Joint Energy and Communication Scheduling for Wireless Powered Networks

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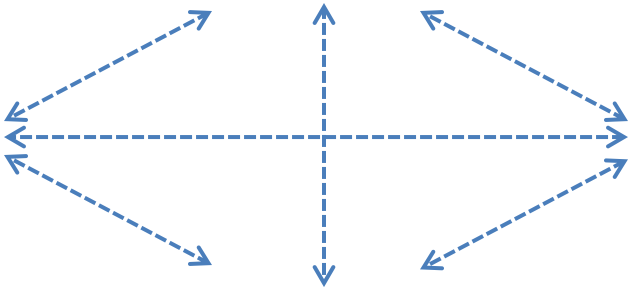
Related Research Areas of Wireless Powered Communications

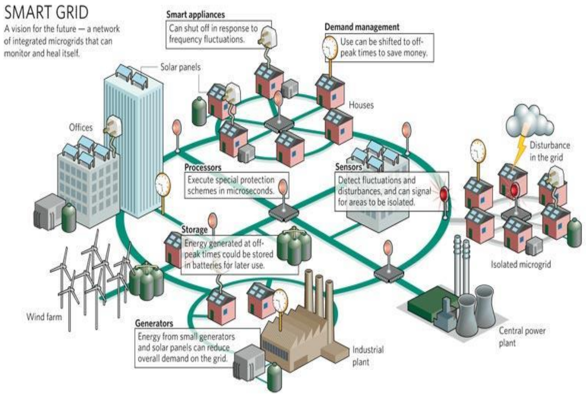
Wireless power transfer

Green communications

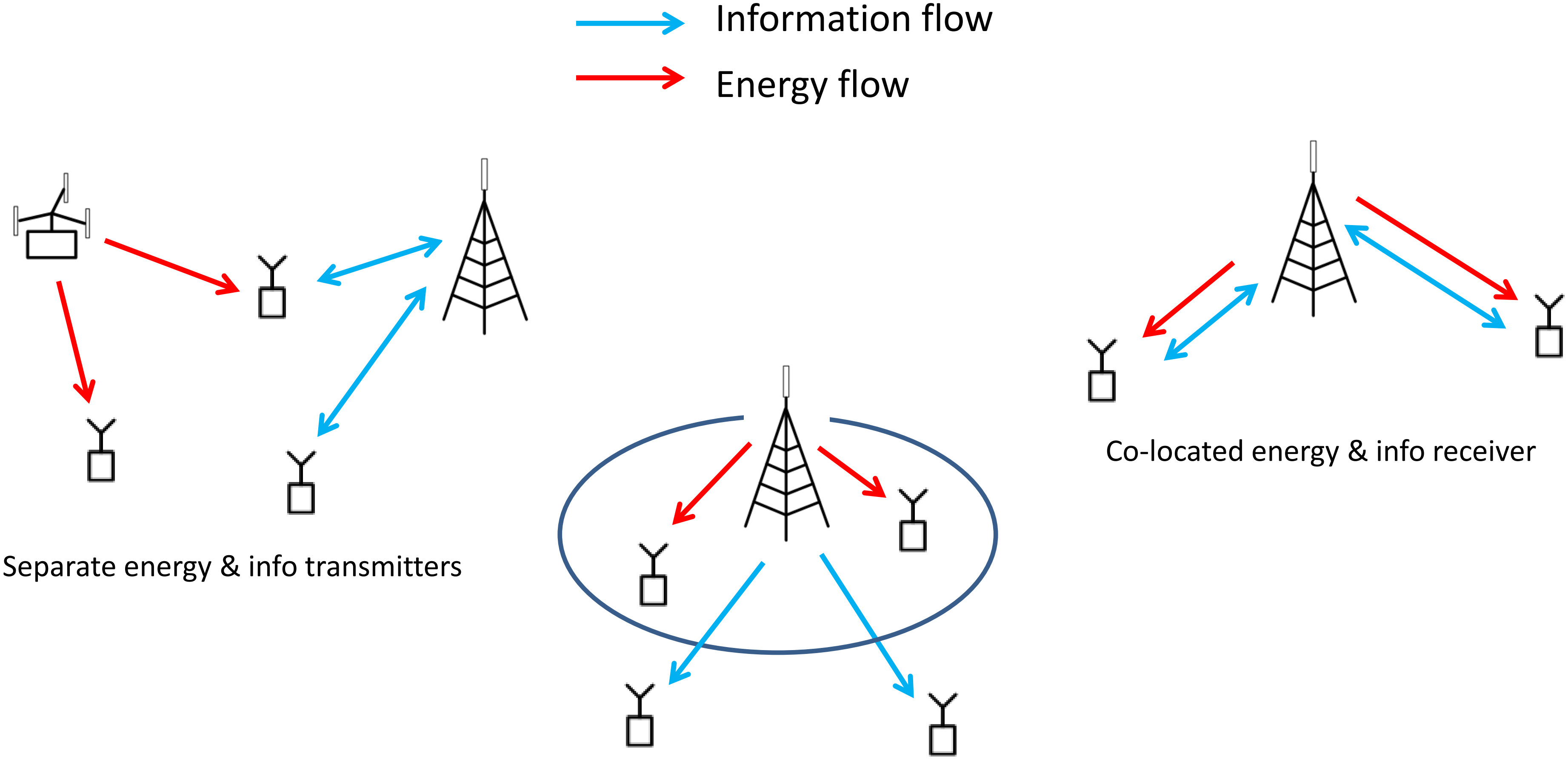


Energy harvesting

Smart grid



Wireless Powered Communication: Network Architectures



Information flow

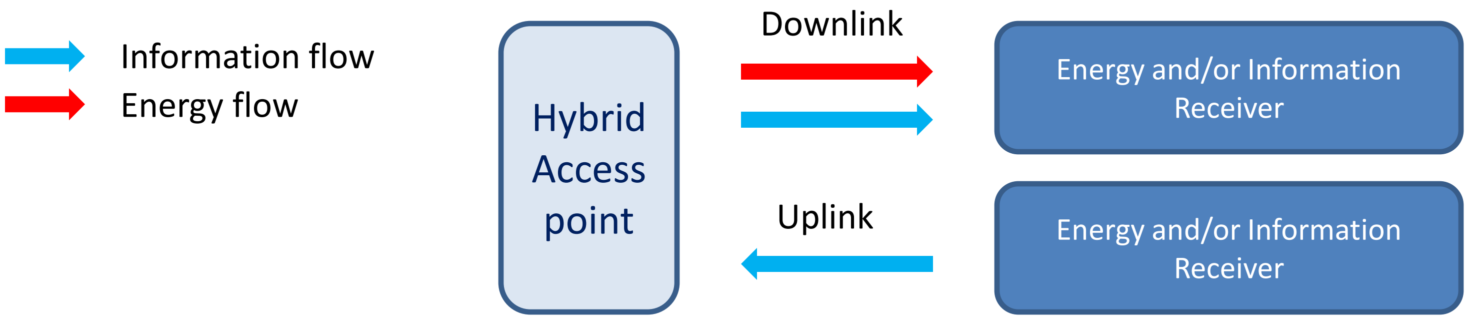
Energy flow

Separate energy & info transmitters

Separate energy & info receivers

Co-located energy & info receiver

A Generic UL/DL System Model [1]



Information flow

Energy flow

Hybrid Access point

Downlink

Uplink

Energy and/or Information Receiver

Energy and/or Information Receiver

- The received baseband-equivalent signal at a receiver

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{e}$$

- If used for energy harvesting (EH), the harvested power is

$$E = \mathrm{E}\left[\alpha||\mathbf{H}\mathbf{x}||^2\right] = \alpha \cdot \mathrm{trace}\left(\mathbf{H}\mathbf{Q}\mathbf{H}^H\right)$$

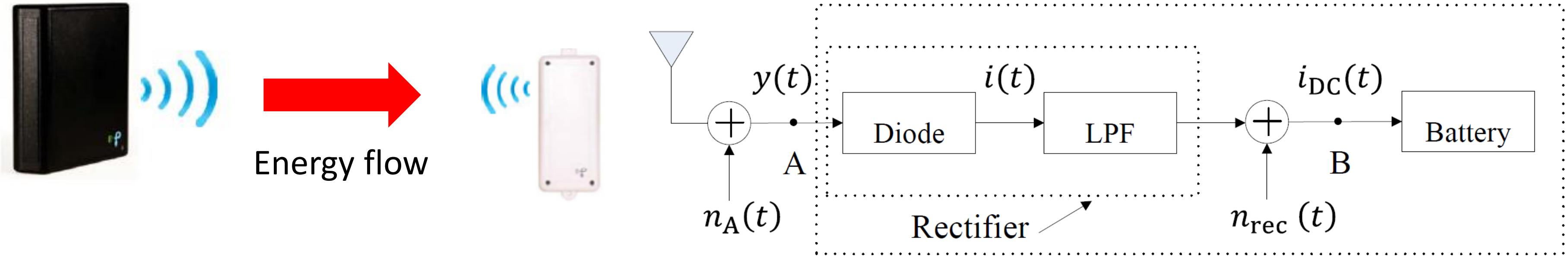
- If used for information decoding (ID), the achievable data rate is

$$R = \log\det\left(\mathbf{I} + \frac{1}{\sigma^2}\mathbf{H}\mathbf{Q}\mathbf{H}^H\right)$$

- In practice, a receiver cannot harvest energy and decode information simultaneously.

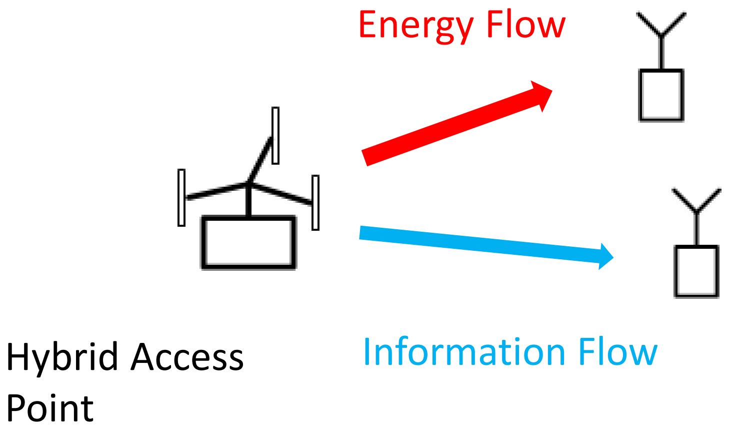
Operating Mode 1: WPT

- ☐ Wireless power transfer (WPT)
  - Only power transfer in one direction
  - Continuous and controllable (vs. ambient RF and other environment energy harvesting, intermittent and random)
  - Application: mobile device and sensor charging, etc.
  - Technologies available (to be detailed)
    - ✓ Inductive coupling
    - ✓ Coupled magnetic resonance
    - ✓ EM radiation

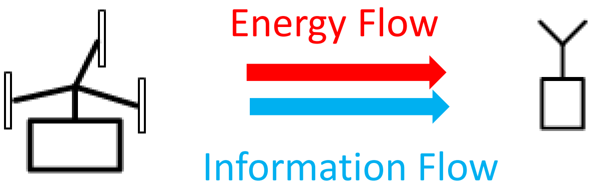


Operating Mode 2: SWIPT

- Simultaneous wireless information and power transfer (SWIPT) [1]
  - Info & energy transmit simultaneously in DL
  - Under limited signal power and bandwidth (vs. power-line communication)
  - Applications: heterogeneous EH and ID receivers, simultaneous ID and EH at one receiver, etc.
  - Rate-and-energy tradeoff
  - Separate or co-located ID and EH receivers



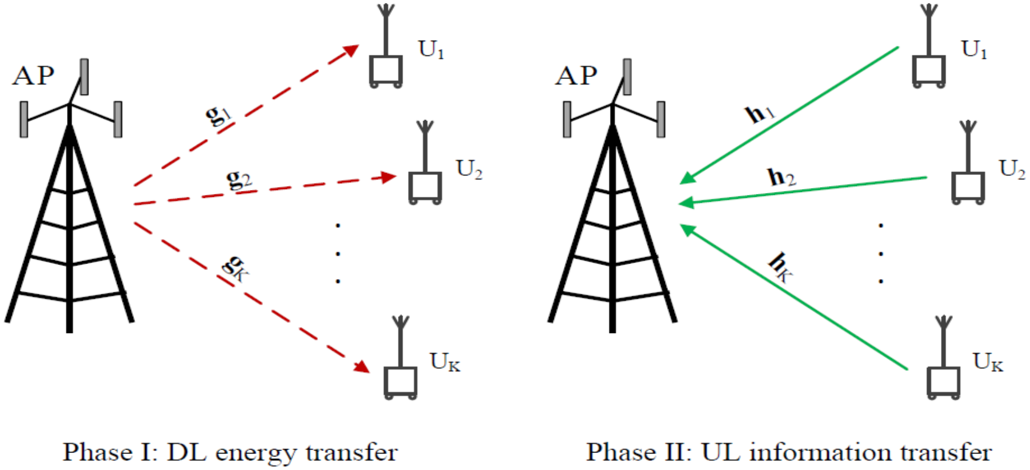
SWIPT with separate ID and EH receivers



SWIPT with co-located ID and EH receivers

Operating Mode 3: WPCN (focus of this talk)

- Wireless powered communication network (WPCN) [2]
  - DL: wireless power transfer
  - UL: Information transfer with wireless harvested energy
  - Applications: sensor network charging and info collection [3], RFID, etc.
  - Power consumptions at the energy receiver
    - ✓ Sensing and info processing
    - ✓ UL info transmission



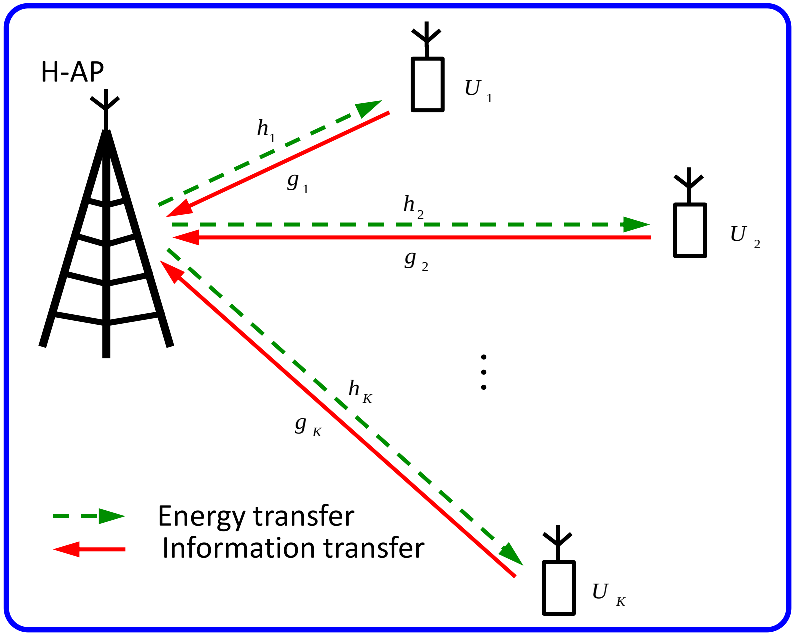
Phase I: DL energy transfer

Phase II: UL information transfer

Agenda

- Single-Antenna Wireless Powered Communication Network
- Multi-Antenna Wireless Powered Communication Network
- Extension and Future Work

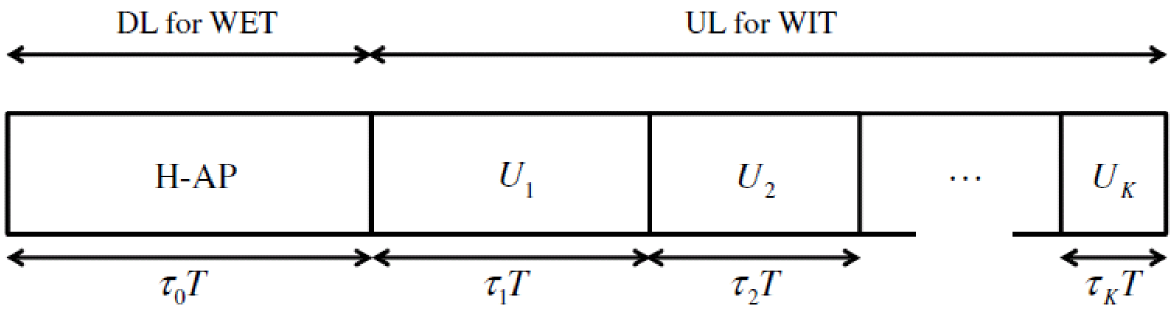
System Model



- ☐ One hybrid AP (H-AP)
- ☐ *K* user terminals
- ☐ Single antenna at all nodes
- ☐ Quasi-static flat-fading channels

- ☐ Wireless power transfer (WPT) from H-AP to users in DL
- ☐ Wireless information transmission (WIT) from users to H-AP in UL by TDMA

Harvest-then-Transmit-Protocol [2]



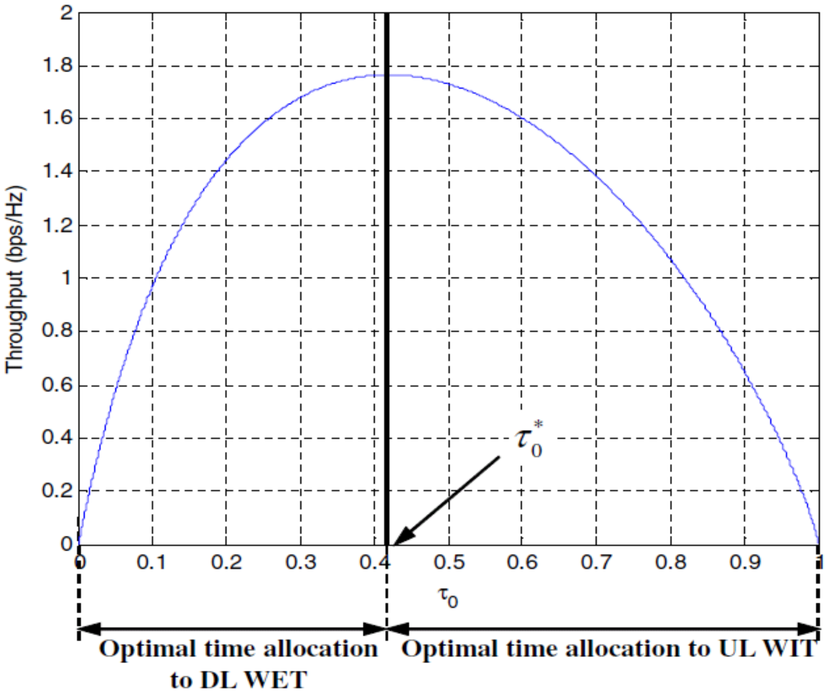
- WPT in DL
  - Energy broadcast with time duration τ_0
  - Energy harvested by user *i*: $E_i = \zeta_i P_A h_i \tau_0, \quad i = 1, \cdots, K$
- WIT in UL
  - TDMA, each user with time duration τ_i
  - Transmit power at user *i*: $P_i = \frac{\eta_i E_i}{\tau_i}$
  - Achievable rate of user *i*:

$$R_i(\boldsymbol{\tau}) = \tau_i \log_2\left(1 + \frac{g_i P_i}{\Gamma\sigma^2}\right) = \tau_i \log_2\left(1 + \gamma_i \frac{\tau_0}{\tau_i}\right)$$

where $\gamma_i = \frac{\zeta_i \boxed{h_i g_i} P_A}{\Gamma\sigma^2}$ is effective channel accounting for both DL and UL channels

- Trade-off: rate per user increases with both DL and UL time allocated given a total time constraint: $\sum_{i=0}^{K} \tau_i \le 1$

DL-UL Time Allocation Trade-off



Throughput versus DL-UL time allocation, τ_0, $1-\tau_0$, in a single-user setup, with effective channel gain $\gamma_1 = 10\text{dB}$

- Zero throughput with $\tau_0 = 1$ or $\tau_1 = 1 - \tau_0 = 0$
- Throughput increases over τ_0 when it is small, decreases over τ_0 otherwise
  - With small τ_0, DL WPT time dominates throughput
  - With large τ_0, UL WIT time dominates throughput
  - Optimal DL vs. UL time allocation?

Sum-Throughput Maximization

- Problem formulation
  - Convex optimization problem
    - ✓ Objective function: concave
    - ✓ Constraints: linear

$$\begin{aligned} \max_{\boldsymbol{\tau}} \quad & R_{\text{sum}}\left(\boldsymbol{\tau}\right) = \sum_{i=1}^{K} R_i\left(\boldsymbol{\tau}\right) \\ \text{s.t.} \quad & \sum_{i=0}^{K} \tau_i \leq 1, \\ & \tau_i \geq 0, \quad i = 0,\ 1,\ \cdots\ K. \end{aligned}$$

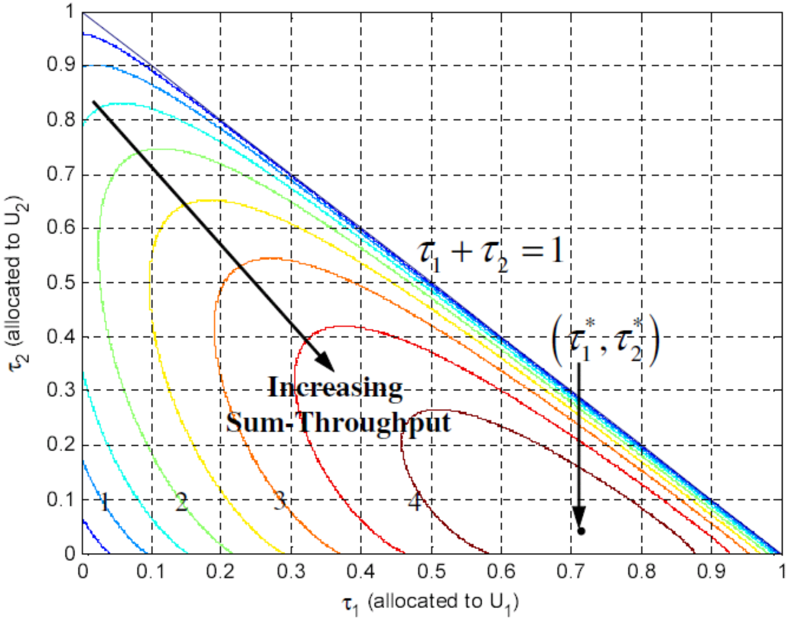
- Closed-form optimal solution
  - Time allocated to DL WPT τ_0^* and users in UL WIT τ_i^*'s should be all non-zero
  - τ_0^* decreases with A , τ_i^* increases with A
  - Ratio between time allocated to two users in UL WIT: $\frac{\tau_i}{\tau_j} = \frac{\gamma_i}{\gamma_j} = \frac{h_i g_i}{h_j g_j}$ **doubly near-far problem**

$$\tau_i^* = \begin{cases} \frac{z^* - 1}{A + z^* - 1}, & i = 0 \\ \frac{\gamma_i}{A + z^* - 1}, & i = 1, \cdots, K \end{cases}$$

where $A \triangleq \sum_{i=1}^{K} \gamma_i$ is the sum of users' effective channel gains, $z^* > 1$ is constant satisfying $z \ln z - z + 1 = A$

Doubly Near-Far Problem

Sum-throughput versus time allocation (two-user)

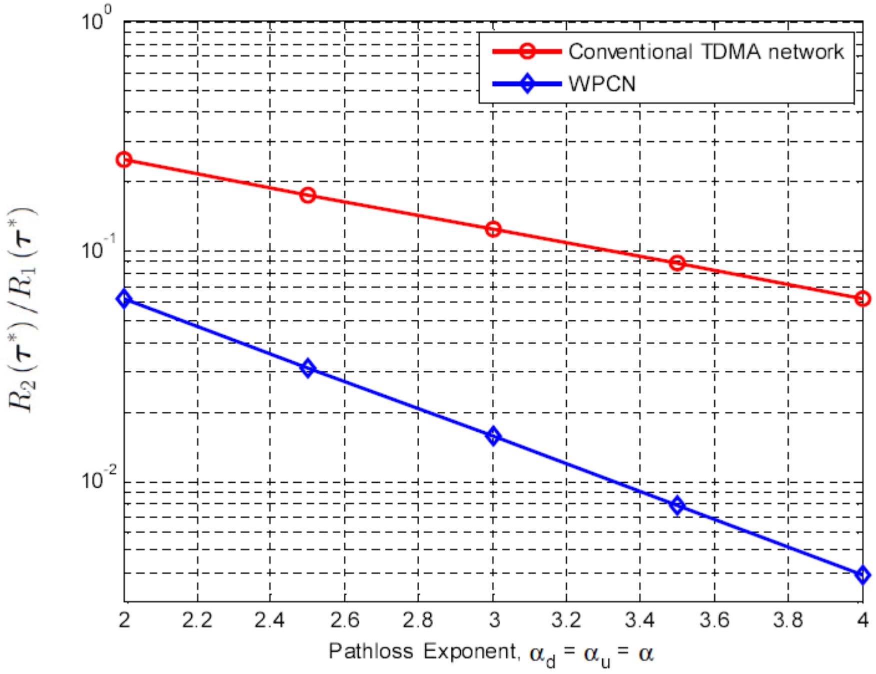


- One H-AP
- Two users: distance to H-AP
  $D_1 = \frac{1}{2} D_2$
- Channel models:
  $h_i \propto D_i^{-\alpha_d}, \; g_i \propto D_i^{-\alpha_u}$
- Pathloss exponents: $\alpha_d = \alpha_u = 2$
- Optimal time allocation: $\tau_1^* = 16\tau_2^*$,
  or $\tau_1^* = (D_2/D_1)^{\boxed{\alpha_d+\alpha_u}}\tau_2^*$
- Optimal rate allocation:
  $\boxed{R_1(\boldsymbol{\tau}^*) = 4.13 \quad R_2(\boldsymbol{\tau}^*) = 0.45}$

- Doubly near-far problem: $\gamma_i = \frac{\zeta \boxed{h_i g_i} P_A}{\Gamma \sigma^2}$
  - Distance-dependent signal attenuation in both DL and UL
    - “Near” user harvests more energy in DL and has less power loss in UL
    - “Far” user harvests less energy in DL but has more power loss in UL
  - Unfair time and rate allocation among users

Doubly Near-Far Problem

Rate ratio versus pathloss exponent (two-user)



- One H-AP
- Two users: distance to H-AP $D_1 = \frac{1}{2} D_2$
- Channel models: $h_i \propto D_i^{-\alpha_d},\ g_i \propto D_i^{-\alpha_u}$
- Identical pathloss exponents: $\alpha_d = \alpha_u = \alpha$

- Rate ratio (user 2 over user 1) decreases twice faster in the logarithm scale than conventional TDMA (with constant transmit power) due to doubly near-far problem
  - Wireless powered communication network: $\tau_i^* \propto D_i^{\boxed{-(\alpha_d+\alpha_u)}}$
  - TDMA network: $\tau_i^* \propto D_i^{-\boxed{\alpha_u}}$
- Fairness issue needs to be solved

Common-Throughput Maximization

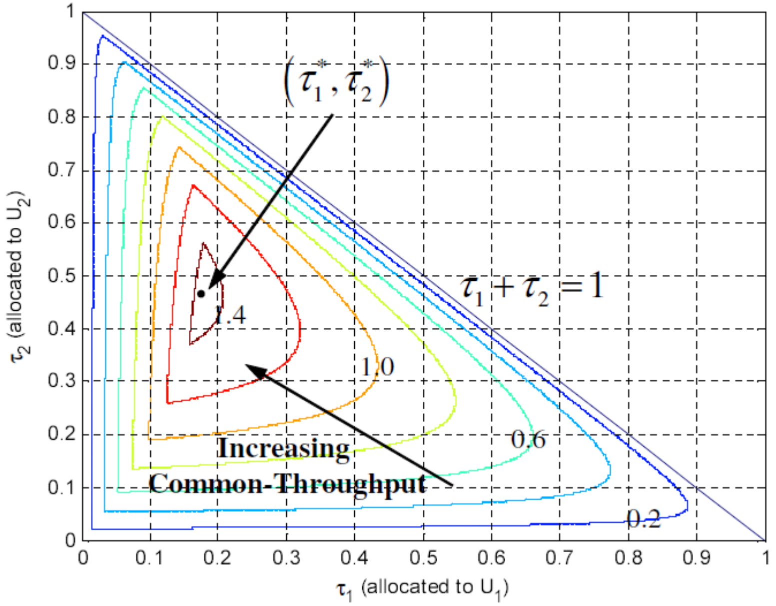
- ☐ Problem formulation
  - ➢ Convex optimization problem
    - ✓ Objective function: single variable
    - ✓ Constraints: all convex
  - ➢ Closed-form optimal solution not available
- ☐ Proposed optimal solution
  - ➢ Use bisection method
  - ➢ Given $\bar{R}$, solve a convex feasibility problem
- ☐ With optimal solution
  - ➢ Equal throughput for all users is ensured

$$\begin{aligned} \max_{\bar{R},\boldsymbol{\tau}} \quad & \bar{R} \\ \text{s.t.} \quad & R_i(\boldsymbol{\tau}) \geq \bar{R}, \quad i = 1 \cdots K \\ & \sum_{i=0}^{K} \tau_i \leq 1, \\ & \tau_i \geq 0, \quad i = 0,\ 1,\ \cdots\ K. \end{aligned}$$

$$\begin{aligned} \text{Find} \quad & \boldsymbol{\tau} \\ \text{s.t.} \quad & R_i(\boldsymbol{\tau}) \geq \bar{R}, \quad i = 1,\ \cdots, K, \\ & \sum_{i=0}^{K} \tau_i \leq 1, \\ & \tau_i \geq 0, \quad i = 0,\ 1,\ \cdots\ K. \end{aligned}$$

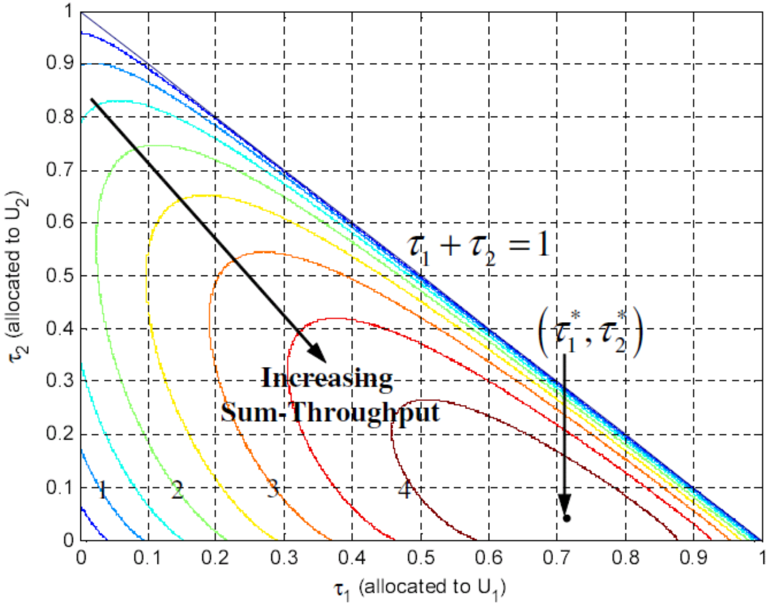
Common-Throughput versus Sum-Throughput

Common-throughput versus time allocation



$$R_1(\boldsymbol{\tau}^*) = R_2(\boldsymbol{\tau}^*) = 1.46$$

Sum-throughput versus time allocation



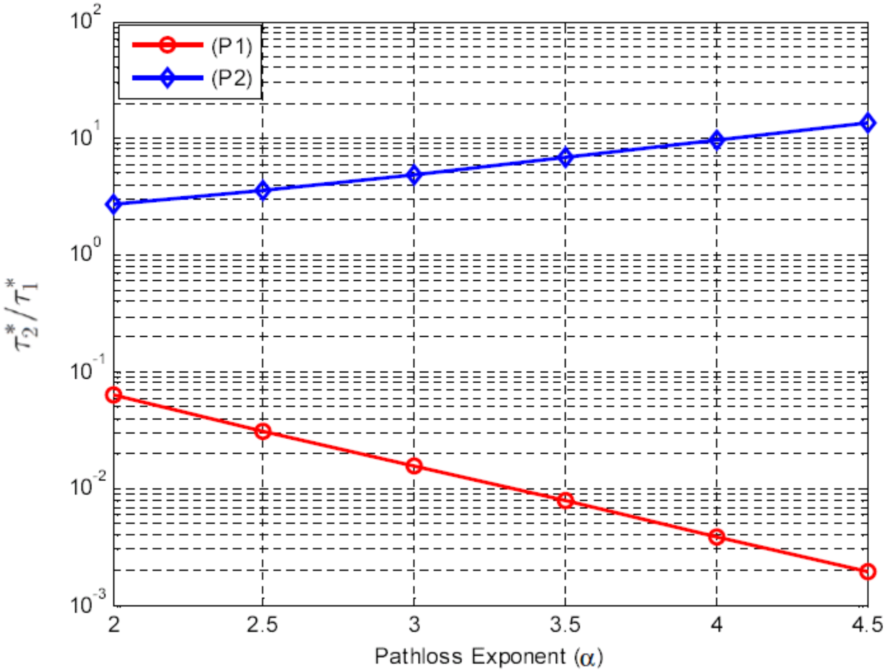
$$R_1(\boldsymbol{\tau}^*) = 4.13 \quad R_2(\boldsymbol{\tau}^*) = 0.45$$

Two users with distance $D_1 = \frac{1}{2} D_2$

- ☐ More time allocated to far user, i.e., user 2
- ☐ Fairness achieved, but sum-throughput reduced

Common-Throughput versus Sum-Throughput

Time allocation ratio versus pathloss exponent

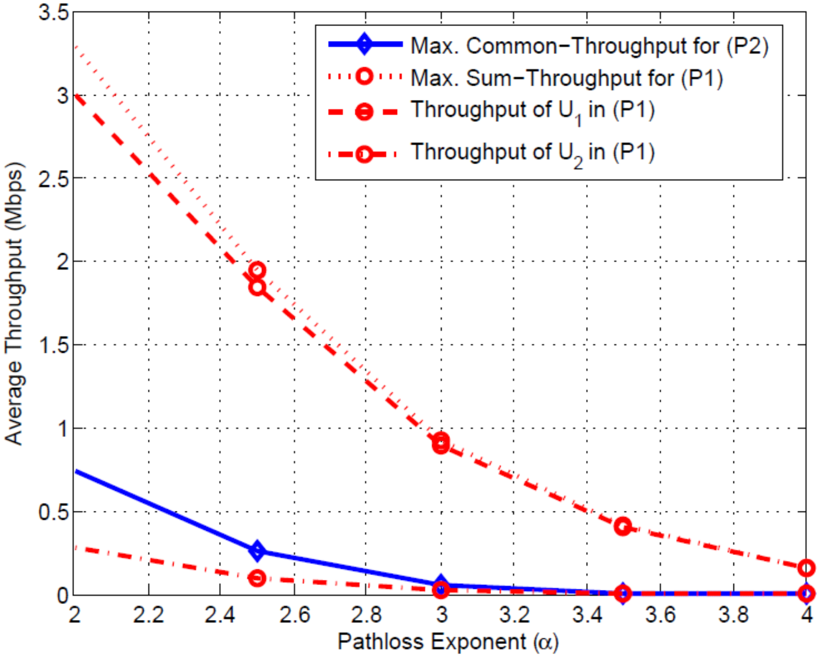


- ❑ Two users with distance $D_1 = \frac{1}{2} D_2$
- ❑ (P1): sum-throughput maximization
- ❑ (P2): common-throughput maximization
- ❑ Comparison of ratio of time allocated to user 2 and user 1 in (P1) versus (P2)

- ❑ Time allocation ratio between (far) user 2 and (near) user 1, τ_2^* / τ_1^*, increases with α in (P2), but decreases with α in (P1) (to tackle the more severe doubly near-far problem)

Simulation Result

Throughput versus pathloss exponent



- Two users
- User 1: 5m away from H-AP
- User 2: 10m away from H-AP

- As pathloss increases,
  - Sum-throughput maximization: user 1’s throughput converges to sum-throughput, user 2’ throughput approaches zero
  - Common-throughput maximization: both users’ throughput decrease quickly towards zero

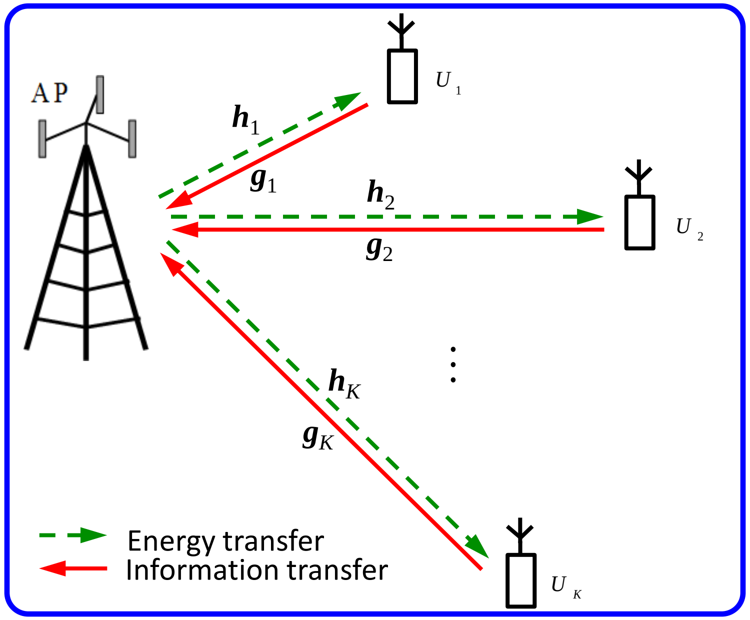
Summary

- ☐ Sum-throughput maximization in single-antenna wireless powered communication network (WPCN)
  - ➢ Trade-off in UL-DL time allocations
  - ➢ Trade-off in UL time/power allocations among users
    - ✓ Doubly near-far problem
- ☐ Common-throughput maximization in single-antenna WPCN
  - ➢ Allocate more time/power to far users
- ☐ Trade-off between sum-throughput and user fairness

Agenda

- Single-Antenna Wireless Powered Communication Network
- Multi-Antenna Wireless Powered Communication Network
- Extension and Future Work

System Model [4]

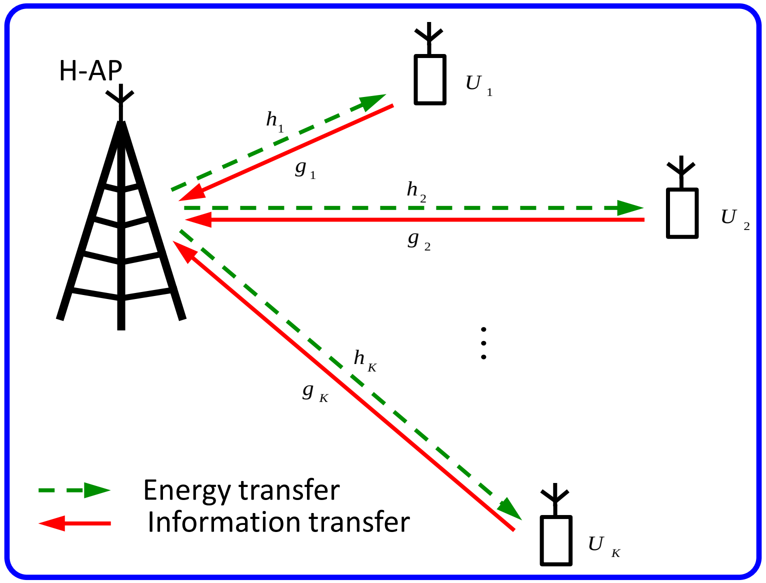


☐ One H-AP with $M>1$ antennas
☐ K single-antenna user terminals

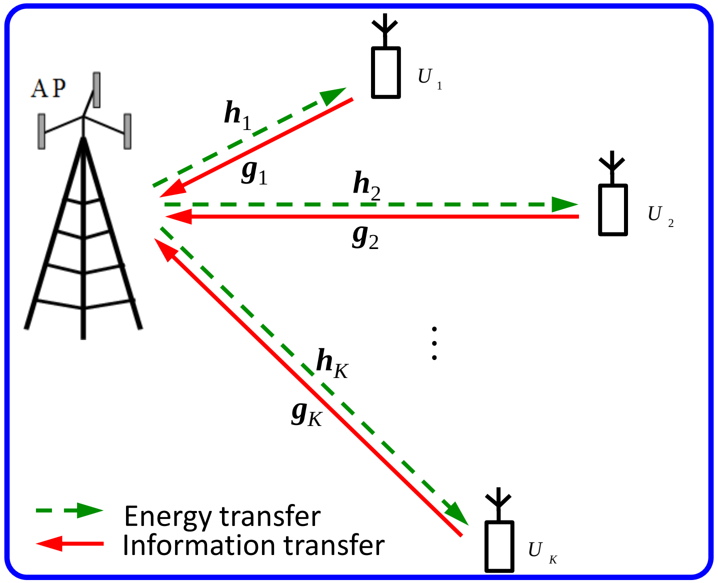
☐ Wireless power transfer (WPT) in DL
☐ Wireless information transmission (WIT) in UL

Single-Antenna versus Multi-Antenna WPCN

SISO WPCN



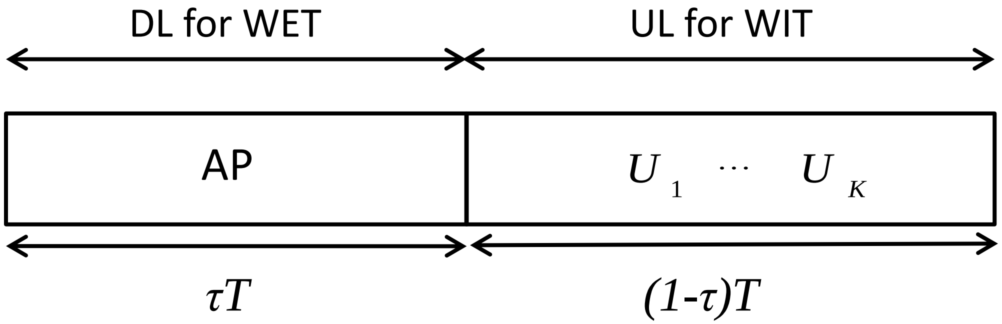
MISO WPCN



- WPT in DL: isotropic energy transmission
- WIT in UL: TDMA
- Design parameter: time/power allocation

- WPT in DL: energy beamforming
  - Higher WPT efficiency than SISO
  - Adjust beam weights to control energy transferred to near/far users: better fairness
- WIT in UL: SDMA
  - Higher spectrum efficiency than TDMA
  - Interference mitigation via receive beamforming
- Design parameters: time/power allocation and transmit/receive beamforming

Revised Harvest-then-Transmit Protocol (1)



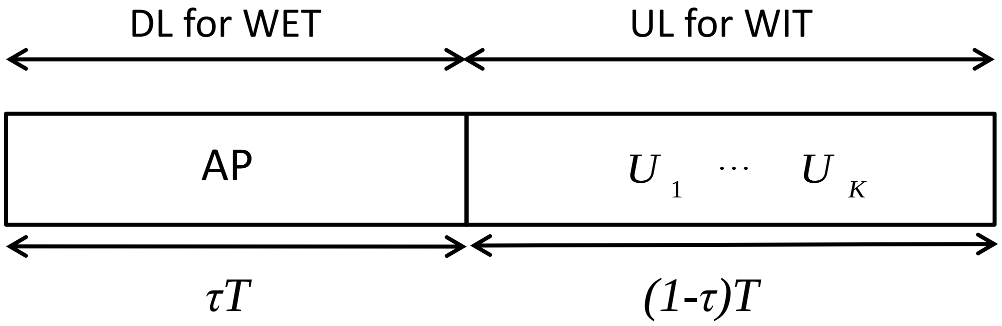
- WPT in DL:
  - H-AP sends $l \leq M$ energy beams:

$$\boldsymbol{x}_0 = \sum_{i=1}^{l} \boldsymbol{v}_i s_i^{\text{dl}}$$

  - Energy harvested by user *k*:

$$E_k = \epsilon\tau \sum_{i=1}^{l} |\boldsymbol{g}_k^H \boldsymbol{v}_i|^2 \longrightarrow \text{controllable by adjusting energy beams}$$

Revised Harvest-then-Transmit Protocol (2)



DL for WET

UL for WIT

AP

$U_1 \cdots U_K$

τT

$(1\text{-}\tau)T$

- ☐ WIT in UL:
  - Available transmit power at user *k*: $\bar{P}_k(\boldsymbol{V}, \tau) = \dfrac{E_k}{1-\tau} = \dfrac{\epsilon\tau \sum_{i=1}^{l} |\boldsymbol{g}_k^H \boldsymbol{v}_i|^2}{1-\tau}$
  - Each user *k* sends $x_k = \sqrt{p_k} s_k^{\mathrm{ul}}$ simultaneously
  - SINR of user *k* with receive beamforming vector $\boldsymbol{w}_k$:

$$\gamma_k(\boldsymbol{p}, \boldsymbol{w}_k) = \frac{p_k \|\boldsymbol{w}_k^H \boldsymbol{h}_k\|^2}{\boldsymbol{w}_k^H \left(\sum_{j \neq k} p_j \boldsymbol{h}_j \boldsymbol{h}_j^H + \sigma^2 \boldsymbol{I} \right) \boldsymbol{w}_k}$$

  - Achievable rate of user *k*: $R_k = (1-\tau)\log_2(1 + \gamma_k(\boldsymbol{p}, \boldsymbol{w}_k))$ →

trade-off in UL/DL time allocation

Common-Throughput Maximization

- ❑ Problem formulation
  - ➢ Common-throughput maximization
  - ➢ Joint optimization of DL-UL time allocation, DL energy beamforming, UL power control and receive beamforming (MMSE)
  - ➢ Non-convex optimization problem
    - ✓ Objective function: non-concave
    - ✓ UL power constraints: non-convex

$$\begin{aligned} \max_{\tau,\boldsymbol{p},\boldsymbol{W},\boldsymbol{V}} \quad & \min_{1\le k\le K} (1-\tau)\log_2\left(1+\gamma_k(\boldsymbol{p},\boldsymbol{w}_k)\right) \\ \text{s.t.} \quad & 0<\tau<1, \\ & p_k \le \bar{P}_k(\boldsymbol{V},\tau),\ \forall k, \\ & \sum_{i=1}^{l} \|\boldsymbol{v}_i\|^2 \le P_{\text{sum}}. \end{aligned}$$

Optimal Solution

- Two-stage Algorithm:
  - Fix $\tau = \bar{\tau}$

$$\begin{aligned} \max_{\tau,\boldsymbol{p},\boldsymbol{W},\boldsymbol{V}} \quad & \min_{1\le k\le K} (1-\tau)\log_2\left(1+\gamma_k(\boldsymbol{p},\boldsymbol{w}_k)\right) \\ \text{s.t.} \quad & 0<\tau<1, \\ & p_k \le \bar{P}_k(\boldsymbol{V},\tau), \ \forall k, \\ & \sum_{i=1}^{l} \|\boldsymbol{v}_i\|^2 \le P_{\text{sum}}. \end{aligned}$$

→

$$\begin{aligned} \max_{\boldsymbol{p},\boldsymbol{W},\boldsymbol{V}} \quad & \min_{1\le k\le K} \gamma_k(\boldsymbol{p},\boldsymbol{w}_k) \\ \text{s.t.} \quad & p_k \le \bar{P}_k(\boldsymbol{V},\bar{\tau}), \ \forall k, \\ & \sum_{i=1}^{l} \|\boldsymbol{v}_i\|^2 \le P_{\text{sum}}. \end{aligned}$$

  - ✓ Main difficulty: coupled UL power control and DL energy beamforming (conventional UL-DL duality not applicable here)
  - ✓ Optimal solution based on alternating optimization and non-negative matrix theory (see [4] for details)

- Let $g(\bar{\tau})$ denote optimal value given $\bar{\tau}$. Solve

$$R^* = \max_{0<\bar{\tau}<1} (1-\bar{\tau})\log_2(1+g(\bar{\tau}))$$

  - ✓ One-dimension search

Suboptimal Solutions

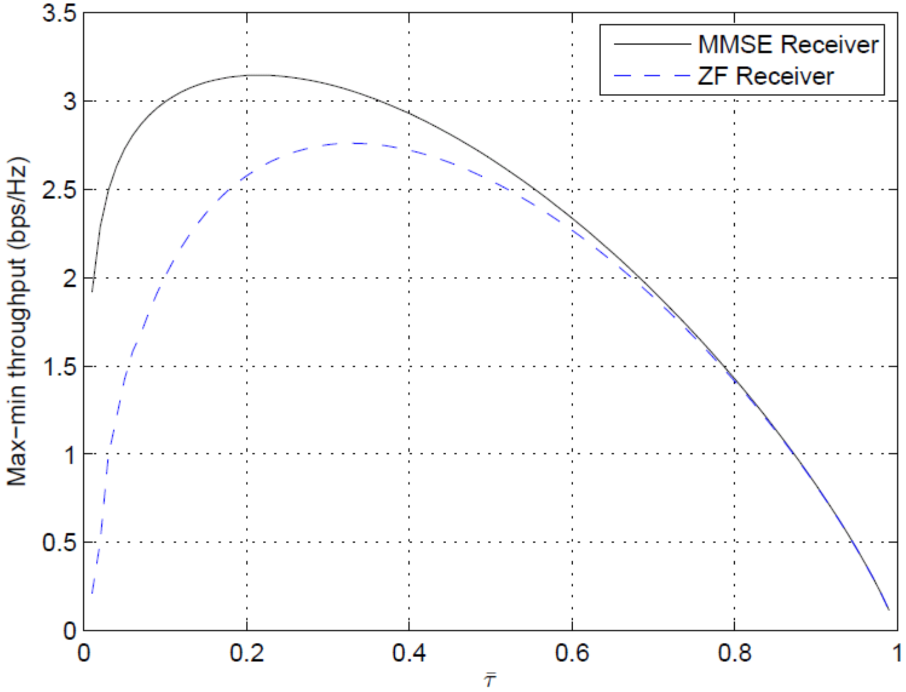
- ❑ Main idea: Using ZF receivers rather than MMSE receivers for $\boldsymbol{W}$
  - ➢ Remove inter-user interference in UL to decouple optimization of $\boldsymbol{W}$ with τ , $\boldsymbol{V}$ and $\boldsymbol{p}$
- ❑ Suboptimal Solution 1: Joint optimization of τ, $\boldsymbol{V}$, and $\boldsymbol{p}$
  - ➢ Convex problem
  - ➢ Complexity still high
- ❑ Suboptimal Solution 2: Separate optimization of $\boldsymbol{V}$ with τ and $\boldsymbol{p}$
  - ➢ Energy beamforming for weighted sum-energy maximization (closed-form rank-one solution available)

$$\begin{aligned} \underset{\boldsymbol{V}}{\texttt{Maximize}} \quad & \sum_{k=1}^{K} \alpha_k \epsilon \left(\sum_{i=1}^{l} |\boldsymbol{g}_k^H \boldsymbol{v}_i|^2 \right) \\ \texttt{Subject to} \quad & \sum_{i=1}^{l} \|\boldsymbol{v}_i\|^2 \leq P_{\text{sum}}, \end{aligned}$$

with energy weights $\alpha_k = 1/(\tilde{h}_k \|\boldsymbol{g}_k\|^2)$

  - ➢ Joint optimization of τ and $\boldsymbol{p}$ only (convex and efficiently solvable)

Simulation Results (1)



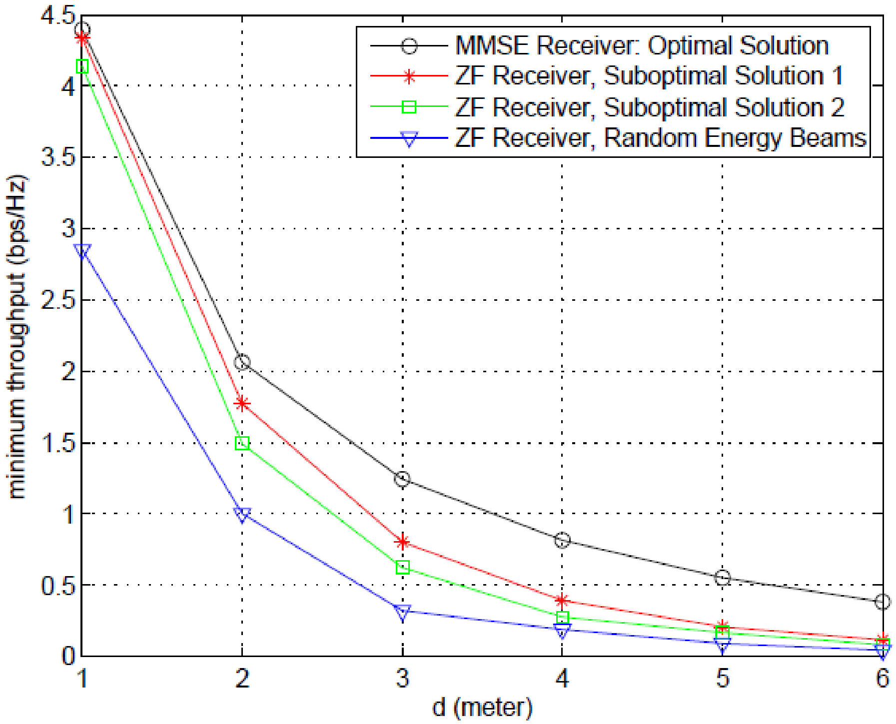
Common throughput versus UL/DL time allocation

- AP is equipped with 6 antennas
- 4 users located between 1-2m from AP
- Rician fading channels
- DL transmit power: $P_{\text{sum}} = 1\text{Watt}$
- Energy harvesting efficiency: $\epsilon = 50\%$
- AWGN at AP: $\sigma^2 = -50\text{dBm}$

- Common throughput first increases then decreases over $\bar{\tau}$
- MMSE receiver outperforms ZF receiver (Suboptimal Solution 1)

Simulation Results (2)

Common throughput versus users' distance

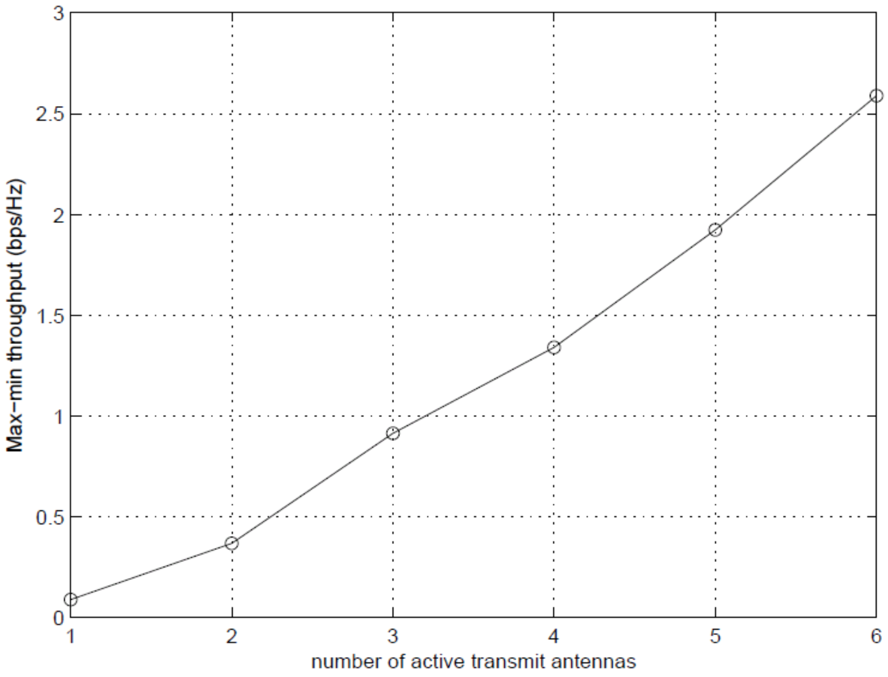


- ❑ AP is equipped with 6 antennas
- ❑ 4 users, identical distance to AP, *d*
- ❑ Rician fading channels
- ❑ DL transmit power: $P_{\text{sum}} = 1\text{Watt}$
- ❑ Energy harvesting efficiency: $\epsilon = 50\%$
- ❑ AWGN at AP: $\sigma^2 = -50\text{dBm}$

- ❑ Common throughput decreases drastically with *d*: doubly near-far problem
- ❑ When *d* is small, ZF receiver performs close to optimal MMSE receiver
- ❑ Random energy beamforming has notable throughput loss when *d* is small

Simulation Results (3)

Common throughput versus No. of antennas



- ☐ 4 users located between 1-2m from AP
- ☐ Rician fading channels
- ☐ DL transmit power: $P_{\text{sum}} = 1\text{Watt}$
- ☐ Energy harvesting efficiency: $\epsilon = 50\%$
- ☐ AWGN at AP: $\sigma^2 = -50\text{dBm}$

- ☐ One antenna reduces to the case of single-antenna WPCN
- ☐ Multi-antenna WPCN improves common throughput significantly over single-antenna WPCN

Summary

- Common-throughput maximization in multi-antenna wireless powered communication network (WPCN)
  - Joint optimization of UL/DL time allocation, DL energy beamforming, UL transmit power allocation and receive beamforming
- Advantage over single-antenna WPCN
  - DL: energy beamforming
    - ✓ Higher power transfer efficiency
    - ✓ Controllable power delivery to each user
  - UL: SDMA
    - ✓ Higher spectrum efficiency for WIT than TDMA

Agenda

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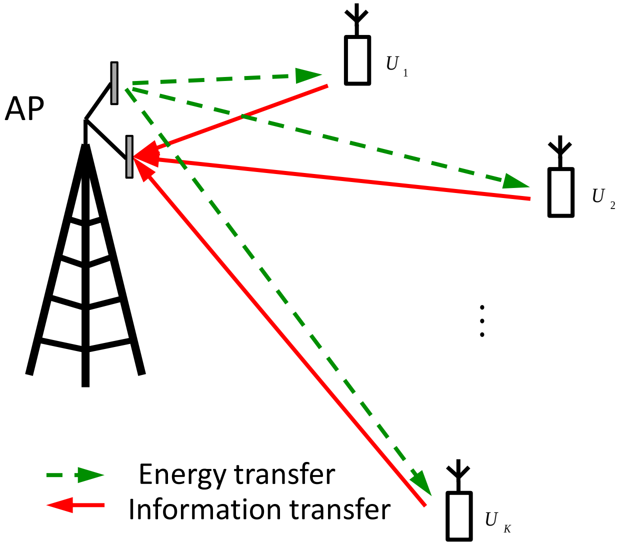
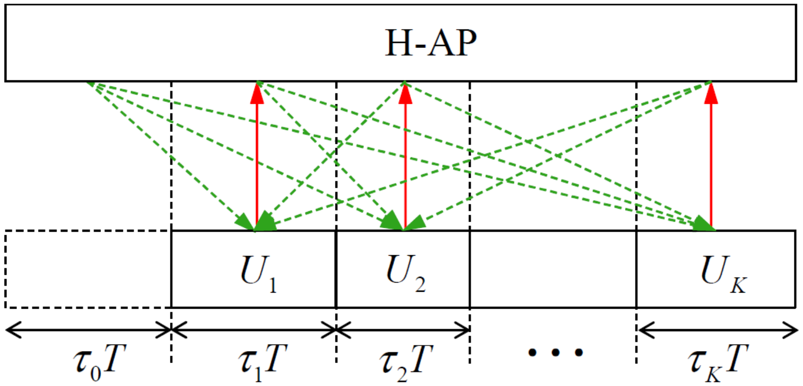
Full-Duplex WPCN [5]

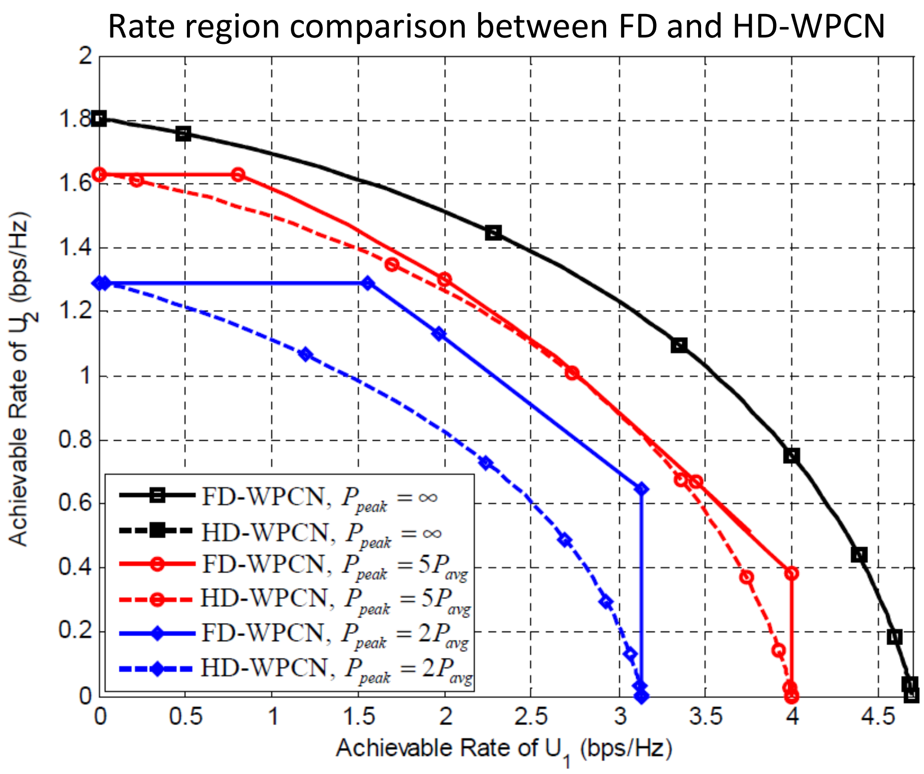


- Full-duplex (FD) AP: broadcasts energy in DL and receives information in UL at the same time and frequency
  - More efficient than half-duplex (HD) WPCN
  - Self-interference cancellation (SIC) needed at AP for decoding information
- AP is equipped with two antennas
  - One for broadcasting energy in DL
  - The other for receiving information in UL (simultaneously)
- *K* single-antenna users operating in half-duplex (TDD) mode



- Harvest-or-transmit protocol:
  - *K*+1 time slots
  - The 0th slot: only DL power transfer
  - The *i*th (*i*>0) slot:
    - ✓ Only user *i* transmits information in UL
    - ✓ AP broadcasts power to all other users in DL and receives user *i*’s information in UL
- Objective: Joint optimization of AP’s transmit power and time allocation to maximize weighted sum-rate subject to AP’s average and peak power constraints

Full-Duplex versus Half-Duplex WPCN



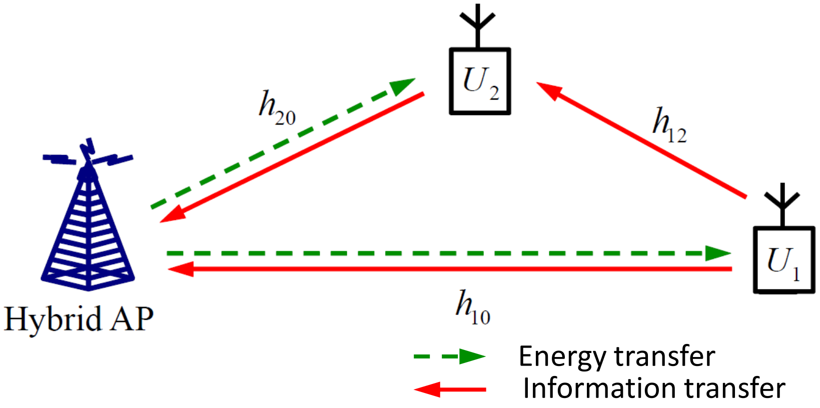
Rate region comparison between FD and HD-WPCN

- ❑ Two users
- ❑ Assuming perfect SIC in FD-WPCN
- ❑ Average power constraint: $P_{avg} = 100$
- ❑ Equivalent channels:

$$H_1 = 0.249 \text{ and } H_2 = 0.025$$

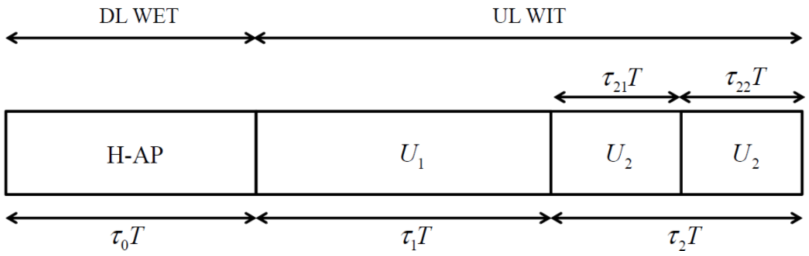
- ❑ With no peak power constraint, FD-WPCN and HD-WPCN achieve identical rate regions
- ❑ With finite peak power constraint, FD-WPCN achieves larger rate region than HD-WPCN
- ❑ Gain over HD-WPCN is more significant with stringent peak power constraint

User Cooperation in WPCN [6]



- One AP and two users
  - User 2 is nearer to AP than user 1
- In each block, user 2 uses part of time and harvested energy to relay user 1’s message to AP
  - Overcome the doubly near-far issue
  - Achieve better throughput and fairness trade-off

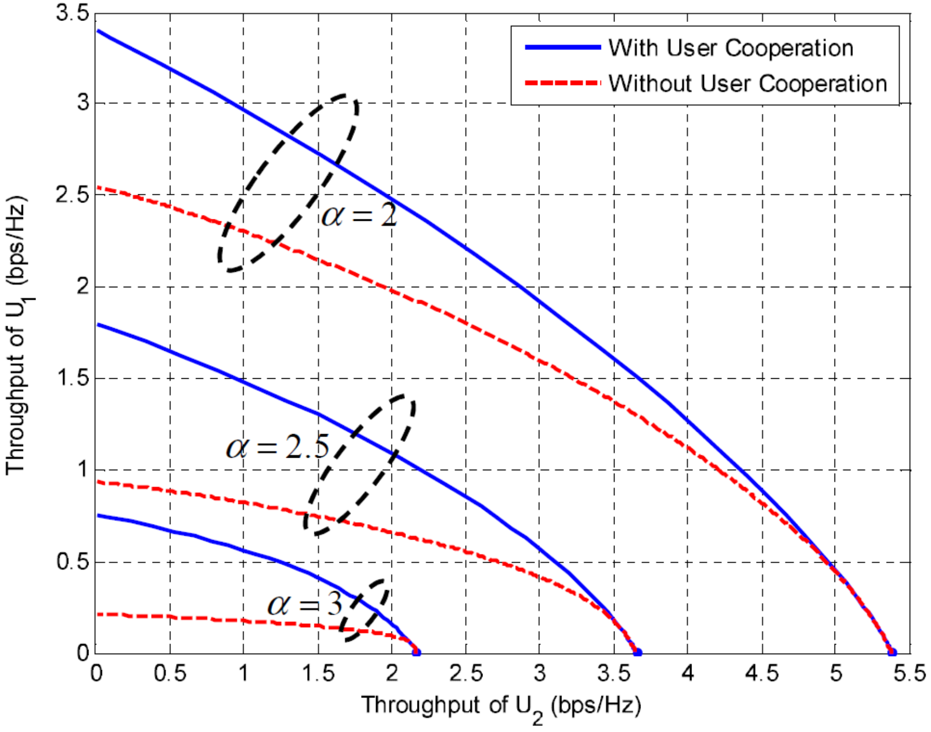
- Harvest-then-transmit protocol (improved):
  - DL wireless power transfer
  - UL wireless information transmission: TDMA
    - ✓ Phase I: user 1 (far user) transmits information, and both AP and user 2 decode
    - ✓ Phase II: user 2 relays user 1’s message to AP
    - ✓ Phase III: user 2 transmits its own message to AP



- Objective: Joint optimization of time allocation and users’ power allocation to maximize weighted sum-rate

Performance Comparison with versus w/o User Cooperation

Rate region comparison with versus w/o user cooperation

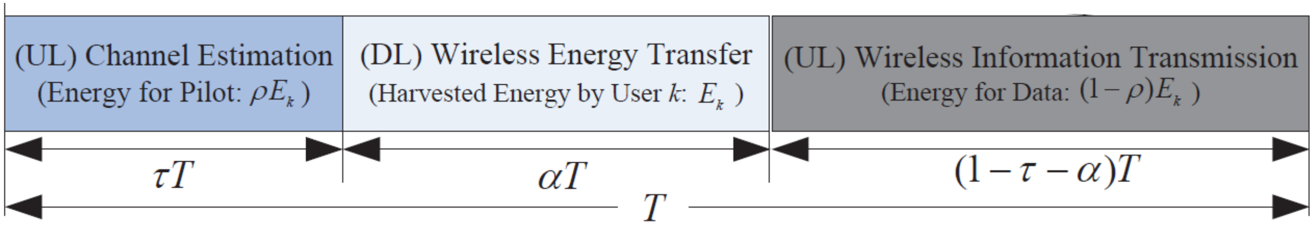


- Two users
- Distance from user 1 to AP: 10m
- Distance from user 2 to AP: 5m
- Distance between users 1 and 2: 5m
- Passloss exponent: α
- Transmit power at AP: $P_0 = 30\text{dBm}$

- User cooperation always outperforms w/o user cooperation
- User 1 (far user)'s rate improvement is more significant with higher pass loss
  - Direct link from user 1 to AP dominates the network throughput

Massive MIMO WPCN [7]

- AP equipped with large No. of antennas, *K* single-antenna users
  - Improve both wireless power transfer and information transmission efficiency
  - Challenge: channel estimation



(UL) Channel Estimation
(Energy for Pilot: ρE_k)

(DL) Wireless Energy Transfer
(Harvested Energy by User k: E_k)

(UL) Wireless Information Transmission
(Energy for Data: $(1-\rho)E_k$)

τT

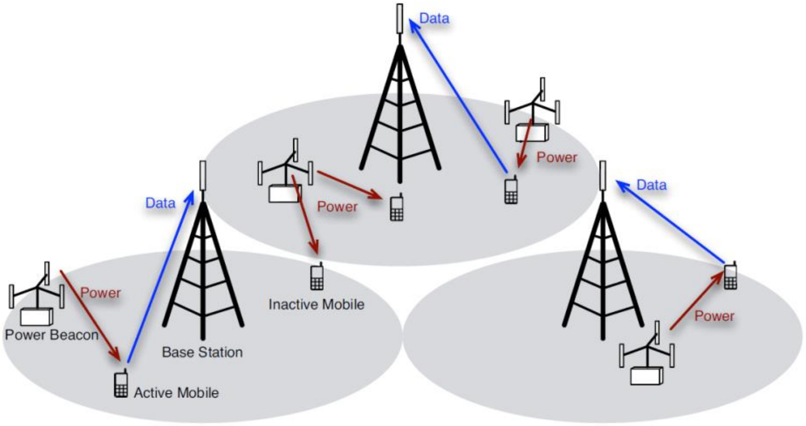
αT

$(1-\tau-\alpha)T$

T

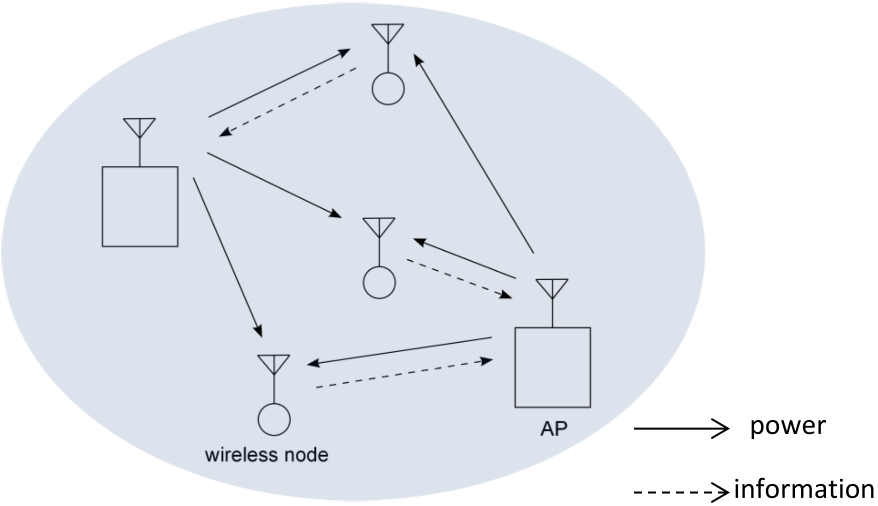
- Harvest-then-transmit protocol (modified):
  - Three-phase protocol: UL channel estimation, DL WPT, UL WIT
  - UL channel estimation (assuming channel reciprocity holds):
    - ✓ Trade-off: channel estimation accuracy versus cost of time and energy
  - DL WPT: energy beamforming based on estimated channels
  - UL WIT: SDMA with MRC or ZF receiver at AP
- Objective: Common throughput optimization
  - Design parameters: time allocation, DL energy beamforming, power allocation between UL channel estimation and WIT
  - Asymptotic solution applies with large No. of antennas

Large-Scale WPCN Capacity (1)

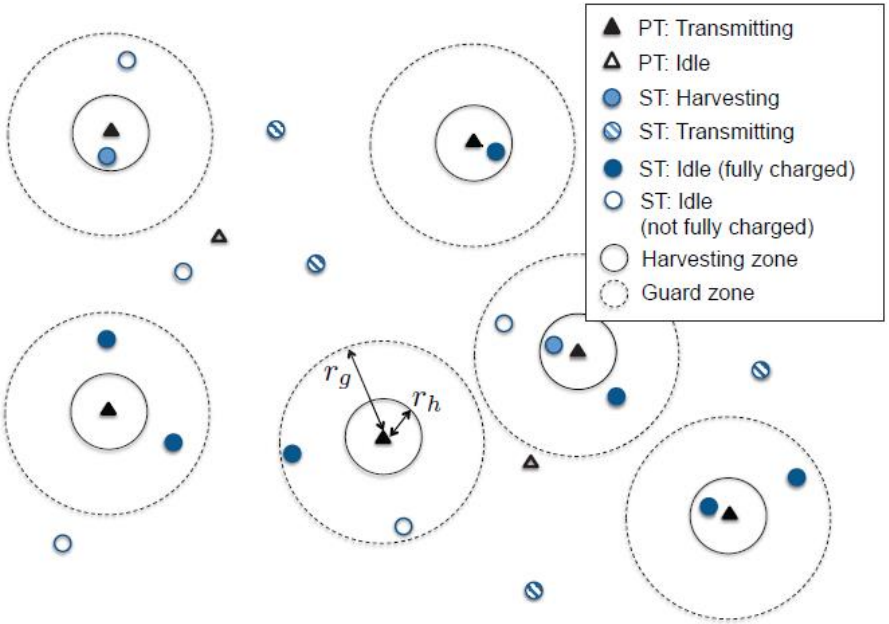


- ❑ Hybrid cellular network: cellular network + power beacons (PBs) to power mobile devices [8]
- ❑ Parameters:
  - ➢ p,q: the transmit power of BSs and PBs
  - ➢ λ_b, λ_p: densities of PPP of BSs and PBs
- ❑ Objective : fix transmit power (p,q) and study effect of deployment (λ_b, λ_p) on network throughput subject to outage performance of information and power transfer

- ❑ Dual-function APs [9]: AP coordinates both information and power transfer
- ❑ Design parameters:
  - ➢ DL/UL time allocation
  - ➢ UL transmit power
- ❑ Objective: maximize network throughput subject to successful information transmission probability constraint



Large-Scale WPCN Capacity (2)



- Cognitive radio network [10]:
  - Harvesting zone: secondary transmitter (ST) can harvest energy from any nearby primary transmitter (PT) if it is in PT's harvesting zone
  - Guard zone: ST cannot transmit if it is in guard zone of any PT
- Objective: maximize the secondary network throughput subject to outage probability of both primary and secondary networks
  - Characterization of STs' transmit probability as well as network outage probability
  - Optimal STs' transmit power and density

Future Working Directions

- Multi-cell and network level optimization
- Optimal trade-off between throughput and fairness
- Broadband channel with frequency selective fading
- Partial/imperfect CSIT
- Effect of battery with finite strorage capacity

Concluding Remarks

❑ Wireless RF Powered Communication

➢ Many new design challenges in PHY, MAC, and Network layers

❑ Hardware Development

➢ Wireless power transfer (energy beamforming, high-efficiency rectenna, waveform design,…)

❑ Applications

➢ Wireless sensor/M2M networks (IoT, IoE)
➢ Cellular networks (small cells? millimeter-wave?)
➢ …

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