Differential Chaos Shift Keying-based Wireless Power Transfer

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IEEE 46th International Conference on Acoustics, Speech, & Signal Processing, 2021

Outline

Introduction

- 5G cellular networks
  - Data rate $\times 1000$ from 4G
  - More than 1.7 billion subscribers by 2025[1]
  - Numerous battery-operated devices
- Wireless power transfer (WPT) $\Longrightarrow$ energy harvesting from ambient/dedicated radio-frequency (RF) signals
- Experimental studies[2] demonstrate that chaotic waveforms outperform conventional single-tone signals in terms of WPT efficiency

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[1] Ericsson Mobility Report, June 2020.

[2] A. Collado and A. Georgiadis, "Improving wireless power transmission efficiency using chaotic waveforms," in *Proc. IEEE Int. Microw. Symp. Dig.*, Montreal, QC, Canada, Aug. 2012, pp. 1–3.

Motivation and 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[3,4] investigate DCSK-based WPT, but by considering a simplified linear model for energy harvesting (EH)

Contribution

- Propose a novel analog correlator-aided DCSK-based WPT architecture by taking into account the nonlinearities of the EH process
- Analyze the system in terms of transmitted waveform parameters

[3] G. Kaddoum, H. Tran, L. Kong, and M. Atallah, "Design of simultaneous wireless information and power transfer scheme for short reference DCSK communication systems," *IEEE Trans. Commun.*, vol. 65, no. 1, pp. 431–443, Jan. 2017.

[4] M. Qian, G. Cai, Y. Fang, and G. Han, "Design of link-selection strategies for buffer-aided DCSK-SWIPT relay system," *IEEE Trans. Commun.*, vol. 68, no. 10, pp. 6023–6038, Oct. 2020.

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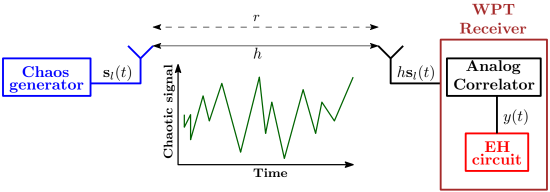
System Model



- Point-to-point WPT set-up, where
  1. Tx employs DCSK signal generator
  2. 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[5]

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

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

[5] B. Clerckx and E. Bayguzina, "Waveform design for wireless power transfer," *IEEE Trans. Signal Process.*, vol. 64, no. 23, pp. 6313–6328, Dec. 2016.

Chaotic signals

- DCSK symbol $\Longrightarrow$ two chaotic components: first one serves as reference and the second carries data ± 1
- l-th transmitted DCSK symbol is characterized as[6]

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

  where $d_l = \pm 1$ is l-th information bit and x_k is chaotic basis signal
- 2β samples spread each $d_l \; \forall \; l \implies \beta$ is the "*spreading factor*"
- Chebyshev chaotic map of degree ξ is consider in this work[6]

[6] F. C. M. Lau, C. K. Tse, Ming Ye, and S. F. Hau, "Coexistence of chaos-based and conventional digital communication systems of equal bit rate," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 51, no. 2, pp. 391–408, Apr. 2004.

Analog correlator

- Motivation for analog correlator[7]:
  1. control the signal at harvester input
  2. enhance signal PAPR
- ψ-bit correlator consists of $(\psi - 1)$ delay blocks
- Considering $\psi = 2\beta$, correlator output for l-th transmitted symbol

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

where P_t is transmission power

Proposition 1

The signal PAPR at the harvester input is

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

[7] V. Mangal and P. R. Kinget, "Clockless, continuous-time analog correlator using time-encoded signal processing demonstrating asynchronous CDMA for wake-up receivers," *IEEE J. Solid-State Circuits*, vol. 55, no. 8, pp. 2069–2081, Aug. 2020.

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Chaotic Signal-based Wireless Power Transfer

Theorem 1

When a correlator is employed, the harvested DC is

$$z_C = \begin{cases} r^{-\alpha}\rho_1 + 6r^{-2\alpha}\rho_2, & \beta = 1, \\ r^{-\alpha}\rho_1\beta + 12r^{-2\alpha}\rho_2\beta^2, & \beta > 1. \end{cases} \quad (5)$$

Theorem 2

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

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

- 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 $\implies$ For fixed r, ρ_1 and ρ_2, we have $z_{\mathrm{C}} > z_{\mathrm{NC}}, \forall\ \beta$

- $z_C = z_{NC}$ if a linear EH model is used, i.e. only the second order term of (1) is considered

Remark 1

If r_C and r_{NC} be the Tx-Rx distances for z_C and z_{NC}, we obtain $z_C > z_{NC}$, even when $r_C > r_{NC}$. To achieve this, β needs to satisfy

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

- N-tone multisine waveform[5] 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

$\Longrightarrow$ **WPT performance of proposed DCSK-based architecture is significantly greater than existing multisine waveform-based set-up**

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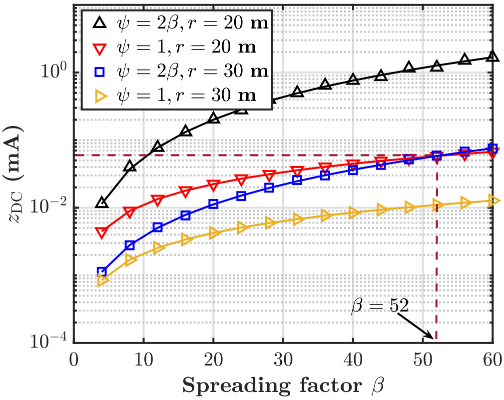

Figure 1: Effect of spreading factor on $z_{\rm DC}$

- Significant performance gain related to high PAPR, which is a function of β, as stated in Proposition 1
- $z_{\rm C}$ with $r_{\rm C} = 30$ m outperforms $z_{\rm NC}$ with $r_{\rm NC} = 20$ m when $\beta > 52$. This matches the bound proposed in (7)

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Conclusion & Future work

Conclusion

- 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

Future work

Investigate the impact of this framework in applications like SWIPT

Thanks for your attention!

This work has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant agreement No. 819819). This work was also co-funded by the European Regional Development Fund and the Republic of Cyprus through the Research and Innovation Foundation, under the projects INFRASTRUCTURES/1216/0017 (IRIDA) and EXCELLENCE/0918/0377 (PRIME).