal components; the first one serves as the reference, while the second carries the data ± 1
- The l-th transmitted DCSK symbol is characterized by a sequence of 2β, $\beta > 0$, samples as [5]

$$s_{l,k} = \begin{cases} x_k, & k = 2(l-1)\beta + 1, \ldots, (2l-1)\beta, \\ d_l x_{k-\beta}, & k = (2l-1)\beta + 1, \ldots, 2l\beta, \end{cases} \tag{2}$$

where $d_l = \pm 1$ is the l-th information bit, and x_k is the chaotic basis signal.

- As 2β chaotic samples are used to spread each information bit, β is termed as the *spreading factor*
- Due to its good correlation properties, we consider the Chebyshev chaotic map of degree ξ [5]

3.3 Analog correlator

- Motivation for analog correlator [6]: control the signal at harvester input and enhance signal PAPR
- ψ-bit correlator consists of $(\psi - 1)$ delay blocks
- Considering $\psi = 2\beta$, correlator output for l-th transmitted symbol

$$y_l(t) = \sqrt{P_t} h_l \sum_{k=1}^{2\beta} s_{l,k}(t), \tag{3}$$

where P_t is transmission power

Proposition 1. The signal PAPR at the harvester input is

$$\mathrm{PAPR} = \begin{cases} 2, & \text{without correlator } (\psi = 1), \\ 4\beta, & \text{with correlator } (\psi = 2\beta). \end{cases} \tag{4}$$

- Since high PAPR signals are desirable for WPT [3], the correlator can significantly enhance the EH performance of the DCSK signals

4 Chaotic signal-based WPT

Theorem 1. When a correlator is employed, the harvested DC is

$$z_{\mathrm{C}} = \begin{cases} r^{-\alpha}\rho_1 + 6r^{-2\alpha}\rho_2, & \beta = 1, \\ r^{-\alpha}\rho_1\beta + 12r^{-2\alpha}\rho_2\beta^2, & \beta > 1. \end{cases} \tag{5}$$

Theorem 2. When a correlator is not employed, the harvested DC is given by

$$z_{\mathrm{NC}} = r^{-\alpha}\rho_1\beta + \frac{3}{2}r^{-2\alpha}\rho_2\beta. \tag{6}$$

- For simplicity, we use $\rho_1 = k_2 R_{ant} P_t$ and $\rho_2 = k_4 R_{ant}^2 P_t^2$
- z_{C} and z_{NC} is a **quadratic** and **linear** function of β, respectively $\implies z_{\mathrm{C}} > z_{\mathrm{NC}}, \forall\, \beta$
- $z_{\mathrm{C}} = z_{\mathrm{NC}}$ if a linear EH model is used, i.e. only the second order term of (1) is considered
- If r_{C} and r_{NC} be the Tx-Rx distances for z_{C} and z_{NC}, we obtain $z_{\mathrm{C}} > z_{\mathrm{NC}}$, even when $r_{\mathrm{C}} > r_{\mathrm{NC}}$. To achieve this, β needs to satisfy

$$\beta > \frac{\rho_1\left(r_{\mathrm{NC}}^{-\alpha} - r_{\mathrm{C}}^{-\alpha}\right) + 1.5\rho_2 r_{\mathrm{NC}}^{-2\alpha}}{12\rho_2 r_{\mathrm{C}}^{-2\alpha}} \tag{7}$$

- N-tone multisine waveform [2] results in a z_{DC} whose linear term is independent of N and nonlinear term is linearly dependent on N
- Linear and nonlinear terms of z_{C} are proportional to β and β^2
  $\implies$ **WPT performance of proposed DCSK-based architecture is significantly greater than existing multisine waveform-based set-up**

5 Numerical Results

Parameters: $P_t = 30$ dBm, path-loss exponent $\alpha = 4$, $k_2 = 0.0034$, $k_4 = 0.3829$, and $R_{ant} = 50\,\Omega$ [2]

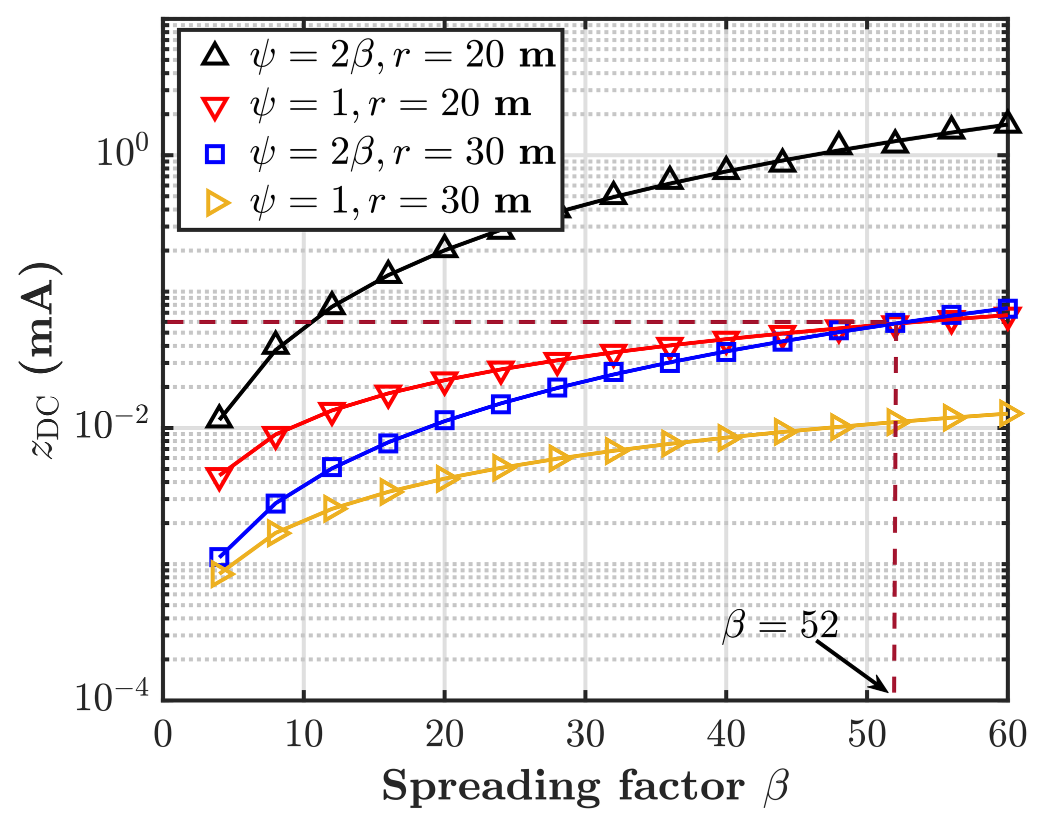

Figure 2: Effect of spreading factor on z_{DC}; lines correspond to analysis and markers correspond to simulation results.

- Significant gain in WPT performance with the correlator is related to the high PAPR, which is a function of the spreading factor β, as stated in Proposition 1
- With/without the correlator at Rx, the harvested DC with Tx-Rx distance 30 m is less compared to the harvested DC with Tx-Rx distance 20 m; this is intuitive due to the path-loss factor
- z_{C} with Tx-Rx distance of 30 m outperforms z_{NC} with a Tx-Rx distance of 20 m for $\beta > 52$, which matches the bound proposed in (7)

6 Conclusions

- Employed a communication-based waveform for WPT and proposed a new analog correlator-aided WPT architecture
- Investigated DCSK-based WPT, by taking into account the nonlinearities of the EH process
- Derived analytical expressions of harvested DC for both cases, i.e. with and without the correlator

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