Performance Analysis of Wireless Powered Communication Networks (WPCNs) with Imperfect CSI and Nonlinear Energy Harvesters

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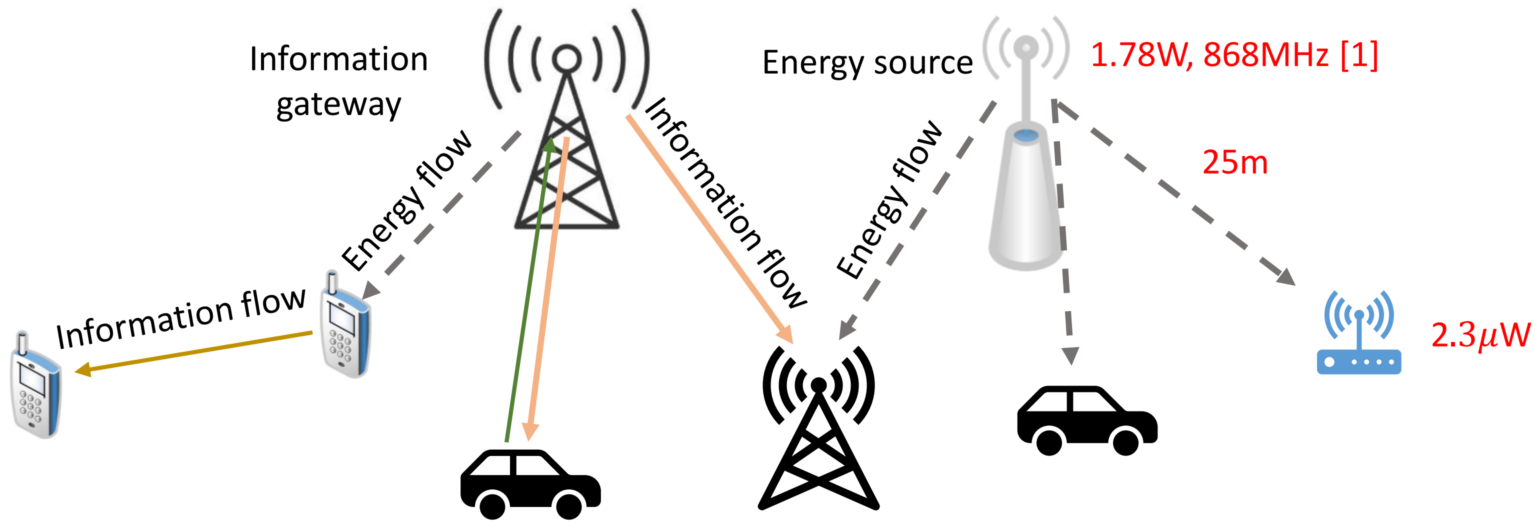
Outline

- Radio Frequency (RF) Energy Harvesting
- Major Contributions
  - Analysis of Imperfect Channel State Information (CSI)
  - Two New Nonlinear EH Models
- Conclusion and Future Research

RF energy harvesting

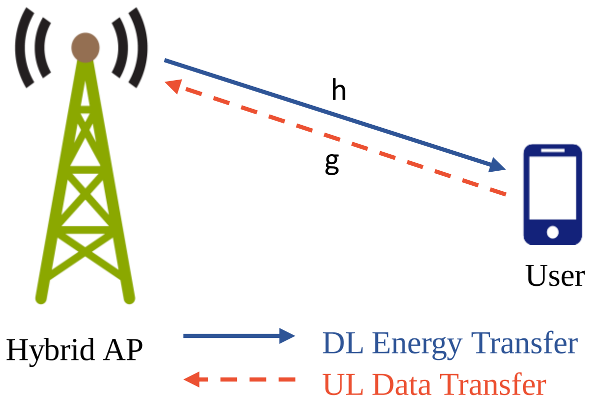


RF Energy Sources

- Cellular Base Stations
- FM & AM Transmitters
- Satellite Transmitters
- Wireless Routers
- Radar

[1] X. Lu et al , "Wireless network with RF energy harvesting: A contemporary survey," *IEEE Commun. Surveys. Tuts.*

Problem 1 - imperfect channel state information?



$$\hat{h} = \rho h + \sqrt{1-\rho^2} n$$

where h – True channel

$\hat{h}$ – CSI

ρ – Correlation coefficient

n – Noise

- $\rho = 1$ Perfect CSI
- $0 \leq \rho < 1$ Imperfect CSI

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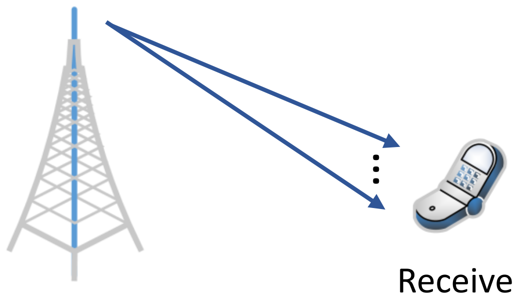
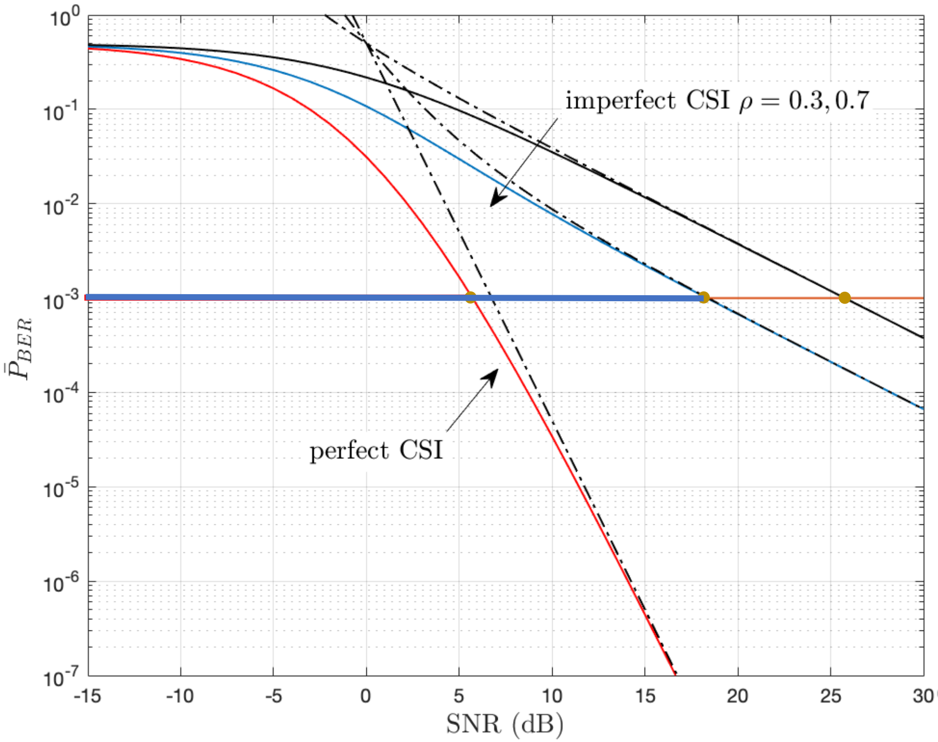
Negative effects for non-EH links



Transmitter: single antenna

Receiver: 4 antennas

Maximal ratio combining (MRC)



Imperfect CSI effects:

- Diversity gain loss
- Coding gain loss

State of the art of imperfect CSI on WPCNs

- Most works - perfect CSI but not imperfect CSI [1-3].
- Some imperfect CSI for optimization, but no performance analysis [4-6].

[1] W. Huang et al , "On the performance of multi-antenna wireless-powered communications with energy beamforming," *TVT* 2016.
[2] N. Deepan et al, "On the performance of wireless powered communication networks over generalized κ-μ fading channels," Physical Communication. 2019.
[3] A. Almradi, "Information and energy beamforming in MIMO wireless powered systems," in Proc. GLOBE-COM, 2016.
[4] G. Yang et al , "Throughput optimization for massive MIMO systems powered by wireless energy transfer," *IJSAC* 2015.
[5] Y. Wu et al, "Robust resource allocation for secrecy wireless powered communication networks," COML,, 2016.
[6] Y. Liu, K.-W. Chin, and C. Yang, "Uplinks schedulers for RF-energy harvesting networks with imperfect CSI," TVT, 2020.

Contributions

- Statistical distribution functions of received SNR at AP
- Performance analysis
- Asymptotic analysis in high SNR region

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SNR at the AP

$$\gamma_A = c\bar{\gamma}\frac{\|\hat{\mathbf{h}}^H\mathbf{h}\|^2}{\hat{\mathbf{h}}^H\hat{\mathbf{h}}}\frac{\|\hat{\mathbf{g}}^H\mathbf{g}\|^2}{\hat{\mathbf{g}}^H\hat{\mathbf{g}}}$$

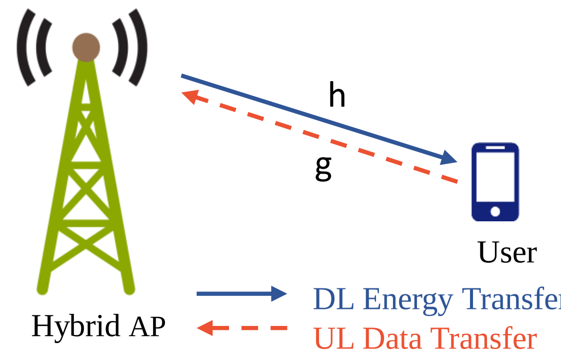
where c $= \frac{\tau\eta}{1-\tau}, \bar{\gamma} = \frac{P}{\sigma^2}$.

τ = energy transfer time fraction

η = energy conversion efficiency

P = transmit power of AP

σ^2 = noise power



Maximal ratio transmission (MRT) with $\mathbf{f} = \frac{\hat{\mathbf{h}}}{\|\hat{\mathbf{h}}\|}$.

Energy harvested at the user: $E_h = \eta\tau\left|\sqrt{P}\mathbf{f}^H\mathbf{h}\right|^2 = \eta\tau P\frac{\|\hat{\mathbf{h}}^H\mathbf{h}\|^2}{\hat{\mathbf{h}}^H\hat{\mathbf{h}}}$.

codeword

Transmission block

Received signal at the AP: $y_A = \sqrt{\frac{E_h}{1-\tau}}\mathbf{g}s + \mathbf{n}$.

M… ght vector $\hat{\mathbf{g}}^H$.

codeword | codeword

buffer

Average Throughput → Delay-limited, Delay-tolerant

Reliability → BER, SER

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Average throughput

CDF of SNR (γ_A) at the AP

$$F_{\gamma_A}(x) \overset{(a)}{=} \sum_{n=1}^{N}\sum_{m=1}^{N} \frac{2B\left(m,n\right)}{c\bar{\gamma}} \int_0^x \left(\frac{z}{c\bar{\gamma}}\right)^{\alpha(m,n)} K_{n-m}\left(2\sqrt{\frac{z}{c\bar{\gamma}}}\right) dz$$

$$\overset{(b)}{=} \sum_{n=1}^{N}\sum_{m=1}^{N} \frac{B\left(m,n\right)}{\left(c\bar{\gamma}\right)^{\left(\alpha(m,n)+1\right)}} x^{\alpha(m,n)+1} G_{1,3}^{2,1}\left(\frac{x}{c\bar{\gamma}}\middle|\begin{matrix}-\alpha(m,n)\\ \frac{n-m}{2}, \frac{m-n}{2}, -\alpha(m,n)-1\end{matrix}\right)$$

where $K_v(\cdot)$ is modified Bessel function of the second kind.

expresses $K_v(\cdot)$ in terms of Meijer G-function $G_{02}^{20}[\cdot]$ → calculate integral→ (b)

Average throughput of delay-limited mode

$$R_{DL} \approx \begin{cases} R(1-\tau)\left[1-\left(1-\rho^2\right)^{2(N-1)}\left(\ln\left(\frac{c\bar{\gamma}}{\gamma_{th}}\right)-2\gamma_{EM}\right)\frac{\gamma_{th}}{c\bar{\gamma}}\right], & 0 \leq \rho < 1, \\ R(1-\tau)\left[1-\frac{1}{\Gamma^2\left(N\right)}\left(\ln\left(\frac{c\bar{\gamma}}{\gamma_{th}}\right)-2\gamma_{EM}\right)\left(\frac{\gamma_{th}}{c\bar{\gamma}}\right)^N\right], & \rho = 1. \end{cases}$$

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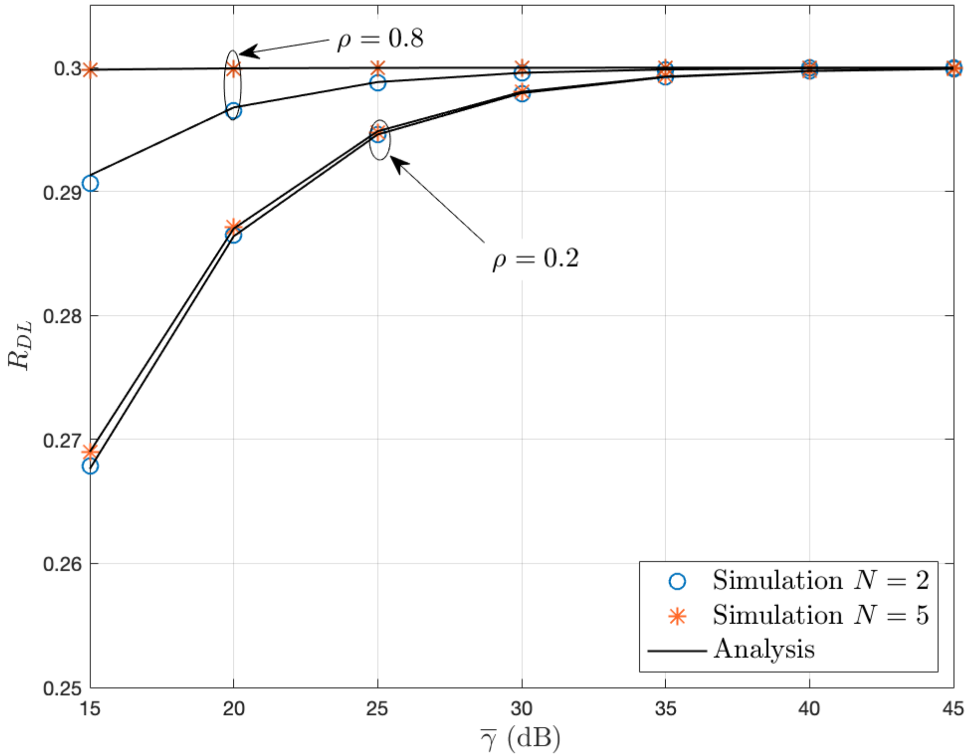
Numerical results



Delay-limited throughput mode versus SNR $\overline{\gamma}$ for $\tau = 0.4, \eta = 0.6$, and $R = 0.5$ bits/s/Hz.

- Better CSI, larger throughput
- Higher SNR, larger throughput
- More antenna, larger throughput

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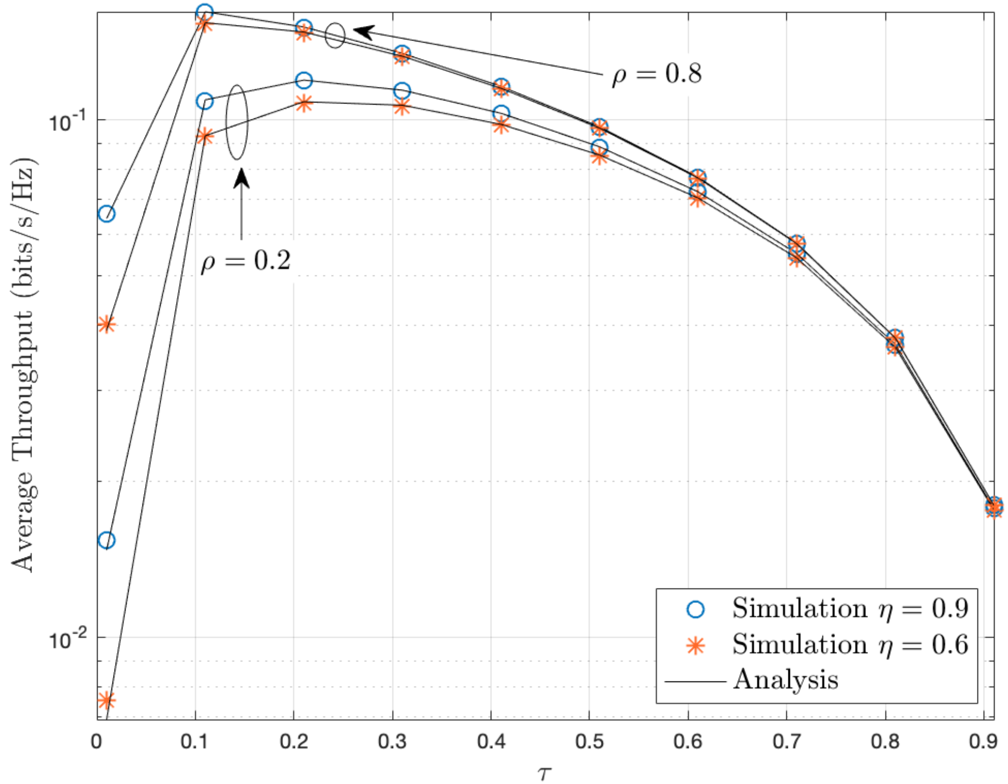
Numerical results



Delay-limit throughput versus EH time τ for $P = 10$ dBm and $N = 3$.

- Better CSI, larger throughput
- Larger energy conversion efficiency, better throughput
- Optimal throughput depends on quality of CSI

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Problem 2 – EH circuits are not linear!

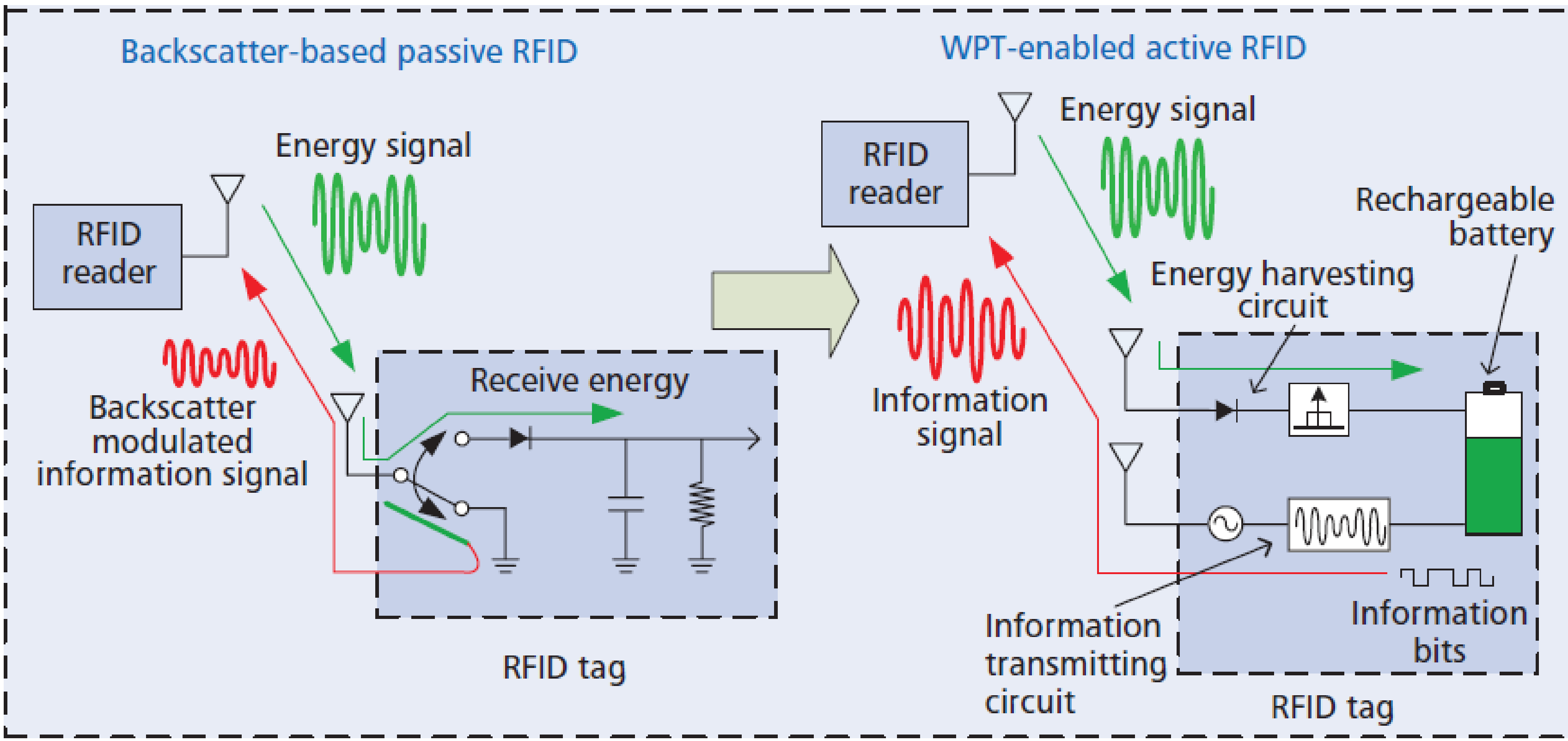
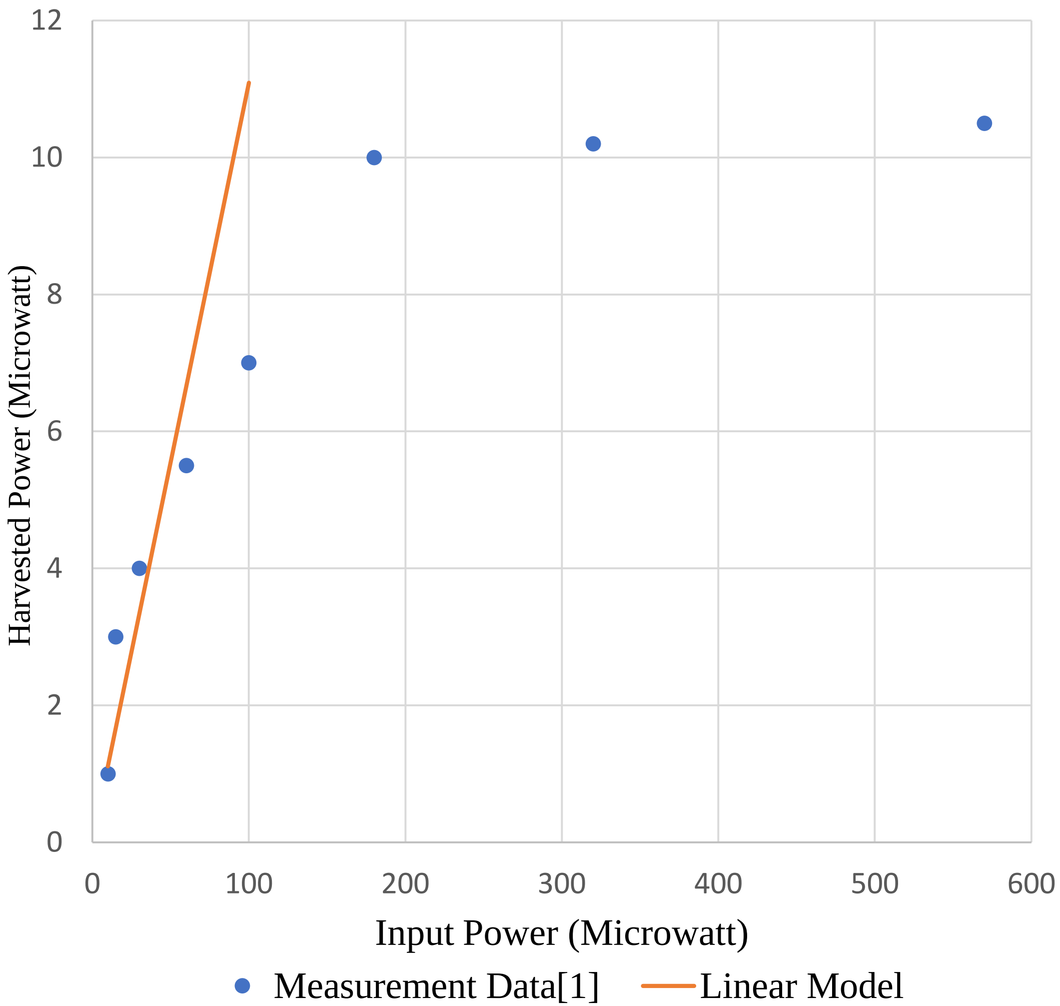


Figure: S. Bi, et. al, "Wireless powered communication networks: An overview," *IEEE Wireless Commun*., 2016.

Problems of linear EH model



- Widely used
- Inaccurate
- Overly simplistic
- Design issues

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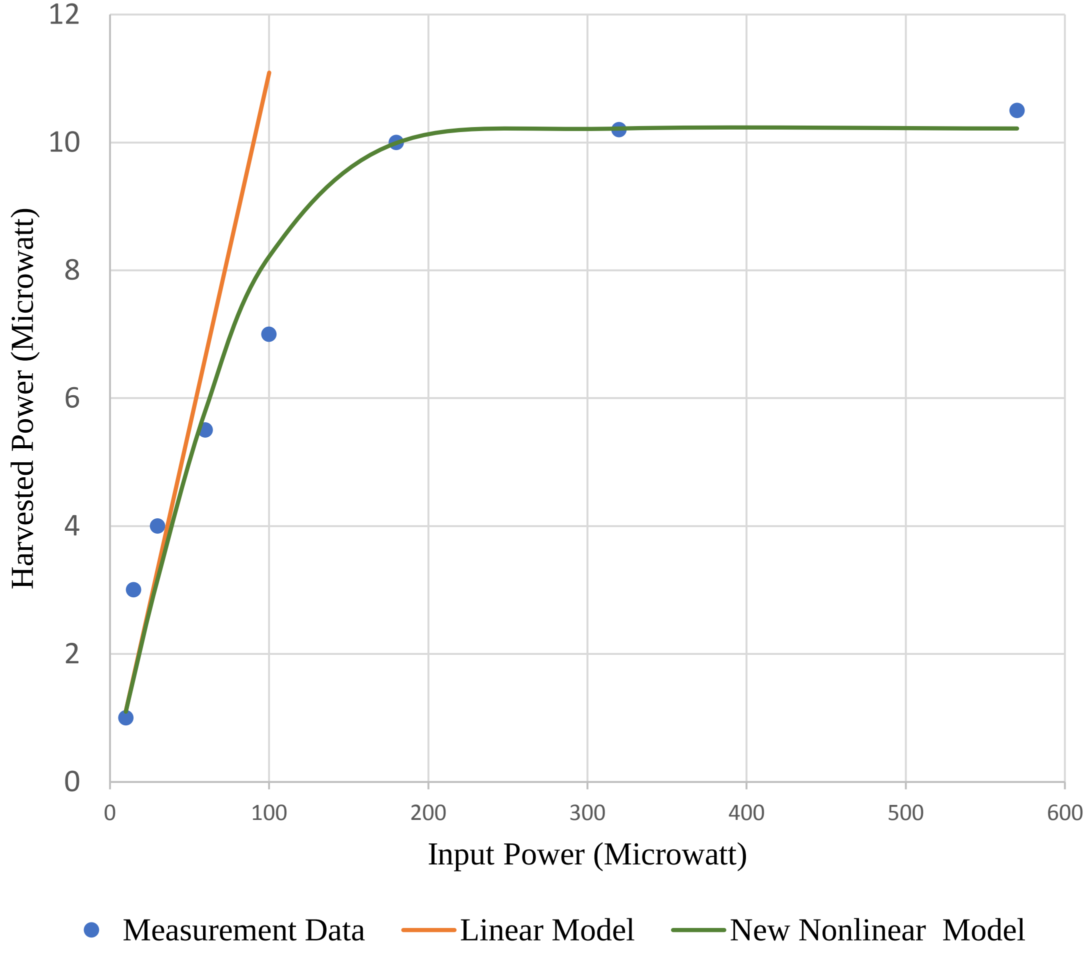
[1] T. Le, K. Mayaram et.al, "Efficient far-field radio frequency energy harvesting for passively powered sensor networks," *IEEE J.Solid-State Circuits*, 2008.

New nonlinear EH model (NLEH)



- Newly proposed
- Three parameters
- Accurate
- Asymptotic version

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Nonlinear EH models

NLEH

$$P_{\mathrm{NLEH}} = P_{\max}\left[\frac{\mathrm{erf}(a(P_r + b)) - \mathrm{erf}(ab)}{1 - \mathrm{erf}(ab)}\right]$$

where a, b, and $P_{\max}$ are parameters.

Asymptotic Model (AM)

$$P_{\mathrm{AM}} = P_{\max}(1 - e^{-\kappa P_r})$$

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Comparison of nonlinear EH models

- Piece-wise model[1]

$$P_{\mathrm{PW}} = \begin{cases} \eta P_i, & P_i < P_{th}, \\ \eta P_0, & P_i \geq P_{th}, \end{cases}$$

- Rational model (RM)[2]

$$P_{\mathrm{RM}} = \frac{aP_i + b}{P_i + c} - \frac{b}{c}$$

$(x_k - y_k)^2$

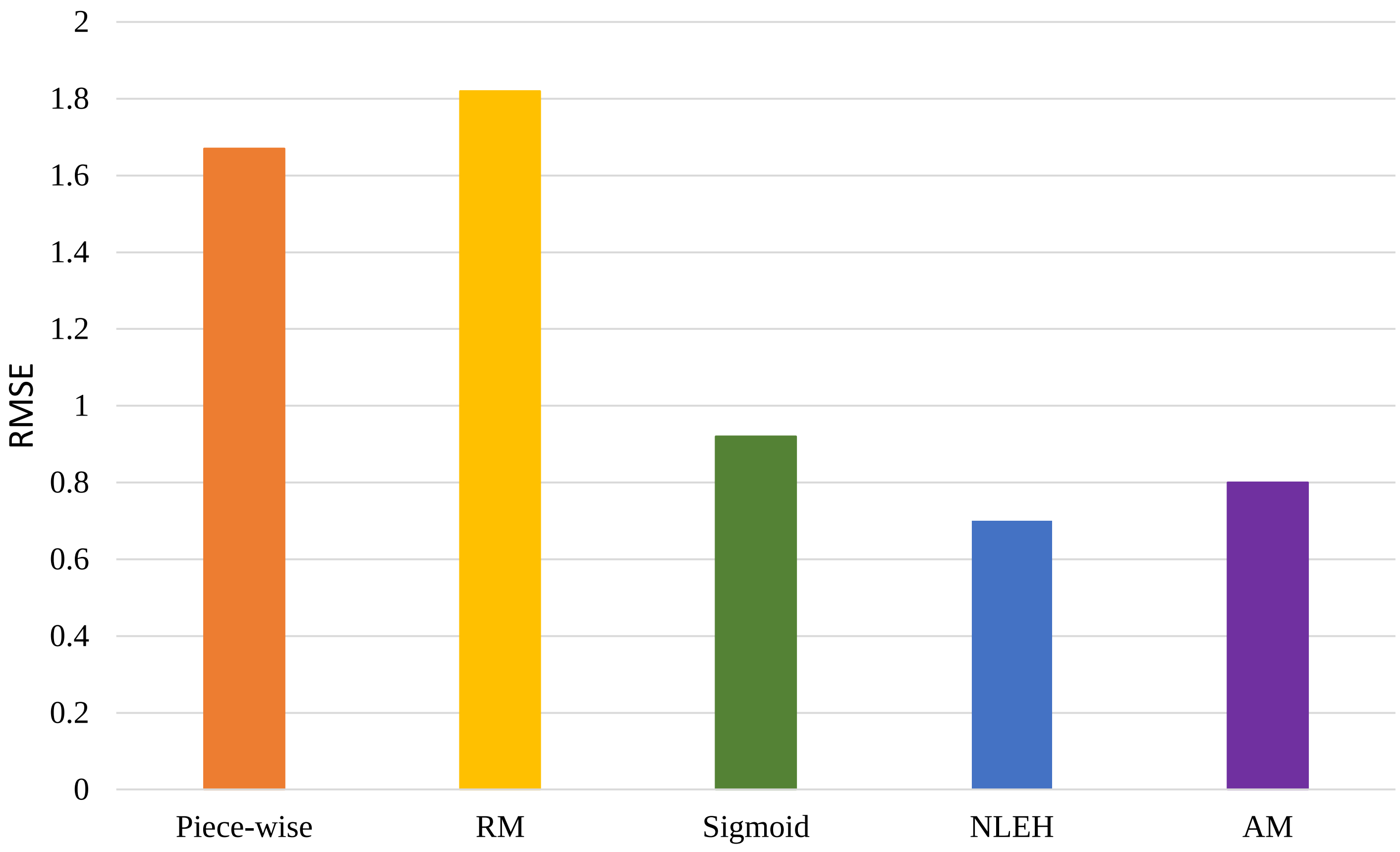
- Sigmoid model[3]

$$P_{\mathrm{S}} = P_{\max} \frac{1 - e^{-uP_i}}{1 + e^{-u(P_i - v)}}$$

- NLEH
- AM

[1] Y. Dong et al, "Performance of wireless powered amplify and forward relaying over Nakagami-*m* fading channels with nonlinear energy harvester," *IEEE Commun. Lett.,* 2016.
[2] Y. Chen et al, "New formula for conversion efficiency of RF EH and its wireless applications," *IEEE Trans. Veh. Technol.*, 2016.
[3] E. Boshkovska, et al, "Practical non-linear energy harvesting model and resource allocation for SWIPT systems," *IEEE Commun. Lett.*, 2015.

Comparison of Nonlinear EH Models



NLEH achieves the minimum RMSE

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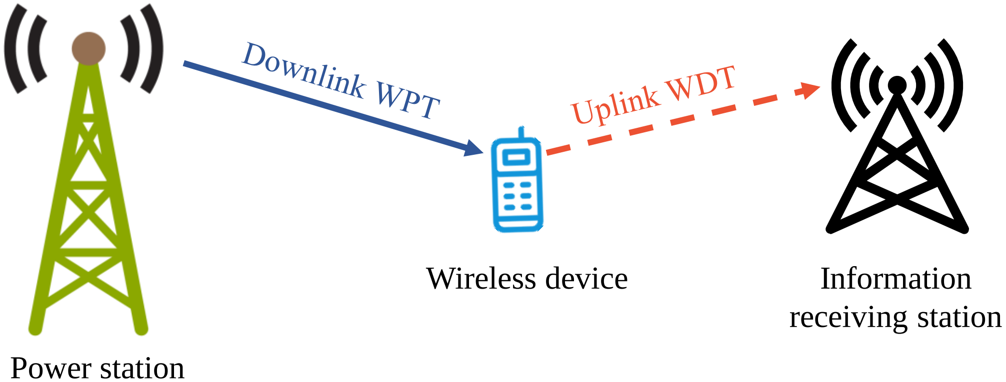
System model



Power station (PS) : $N \geq 1$ antennas

Wireless device (WD): single antenna

Information receiving station (IRS): $M \geq 1$ antennas

Performance:

Average throughput

BER

Average throughput

SNR at the IRS

$$\gamma = \frac{\tau\eta P_h \Omega_2 G_{\mathrm{WD}} G_{\mathrm{IRS}} ||\mathbf{g}||^2}{(1-\tau)\sigma^2},$$

where $\tau =$ energy harvesting time, $\eta =$ power amplify efficiency,
$\Omega_2 =$ path loss factor, G_{WD} = antenna gain of WD,
G_{IRS} = antenna gain of IRS, and σ^2 = noise power.

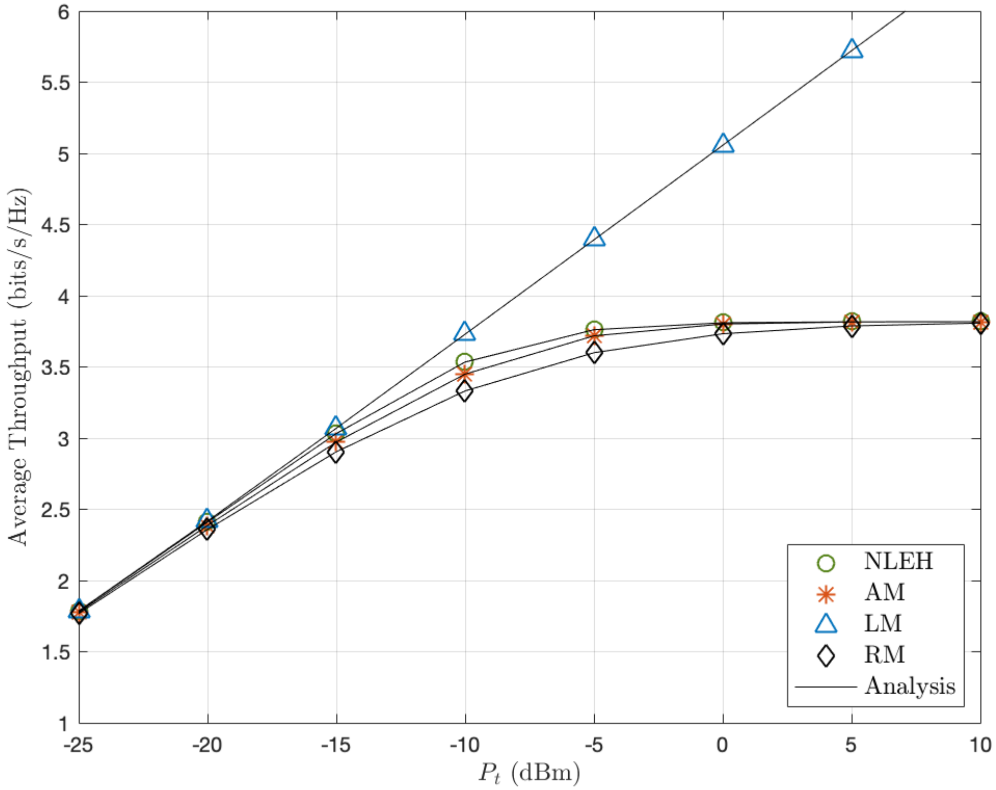
Average throughput of delay-tolerant mode

$$R_{DT} = \frac{(1-\tau)}{\Gamma(N)\Gamma(M)} \int_0^\infty I_{M-1}\left(\frac{1}{cq\left(\bar{P}_t x\right)}\right) \frac{x^{N-1}e^{-x}}{\left(cq\left(\bar{P}_t x\right)\right)^M} dx,$$

where $\bar{P}_t$ is the input power at WD with antenna gains and path loss. $I_n(\cdot)$ is given in Appendix B.2.

Integration → Generalized Gauss-Laguerre quadrature

Numerical results



Average throughput of the delay-tolerant mode versus $P_t, \tau = 0.6$, $N = 2$, and $M = 2$. The markers represent simulation points.

- $P_t \rightarrow \infty$, nonlinear models have saturation.
- $P_t \rightarrow \infty$, linear model increases without bound.

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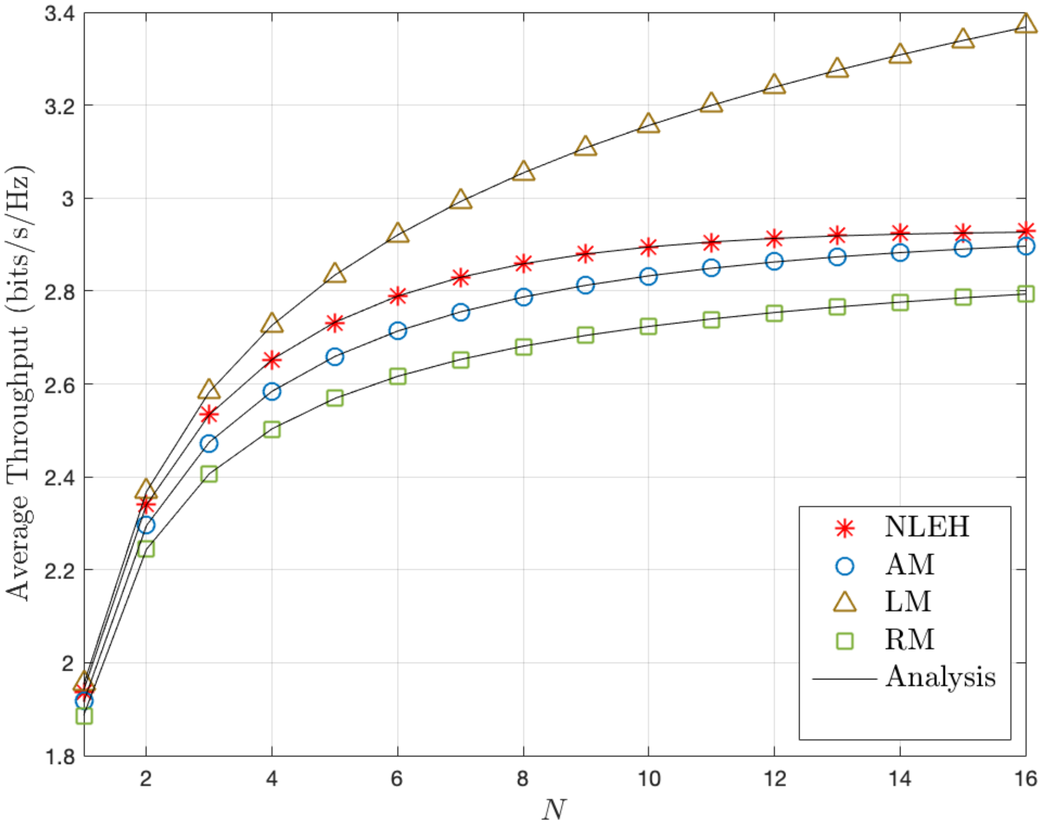
Numerical results



Average throughput of the delay-tolerant mode versus *N* for $P_t = -15$ dBm, , $\tau = 0.7$, $\eta = 0.6$, and $M = 2$. The markers represent simulation points.

- More antenna, better throughput.
- $N > 7$, throughput flatten.
- LM, no saturation.

Conclusion

- In WPCN
  - Derived exact & asymptotic OP for delay-limited throughput and EC for delay-tolerant throughput.
  - Derived exact & asymptotic BER and SER.

- EH models
  - Proposed NLEH & AM to model energy harvesters.
  - Demonstrated the superiority of NLEH and AM by comparing RMSE with sigmoid, piece-wise, and RM.
  - Derived delay-limited throughput, delay-tolerant throughput, and BER for NLEH, AM, LM, and RM.

Future research

- MIMO WPCN systems.
- Imperfect CSI with non-orthogonal multiple access (NOMA) assisted WPCNs.
- NLEH model in simultaneous wireless information and power transfer (SWIPT) systems.

Thank You!