The Road to Ubiquitous Communication Networks: Wireless Information and Power Transfer

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Outline

1. Introduction
   - Overview - 5G Communication Systems
   - Overview - Energy Harvesting: Wireless Powered Communications
2. Problem 1 - Efficient and Secure Wireless Powered Communications
3. Problem 2 - Practical Non-linear Energy Harvesting Model and Resource Allocation [1]
4. Future Works

Overview - 5G Communication Systems

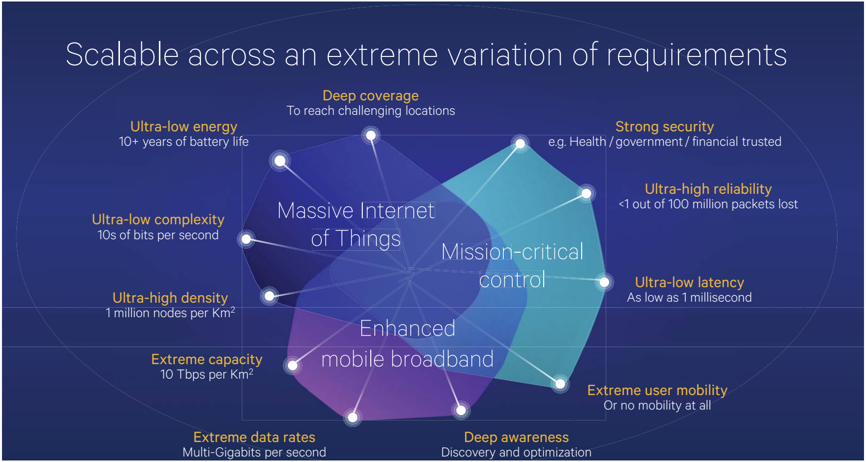


Figure: Qualcomm's 5G Vision [2].

5G Emerging Technologies

Core technologies/methods for fulfilling the strengthen quality of service (QoS) requirements:

- Multiple input multiple output (MIMO)
  - Extra degrees of freedom in resource allocation (diversity and multiplexing $\Rightarrow$ high data rate)
  - Artificial noise generation for degrading the channel of eavesdroppers (communication security) [3]
  - Information signal beamforming, zero forcing etc. (communication security)

5G Emerging Technologies

However, multiple antenna technology requires a high computational complexity at the receivers which may be not suitable for portable devices.

- Massive MIMO: Transmitter equipped with hundreds antennas serve multiple (e.g. single antenna) receivers [4, 5]
  - Shift the signal processing burden from the receivers to transmitter
  - Allow simple design and cheap receiver
  - Achieve asymptotically optimal performance by using simple precoding design

5G Emerging Technologies

- Ubiquitous and Self-sustainable Networks
  - Technologies
    - Conventional energy harvesting (scavenging): Collect energy from natural renewable energy sources such as solar, wind, and geothermal heat
    - Advantages: Self- substantiable network
    - Technical challenges (engineering problems): Time varying availability of the energy generated from renewable energy sources $\Rightarrow$ Perpetual but intermittent energy supply $\Rightarrow$ Unstable communication service.
    - E.g., solar energy and wind energy are varying significantly over time due to weather and climate conditions [6, 7]
    - Disadvantages: 1) Location and/or climate dependent $\Rightarrow$ Not suitable for mobile devices in indoor, enclosed areas; 2) Perpetual but intermittent energy supply $\Rightarrow$ Unstable communication service.

Overview - Energy Harvesting

- “New" energy harvesting technology: RF-based Energy Harvesting [8]–[13]
    - Collect energy from background radio frequency (RF) electromagnetic (EM) waves from ambient transmitters
        - Major Applications: RFID, body area networks, wireless sensor networks, Machine-to-Machine (M2M) communications, Internet of things (IoT), etc [14, 15].

Overview - RF-based Energy Harvesting

RF-based Energy Harvesting: Signal from ambient transmitters

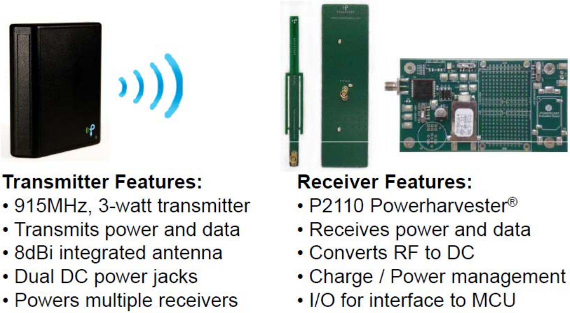
On going research over the world: Intel (far filed energy harvesting)

TV antenna, LoS to the KING-TV tower 4.1 km away. Carrier frequency: 680 MHz with an effective radiation power (ERP) of 960 KW. Harvested power: 60 microwatts, enough for powering up the thermometer/hygrometer and its LCD display.

Overview - RF-based Energy Harvesting

RF-based Energy Harvesting: Dedicated Energy Transmitter

Commercial Development Kits



Transmitter Features:

- 915MHz, 3-watt transmitter
- Transmits power and data
- 8dBi integrated antenna
- Dual DC power jacks
- Powers multiple receivers

Receiver Features:

- P2110 Powerharvester®
- Receives power and data
- Converts RF to DC
- Charge / Power management
- I/O for interface to MCU

915 MHz, 6 dBi receiver antenna, distance 4 meters, 3 watt equivalent isotropically radiated power $\Rightarrow$ 26μ Watt harvested power.
Enough to power on small wireless sensors!

www.powercastco.com

Overview - RF-based Energy Harvesting

RF Energy Harvesting

- Advantages:
  - Enable Wireless Information and Power Transfer.
  - Power source is controlled/deterministic
  - Reduces/eliminates battery replacement
  - One-to-many charging
  - Eliminates wires, simplifies installation
  - Suitable for enclosed environment
- Technical challenges (engineering problems):
  - Fundamental tradeoff between energy and information delivery (non-trivial in most cases) [8]
  - Optimal receiver structure? [16]

Overview - RF-based Energy Harvesting

Fundamental problem 1 [17]:

- High carrier frequency $\Rightarrow$ severe path loss. e.g. For 10 meters in free space, the attenuation of a wireless signal can be up to 50 dB for a carrier frequency of 915 MHz

To facilitate energy harvesting at the receivers, the transmitter can increase the transmit power of information signal

- Disadvantage:
  - Increases the susceptibility to eavesdropping due to a higher potential for information leakage [18]–[21]

Overview - RF-based Energy Harvesting

On the other hand, artificial noise is generated for combating the eavesdroppers

- A controllable energy source in RF to the energy harvesting receivers

Dual use of artificial noise

- Ensure communication security
- Facilitate wireless energy transfer

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System Model

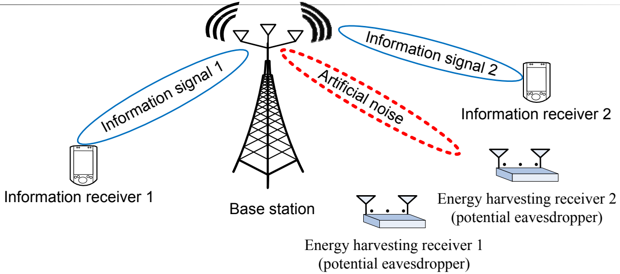

Figure: Downlink SWIPT communication system model with $K = 2$ single-antenna information receivers and $J = 2$ multiple-antenna energy harvesting receivers.

- The transmitter is equipped with $N_{\mathrm{T}} > 1$ antennas.
- Each information receiver is equipped with a single antenna.
- Each energy receiver is equipped with N_{R} multiple receive antennas.
- Channel state information of desire all the receivers is known at the transmitter

Channel Model

The received signals at the information receiver k and the energy harvesting receiver j are given by

$$\begin{aligned} y_k &= \mathbf{h}_k^H \mathbf{x} + n_k, \ \forall k \in \{1,\ldots,K\}, \text{ and} && (1)\\ \mathbf{y}_{\mathrm{ER}_j} &= \mathbf{G}_j^H \mathbf{x} + \mathbf{n}_{\mathrm{ER}_j}, \ \forall j \in \{1,\ldots,J\}, && (2) \end{aligned}$$

respectively. The transmitter constructs a transmit symbol vector $\mathbf{x}$ as

$$\mathbf{x} = \underbrace{\sum_{k=1}^{K} \mathbf{w}_k s_k}_{\text{desired signals}} + \underbrace{\mathbf{v}}_{\text{artifical noise}}, \qquad (3)$$

Performance measure

Achievable Rate of desired information receiver k:

$$C_k = \log_2(1+\Gamma_k), \quad \text{where} \tag{4}$$

$$\Gamma_k = \frac{|\mathbf{h}_k^H \mathbf{w}_k|^2}{\sum\limits_{m\neq k}^{K} |\mathbf{h}_k^H \mathbf{w}_m|^2 + \mathrm{Tr}(\mathbf{H}_k \mathbf{V}) + \sigma_s^2} \tag{5}$$

Performance measure

We focus on an unfavourable scenario for the decoding capability of the energy harvesting receivers for providing communication security to the information receivers.

Achievable Rate of energy harvesting receiver j (potential eavesdropper):

$$\begin{aligned} C^{k}_{\mathrm{ER}_j} &= \log_2 \det(\mathbf{I}_{N_\mathrm{R}} + \mathbf{Q}_j^{-1}\mathbf{G}_j^H \mathbf{w}_k \mathbf{w}_k^H \mathbf{G}_j), \\ \mathbf{Q}_j &= \mathbf{G}_j^H \mathbf{V} \mathbf{G}_j + \sigma_\mathrm{s}^2 \mathbf{I}_{N_\mathrm{R}} \succ 0, \end{aligned} \tag{6}$$

Assumption: The energy harvesting receivers are able to perform successive interference cancellation before decoding the desired information

Performance measure

Achievable Secrecy Rate of information receiver k

$$C_{\mathrm{sec}_k} = \left[C_k - \max_{\forall j} \left\{ C^k_{\mathrm{ER}_j} \right\} \right]^+ . \tag{7}$$

Total harvested power by energy harvesting receiver j [22]–[32]

$$E_{\mathrm{ER}_j} = \eta_j \,\mathrm{Tr}\left(\mathbf{G}_j^H \Big(\sum_{k=1}^{K} \mathbf{w}_k \mathbf{w}_k^H + \mathbf{V} \Big) \mathbf{G}_j \right), \tag{8}$$

where $0 \le \eta_j \le 1$ is a constant which denotes the energy conversion efficiency of energy harvesting receiver j.

Resource Allocation: Problem Formulation

Resource Allocation Optimization

$$\underset{\mathbf{V}\in\mathbb{H}^{N_\mathrm{T}},\mathbf{w}_k}{\text{maximize}} \ \min_{j\in\{1,\ldots,J\}} \left\{\eta_j \,\mathrm{Tr}\left(\mathbf{G}_j^H\Big(\sum_{k=1}^{K}\mathbf{w}_k\mathbf{w}_k^H+\mathbf{V}\Big)\mathbf{G}_j\right)\right\}$$

$$\text{s.t.} \quad \text{C1: } \frac{|\mathbf{h}_k^H\mathbf{w}_k|^2}{\sum\limits_{m\neq k}^{K}|\mathbf{h}_k^H\mathbf{w}_m|^2+\mathrm{Tr}(\mathbf{H}_k\mathbf{V})+\sigma_\mathrm{s}^2}\geq\Gamma_{\mathrm{req}_k},\ \forall k,$$

$$\text{C2: } \log_2\det(\mathbf{I}_{N_\mathrm{R}}+\mathbf{Q}_j^{-1}\mathbf{G}_j^H\mathbf{w}_k\mathbf{w}_k^H\mathbf{G}_j)\leq R_{\mathrm{ER}_{j,k}},\ \forall k,\forall j,$$

$$\text{C3: } \mathrm{Tr}(\mathbf{V})+\sum_{k=1}^{K}\|\mathbf{w}_k\|^2\leq P_{\max},\ \text{C4: } \mathbf{V}\succeq\mathbf{0}. \qquad (9)$$

Blue color = non-convex elements

Optimization Solution: Equivalent constraint

To handle the non-convex constraint C2, we introduce the following proposition:

Proposition

For $R_{\mathrm{ER}_{j,k}} > 0, \forall j, k$, the following implication on constraint C2 holds:

$$\mathrm{C2} \Rightarrow \overline{\mathrm{C2}}\text{:}\ \mathbf{G}_j^H \mathbf{W}_k \mathbf{G}_j \preceq \alpha_{\mathrm{ER}_{j,k}} \mathbf{Q}_j, \ \forall j, k, \tag{10}$$

where $\mathbf{W}_k = \mathbf{w}_k \mathbf{w}_k^H$ and $\alpha_{\mathrm{ER}_{j,k}} = 2^{R_{\mathrm{ER}_{j,k}}} - 1$ is an auxiliary constant. $\overline{\mathrm{C2}}$ is a linear matrix inequality (LMI) constraint. We note that constraints $\overline{\mathrm{C2}}$ and C2 are equivalent if $\mathrm{Rank}(\mathbf{W}_k) \leq 1, \forall k$.

Semi-definite Programming Relaxation

For facilitating the SDP relaxation, we define $\mathbf{W}_k = \mathbf{w}_k\mathbf{w}_k^H$ and rewrite the original problem in terms of $\mathbf{W}_k$ as

SDP Relaxation

$$\underset{\mathbf{W}_k,\mathbf{V}\in\mathbb{H}^{N_\mathrm{T}},\tau}{\text{maximize}} \quad \tau \tag{11}$$

$$\begin{aligned}
\text{s.t.}\quad &\text{C1: } \frac{\mathrm{Tr}(\mathbf{H}_k\mathbf{W}_k)}{\Gamma_{\mathrm{req}_k}} - \mathrm{Tr}\Big(\mathbf{H}_k\big(\sum_{m\neq k}^{K}\mathbf{W}_m + \mathbf{V}\big)\Big) \geq \sigma_\mathrm{s}^2,\ \forall k,\\
&\overline{\text{C2}}\text{: } \mathbf{G}_j^H\mathbf{W}_k\mathbf{G}_j \preceq \alpha_{\mathrm{ER}_{j,k}}\mathbf{Q}_j,\ \forall j,k,\\
&\text{C3: } \mathrm{Tr}\Big(\mathbf{V} + \sum_{k=1}^{K}\mathbf{W}_k\Big) \leq P_{\max},\\
&\text{C4: } \mathbf{V}\succeq 0,\ \text{C5: } \mathbf{W}_k\succeq 0, \forall k,\ \text{C6: } \mathrm{Rank}(\mathbf{W}_k)\leq 1,\ \forall k,\\
&\text{C7: } \eta_j\,\mathrm{Tr}\Big(\mathbf{G}_j^H\big(\sum_{k=1}^{K}\mathbf{W}_k + \mathbf{V}\big)\mathbf{G}_j\Big) \geq \tau, \forall j\in\{1,\dots,J\},
\end{aligned}$$

For facilitating the SDP relaxation, we define $\mathbf{W}_k = \mathbf{w}_k\mathbf{w}_k^H$ and rewrite the original problem in terms of $\mathbf{W}_k$ as

Optimality Conditions

Theorem 1:

There exist an optimal solution with $\mathrm{Rank}(\mathbf{W}_k^*) \le 1$. Besides, by exploiting the solution of the dual problem, the rank-one solution can be obtained via construction.

Simulation Results – Simulation Parameters

Table: System parameters

User distances (uniformly distributed)	2 m to 50 meters
Number of information receivers	3
Number of energy harvesting receivers	2
Carrier center frequency	915 MHz
Small-scale fading distribution	Rician fading with Rician factor 3 dB
Total noise variance, σ_{s}^2	-23 dBm
Transmit power budget, $P_{\max}$	46 dBm
Number of receive antennas at each ER, N_{R}	2
Receive antenna gain	6 dB
Max. tolerable channel capacity at ERs, $R_{\mathrm{ER}_{j,k}}$	1 bit/s/Hz
RF energy to electrical energy conversion efficiency for ER j, η_j	0.5

Average Total Transmit Power versus Γ_{req}

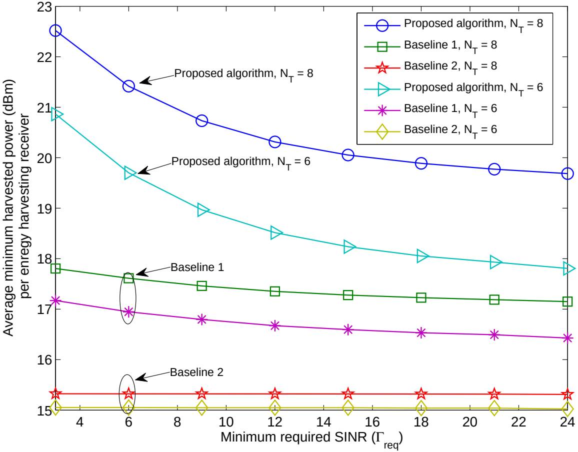

Figure: Average total harvested power (dBm) per energy harvesting receivers versus the minimum required SINR of the information receivers, Γ_{req}.

Summary of Problem 1

- The power allocation algorithm design for secure SWIPT transmission was formulated as a non-convex optimization problem
- SDP relaxation was adopted to solve the optimization problem optimally
- Simulation results unveiled the high wireless energy transfer efficiency enabled by the optimization of beamforming and artificial noise generation

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RF-based Energy Harvesting

Fundamental problem 2:

Efficient resource allocation algorithm design relies on accurate system model

- RF energy harvesting circuits are complicated and implementation dependent
- It is expected that energy harvesting circuits introduce non-linearity in the EH process

Practical Non-linear EH Model

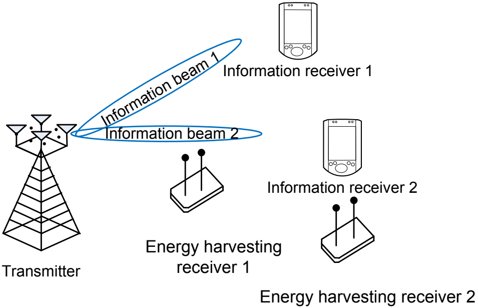

Figure: A downlink SWIPT system with $K = 2$ information receivers (IRs) and $J = 2$ energy harvesting receivers (ERs).

- The transmitter is equipped with $N_{\mathrm{T}} > 1$ antennas.
- Each information receiver is equipped with a single antenna.
- Each energy receiver is equipped with N_{R} multiple receive antennas.
- Channel state information of desire all the receivers is known at

Signal Model

In each time slot, the transmitter sends a vector of data symbols to the K IRs. The received signals at IR k and ER j are given by

$$y_k = \mathbf{h}_k^H \sum_{k=1}^{K} \mathbf{w}_k s_k + n_k, \ \forall k \in \{1, \ldots, K\}, \text{ and} \quad (13)$$

$$\mathbf{y}_{\mathrm{ER}_j} = \mathbf{G}_j^H \sum_{k=1}^{K} \mathbf{w}_k s_k + \mathbf{n}_{\mathrm{ER}_j}, \ \forall j \in \{1, \ldots, J\}. \quad (14)$$

RF-based Energy Harvesting

In the literature, the total harvested energy at ER j, $\Phi_{\mathrm{ER}_j}^{\mathrm{Linear}}$, is typically modelled by the following linear model [10]–[13]:

Linear EH Model

$$\Phi_{\mathrm{ER}_j}^{\mathrm{Linear}} = \eta_j P_{\mathrm{ER}_j}, \quad P_{\mathrm{ER}_j} = \sum_{k=1}^{K} \mathrm{Tr}\left(\mathbf{w}_k \mathbf{w}_k^H \mathbf{G}_j \mathbf{G}_j^H\right), \tag{15}$$

However, in practice, EH circuits result in a non-linear end-to-end wireless power transfer. Besides, the RF-to-DC power conversion efficiency changes with the input power. Is the linear EH model valid?

Practical Non-linear EH Model

Design Goals

- Propose a mathematically tractable non-linear EH model that matches experimental results [33, 34] for the wireless power harvested by practical EH circuits
- Non-linear EH model captures joint effect of the non-linear phenomena caused by the EH circuit hardware limitations such as circuit sensitivity and current leakage

Practical Non-linear EH Model

Proposition for EH model with respect to practical EH circuits:

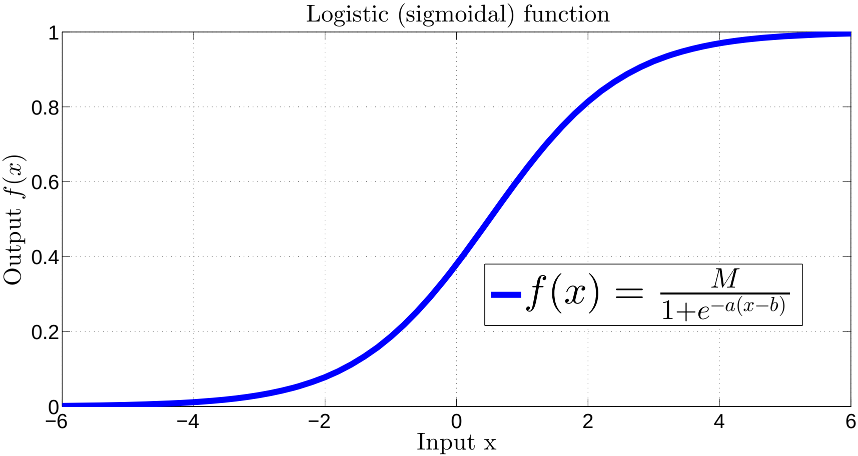

Figure: A standard logistic function.

Practical Non-linear EH Model Proposition

Proposed Parametric Non-linear EH Model [1]

Total harvested power at energy harvester k is given by

$$E_k(n) = \frac{\Big[\Psi_k(n) - M\Omega\Big]}{1-\Omega}, \ \Omega = \frac{1}{1+e^{ab}}, \tag{16}$$
$$\Psi_k(n) = \frac{M}{1+e^{-a(P_{\mathrm{ER}_k}(n)h_k(n))-b)}}.$$

- $\Psi_k(n)$ - traditional logistic function with respect to the received RF power $P_{\mathrm{ER}_k}(n)$ at EH receiver (ER) k, in time slot n, $\forall n, k$
- Ω - constant term to guarantee zero-input/zero-output response for the EH circuit
- M - constant that stands for the maximum harvested power at the ER, when the **EH circuit is saturated**; a and b are related to the detailed specifications of the EH circuit such as resistance, capacitance, and turn-on voltage

Practical Non-linear EH Model Proposition

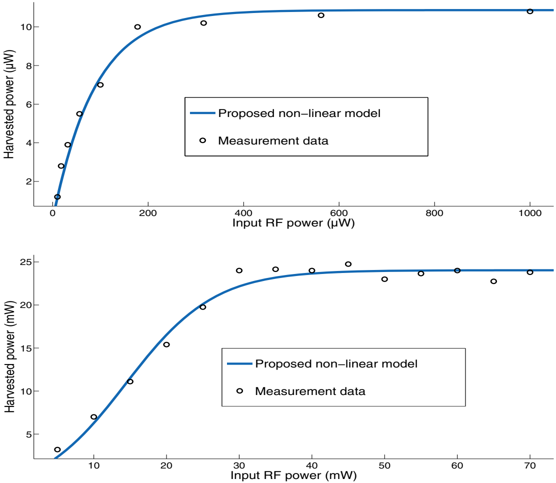

Figure: Curve fitting of measurement data from [33] and [34]

Optimization Problem Formulation

Optimization Problem

$$\begin{aligned} \underset{\mathbf{w}_k}{\text{maximize}} \quad & \sum_{j=1}^{J} \Psi_{\mathrm{ER}_j}^{\mathrm{Practical}} \quad \text{[sum of ratios function]} \\ \text{subject to} \quad & \mathrm{C1}: \sum_{k=1}^{K} \|\mathbf{w}_k\|^2 \leq P_{\max}, \\ & \mathrm{C2}: \frac{\mathbf{w}_k^H \mathbf{H}_k \mathbf{w}_k}{\sum_{j \neq k} \mathbf{w}_j^H \mathbf{H}_k \mathbf{w}_j + \sigma_{\mathrm{s}}^2} \geq \Gamma_k^{\mathrm{req}}, \forall k, \end{aligned} \tag{17}$$

Blue color = non-convex elements

Optimization Problem Formulation

Non-convex optimization problem:

- Sum-of-ratios objective function
- Non-convex constraint for beamforming vector

Solution:

- Transform sum-of-ratios objective function using algorithm from [35]
- Solve resource allocation optimization problem through an iterative algorithm

Optimization Solution

Theorem 1 [35]:

Suppose $\mathbf{w}_k^*$ is the optimal solution to (17), then there exist two vectors $\boldsymbol{\mu}^* = [\mu_1^*, \dots, \mu_J^*]$ and $\boldsymbol{\beta}^* = [\beta_1^*, \dots, \beta_J^*]$ such that $\mathbf{w}_k^*$ is an optimal solution to the following optimization problem

$$\underset{\mathbf{w}_k^* \in \mathcal{F}}{\text{maximize}} \sum_{j=1}^{J} \mu_j^* \left[M_j - \beta_j^* \Big(1 + \exp\big(-a_j(P_{\mathrm{ER}_j} - b_j)\big) \Big) \right], \tag{18}$$

where $\mathcal{F}$ is the feasible solution set of (17). Besides, $\mathbf{w}_k^*$ also satisfies the following system of equations:

$$\beta_j^* \Big(1 + \exp\big(-a_j(P^*_{\mathrm{ER}_j} - b_j)\big) \Big) - M_j = 0, \tag{19}$$

$$\mu_j^* \Big(1 + \exp\big(-a_j(P^*_{\mathrm{ER}_j} - b_j)\big) \Big) - 1 = 0, \tag{20}$$

and $P^*_{\mathrm{ER}_j} = \sum_{k=1}^{K} \mathrm{Tr}\left(\mathbf{w}_k^* (\mathbf{w}_k^*)^H \mathbf{G}_j \mathbf{G}_j^H \right)$.

Optimization Solution

In each iteration, we solve the following optimization problem for given parameters $(\boldsymbol{\mu}, \boldsymbol{\beta})$:

Transformed Optimization Problem

$$\underset{\mathbf{W}_k \in \mathbb{H}^{N_\mathrm{T}}, \tau_j}{\text{maximize}} \quad \sum_{j=1}^{J} \mu_j \Big[M_j - \beta_j \Big(1 + \exp\big(-a_j(\tau_j - b_j) \big) \Big) \Big] \tag{21}$$

$$\begin{aligned}
\text{subject to} \quad & \mathrm{C1}: \sum_{k=1}^{K} \mathrm{Tr}(\mathbf{W}_k) \le P_{\max}, \\
& \mathrm{C2}: \frac{\mathrm{Tr}(\mathbf{H}_k \mathbf{W}_k)}{\Gamma_k^{\mathrm{req}}} \ge \sum_{j \neq k} \mathrm{Tr}(\mathbf{H}_k \mathbf{W}_j) + \sigma_\mathrm{s}^2, \forall k. \\
& \mathrm{C3}: \mathrm{Rank}(\mathbf{W}_k) \le 1, \forall k,
\end{aligned}$$

$$\mathrm{C4}: \ \tau_j \le \sum_{k=1}^{K} \mathrm{Tr}\left(\mathbf{W}_k \mathbf{G}_j \mathbf{G}_j^H \right), \forall j, \quad \mathrm{C5}: \ \mathbf{W}_k \succeq \mathbf{0}, \forall k,$$

$$\text{maximize} \quad \sum_{j=1}^{J} \mu_j \Big[M_j - \beta_j \Big(1 + \exp\big(-a_j(\tau_j - b_j) \big) \Big) \Big] \tag{22}$$

Optimization Solution

Theorem 2:

Assuming that the channels, i.e., $\mathbf{h}_k$ and $\mathbf{G}_j$, are statistically independent and (22) is feasible, the optimal beamforming matrix of the SDP relaxed problem of (22) is a rank-one matrix with probability one, i.e., $\mathrm{Rank}(\mathbf{W}_k^*) = 1, \forall k$, for $\Gamma_k^{\mathrm{req}} > 0$.

Iterative Update Equation

In the n-th iteration, we use the well-known damped Newton method to update $(\boldsymbol{\mu},\boldsymbol{\beta})$ iteratively. In particular, $\boldsymbol{\mu}^{n+1}$ and $\boldsymbol{\beta}^{n+1}$ can be updated as, respectively,

$$\begin{aligned} \boldsymbol{\mu}^{n+1} &= \boldsymbol{\mu}^{n}+\zeta^{n}\mathbf{q}^{n} \text{ and } \boldsymbol{\beta}^{n+1}=\boldsymbol{\beta}^{n}+\zeta^{n}\mathbf{q}^{n}, && (23)\\ \text{where}\quad \mathbf{q}^{n} &= [\boldsymbol{\varphi}'(\boldsymbol{\mu},\boldsymbol{\beta})]^{-1}\boldsymbol{\varphi}(\boldsymbol{\mu},\boldsymbol{\beta}) && (24)\end{aligned}$$

and $\boldsymbol{\varphi}'(\boldsymbol{\mu},\boldsymbol{\beta})$ is the Jacobian matrix of $\boldsymbol{\varphi}(\boldsymbol{\mu},\boldsymbol{\beta})$. ζ^{n} is the largest ε^{l} satisfying

$$\left\|\boldsymbol{\varphi}\left(\boldsymbol{\mu}^{n}+\varepsilon^{l}\mathbf{q}^{n},\boldsymbol{\beta}^{n}+\varepsilon^{l}\mathbf{q}^{n}\right)\right\| \le (1-\delta\varepsilon^{l})\|\boldsymbol{\varphi}(\boldsymbol{\mu},\boldsymbol{\beta})\|, \qquad (25)$$

where $l\in\{1,2,\ldots\}$, $\varepsilon^{l}\in(0,1)$, $\delta\in(0,1)$.
$\varphi_j(\beta_j)=\beta_j\Big(1+\exp\big(-a_j(P_{\mathrm{ER}_j}-b_j)\big)\Big)-M_j$ and
$\varphi_{J+i}(\mu_i)=\mu_i\Big(1+\exp\big(-a_i(P_{\mathrm{ER}_i}-b_i)\big)\Big)-1$, $i\in\{1,\ldots,J\}$.

Iterative Algorithm

Table: Iterative Resource Allocation Algorithm.

Algorithm Iterative Resource Allocation Algorithm

```
Initialize the maximum number of iterations $L_{\max}$, iteration index $n = 0$, $\boldsymbol{\mu}$, and $\boldsymbol{\beta}$
repeat {Outer Loop}
    Solve the inner loop problem in (22) via SDP relaxation for given $(\boldsymbol{\mu}^n, \boldsymbol{\beta}^n)$ and obtain the intermediate beamformer $\mathbf{w}_k'$
    if (25) is satisfied then
        return Optimal beamformer $\mathbf{w}_k^* = \mathbf{w}_k'$
    else
        Update $\boldsymbol{\mu}$ and $\boldsymbol{\beta}$ according to (23) and $n = n + 1$
    end if
until (25) is satisfied or $n = L_{\max}$
```

Results – Simulation Parameters

Table: System parameters

Location of information receivers	50 meters
Location of ERs	10 meters
Number of information receivers	2
Carrier center frequency	915 MHz
Small-scale fading distribution	Rician fading with Rician factor 3 dB
Total noise variance, σ_{s}^2	-23 dBm
Transmit power budget, $P_{\max}$	30 dBm
Number of receive antennas at each ER, N_{R}	2
Antenna gain	10 dBi
a_j, b_j, M_j	6400, 0.003, 20 mW

Average total harvested power (dBm)

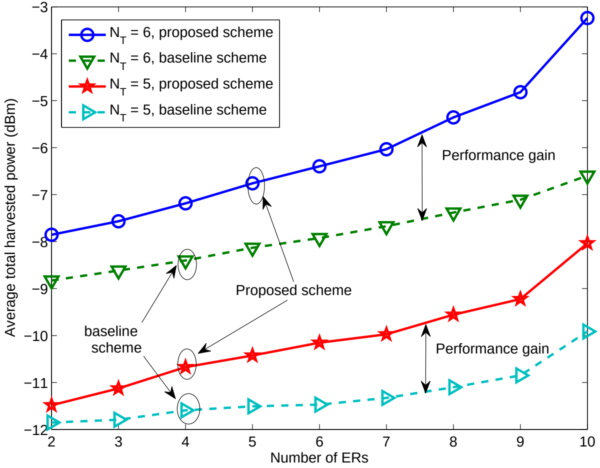

Figure: Average total harvested power (dBm) versus the number of ERs.

Summary of Problem 2

- We proposed a practical non-linear EH model and study the corresponding resource allocation problem
- An iterative algorithm and SDP relaxation were adopted to solve the optimization problem optimally
- Simulation results unveiled that resources allocation algorithms designed for linear model will lead to resource allocation mismatches for practical non-linear EH circuits.

Future Works

- Partial/imperfect CSIT
  - Pure energy harvesting devices do not equip with communication circuit $\Longrightarrow$ No CSI
- Waveform design for efficient energy transfer
  - Is Gaussian signal optimal for energy transfer?
- Wideband or narrow band?
  - Wideband is good for information transmission. Yet, narrow band is good for energy transfer
- Cross-layer scheduling
  - Heterogenous requirements: Energy and information
- Interference Management
  - Strong interference is a vital energy source
  - Information Transmission: Suppress interference vs. Energy Harvesting: Embrace interference $\Longrightarrow$ There are multiple conflicting system design objectives in a system.

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