

Wireless Powered Communications in the Era of 6G

CNI Seminar Series

Ioannis Krikidis, *FIEEE*

IRIDA Research Laboratory for Communication Technologies
Department of Electrical and Computer Engineering
University of Cyprus

e-mail: krikidis@ucy.ac.cy

September 28, 2026



European
Research
Council





1 Introduction & Basic Background

- Wireless Power Transfer Technologies
- Wireless Powered Communications

3 Conclusion

2 Research Studies

- Mathematical modelling
- Fundamental limits
- Link-layer design
- System-level design
- Experimental studies



1 Introduction & Basic Background

- Wireless Power Transfer Technologies
- Wireless Powered Communications

3 Conclusion

2 Research Studies

- Mathematical modelling
- Fundamental limits
- Link-layer design
- System-level design
- Experimental studies



1 Introduction & Basic Background

- Wireless Power Transfer Technologies
- Wireless Powered Communications

3 Conclusion

2 Research Studies

- Mathematical modelling
- Fundamental limits
- Link-layer design
- System-level design
- Experimental studies

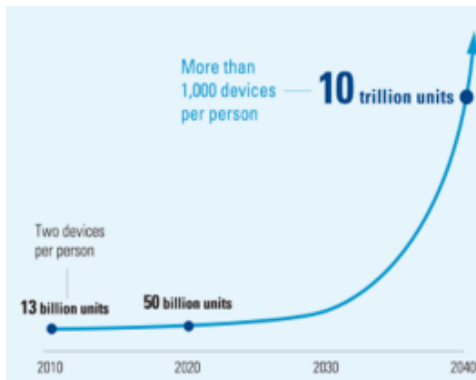
Motivation



Conventional wireless technologies → limited battery lifetime.

- Frequent battery replacement/recharging.
- Infeasible (e.g., implanted medical devices, hazardous environments).
- High cost (massive number of wireless devices in 5G/6G); battery disposal.

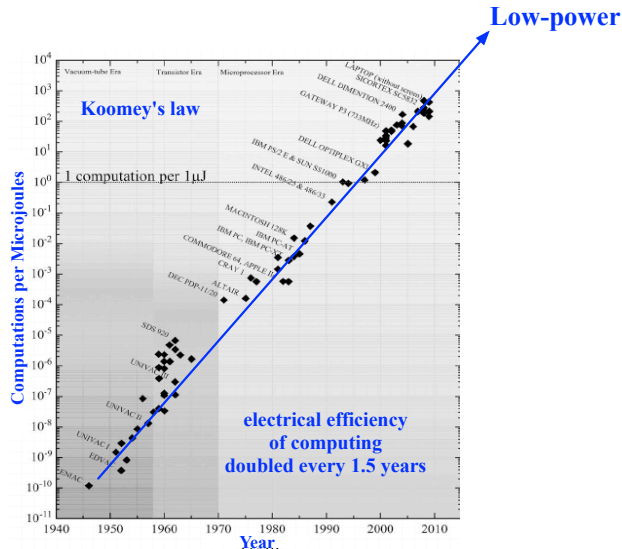
- 2022: 50 Billion of phones.
- 2035: 10 Trillion of IoT devices.



Wireless Energy Harvesting



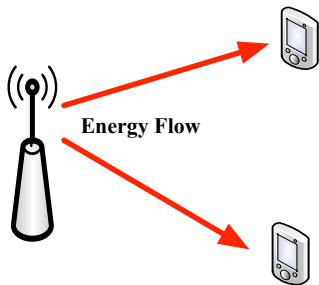
- Harvest energy from
→ ambient RF radiation
- Low power consumption
→ state-of-the-art sensors $10\mu\text{Watt}$
- Exponential growth of wireless systems
→ TV, radio, cellular, WiFi, etc.
- Unreliable and unpredictable process.





Wireless Power Transfer (WPT) → deliver power wirelessly (without wires) through a generated/controlled electromagnetic field.

- Continuous, stable, and fully-controlled (vs. ambient energy harvesting).
- Applications with critical quality-of-service (QoS) constraints.



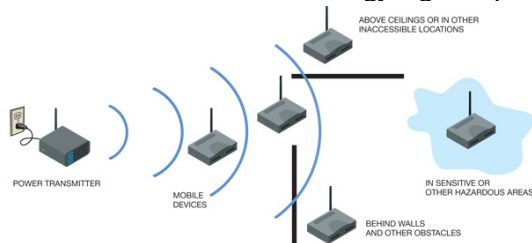
Three technologies available:

- ① Inductive coupling.
- ② Coupled magnetic resonance.
- ③ Electromagnetic (EM) radiation.

Electromagnetic Radiation

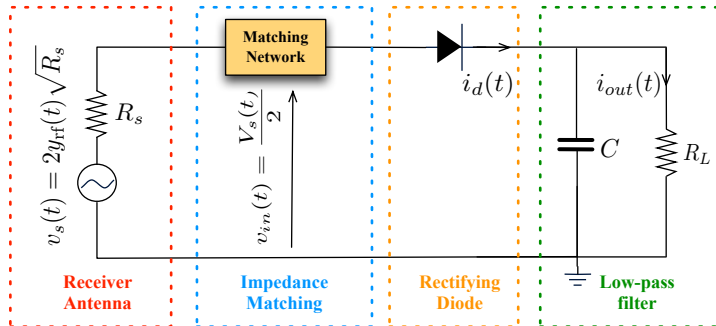


- Electromagnetic radiation uses propagation waves for WPT
→ antennas are used to transmit and receive energy signals (**far-field**).



- **Long range**, small TX/RX devices, flexibility, multicasting, mobility, LOS/NLOS environments, easy implementation in wireless communication systems.
- Low efficiency, safety issues.
- Industry: PowerCast, Ossia, Energous etc
- Industrial standard: Airfuel Alliance, **3GPP Passive IoT**.
- Applications: Wireless sensor networks, consumer electronics, IoT, RFID tags etc.

Rectenna Model



Physics-based diode model

Output DC current: Time average of the diode current $i_d(t)$

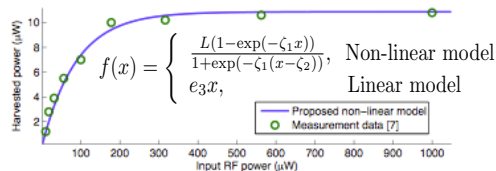
$$i_{out} = \mathbb{E}[i_d(t)] \approx \sum_{i \text{ even}}^{n_0} k_i \mathbb{E}[y_{rf}(t)^i]$$

Linear model ($n_0 = 2$): $i_{out} = k_2 P_{RF}^r$

Non-linear model ($n_0 = 4$): $i_{out} = k_2 P_{RF}^r + k_4 (P_{RF}^r)^2$

Curve fitting diode model

Parametric non-linear function/curve fitting $P_{DC}^r = f(P_{RF}^r)$

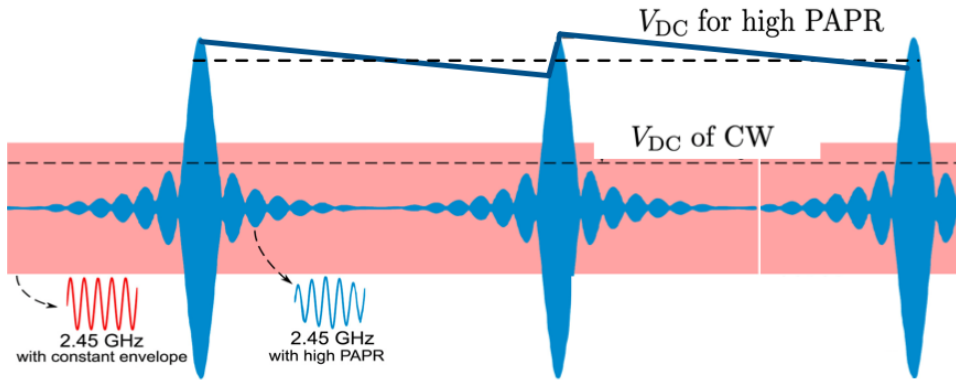




Wireless Power Transfer: PAPR

Signals with high peak-to-average power ratio (PAPR) boost the wireless energy harvesting e.g., multisine signals, OFDM, chaotic signals etc.

- High-power amplifier (HPA) nonlinearities (?)
- PAPR enhances WPT but deteriorates information transfer.





1 Introduction & Basic Background

- Wireless Power Transfer Technologies
- Wireless Powered Communications

3 Conclusion

2 Research Studies

- Mathematical modelling
- Fundamental limits
- Link-layer design
- System-level design
- Experimental studies

Wireless Powered Communications- Network architectures



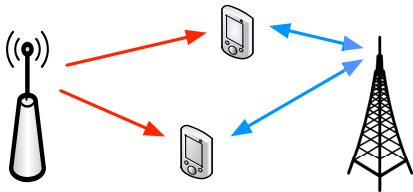
Wireless Powered Communications (WPC) - integration of the WPT process in wireless communication systems (**energy** and **information** flows co-exist).

1 Wireless Powered Communications Networks (WPCN)

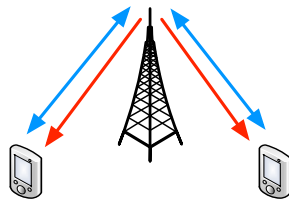
- **Orthogonal (frequency/time)** information and power transfer.
- Trade-off due to orthogonality of resources; design is optimized for each operation mode.

→ Energy Flow

→ Information Flow



Separate Information & Energy Transmitters



Co-located Information & Energy Transmitters

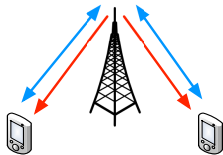
Wireless Powered Communications: Network Architectures (2)



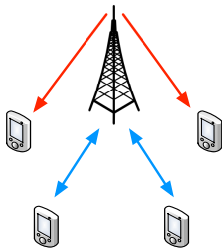
② Simultaneous Wireless Information and Power Transfer (SWIPT)

- **Simultaneous (same waveform)** information and power transfer.

→ Energy Flow
→ Information Flow

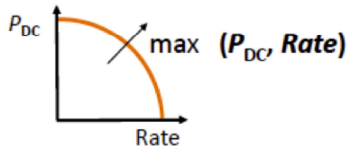


Co-located Information & Energy Receivers



Separate Information & Energy Receivers

Information-Energy Trade-off



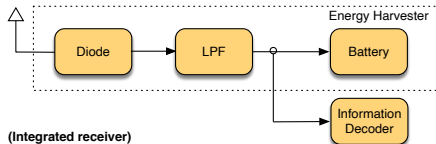
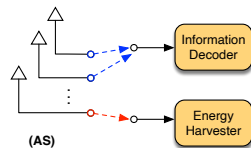
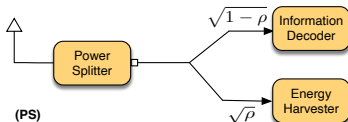
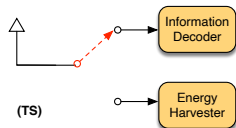
• Fundamental information-energy trade-off

- TX signal design; input distribution, modulation, waveform, precoding etc.
- Receiver structure/signal processing techniques (Wireless devices).

Practical Receiver Structures



- Information theoretic studies assume that a signal simultaneously can be used for decoding/harvesting (outer bound) [Varshney'08].
- Practical techniques: time switching (TS), power splitting (PS), antenna switching (AS); integrated receiver.

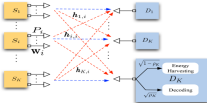
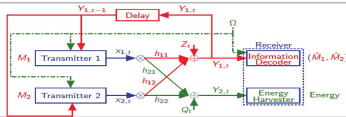
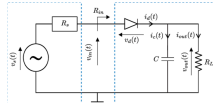


A Bottom-up Cross-Layer Research Approach



Advanced signal processing technologies for wireless powered communications (APOLLO)

erc
European Research Council
Established by the European Commission

Experimental		- Software-defined Radio - Fine-tune theoretical models ✓ Microwaves/antenna
System-level		- Macroscopic modeling, analysis - Cellular, ad-hoc architectures - Multi-user interference, randomness ✓ Stochastic Geometry, probability theory
Link Design		- Waveforms, modulation, precoding - SWIPT architectures ✓ Signal processing ✓ Optimization theory
Fundamentals Limits		- Trade-off information-energy - Input distribution ✓ Information theory
Modelling		- Accurate rectenna modeling - Non-idealities (RC filter etc) ✓ Circuit analysis

Bottom-up design approach



1 Introduction & Basic Background

- Wireless Power Transfer Technologies
- Wireless Powered Communications

3 Conclusion

2 Research Studies

- Mathematical modelling
- Fundamental limits
- Link-layer design
- System-level design
- Experimental studies



1 Introduction & Basic Background

- Wireless Power Transfer Technologies
- Wireless Powered Communications

3 Conclusion

2 Research Studies

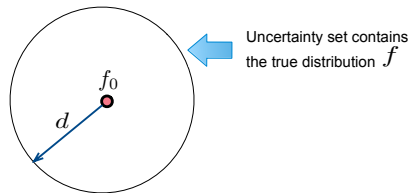
- Mathematical modelling
- Fundamental limits
- Link-layer design
- System-level design
- Experimental studies

WPT under Kullback-Leibler Distribution Uncertainty



- Existing models neglect important practical phenomena e.g., antenna mismatching, parasitic effects, RC filter etc. (distribution uncertainty)
- the (unknown) distribution is within a given Kullback-Leibler divergence from a nominal distribution i.e., $\mathcal{D}_{\text{KL}}(f_0||f) \leq d$.

$$(P1) \quad \min_f \int x f(x) dx \quad (\text{Av. harvested energy})$$
$$\text{s.t. } \mathcal{D}_{\text{KL}}(f_0||f) \leq d, \quad \int f(x) dx = 1.$$



Theorem

The actual distribution that achieves the minimum average harvested energy is $f(x) = \frac{1}{q(\mu^*)} \frac{f_0(x)}{x + \mu^*}$, where μ^* is the solution of the (1- dimensional) equation $\int f_0(x) \log[q(\mu)(x + \mu)] dx = d$ and $q(\mu) = \int \frac{f_0(x)}{x + \mu} dx$.

- KL divergence asymmetry i.e., $\mathcal{D}_{\text{KL}}(f||f_0) \leq d$.
- Symmetrized divergence i.e., $\mathcal{D}_{\text{SYM}}(f_0, f) = \frac{1}{2} [\mathcal{D}_{\text{KL}}(f_0||f) + \mathcal{D}_{\text{KL}}(f||f_0)]$.

WPT under KL Distribution Uncertainty (2)

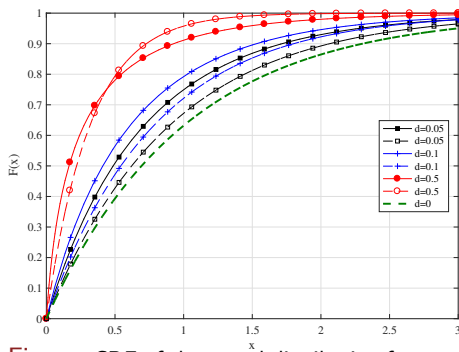


Figure: CDF of the actual distribution for different values of d ; solid-lines and dashed-lines correspond to the KL divergence $\mathcal{D}_{\text{KL}}(f_0||f)$ and $\mathcal{D}_{\text{KL}}(f||f_0)$, respectively; nominal distribution $f_0(x) = \exp(-x)$.

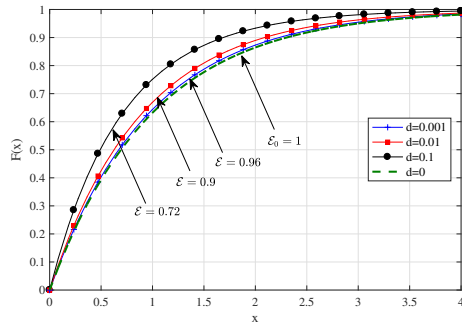


Figure: CDF of the actual distribution under symmetrized divergence uncertainty for different values of d ; nominal distribution $f_0(x) = \exp(-x)$.

- Uncertainty (d) affects the harvested energy.
- Symmetrized divergence is a balance between the two KL metrics.



1 Introduction & Basic Background

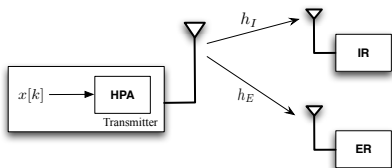
- Wireless Power Transfer Technologies
- Wireless Powered Communications

3 Conclusion

2 Research Studies

- Mathematical modelling
- Fundamental limits
- Link-layer design
- System-level design
- Experimental studies

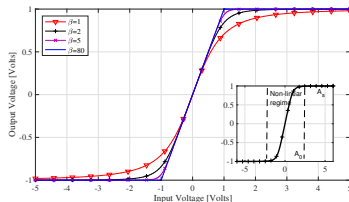
SWIPT with Power Amplifier Nonlinearity



- Information-Energy capacity region (?)
- Input distribution (?)

- PAM signal $x(t) = \sum_{k=-\infty}^{\infty} x[k]p(t - kT)$, with rectangular $p(t)$.
- $x[k]$ i.i.d real random variable X with CDF $F_X(x)$.
- AP: $\mathbb{E}[X^2] \leq \sigma_x^2$, PP: $|X| \leq A$, where A is the peak amplitude.
- Energy harvesting $\propto \mathbb{E}[I_0(Bh_E|\hat{X}|)]$ (power channel).
- Solid state power amplifier (SSPA) model i.e., $\hat{X} = d(X)$.

$$d(r) = \frac{r}{\left[1 + \left(\frac{r}{A_s}\right)^{2\beta}\right]^{\frac{1}{2\beta}}},$$



Power Ampl. Nonlinearity: Information-Energy Capacity Region



- We consider firstly the case where the IR is not present/active.

$$(P1) \quad \max_{F_X} \quad \mathbb{E}[I_0(Bh_E|\hat{X}|)]$$
$$\text{s.t.} \quad \mathbb{E}[X^2] \leq \sigma_X^2, |X| \leq A.$$

- The optimal input probability function F_X is binary or ternary.
- We consider the case where the target of the system is to maximize the Shannon information capacity under both AP and PP constraints.

$$(P2) \quad \max_{F_X} \quad I(X; Y)$$
$$\text{s.t.} \quad \mathbb{E}[X^2] \leq \sigma_X^2, |X| \leq A,$$

- F_X is unique, finite and discrete [Smith, 1971].
- For small A , there is no trade-off between information/energy (binary input distribution)
- The other points of the boundary $I_{\min} \leq I \leq I_{\max}$ and $\mathcal{E}_{\min} \leq \mathcal{E} \leq \mathcal{E}_{\max}$; see (P2) with the extra constraint $\mathcal{E}_{\min} \leq \mathbb{E}[I_0(Bh_E|\hat{X}|)] \leq \mathcal{E}_{\max}$.

Power Ampl. Nonlinearity: Numerical Results

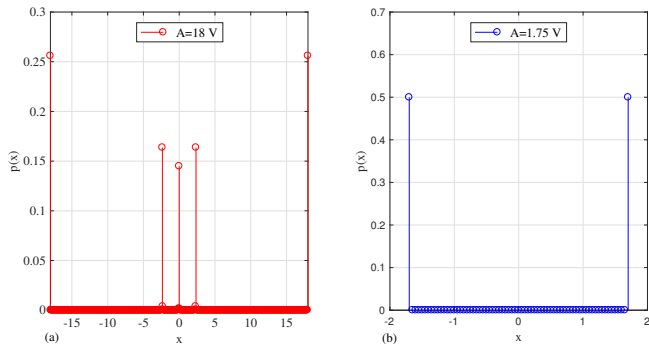


Figure: Input mass probability distribution for maximum information transfer; $\beta = 1$, $B = 0.5$, $\sigma_x^2 = 30$ dB, and (a) $A = 18$, and (b) $A = 1.75$.

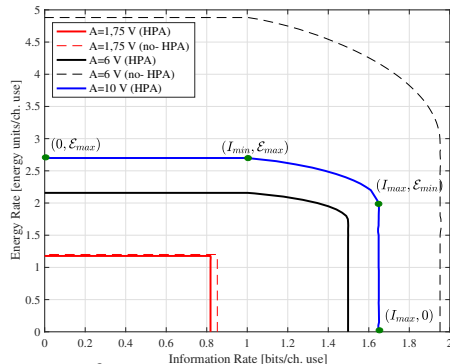


Figure: Information-energy capacity region; $A_s = 5$, $\beta = 1$, $B = 0.5$, $\sigma_x^2 = 30$ dB.

- ✓ A digital pre-distortion is proposed to compensate HPA nonlinearities [ISIT'20].
- ✓ Extension for scenarios with Rayleigh fading channel [TCOM'23].



1 Introduction & Basic Background

- Wireless Power Transfer Technologies
- Wireless Powered Communications

3 Conclusion

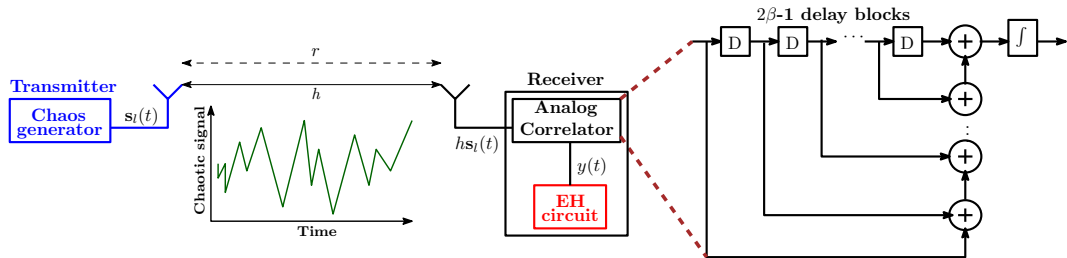
2 Research Studies

- Mathematical modelling
- Fundamental limits
- Link-layer design
- System-level design
- Experimental studies

Differential Chaos Shift Keying (DCSK) for WPT



- Chaotic signals provide high PAPR and are promising for WPT (experimental).
- No mathematical framework to prove/validate these observations.
- Design DCSK-based waveforms for WPT.

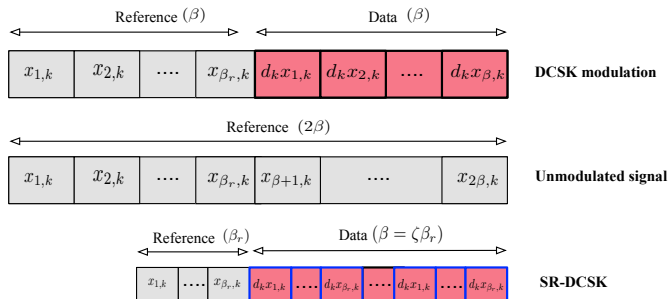


- ✓ A new receiver architecture- analog correlator (AC) to boost WPT performance.
- ✓ AC controls the input signal; enhances PAPR [DCSK: from 2 (no AC) to 4β (AC)].

DCSK-based chaotic signals



- Chebyshev chaotic map of degree ξ i.e., $x_{k+1} = \cos(\xi \cos^{-1}(x_k))$, $\forall |x_k| < 1$.

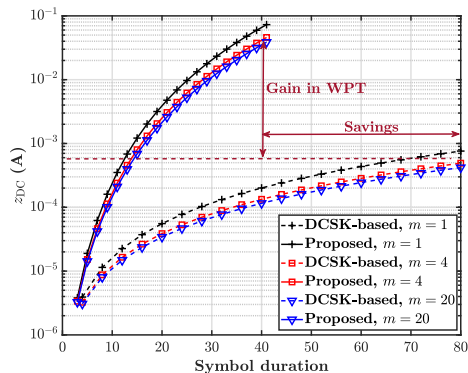
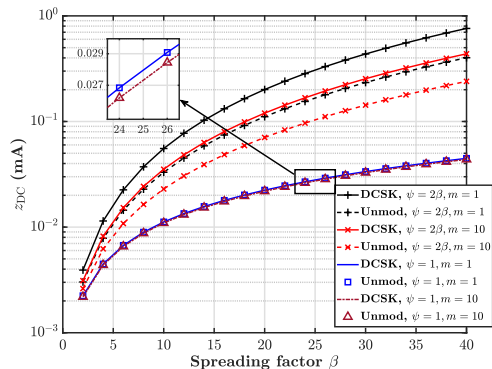


- DCSK Modulation-** two chaotic components i.e., the first one serves as reference and the second carries data $d_k = \pm 1$; β is the “*spreading factor*”.
- Unmodulated signal-** deterministic chaotic signals of length 2β .
- Short-reference DCSK (SR-DCSK)-** unmodulated reference of length β_r , followed by ζ modulated replicas.
 - ✓ Mathematical framework to study the performance of the proposed waveforms.
 - ✓ Optimal SR-DCSK configuration; $\beta_r = 1$ (*one chaotic chip $\rightarrow$ half symbol length*).

DCSK-based chaotic signals- Numerical Results



- $P_t=30$ dBm, $r = 20$ m, $\alpha = 4$, Nakagami- m .



- ✓ DCSK outperforms unmodulated signal when AC is employed; identical performance when AC is not used- beneficial role of PAPR.
- ✓ Increasing m (Nakagami- m) decreases WPT performance- beneficial role of fading.
- ✓ SR-DCSK results provides the highest harvested DC e.g., two orders of magnitude - half symbol length; beneficial role of correlation.



1 Introduction & Basic Background

- Wireless Power Transfer Technologies
- Wireless Powered Communications

3 Conclusion

2 Research Studies

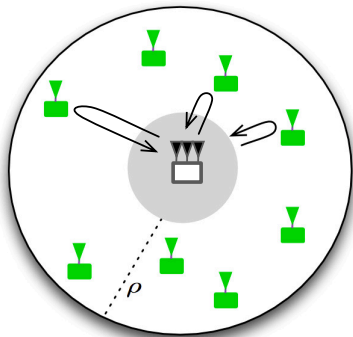
- Mathematical modelling
- Fundamental limits
- Link-layer design
- System-level design
- Experimental studies

Retrodirective Energy Beamforming in Backscatter Multi-User Networks



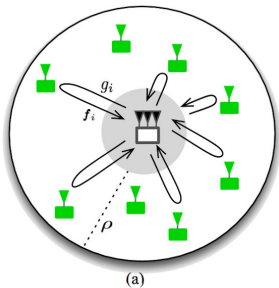
- Energy beamforming (EB) i.e., focusing the transmitted energy to the receivers' direction.
- Channel state information (CSI) at the transmitter e.g., feedback channel.

Retrodirective EB with backscattering: (a) Retrodirectivity i.e., retransmitting to the direction of arrival without processing, (b) Backscattering.



- Disc of radius ρ ; exclusive zone of radius ξ .
- Energy transmitter (ET) has a large number of antennas M .
- Energy receivers (ERs) form an HPPP $\Phi = \{x_i\}$ with density λ .
- Transmission power P_T and $M \gg K$ (massive MIMO); channel reciprocity.
- β_i reflection coefficient for the i -th ER.
- Path-loss $d^{-\alpha}$ with $\alpha > 2$, Rayleigh fading.

Retrodirective Energy Beamforming: Two Phases



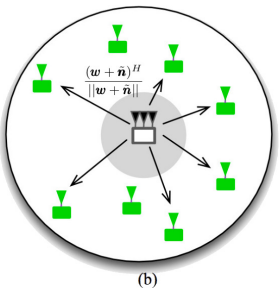
(a) Backscattering Phase

- ET broadcasts an unmodulated single-tone

$$x(t) = \sqrt{2P_t} \cos(2\pi f_c t), \quad t \in [0, \tau]$$

- The received signal (complex equivalent) at the ET is given by

$$\mathbf{y}(t) = \sum_{x_k \in \Phi} \sqrt{\frac{\beta_k P_t}{M d_k^{2\alpha}}} g_k \mathbf{f}_k + \mathbf{n}(t), \quad \text{where } g_k = \sum_{m=1}^M f_{k,m}.$$



(b) Energy Beamforming Phase

- Energy signal $\mathbf{x}_e = (\mathbf{w} + \tilde{\mathbf{n}})^H / \|\mathbf{w} + \tilde{\mathbf{n}}\|$, where $\mathbf{w} = \sum_{x_k \in \Phi} \sqrt{\frac{\beta_k P_t}{M d_k^{2\alpha}}} g_k^* \mathbf{f}_k^H$;

$$\text{received signal } y_i = \sqrt{P_t d_i^{-\alpha}} \mathbf{x}_e \mathbf{f}_i + z.$$

- Harvested energy at the i -th ER i.e.,

$$Q(\beta, d_i) = \zeta |y_i|^2 = \underbrace{\zeta P_t d_i^{-\alpha}}_{Q_{\text{OM}}(d_i)} + \underbrace{\frac{\zeta P_t M d_i^{-3\alpha} \beta_i |g_i|^2}{\sum_{x_k \in \Phi} d_k^{-2\alpha} \beta_k |g_k|^2 + \frac{M \sigma^2}{P_t \tau}}}_{Q_{\text{RE}}^\Phi(\beta, d_i)}.$$



① **Distance-Inversion Backscattering (DIB)** i.e., the reflection coefficient is a function of the location i.e., $\beta_i = (d_i/\rho)^{2\alpha}$; user fairness.

② **Full Backscattering (FB)** i.e., $\beta_i = 1$ ($\forall x_i \in \Phi$).

$$Q_{\text{FB}} \rightarrow \Lambda(\xi, \rho) \quad \text{for } \lambda \rightarrow \infty, \text{ [Non-backscattering]},$$

$$Q_{\text{FB}} \rightarrow M\Lambda(\xi, \rho) \text{ for } \lambda \rightarrow 0, \text{ [CSI/Beamforming]}.$$

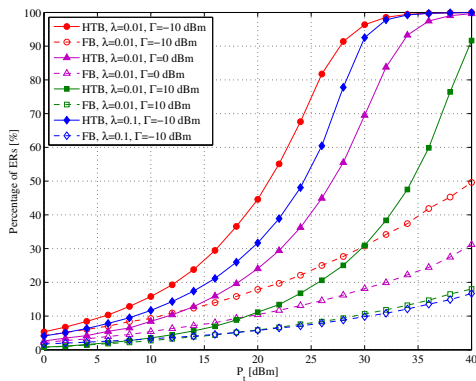
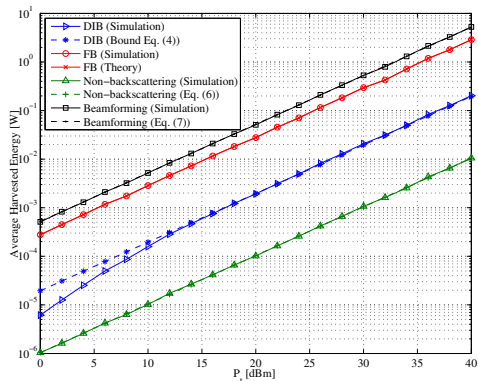
③ **Harvesting-Target Backscattering (HTB)**; a minimum harvested energy from the retrodirective component i.e., $Q_{\text{RE}}^{\Phi}(\beta, d_i) \geq \Gamma_i$.

- Power control problem (Foschini-Miljanic algorithm) i.e., $\beta_i(l+1) = \min \left(1, \frac{\Gamma_i \beta_i(l)}{Q_{\text{RE}}^{\Phi}(\beta(l), d_i)} \right)$

Retrodirective Energy Beamforming: Numerical Results



- $M = 500$, $\lambda = 0.01$, $f_c = 900$ MHz, $\alpha = 3$, $\sigma^2 = -150$ dBm, $\tau = 10^{-8}$ sec, $\xi = 2$ m, $\rho = 30$ m, $\zeta = 1$, $\Gamma_i = \Gamma$.



- FB provides a performance that is close to the perfect beamforming
- DIB provides fairness among ERs.
- The percentage of the ERs that satisfy Γ decreases, as Γ and λ increase.
- HTB outperforms FB; performance gain increases as P_t increases.



1 Introduction & Basic Background

- Wireless Power Transfer Technologies
- Wireless Powered Communications

3 Conclusion

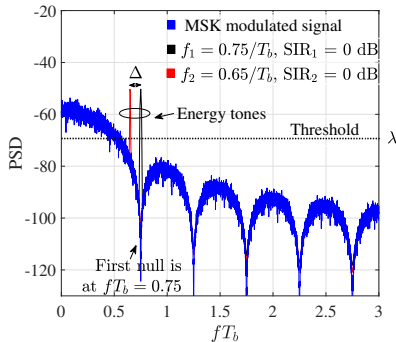
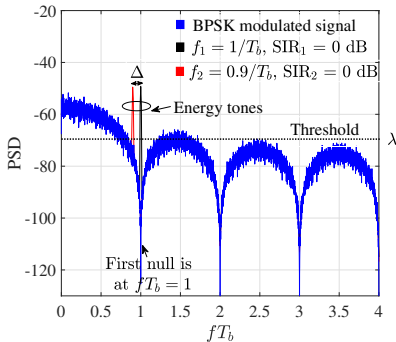
2 Research Studies

- Mathematical modelling
- Fundamental limits
- Link-layer design
- System-level design
- Experimental studies

Frequency-domain SWIPT Waveform



- Design of a SWIPT waveform in the frequency domain.
 - Energy tones are superimposed at the **spectral nulls or/and low-power sub-bands** that characterize the PSD of the information-bearing signal.
 - Consequently, the resulting interference is tolerable (i.e., below a threshold λ).



FD-SWIPT does not require complicated structural/system modifications; promising solution for practical systems (e.g., 5G, WiFi etc).

Experimental Validation



- Harvested energy vs. Tx-Rx distance for different number of energy tones; MSK modulation, TX gain 30 dB (20 dBm).

Hardware Configuration	Details
Computer	Hp Probook 16GB RAM Core i5 processor
SDR (TX and ID RX)	USRP-2920
RF energy harvester	Powercast P21XXCSR
Access point (WPT measurements)	Microchip MRF24J40
Experimental parameters	
RF carrier frequency	915 MHz
Sampling rate	1 MSamples/s

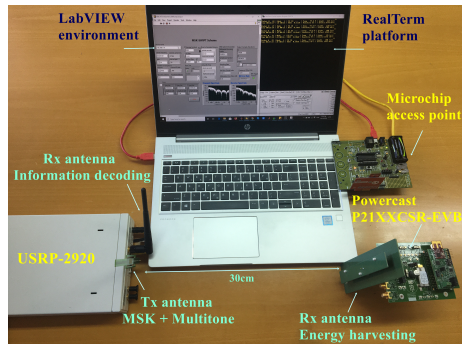


Figure: SDR-based testbed.

Experimental Validation

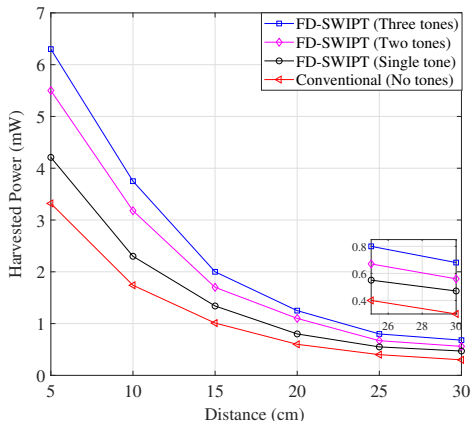


Figure: Harvested power vs. Tx-Rx distance for different number of energy tones.

- Harvested power increases as the number of tones increases.
- Negligible loss in probability of error; transparent EH process.

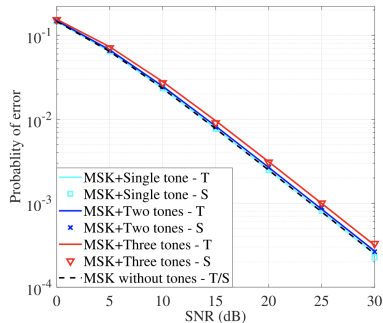


Figure: Error Probability vs. SNR.



1 Introduction & Basic Background

- Wireless Power Transfer Technologies
- Wireless Powered Communications

3 Conclusion

2 Research Studies

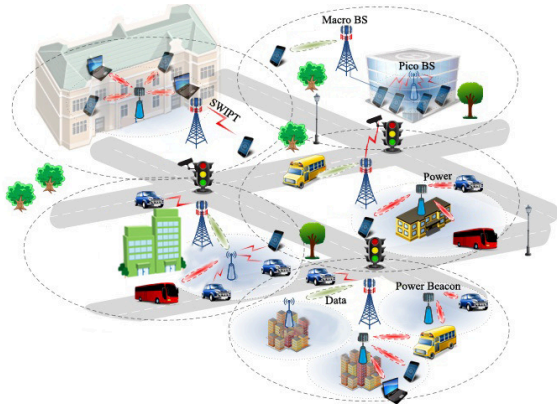
- Mathematical modelling
- Fundamental limits
- Link-layer design
- System-level design
- Experimental studies

Concluding Remarks



Information and Energy co-engineering and co-design.

- Smart Grids, Energy Harvesting, Green Radio, Power Line Communications etc.
- **Wireless Powered Communications**
 - Enabling technology, building block for the upcoming 6G wireless technologies.

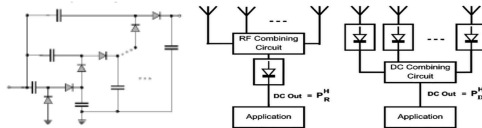


Future Research Directions (1)



① Mathematical Modelling

- More accurate rectenna mathematical models (balance between “simplistic” communication theory models and “complex” microwave theory models).
- More sophisticated rectenna circuits (e.g., voltage multiplier, rectenna arrays).
- Rectenna circuits based on CMOS technology, Resonant Tunneling Diodes (RTD).



② Theoretical Advances

- Fundamental limits of WPC (non-linear wireless power channel).
- Signal/waveform design for WPC systems e.g., chirp signals [ICASSP'23].
- New SWIPT architectures (without splitting e.g., RF diplexer).
- Safety issues (specific absorption rate, maximum permissible exposure).

③ Hardware Implementations

- Energy receivers/Rectenna designs.
- Limited proof of concepts for SWIPT; attract industrial interest.

Future Research Directions (2)

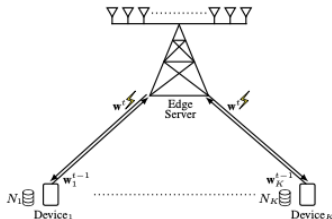


4 Applications of interest

- Wireless sensor networks/machine-type communications.
- Wireless powered backscatter communications.
- 6G networks (e.g., ultra densification, ultra-massive MIMO, Intelligent reflecting surfaces, fluid antennas, semantic communications, radiated near-field communications).

5 Machine Learning for WPC

- A new design methodology- from “Model and Optimize” approach to “Learning”.
 - Optimize WPC without intermediate blocks/models etc (e.g. autoencoders).
- Useful tool to solve complicated optimization problems/cross-layer design.
- WPC is also an enabler for ML algorithms.
 - e.g., WPC and federated learning (co-design communication, energy, and learning).



Acknowledgements



- IRIDA Research Laboratory for Communication Technologies





- I. Krikidis and C. Psomas, "Wireless information and power transfer: A bottom-up multi-layer design framework," *IEEE Internet of Things Magazine*, vol. 6, pp. 142–147, March 2023.
- N. Khalfet and I. Krikidis, "Information energy capacity region for SWIPT systems over Rayleigh-fading channels," *IEEE Transactions on Communications*, vol. 71, pp. 1416–1429, March 2023.
- C. Psomas and I. Krikidis, "RC filter design for wireless power transfer: A Fourier series approach," *IEEE Signal Processing Letters*, vol. 29, pp. 597–601, February 2022.
- E. Demarchou, C. Psomas, and I. Krikidis, "On the design of magnetic resonant coupling for wireless power transfer in multi-coil networks," *IEEE Wireless Communications Letters*, vol. 11, pp. 406–410, February 2022.
- R. Gupta, K. Ntougias, and I. Krikidis, "Frequency-domain SWIPT and modulation classification: Design and experimental validation," *IEEE Open Journal of the Communications Society*, pp. 2581–2596, November 2021.
- P. Mukherjee, C. Psomas, and I. Krikidis, "Differential chaos shift keying-based wireless power transfer with nonlinearities," *IEEE Journal of Selected Topics in Signal Processing*, Special Issue on Signal Processing Advances in Wireless Transmission of Information and Power, vol. 15, pp. 1185–1197, August 2021.
- J. Zhang, G. Zheng, I. Krikidis, and R. Zhang, "Fast specific absorption rate aware beamforming for downlink SWIPT via deep learning," *IEEE Transactions on Vehicular Technology*, vol. 69, pp. 16178–16182, December 2020.
- I. Krikidis, "Wireless Power Transfer Under Kullback-Leibler Distribution Uncertainty: A Mathematical Framework," *IEEE Wireless Communications Letters*, vol. 9, pp. 1591–1595, September 2020.
- I. Krikidis, "Information-energy capacity region for SWIPT systems with power amplifier nonlinearity," *IEEE International Symposium on Information Theory (ISIT)*, Los Angeles, USA, June 2020.
- J. Zhang, G. Zheng, I. Krikidis, and R. Zhang, "Specific absorption rate-aware beamforming in MISO downlink SWIPT systems," *IEEE Transactions on Communications*, vol. 68, pp. 1312–1326, February 2020.
- I. Krikidis and C. Psomas, "Tone-index multisine modulation for SWIPT," *IEEE Signal Processing Letters*, vol. 26, pp. 1252–1256, August 2019.
- I. Krikidis, "Retrodirective large antenna energy beamforming in backscatter multi-user networks," *IEEE Wireless Communications Letters*, vol. 7, pp. 678–681, August 2018.

Wireless Powered Communications in the Era of 6G

Thank you! Questions?

This work has received funding from the European Research Council (ERC) under the European Union's Horizon Europe programme (ERC PoC WAVE, Grant agreement No. 101112697).

