Wireless Powered Communication as an Enabling Technology for the Internet of Things: Overview, Recent Results, and Challenges

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Joint work with Rania Morsi, Elena Boshkovska, and Prof. Derrick Wing Kwan Ng

1. Introduction
2. Rate-Energy Tradeoff
3. Non-linear Energy Harvesting Model
4. Importance of Modeling Imperfections
5. Conclusions

Vision of the Internet of Things (IoT)



- Link physical world with digital world
- Enable informed decision making based on large number of observations
- Deployment of large number of interconnected wireless nodes - 50 billion by 2020

Key challenges



- Efficient communication protocols
- Security and privacy
- Energy supply

Energy supply

- Lifetime of wireless nodes is limited by the energy available for transmission
- Replacement of batteries is cumbersome and may not even be possible, especially if the nodes are difficult to access and plentiful

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Energy harvesting communication systems





Energy harvesting communication systems

- Nodes can generate their "own" energy using renewable sources such as solar, wind, pressure, etc.
- Advantages:
  - External energy sources are not needed anymore
  - Lifetime of networks is no longer energy limited
- Disadvantages:
  - Renewable energy sources are typically intermittent and time-variant
  - Additional components may not be compatible with form factor requirements
  - In some environments (e.g. indoors, inside a body, etc.), conventional energy harvesting may be difficult

Energy harvesting communication systems

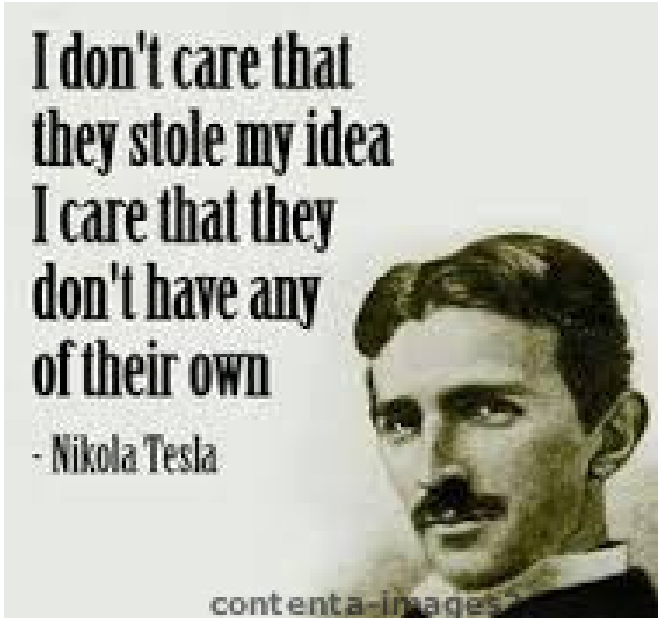
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Possible solution: Wireless Power Transfer

Wireless power transfer: Not an entirely new idea

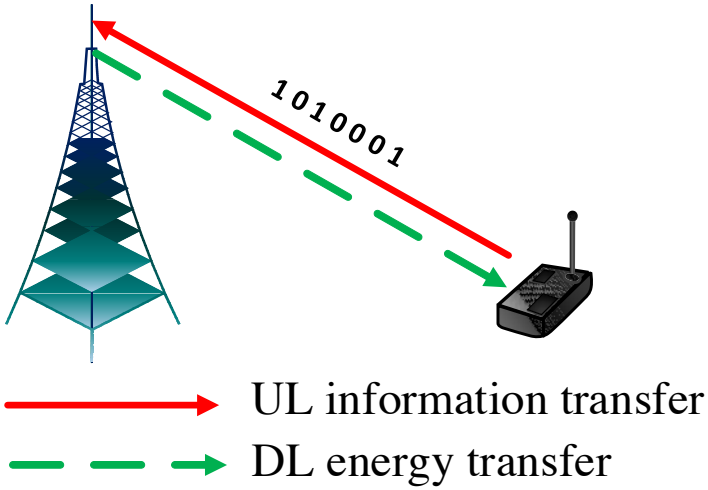
- Patented by Nikola Tesla in 1900
- Wireless powered helicopter by William Brown in 1968
- Wireless powered aircraft in Canada in 1987

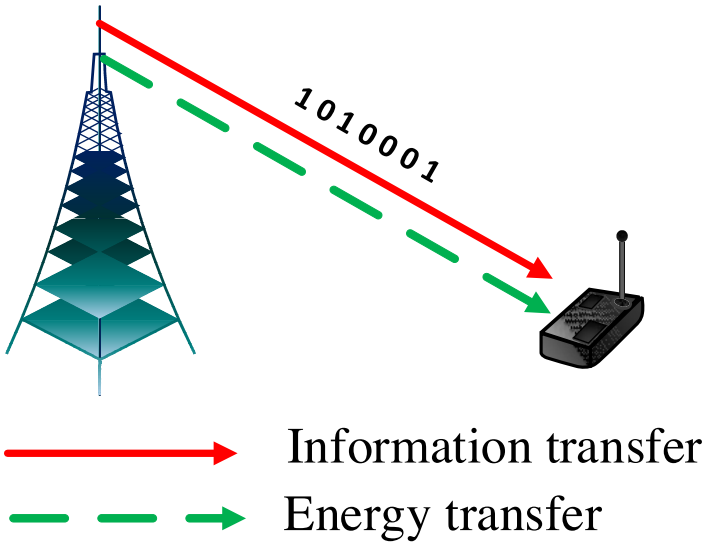




Possible implementations in an IoT

- Opportunistic RF energy harvesting $\Rightarrow$ Low energy density (typical: $10^{-3} - 0.1\mu\mathrm{W/cm}^2$
- Wireless powered communication (WPC)
- Simultaneous wireless information and power transfer (SWIPT)



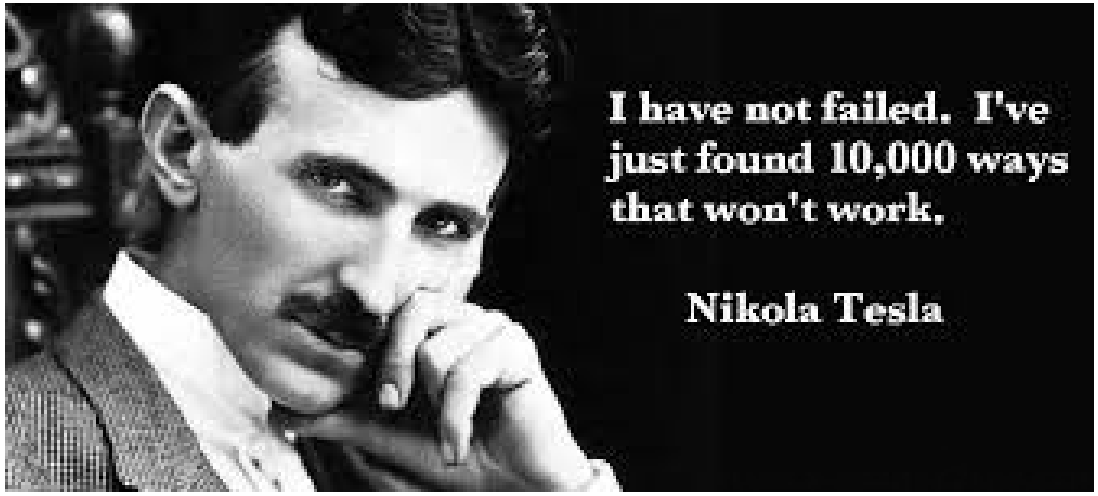


Wireless Power Transfer

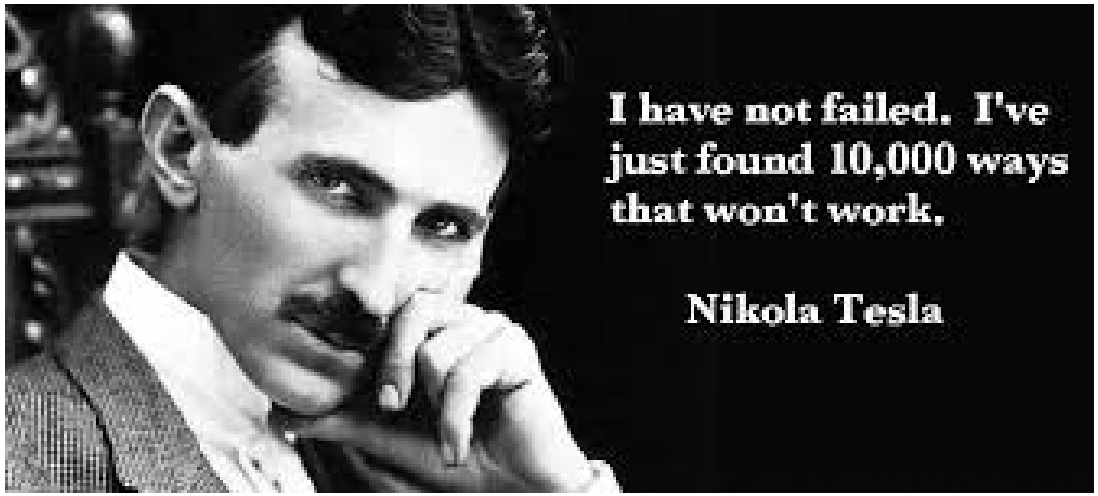
- Advantages
  - How much energy is available for harvesting can be controlled (to some extent at least)
  - Replacement of batteries can be avoided
  - Many nodes can be charged simultaneously (broadcast nature)
  - Small form factor
- Challenges
  - High signal attention due to path loss
  - Energy harvesting circuits are non-linear
  - Imperfect hardware and channel estimation

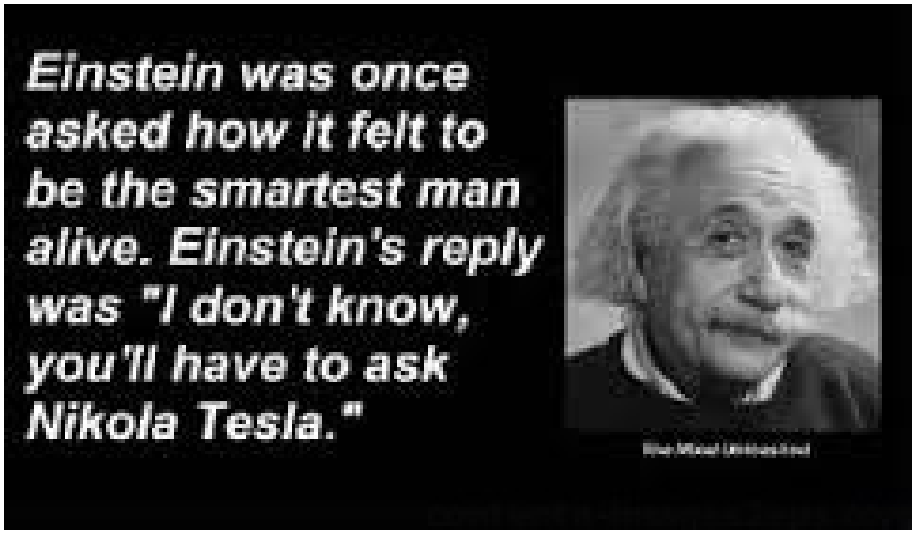
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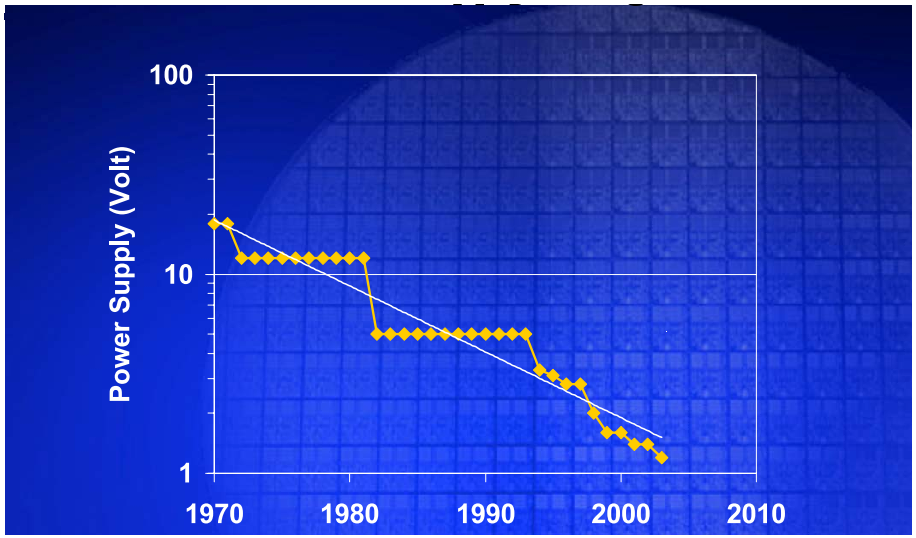
Why is it not widely used, yet?





Why is wireless power transfer attractive for IoT?

- IoT nodes are often low power
- WPT enables one-to-many charging
- Can provide predictable, stable energy supply
- Can penetrate walls and can reach difficult to access areas
- Energy harvesting circuitry allows small form factor



source: intel.com

Topics addressed in this presentation:

- Tradeoff between information and energy transfer
  - Transferring energy restricts information transfer
  - Tradeoff depends on considered network and underlying hardware
- Models for energy harvesting circuits
  - Energy harvesting circuits are non-linear
  - Impact on multiple antenna techniques
- Impact of imperfections
  - Imperfect channel state information (CSI)
  - Hardware impairments

1. Introduction

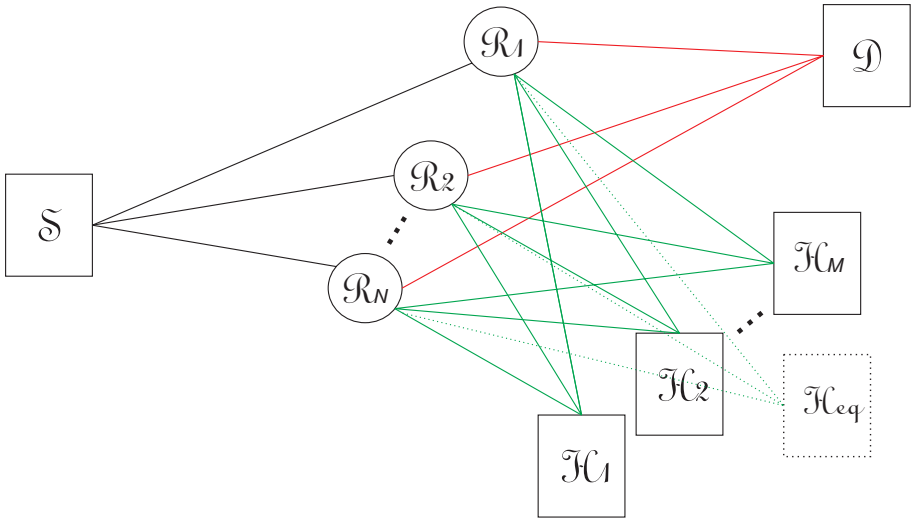
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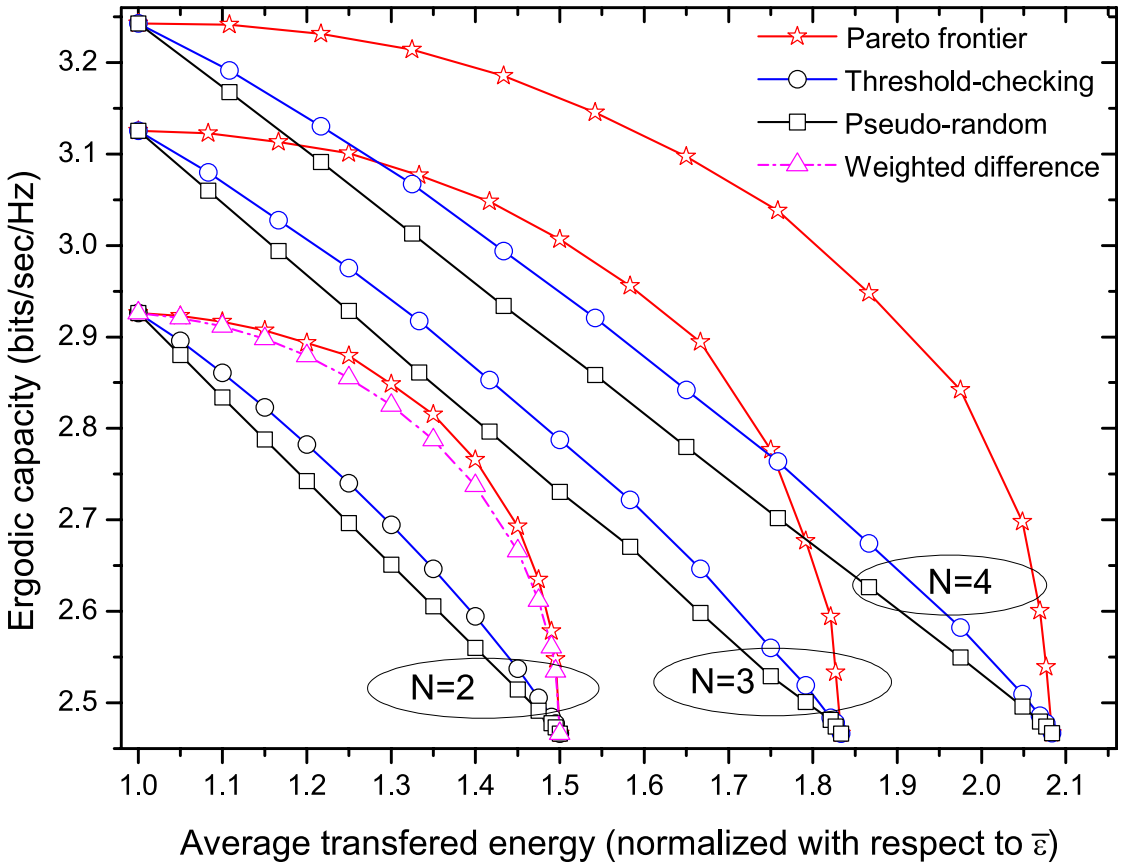
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SWIPT relay selection problem



- The best relay, $\mathcal{R}_\kappa$, for information transfer to $\mathcal{D}$: Maximizes bottleneck SNR
- The best relay, $\mathcal{R}_\lambda$, for energy transfer to $\mathcal{H}_i$: Maximizes transferred energy
- $\mathcal{R}_\kappa$ and $\mathcal{R}_\lambda$ may not be identical
- **There is a tradeoff between information and energy transfer!**



- I.i.d. Rayleigh fading, $\bar{\gamma} = 20$ dB, $\bar{\epsilon} = \eta N_0 \bar{\gamma}/M$
- Pareto optimal scheme: Most favourable tradeoff but highest CSI requirements
- Pseudo-random scheme: Least favourable tradeoff but lowest CSI requirements

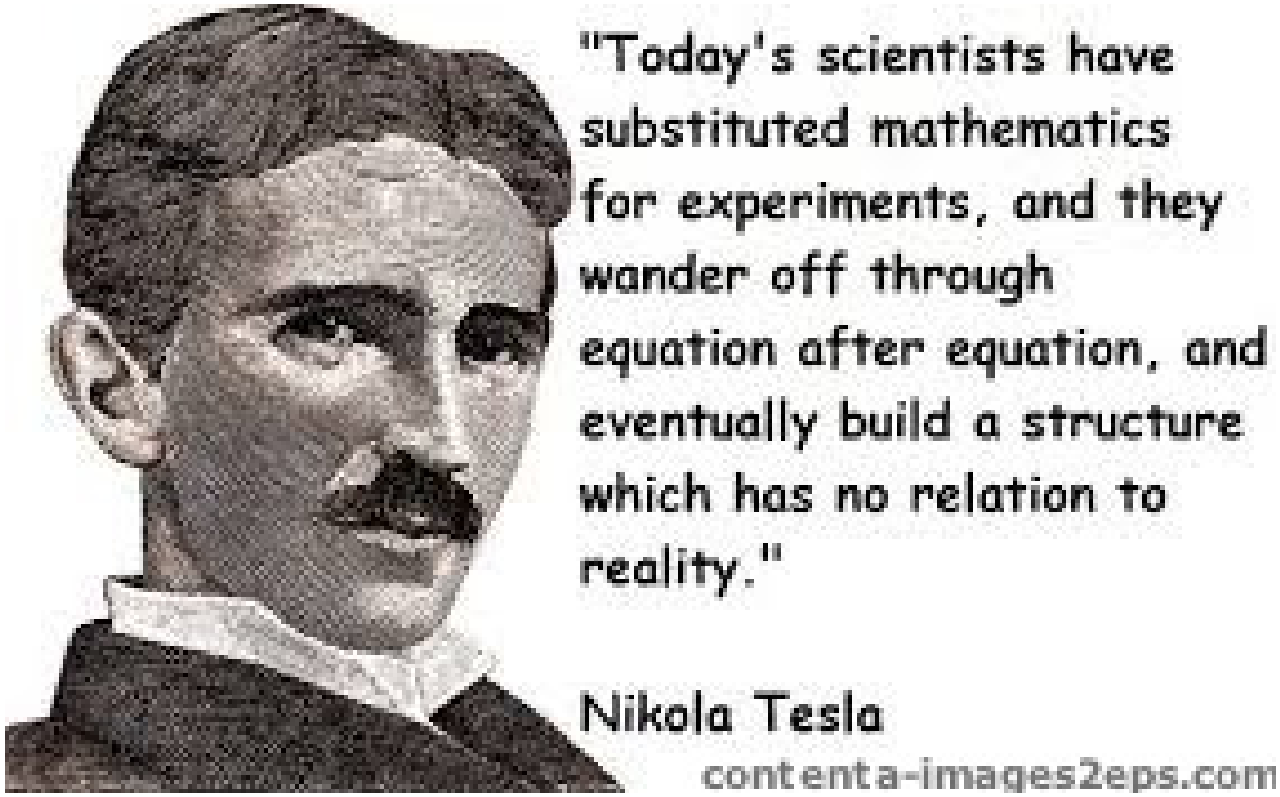
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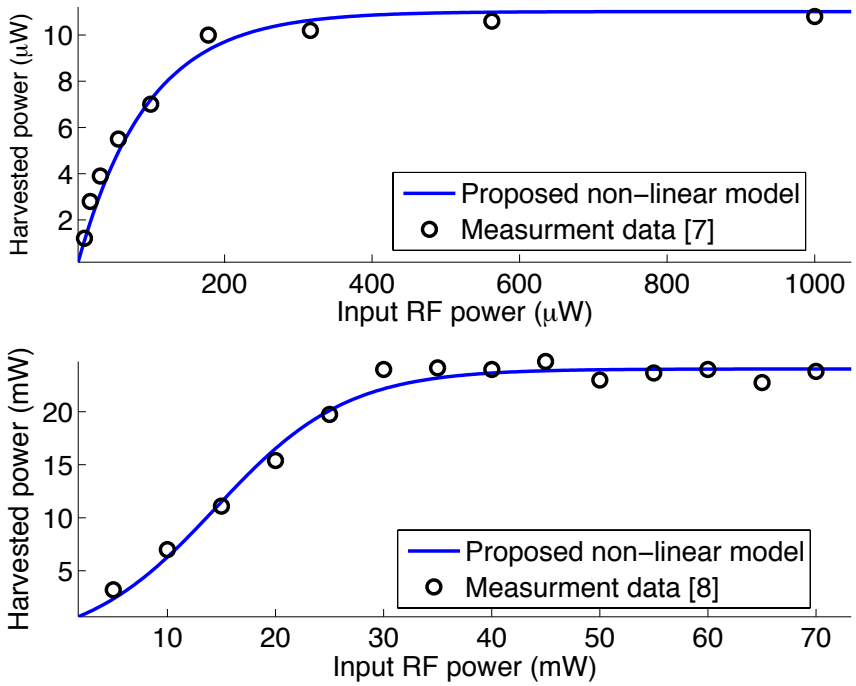
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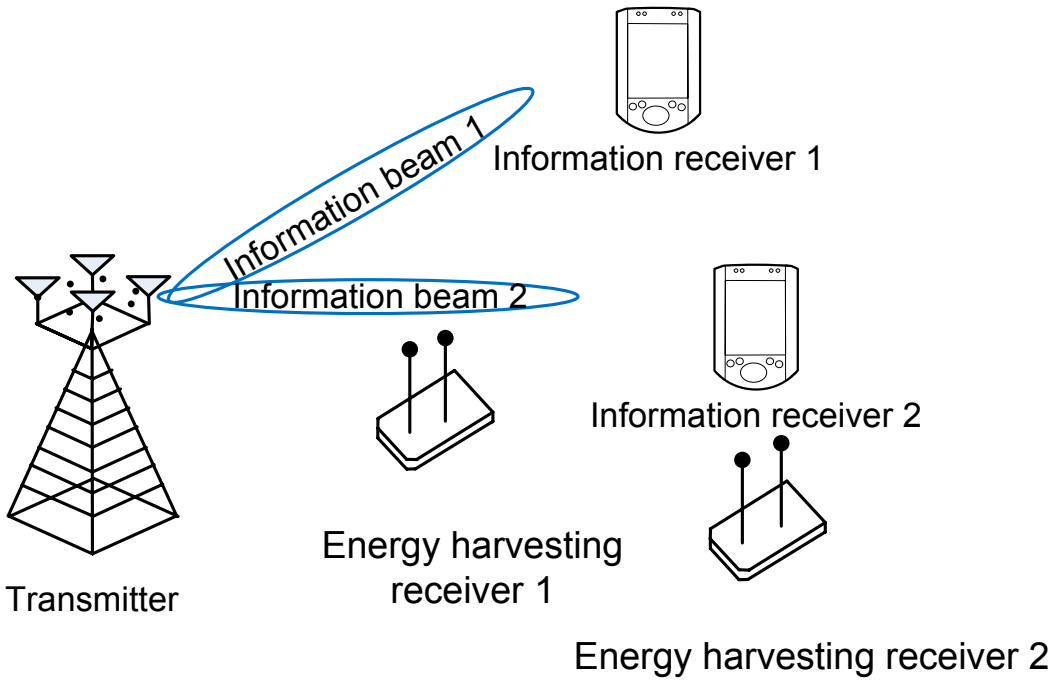

"Today's scientists have substituted mathematics for experiments, and they wander off through equation after equation, and eventually build a structure which has no relation to reality."
Nikola Tesla
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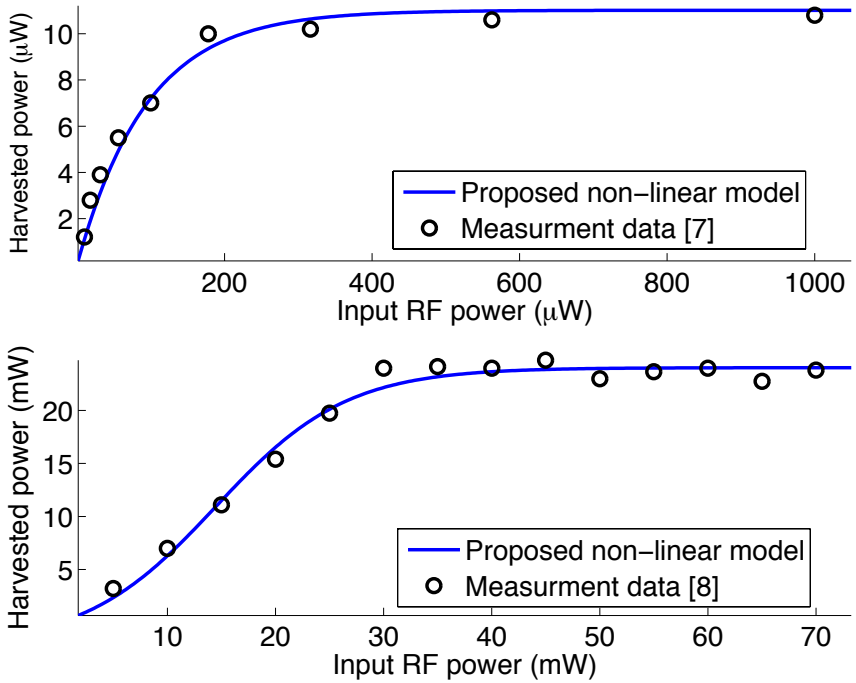
- Measurements reveal that the relationship between the received RF power, P_{RF}, and the harvested energy, E_{EH}, is non-linear
- Yet, practically all existing literature assumes a linear model

$$E_{\mathrm{EH}} = \eta P_{\mathrm{RF}}$$

- This mismatch is expected to lead to a suboptimal system design



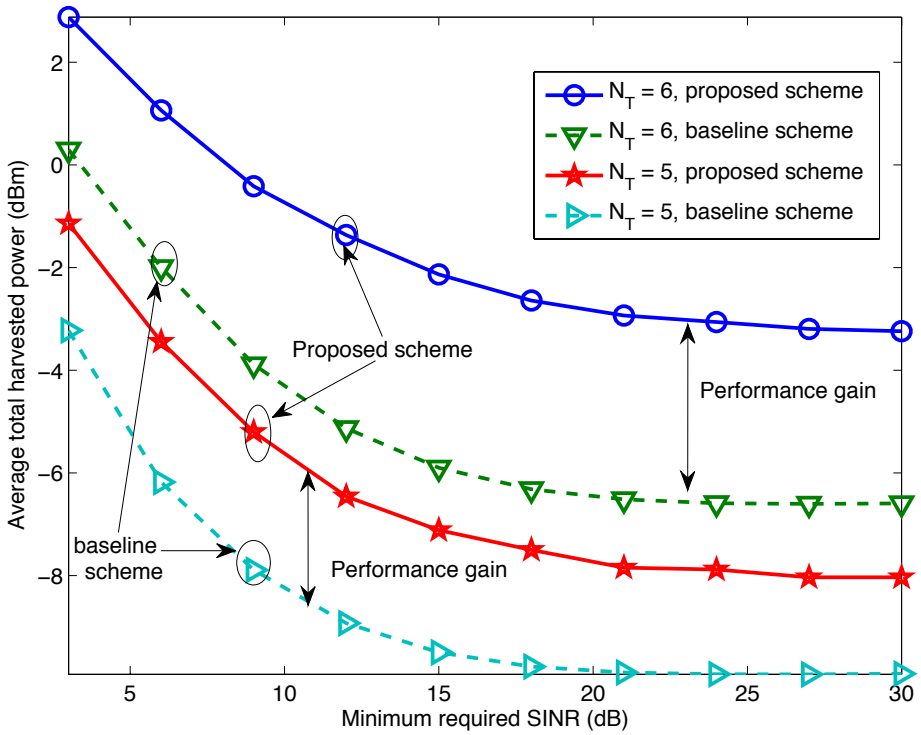
- Transmit energy and information simultaneously
- A multi-antenna transmitter communicates with K information receivers
- J energy harvesting receivers draw energy



- We model the EH non-linearity as a logistic (sigmoidal) function

$$E_{\mathrm{EH},j} = \frac{M_j}{1-\Omega_j}\left(\frac{1}{1+\exp(-a_j(P_{\mathrm{RF}_j}-b_j))}-\Omega_j\right)$$

with curve fitting constants a_j, b_j, M_j, and Ω_j



- Maximize harvested energy under quality-of-service (QoS) constrained at information receiver
- System optimized for actual non-linear EH circuit performs much better than system optimized for a linear model
- Multiple antennas at AP are beneficial

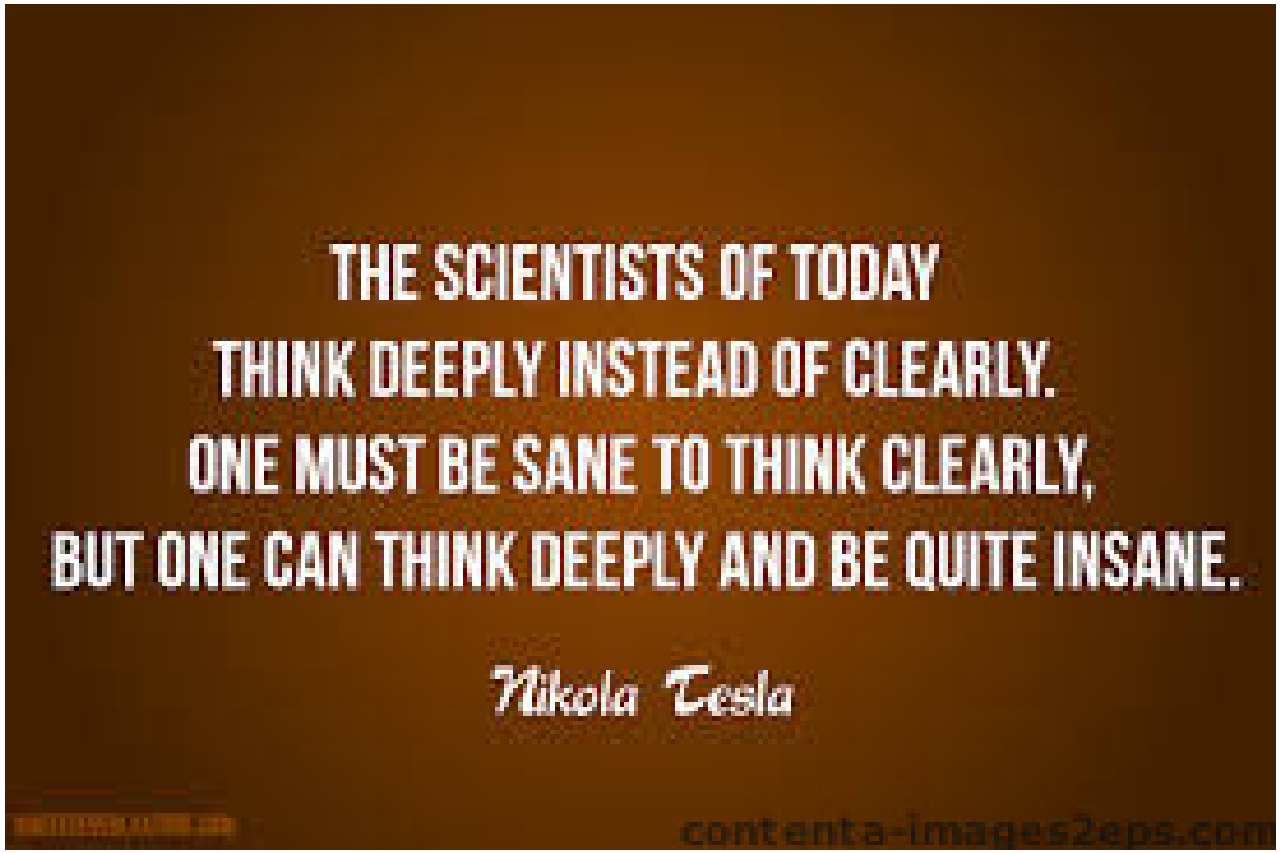
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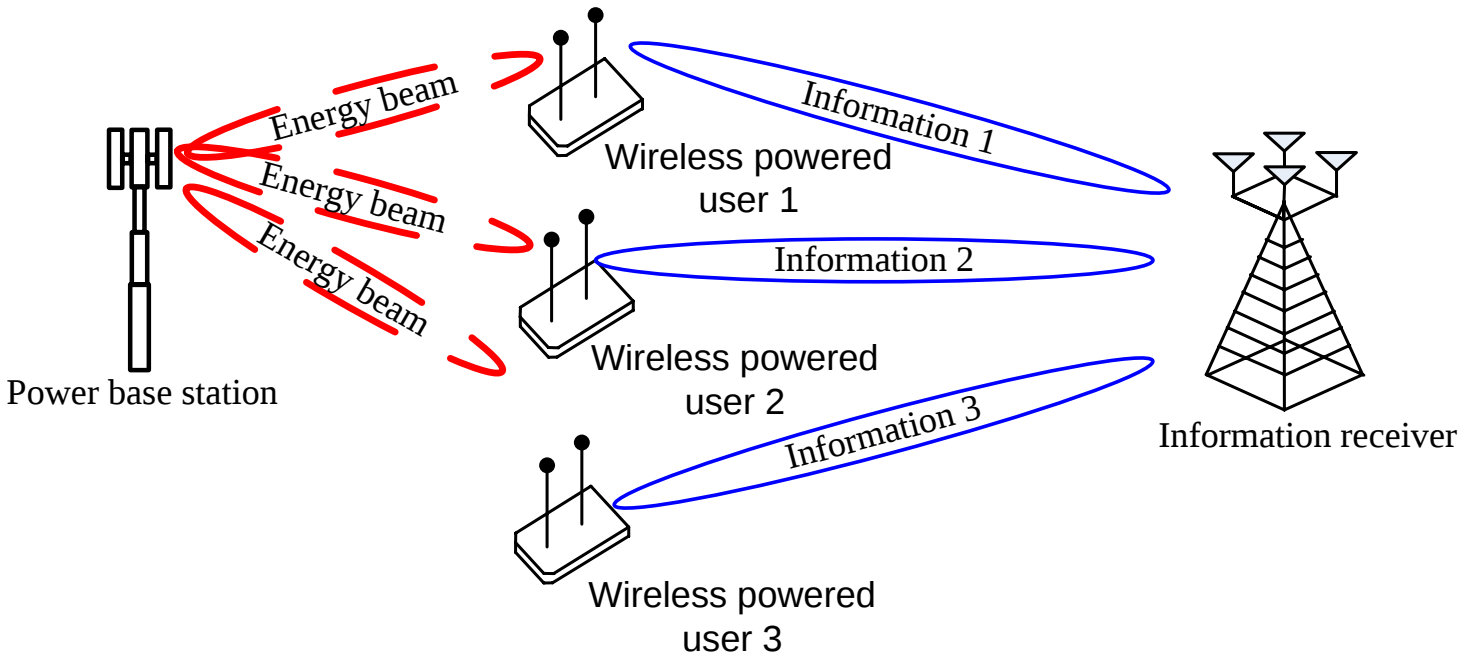
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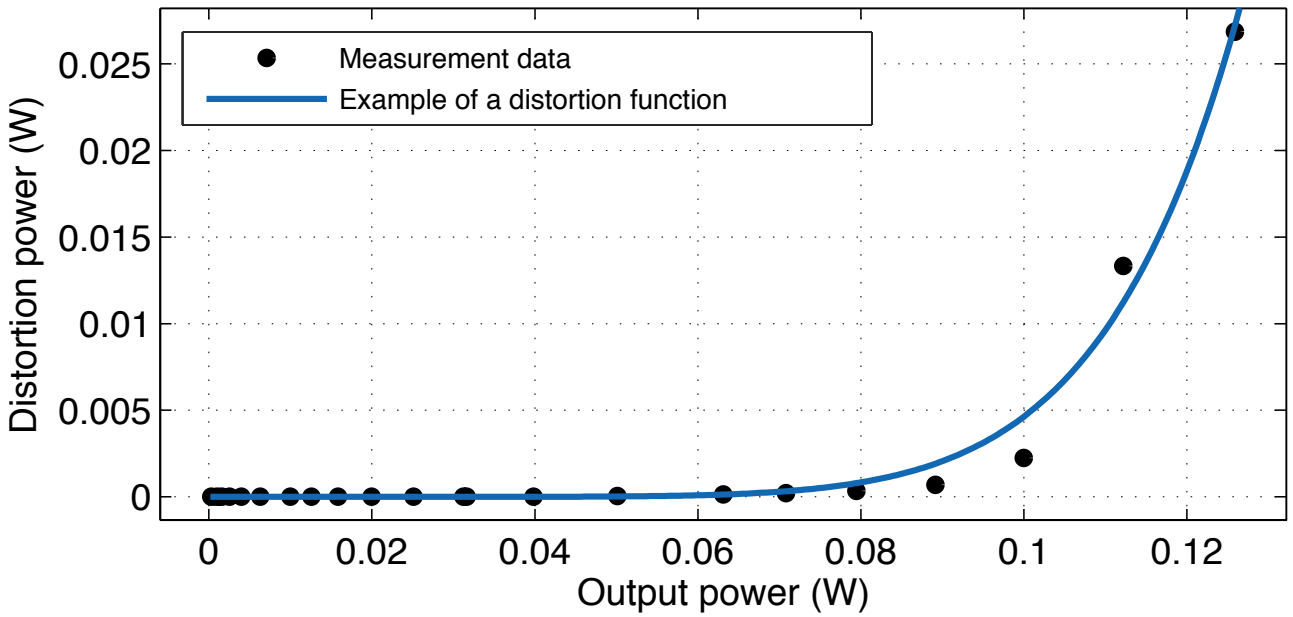
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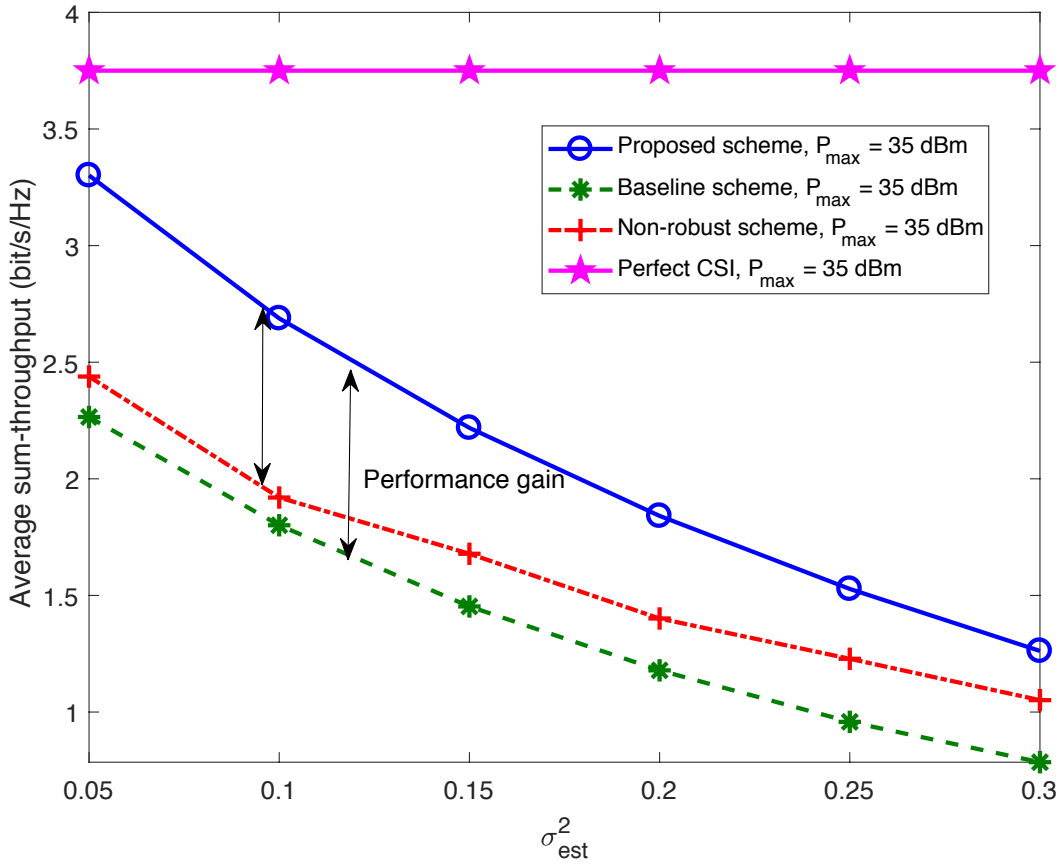

THE SCIENTISTS OF TODAY
THINK DEEPLY INSTEAD OF CLEARLY.
ONE MUST BE SANE TO THINK CLEARLY,
BUT ONE CAN THINK DEEPLY AND BE QUITE INSANE.
Nikola Tesla
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- Wireless powered communication system with multiple TDMA users
- Optimize beamforming vector at power station, beamforming vector at users, and time allocation to users



- Residual TX and RX hardware impairments: Model as Gaussian noise whose variance is monotonic increasing function of TX and RX powers
- Imperfect CSI: Model the channel estimation error as unknown but bounded
- Optimize system performance taking the residual HWIs and CSI uncertainty into account $\Rightarrow$ Robust design



- Imperfect CSI leads to considerable performance loss
- Robust design can mitigate loss

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- Wireless power transfer is a key enabling technology for IoT
- Makes devices truly "wireless" and removes energy constraints
- Requires careful joint design of communication and energy transfer

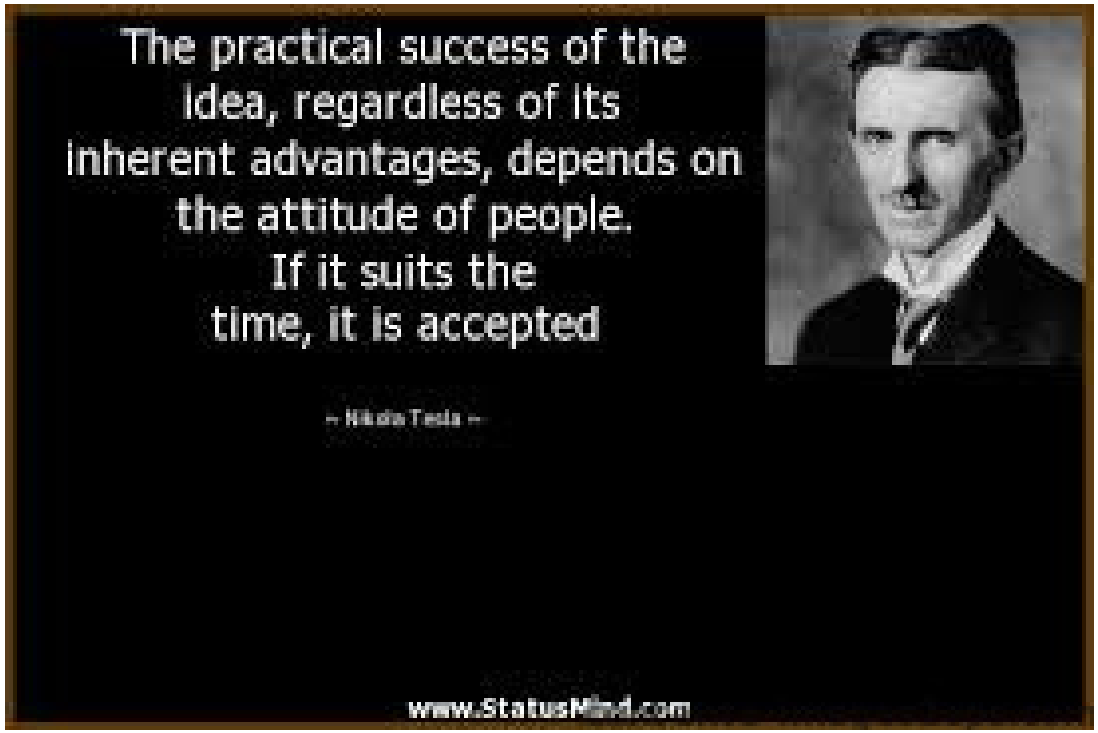
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Key Insights

- Fundamental trade-off between energy and information
- Non-linear behaviour of energy harvesting circuit has severe implications for system design
- Multiple antennas at power station and information receivers affect performance differently
- Imperfect CSI and HWIs have significant impact on performance and require robust design

Some final thoughts on wireless power transfer



Overview Articles

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- Z. Ding, C. Zhong, K. Ng, M. Peng, H. Suraweera, R. Schober, and V. Poor. Application of Smart Antenna Technologies in Simultaneous Wireless Information and Power Transfer. *IEEE Communication Magazine*. 2015.

Non-linear Energy Harvesting Circuit

- E. Boshkovska, K. Ng, and R. Schober. Practical Non-linear Energy Harvesting Model and Resource Allocation for SWIPT Systems. *IEEE Commun. Letters*, 2015.
- R. Morsi, E. Boshkovska, E. Ramadan, K. Ng, and R. Schober. On the Performance of Wireless Powered Communication with Non-linear Energy Harvesting. *IEEE SPAWC*, 2017.

Robust Design under Imperfect CSI

- E. Boshkovska, K. Ng, N. Zlatanov, A. Koelpin, and R. Schober. Robust Resource Allocation for MIMO Wireless Powered Communication Networks Based on a Non-linear EH Model. *IEEE Trans. Commun.*, 2017.

Robust Design under HWIs

- E. Boshkovska, L. Dai, K. Ng, and R. Schober. Power-Efficient and Secure WPCNs with Hardware Impairments and Non-linear EH Circuit. *IEEE Trans. Wireless Commun.*, 2018.