Wireless Communications in the Era of Energism

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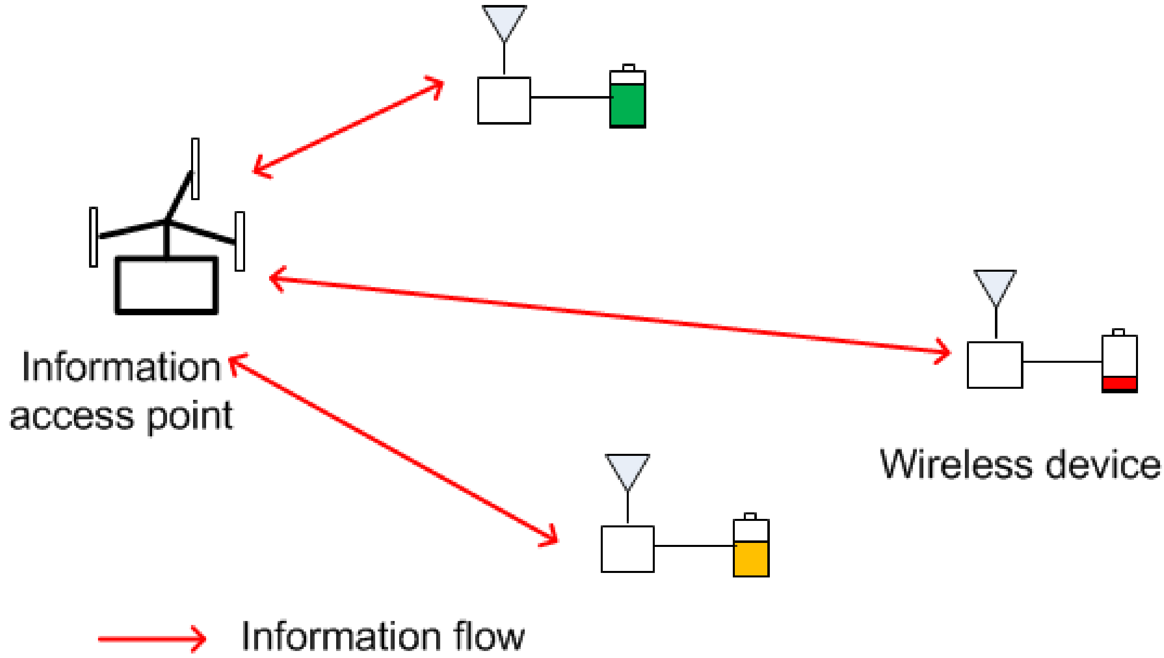
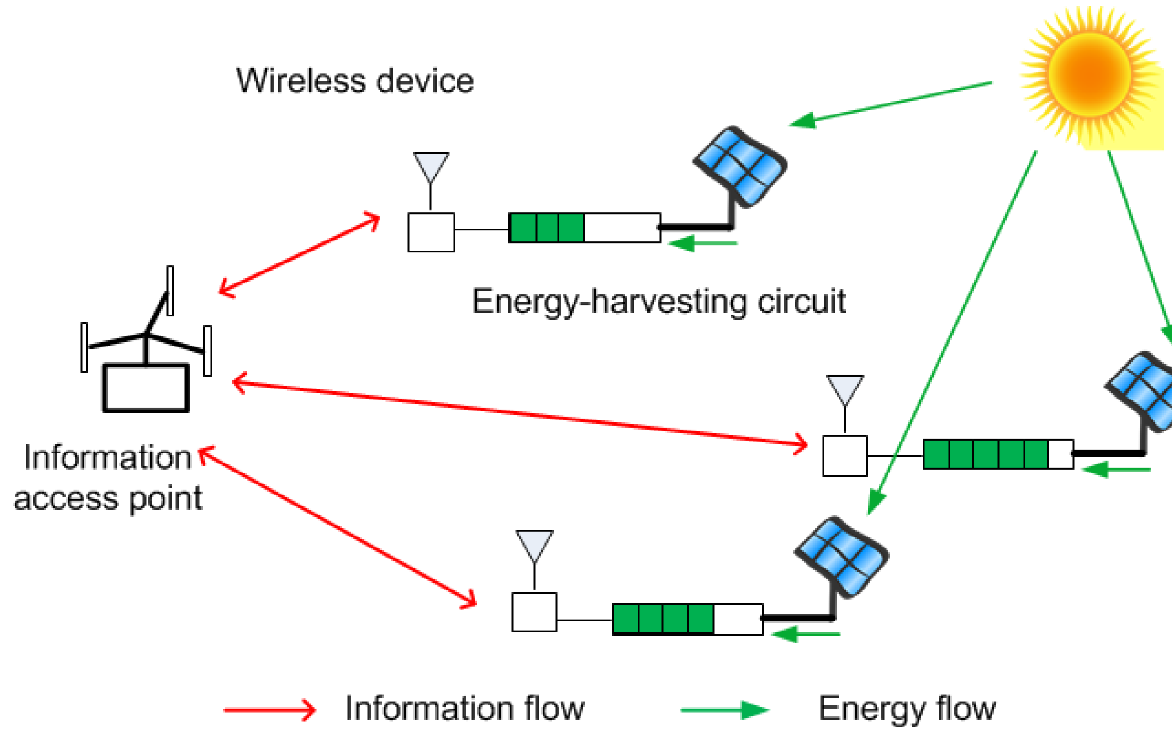
Wireless Communication Powered by Batteries (Conventional)



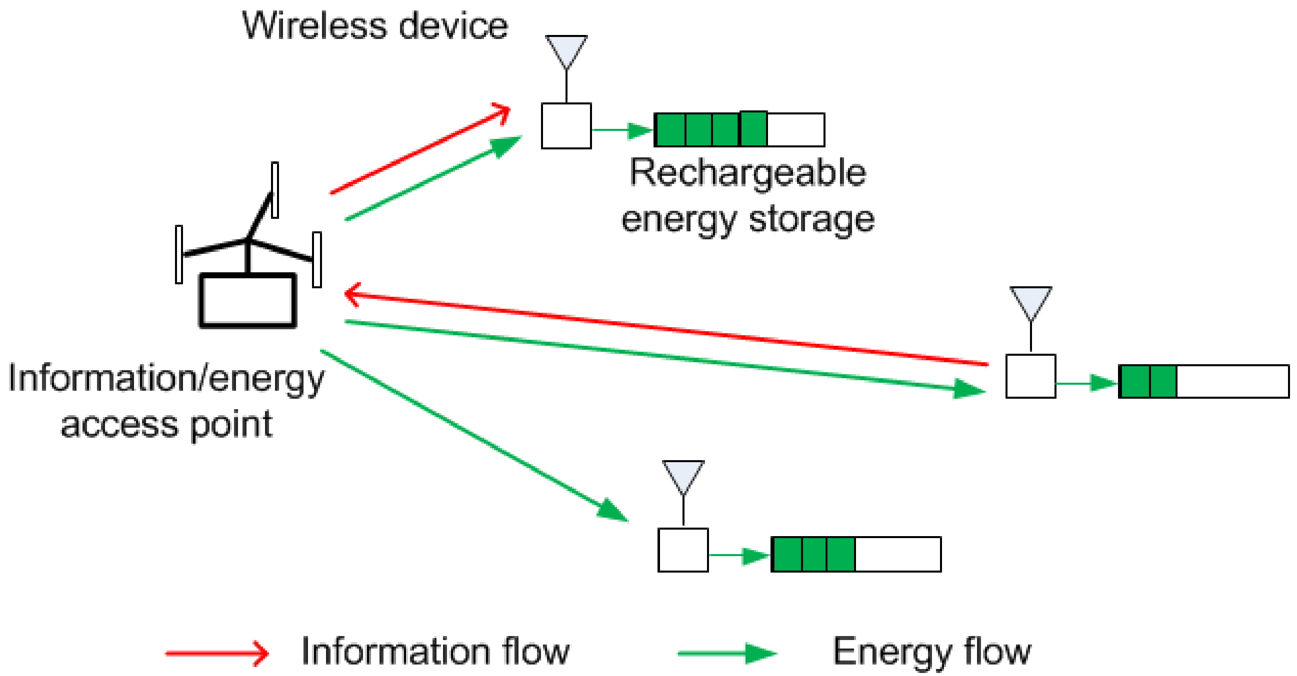
- ❑ Need manual battery recharging/replacement
- ❑ Costly, inconvenient, abruption to use
- ❑ Inapplicable in some scenarios, e.g., implanted medical devices, sensors built in cement structures
- ❑ Communication system design metric: energy saving

Wireless Communication Powered by Energy Harvesting (More Recent)



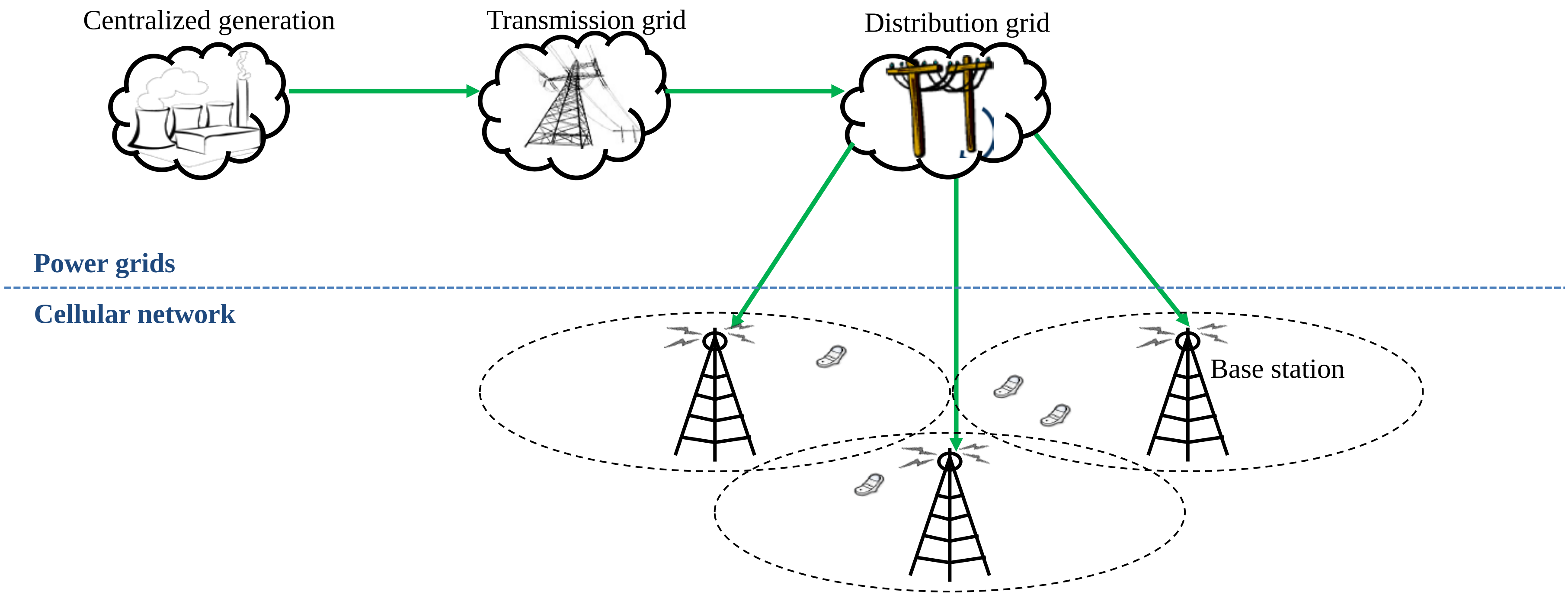
- External energy source: solar, wind, vibration, ambient radio power, etc.
- Inexpensive, green, renewable
- However, environment energy is intermittent and unpredictable, uneven temporally and geographically, low in power, costly/bulky energy harvesting device, etc.
- In practice, storage device often used to store excessive energy for future use
- Communication design paradigm shift: "energy saving" → "energy awareness"

Wireless Communication Powered by Wireless Power Transfer (Emerging)



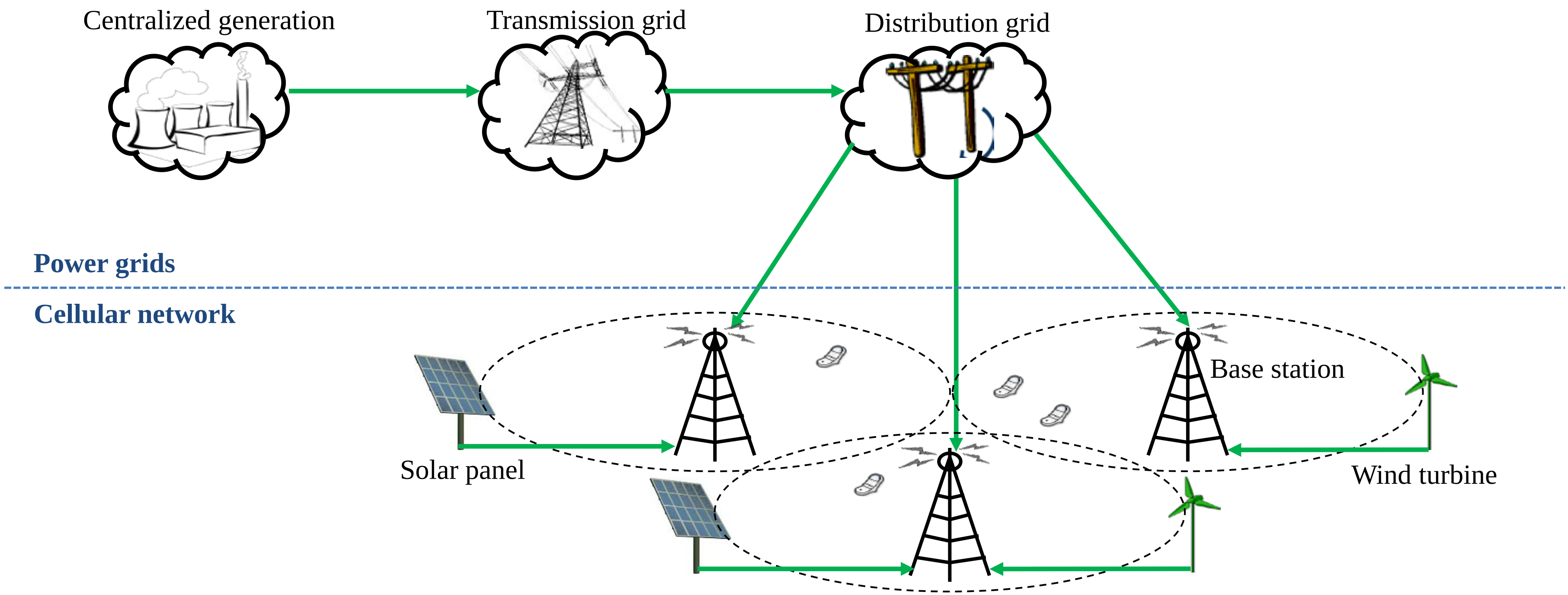
- ❑ Dedicated wireless power transmitter connected to fixed/renewable power source
- ❑ Wireless charging fully controllable in transmit power, frequency, waveform, etc.
- ❑ Charging and communicating simultaneously, no disruption to use
- ❑ Wide coverage, low production cost, and small receiver form factor
- ❑ Main challenges: efficient wireless power transfer, wireless powered communication network (WPCN) design, simultaneous wireless information and power transfer (SWIPT)

Cellular Networks Powered by Power Grid (Conventional)



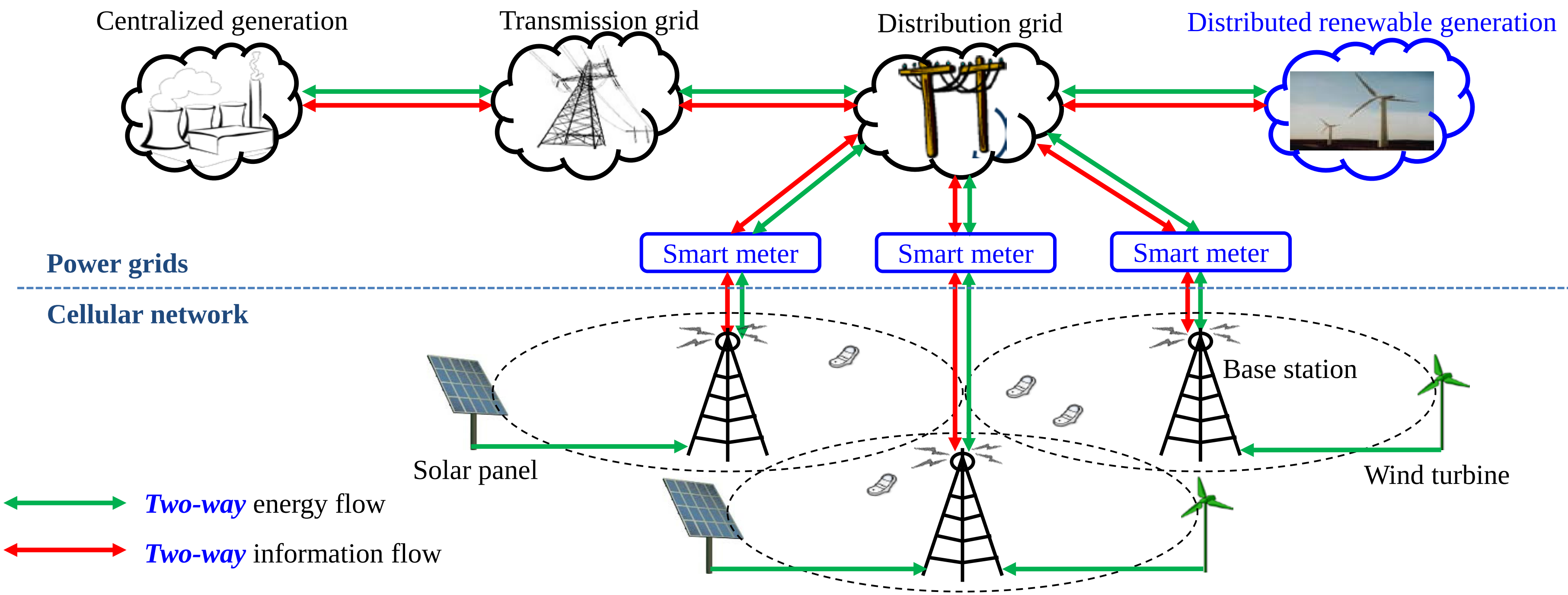
- One-way energy flow from power grid to base stations (BSs)
- Fixed energy pricing
- Energy cost minimization = total energy consumption minimization
- Techniques for energy saving: BSs on/off switching, cell zooming, load balancing, energy-efficient transmission, etc.

Cellular Networks with Renewable Energy Integration (More Recent)



- ❑ Use renewable energy (solar/wind) when available to substitute conventional on-grid energy since lower cost (mainly deployment), more environmentally friendly
- ❑ Practical challenges: intermittent, unpredictable, spatially and temporally varying
- ❑ Network operation needs re-design to be adaptable with "energy fluctuation"
- ❑ Energy cost minimization = "on-grid" energy consumption minimization

Cellular Networks Powered by Smart Grid (Emerging)



- ❑ Two-way energy/information flows between power grids and cellular network
- ❑ Possible energy sharing among BSs with individual harvested energy
- ❑ Two-way energy trading between power grids and cellular network
- ❑ Dynamic energy pricing and demand side management
- ❑ Distributed BSs can be formed as one or more microgrids
- ❑ Energy cost minimization ≠ energy consumption minimization

Rui Zhang, National University of Singapore

Organization of this Talk

Staircase/directional water-filling

Energy harvesting cooperative communication

Energy diversity

Energy full/half duplex

Offline vs. Online energy control

Energy beamforming

Joint communication and energy transfer scheduling & design

Doubly near-far problem

Rate-energy tradeoff

Separated vs. Integrated receiver for SWIPT

Hybrid powered base stations (BSs)

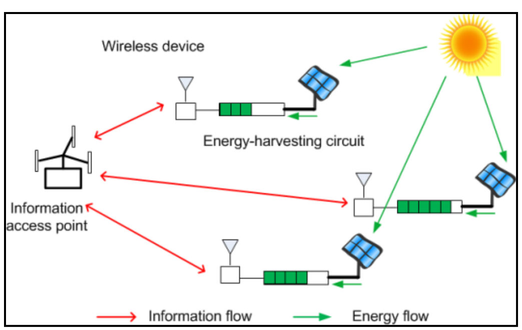
Energy cooperation

Two-way energy trading

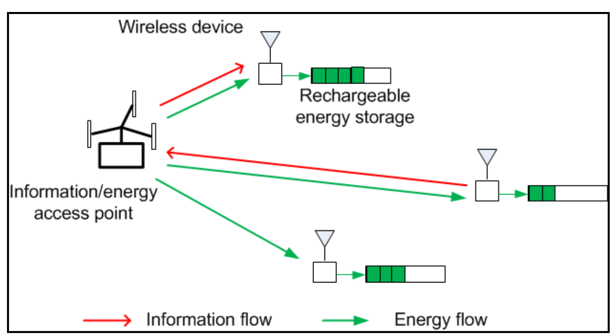
Energy cost-aware resource allocation & optimization

Joint energy/communication cooperation design

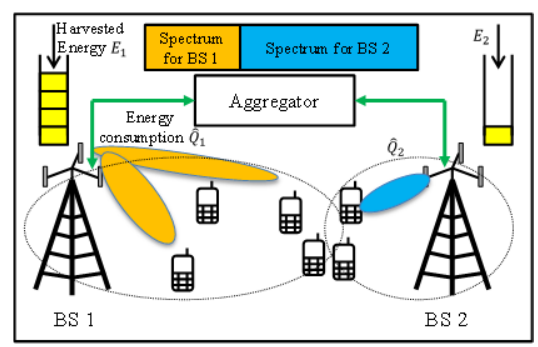
Energy-harvesting Communications



Wireless-powered Communications



SmartGrid-powered Communications



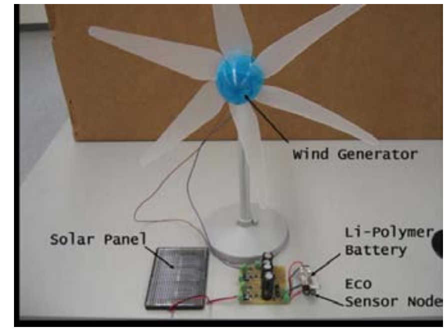
Outlines

- ❑ Energy-Harvesting Communications
- ❑ Wireless-Powered Communications
- ❑ SmartGrid-Powered Communications

Example Applications

Low-power RFID tag that harvests energy from ambient light or RF energy

EH-link wireless sensor node that harvests energy from piezoelectric, electrodynamic, and/or thermoelectric generators



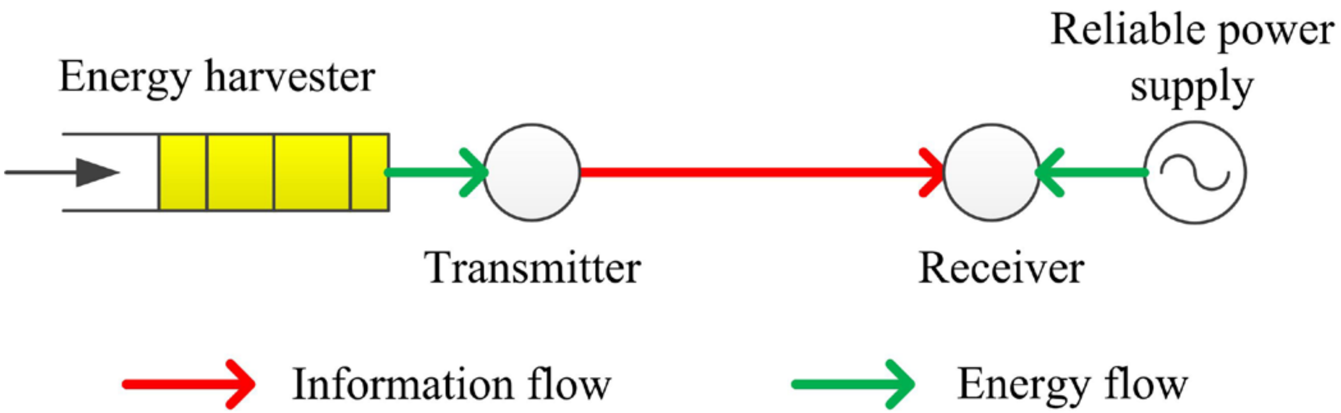
AmbiMax wireless sensor node with a solar panel and a wind generator

Functional prototype of piezoelectric-powered RFID shoes with mounted electronics

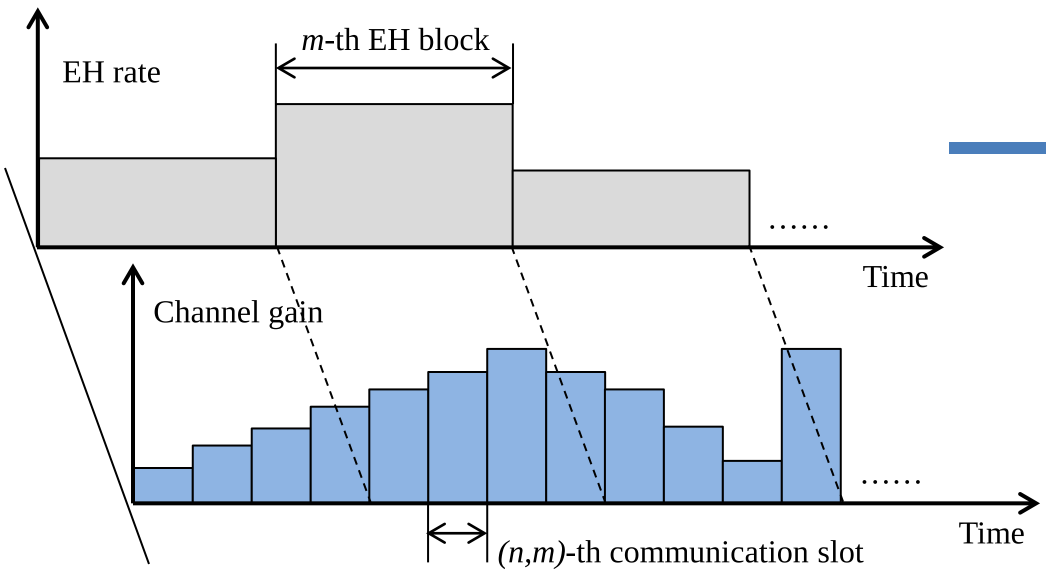
Cellular BS powered by hybrid solar and wind energy

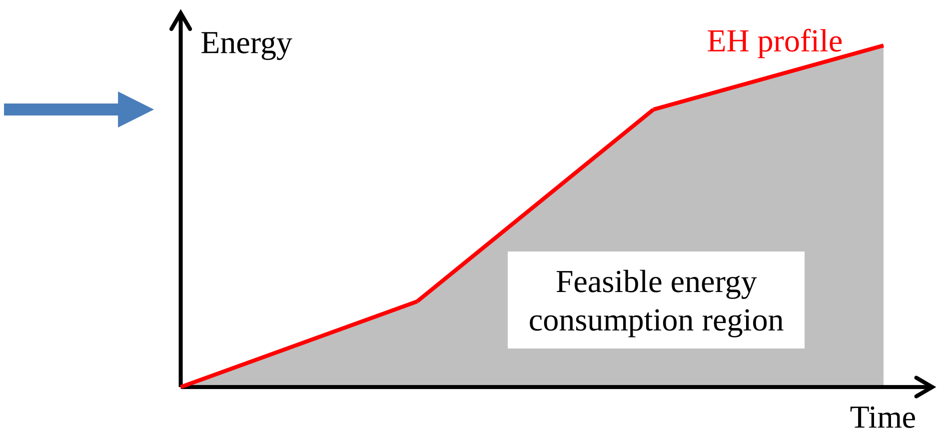
Titan Aerospace’s solar-powered unmanned plane for delivering wireless internet access to developing nations

A point-to-point communication link with an EH transmitter



- Time-varying EH rates and wireless communication channels





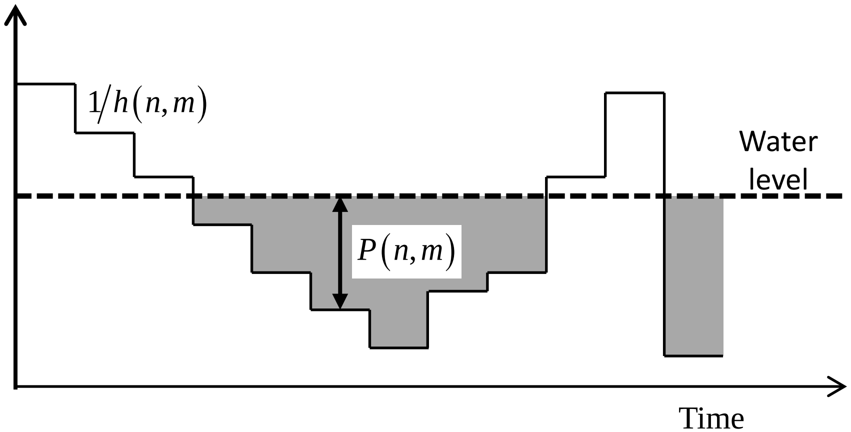
EH constraints

Optimal "Offline" Power Allocation for Throughput Maximization

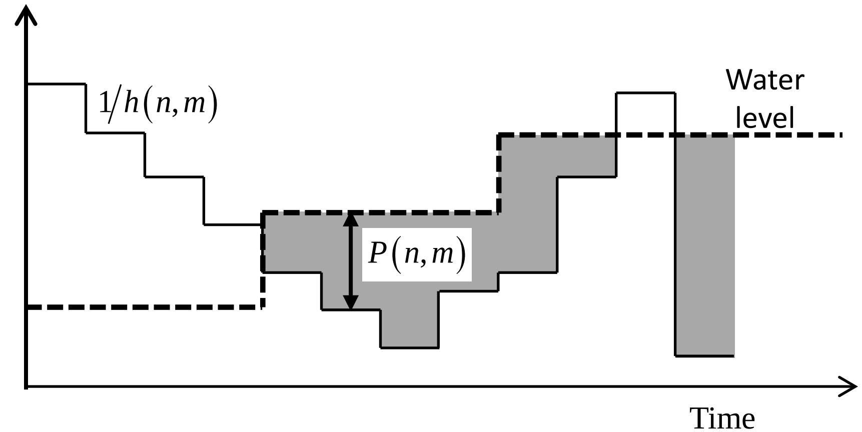
- Problem formulation for throughput maximization subject to EH constraints

$$\begin{aligned}&\underset{\{P(n,m)\geq 0\}}{\text{maximize}} \sum_{m=1}^{M}\sum_{n=1}^{N}\log_2\left(1+h(n,m)P(n,m)\right)\\ &\text{subject to} \sum_{j=1}^{m-1}\sum_{i=1}^{N}P(i,j)+\sum_{i=1}^{n}P(i,m)\leq N\sum_{j=1}^{m-1}E(j)+nE(m),\ \forall n,m\end{aligned}$$

- Optimal solution: staircase (directional) water-filling power allocation



Conventional water-filling with sum-power constraint



Staircase water-filling with EH constraints

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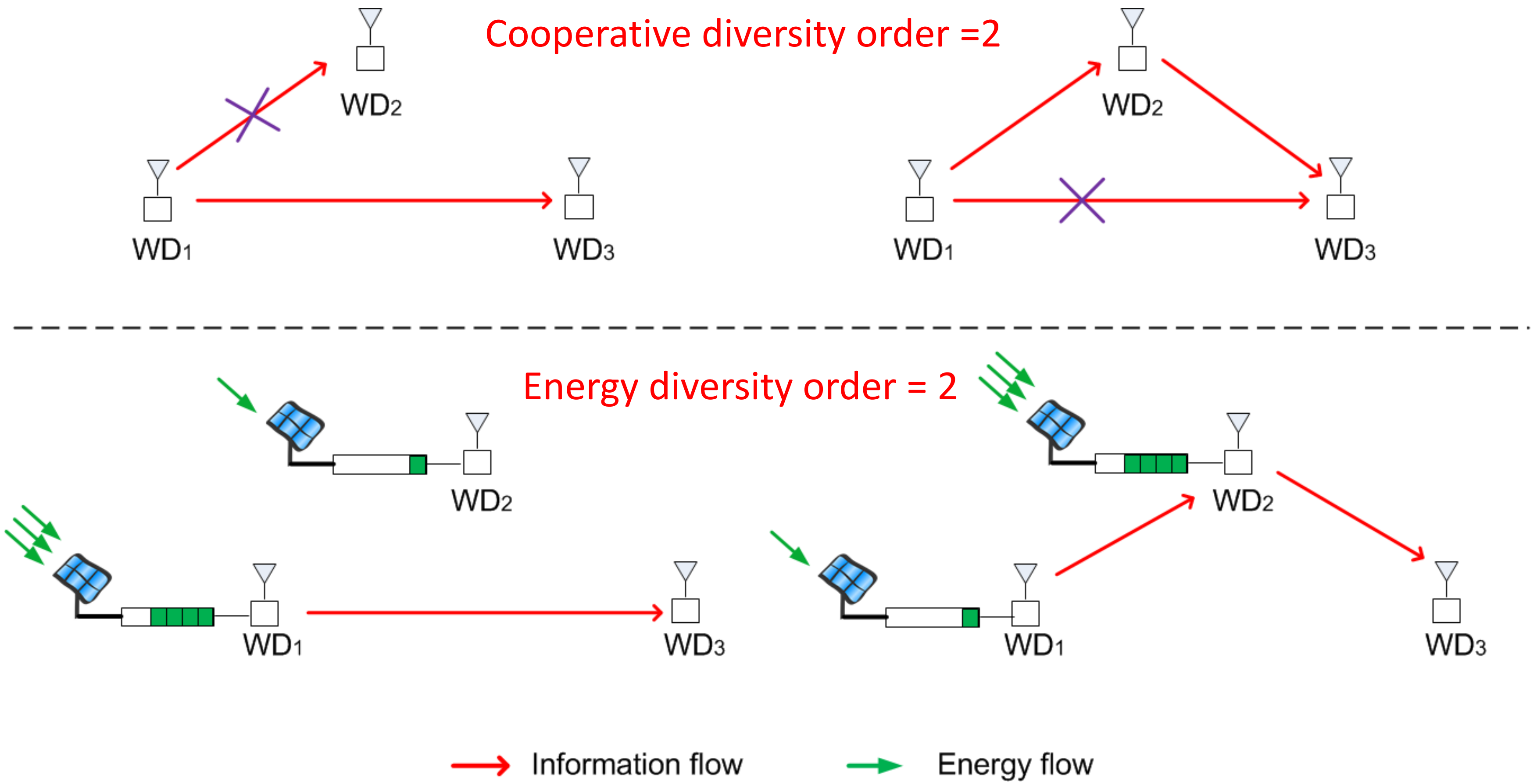
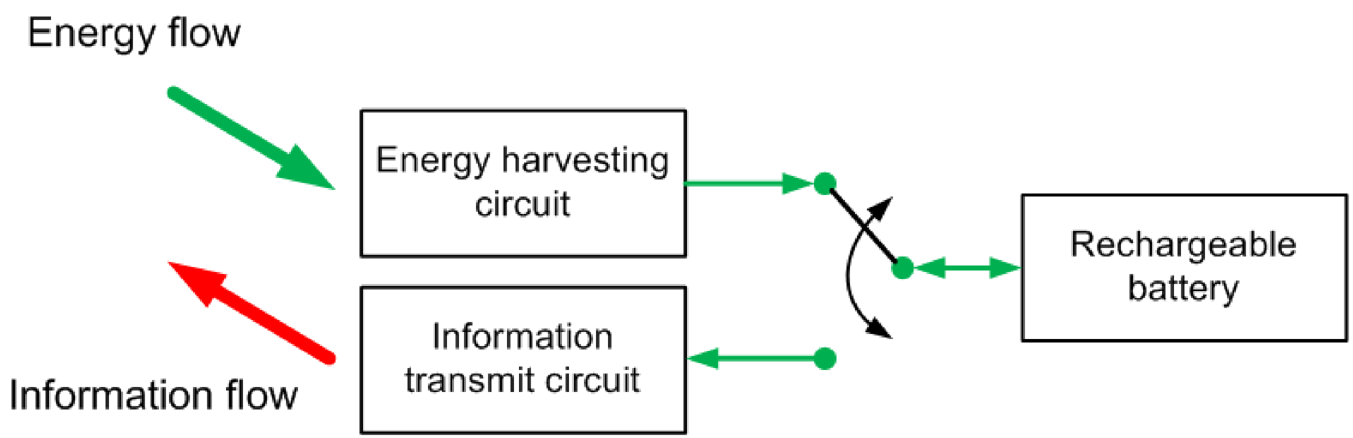
Energy Harvesting Cooperative Communications



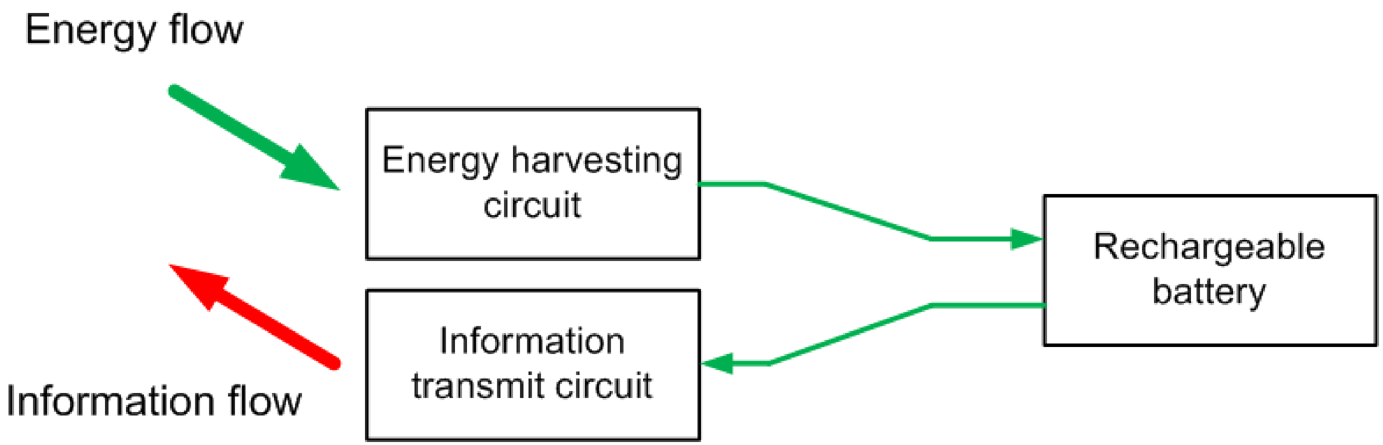
- ❑ Exploiting a new form of energy diversity resulted from independent energy arrivals over time at the source and relay

Energy Half/full Duplex

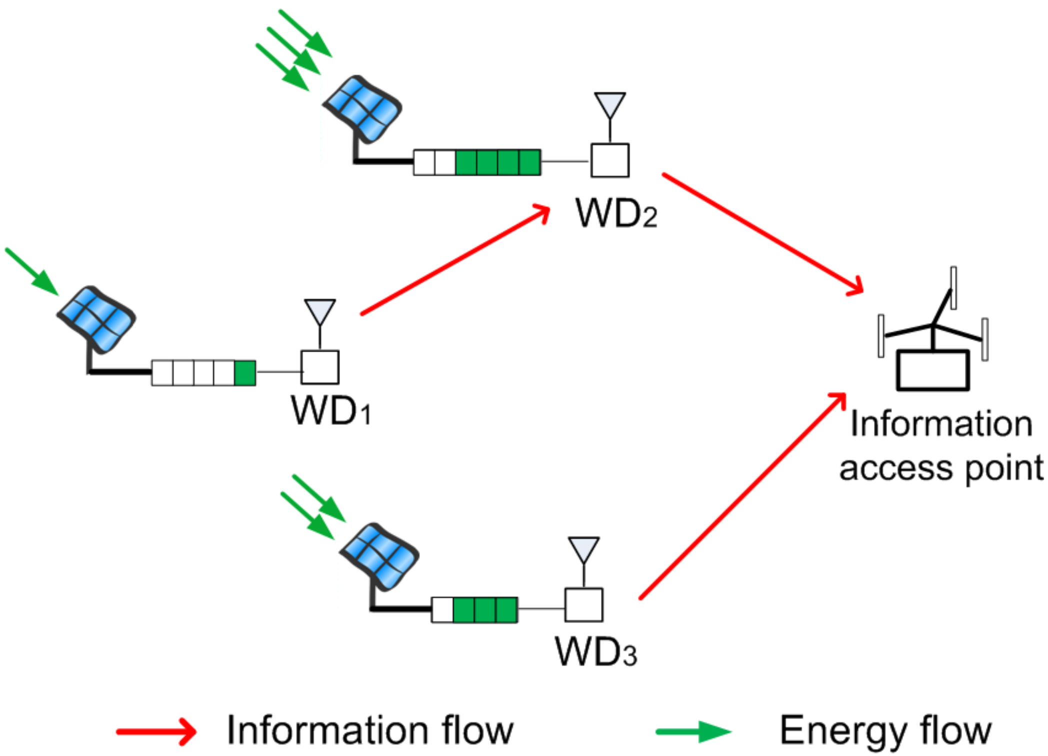
Energy Half Duplex



Energy Full Duplex



Energy Harvesting Wireless Communication Networks



- "Energy heterogeneous" networks: time and spatially varying energy availability, different energy harvesting device/storage capacity over nodes, etc.
- Joint "data queue" and "energy queue" management
- Throughput-optimal "on-line" (real-time) policy is in general unknown

Selected Publications

- Point-to-point EH communication for throughput maximization
  - Staircase/directional water-filling power allocation: [HoZhang-TSP2012] [OzelTutuncuogluYangUlukusYener-JSAC2011]
- Point-to-point EH communication for outage minimization: [HuangZhangCui-TWC2014]
- Imperfect circuits and/or storage: [DevillersGunduz-JCN2012], [LuoZhangLim-TWC2013], [XuZhang-JSAC2014]
- Online energy scheduling: [SharmaMukherjiJosephGupta-TWC2010], [BlascoGunduzDohler-TWC2013]
- EH relay channels: [HuangZhangCui-JSAC2013], [LuoZhangLetaief-TWC2013], [GurakanOzelYangUlukus-TCOM2013]
- EH communications under other setups
  - Multiple-access channels: [YangUlukus-JCN2012]
  - Broadcast channels: [YangOzelUlukus-TWC2012]
  - Interference channels: [TutuncuogluYener-JCN2011]

Future Directions

- Different assumptions about the channel state information (CSI) and energy state information (ESI) at EH transmitters
  - Optimal energy management policies under causal/non-causal CSI and causal/non-causal ESI at transmitters
- Case with EH receivers
  - EH constraints are imposed at the EH receiver for signal decoding energy consumption
- Real-time design
  - Jointly schedule the energy usage and data packet transmission by considering the uncertainties in both energy and data arrivals
- Hybrid energy sources and imperfect energy storage devices
  - How to optimally design the energy management policies under practical energy cost and storage considerations

Recent Results

[1] H. Li, J. Xu, R. Zhang, and S. Cui, "A general utility optimization framework for energy harvesting based wireless communications," *IEEE Communications Magazine,* vol. 53, no. 4, pp.79-85, April, 2015.

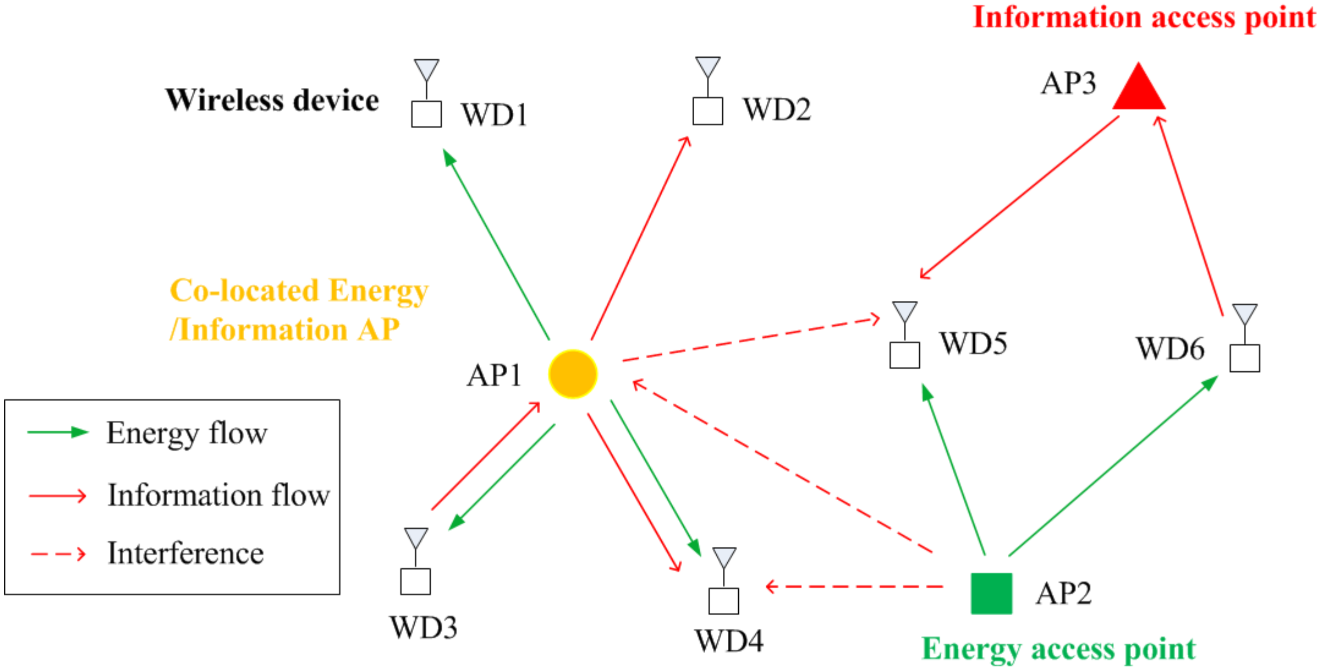
[2] S. Ulukus, A. Yener, E. Erkip, O. Simeone, M. Zorzi, P. Grover, and K. Huang, "Energy harvesting wireless communications: a review of recent advances," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 3, pp. 360-381, March 2015.

[3] D. Gunduz, K. Stamatiou, N. Michelusi, and M. Zorzi, "Designing intelligent energy harvesting communication systems," *IEEE Communications Magazine*, vol. 52, no. 1, pp. 210–16, January 2014.

Outlines

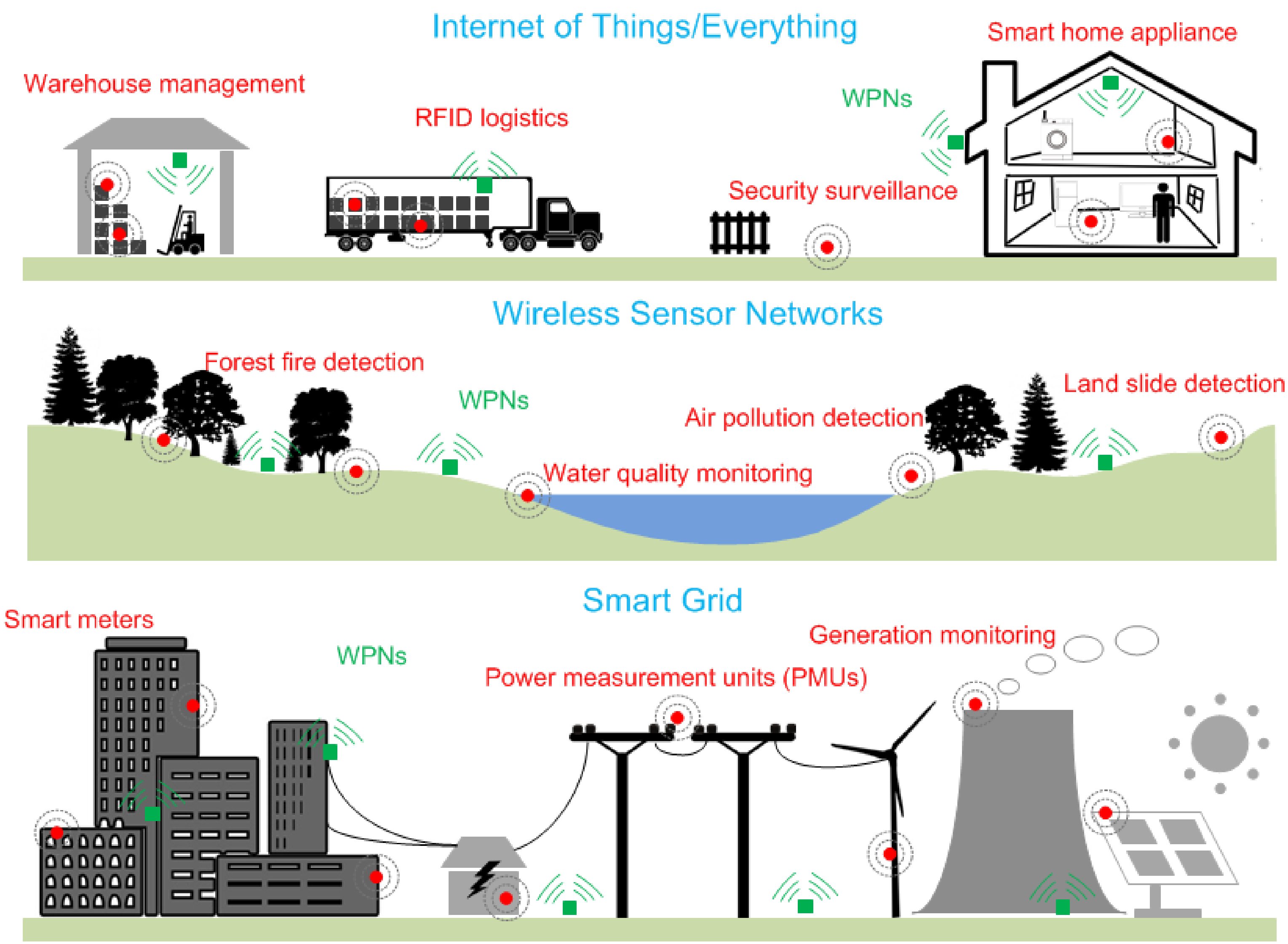
- ❑ Energy-Harvesting Communications
- ❑ Wireless-Powered Communications
- ❑ SmartGrid-Powered Communications

Wireless-Powered Communications: A General Model



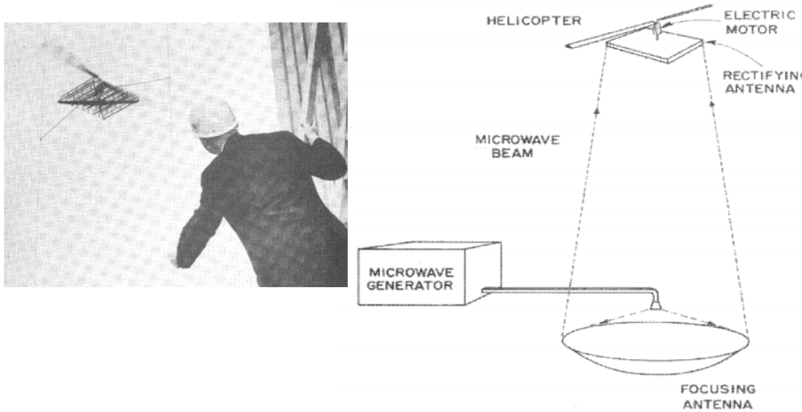
- Wireless power transfer (WPT): deliver **mW-level** power using radio frequency (RF) signals from a range up to **tens of meters**
- Three canonical operating modes
  - Wireless power transfer: AP2 -> WD5;
  - Wireless powered communication: AP1 <-> WD3, AP2->WD6->AP3;
  - Simultaneous wireless information and power transfer: AP1->WD4, AP1->WD1/WD2

Applications



Historical Development of WPT

Nikola Tesla’s
Wardenclyffe Project in early 1900’s

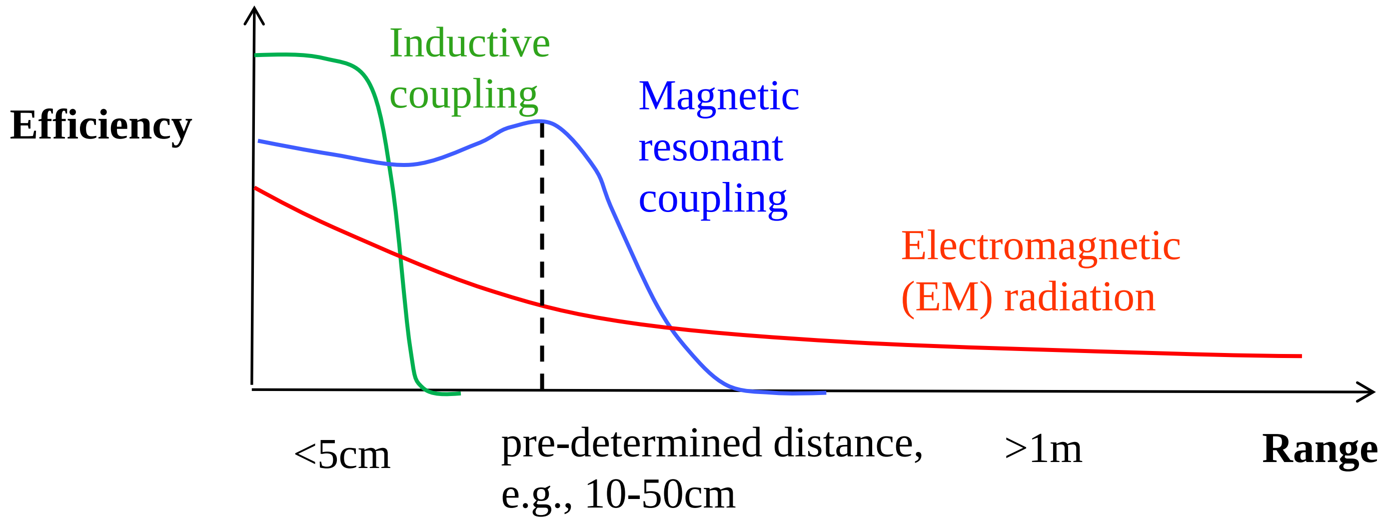


William C. Brown
invented “rectenna” in 1960’s

RF and magnetic resonant coupling
enabled commercial devices from 2000’s

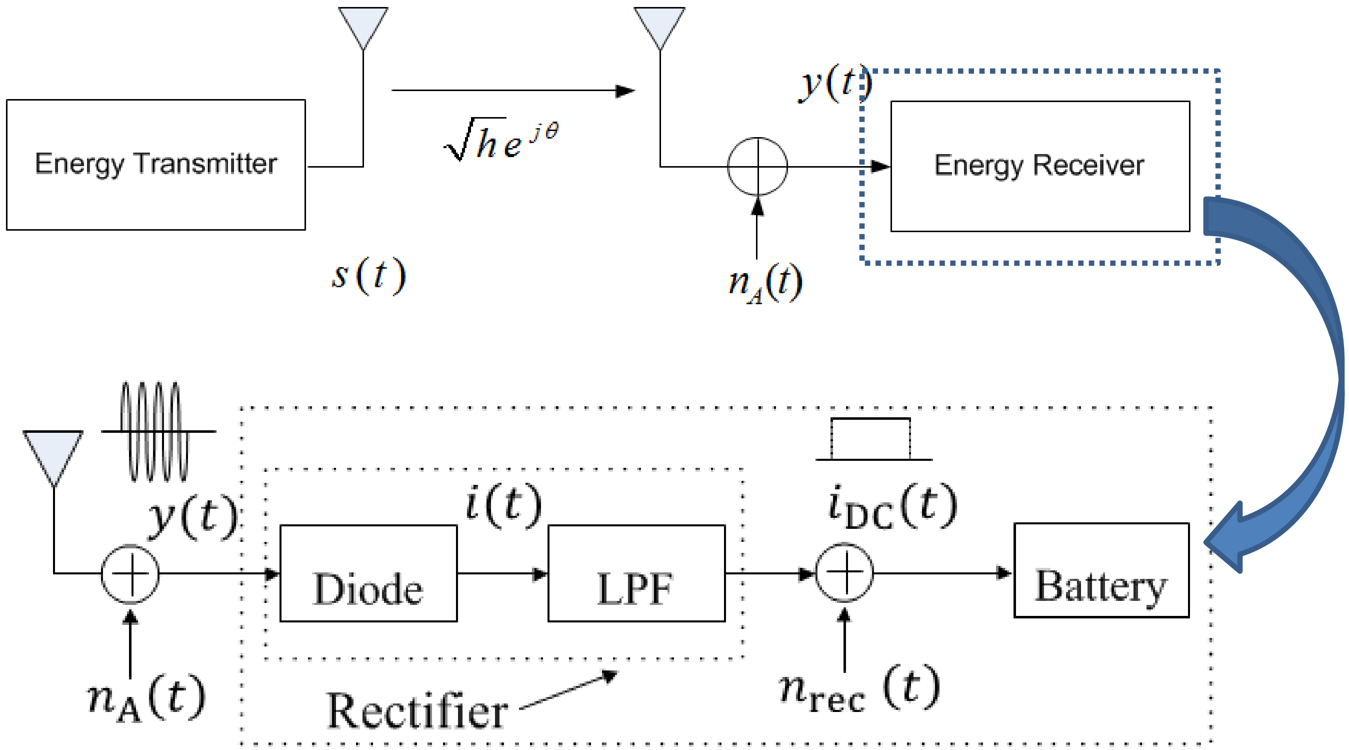
Inductive coupling for RFID
remote power supply in 1970’s

Summary of Wireless Power Transfer Technologies



		Strength	Efficiency	Distance	Multicast	Mobility	Safety
Inductive Coupling		Very high	Very high	Very short	Yes	No	Yes
Magnetic Resonant Coupling		High	High	Short	Difficult	No	Yes
EM Radiation	Omnidirectional	Low	Low	Long	Yes	Yes	Yes
	Unidirectional (e.g. microwave, laser)	High	High	Very long (LOS)	Difficult	Difficult	?

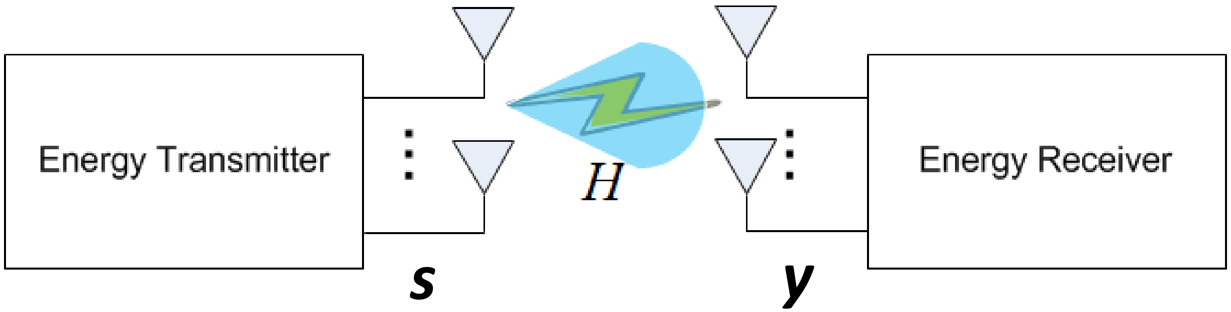
WPT Transceiver Structure



- The receiver uses rectifier to convert RF signal into DC signal
- Neglecting the noise power, the harvested power by the battery:

$$\boxed{Q = \mathbb{E}\left[i_{DC}(t)\right] = \zeta\mathbb{E}\left[||y(t)||^2\right] = \zeta h P}$$

Scaling Up WPT: Energy Beamforming in MIMO Channel



$$P_r = P_t \times G_a \times D^{-\alpha} \times \zeta$$

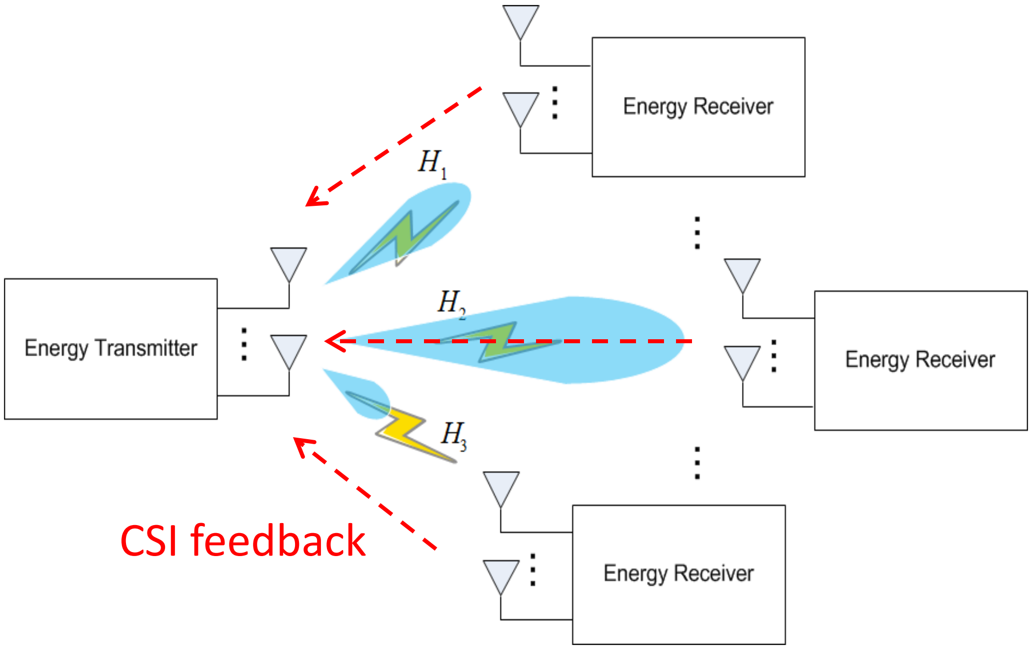
Antenna gain
Path loss
Energy conversion efficiency: 30% - 70%

- ❑ The harvested energy is $\zeta ||\mathbf{y}||^2 = \zeta ||\mathbf{H}\mathbf{s}||^2 = \zeta \mathrm{tr}(\mathbf{G}\mathbf{S})$
- ❑ Q:What's the optimal transmit strategy given a limited Tx power budget?
- ❑ A: Energy Beamforming (EB)
  - ➢ Optimize the transmit covariance matrix ***S***
- ❑ The optimal EB is the principal eigenvector beamforming

$$\begin{aligned} \underset{\mathbf{S}}{\text{maximize}} \quad & \mathrm{tr}(\mathbf{G}\mathbf{S}) \\ \text{subject to} \quad & \mathrm{tr}(\mathbf{S}) \le P, \quad \mathbf{S} \succeq \mathbf{0} \\ \text{where } \mathbf{G} = \mathbf{H}^H\mathbf{H} & \end{aligned}$$

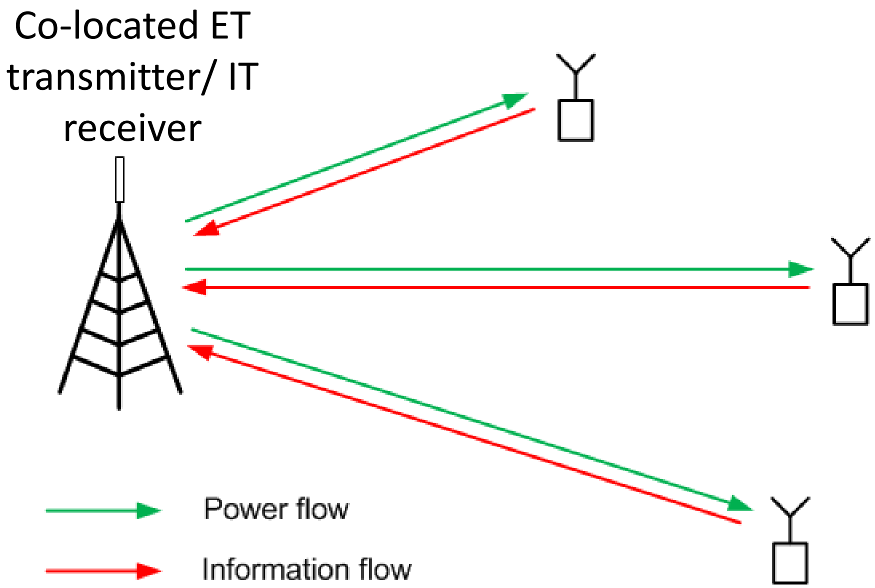
$$\mathbf{S}^* = P\mathbf{v}_E\mathbf{v}_E^H \quad \mathbf{v}_E \text{ is the principal eigenvector of } \mathbf{G}$$

MIMO Wireless Power Multicasting



- ❑ Energy near-far problem: fairness is a key issue in the multicast EB design
- ❑ EB requires the accurate knowledge of channel state information at the transmitter (CSIT)
- ❑ Full CSIT is often absent, solutions:
  - ➢ Isotropic transmission (no CSIT needed, low efficiency)
  - ➢ EB based on reverse-link training (energy constrained)
  - ➢ EB based on statistical CSIT
  - ➢ EB based on limited feedback (energy and hardware constrained)

Wireless Powered Communications Networks (WPCN)

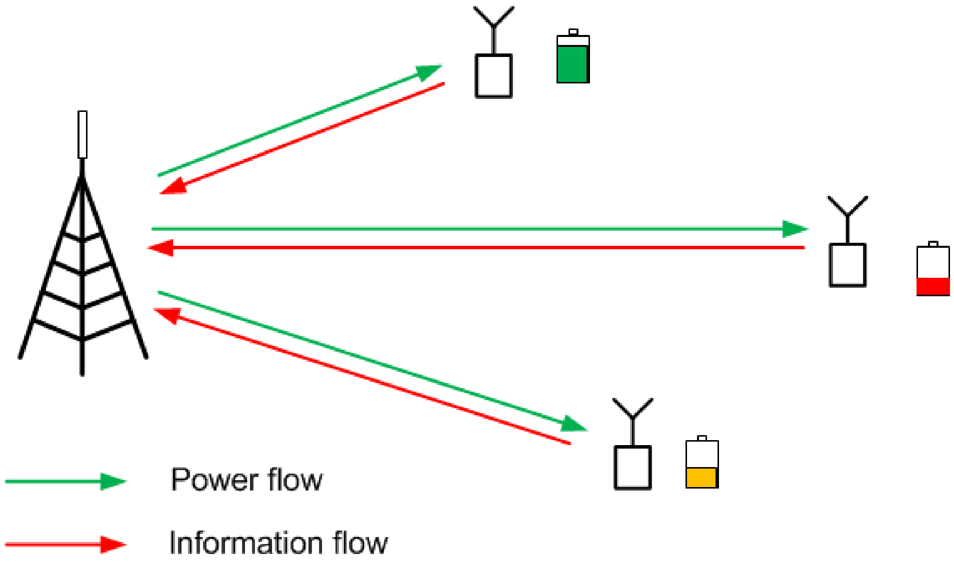


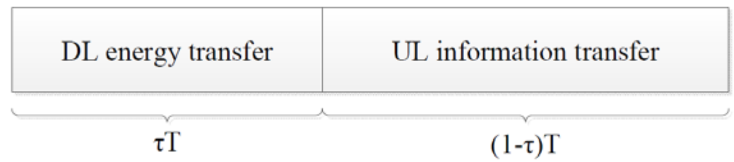
In/out-band
DL energy transmission (**ET**)
and
UL information transmissions (**IT**)

Co-located/Separated
ET transmitter
and
IT receiver

- Performance tradeoff between DL (energy) vs. UL (information) transmissions
  - How fast to transmit in UL IT related to the energy harvested from DL ET
  - How much energy harvested in DL is also related to the UL channel training/feedback
  - Need joint energy and communication scheduling and resource allocation

"Doubly" Near-far Problem

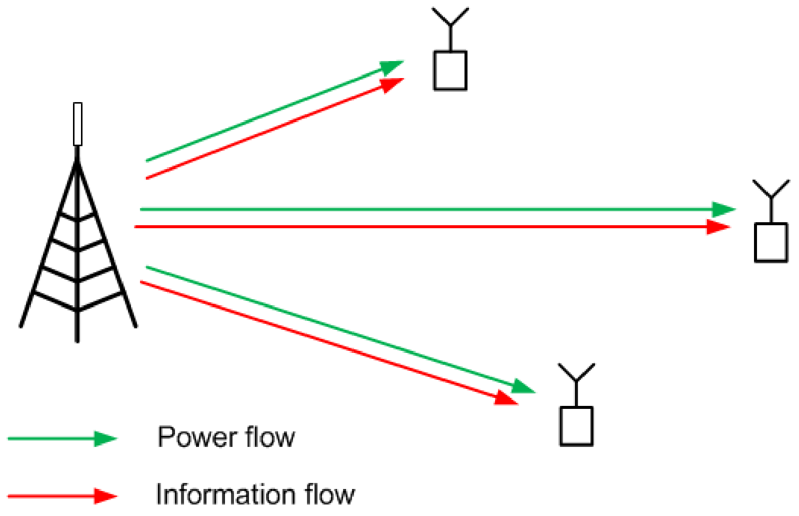




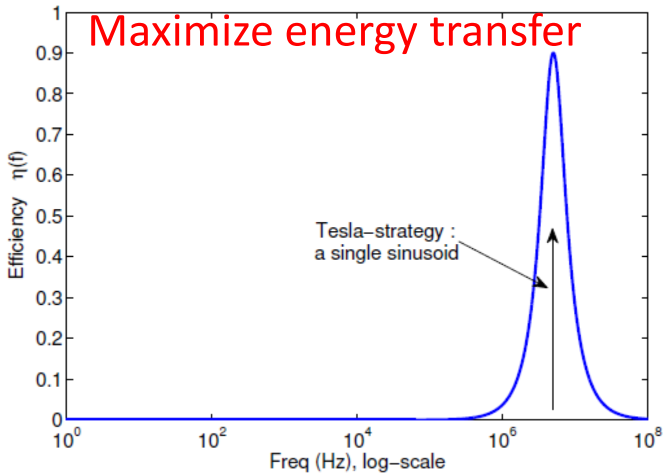
Harvest-then-transmit protocol

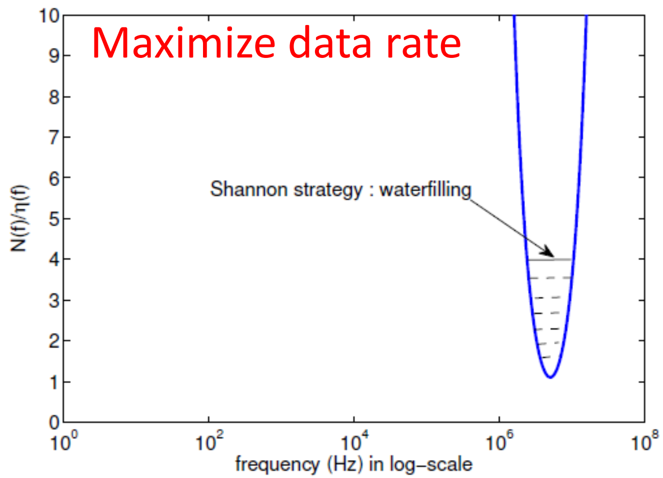
- ❑ Doubly Near-Far Problem
  - ➢ Due to distance-dependent signal attenuation in both DL and UL
  - ➢ "Near" user harvests more energy in DL but transmits less power in UL
  - ➢ "Far" user harvests less energy in DL but transmits more power in UL
- ❑ Possible Solutions:
  - ➢ Adaptive UL and UL transmission scheduling (TDMA)
  - ➢ Joint DL EB and UL power control (SDMA)
  - ➢ User cooperation (near user helps relay far user's message)

Simultaneous Wireless Information and Power Transfer (SWIPT)



- **Wireless Power Transfer** vs. **Wireless Information Transfer**
  - Power Transfer : Energy (in Joule) is linearly proportional to both time and power
  - Information Transfer :
    - ✓ Information quantity (in bits) increases linearly with time
    - ✓ but logarithmically with power





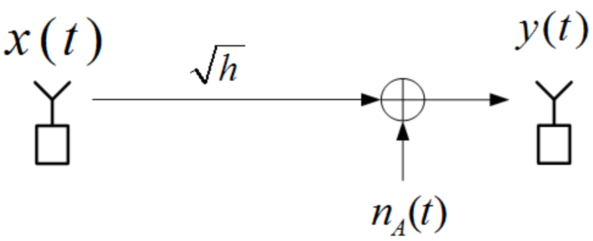
Optimal transmit power allocation over frequency-selective channel

Rate-Energy Tradeoff for an Ideal EH/ID Receiver

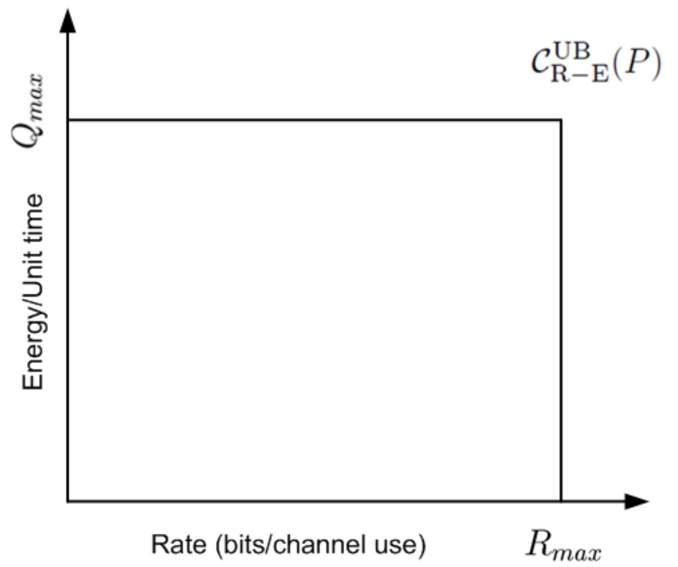
- An "ideal" receiver can harvest the energy and decode information simultaneously
  - However, practical receiver cannot achieve both from the same signal

- **Rate-energy region:** all the achievable rate and energy pairs under a given transmit power constraint *P*

- Example: Rate-energy tradeoff in a SISO AWGN channel

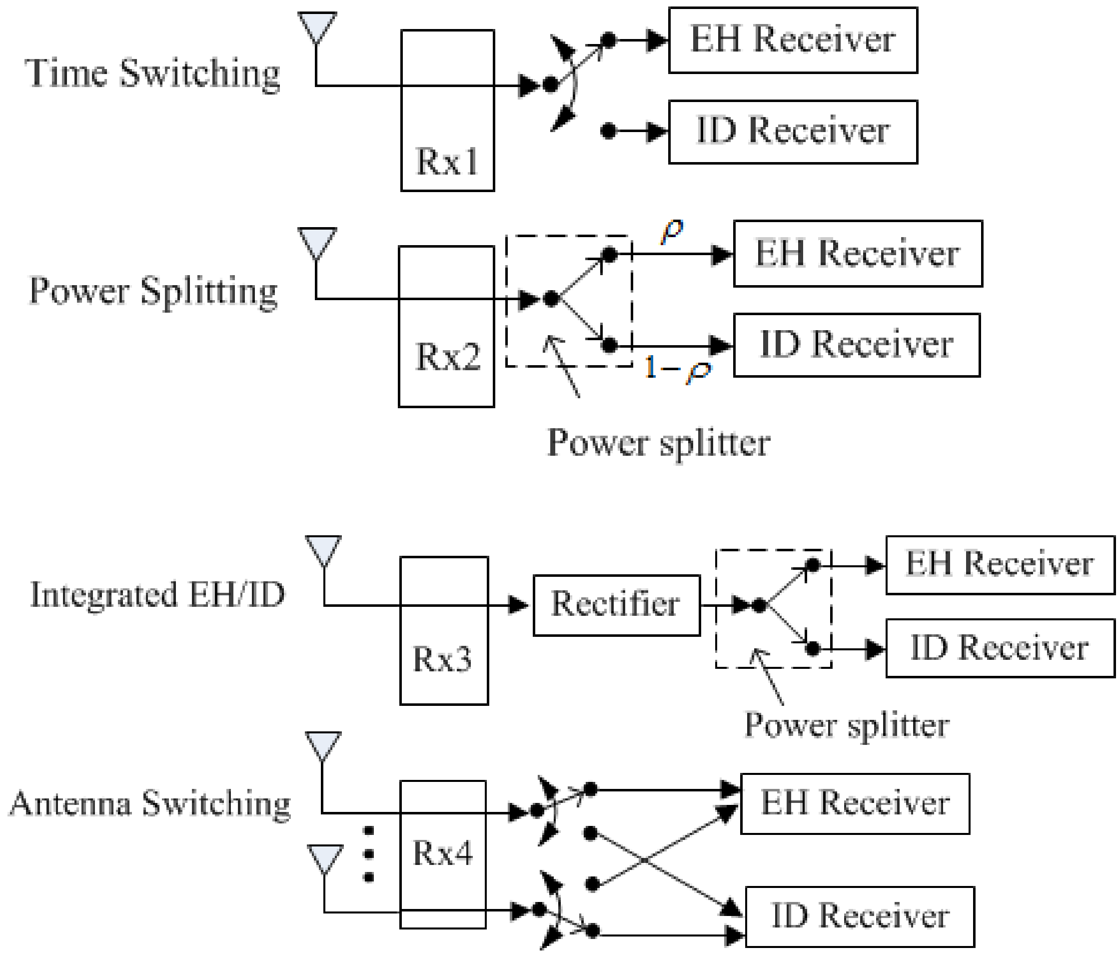


$$\mathcal{C}_{\mathrm{R-E}}^{\mathrm{UB}}(P) \triangleq \left\{ (R, Q) : R \le \log_2\left(1 + \frac{hP}{\sigma_{\mathrm{A}}^2}\right), Q \le hP \right\}$$

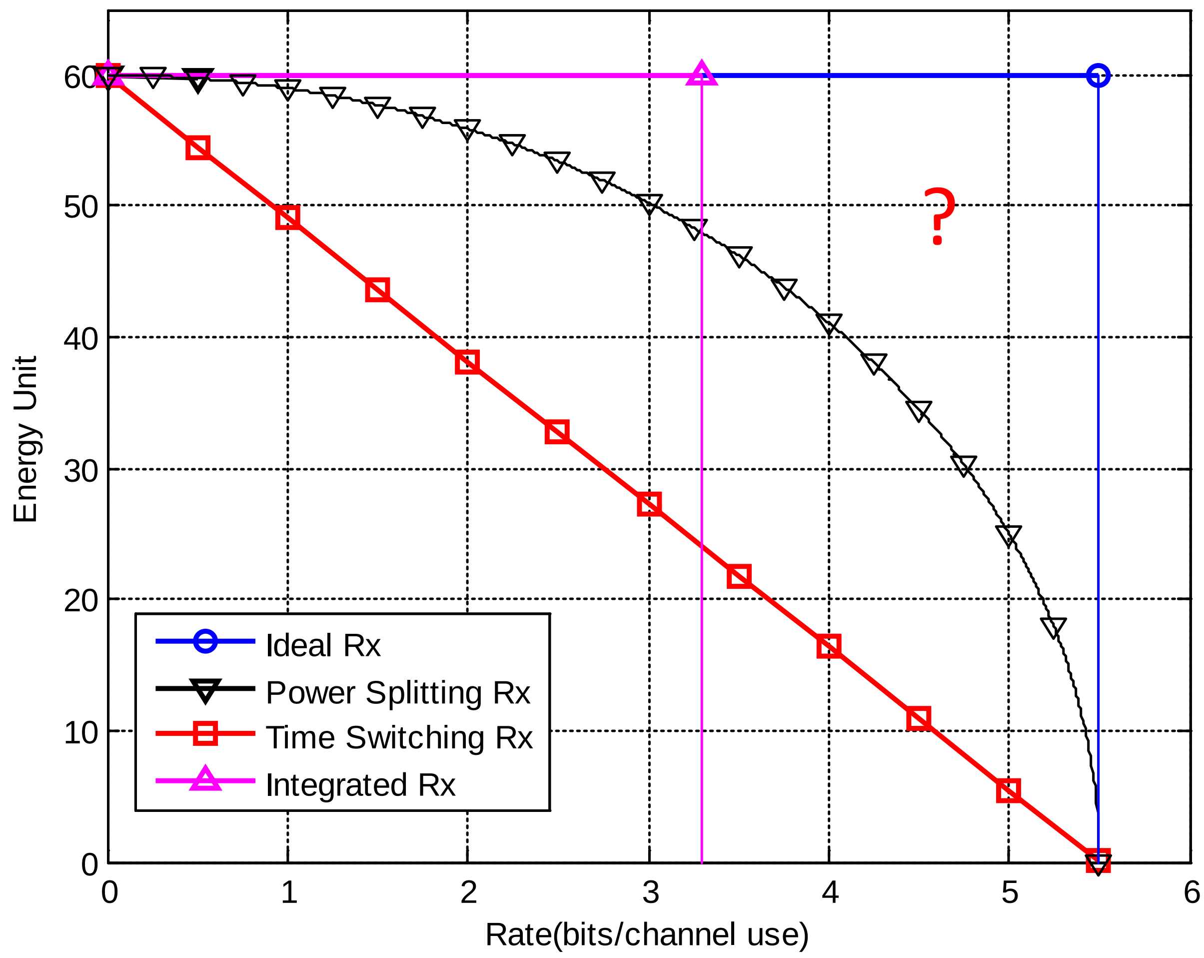


Practical SWIPT Receiver Structures

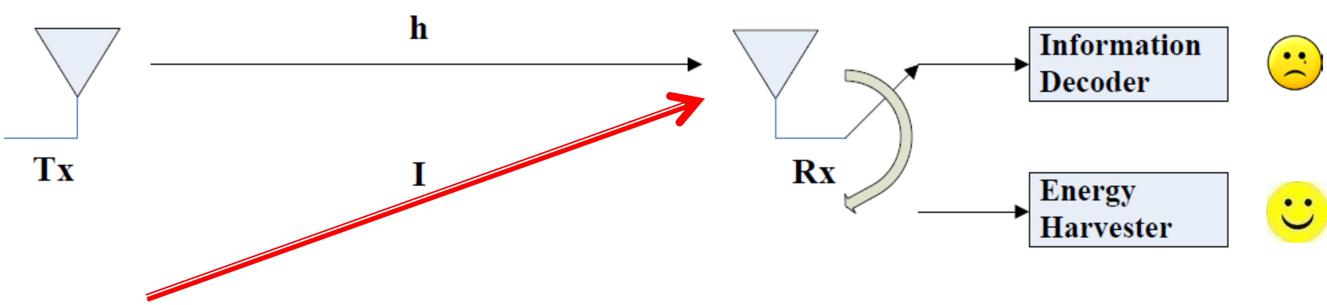
- ❑ Time switching receiver
- ❑ Power splitting receiver
- ❑ Integrated EH/ID receiver
- ❑ Antenna switching receiver



Rate-Energy Regions of SWIPT in Point-to-Point AWGN



Dual Role of Interference in SWIPT

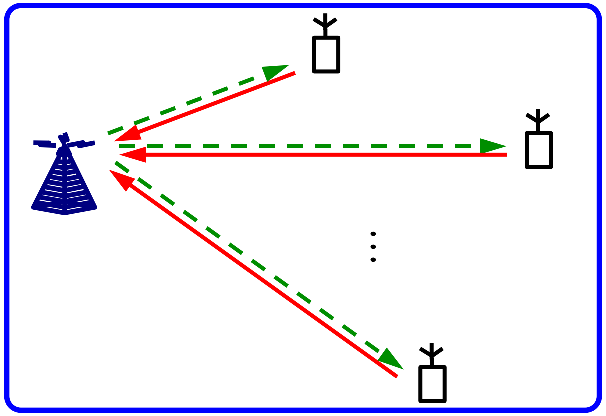


- Interference is harmful to information decoding but useful to energy harvesting

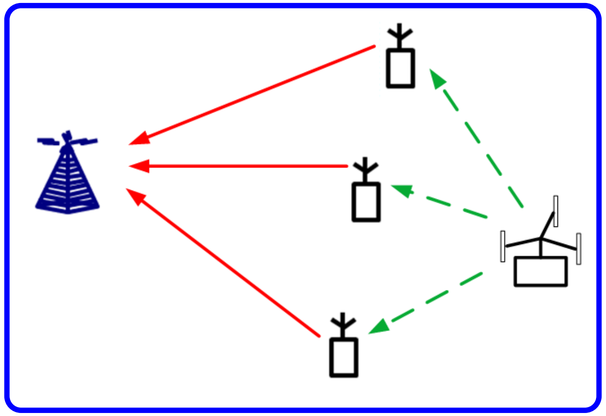
- Opportunistic EH and ID in fading channel
  - Decode information when SNR is sufficiently high and received signal (information + interference) is weak
  - Harvest energy otherwise

Section Summary

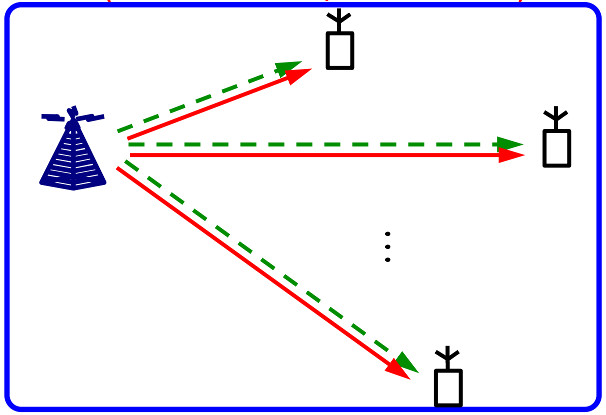
WPCN
(Co-located ET transmitter/IT receiver)



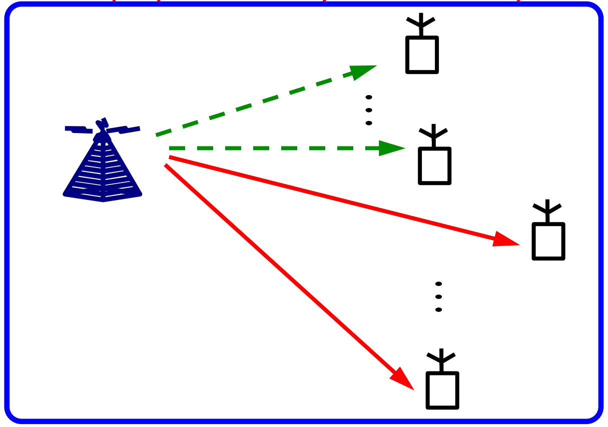
WPCN
(Separated ET transmitter/IT receiver)



SWIPT
(Co-located EH/ID receivers)



SWIPT
(Separated EH/ID receivers)



Energy transfer   Information transfer

Selected Publications

- Coding and information theory for ideal SWIPT receiver: [Varshney-ISIT2008],[GroverSahai-ISIT2010], [PopovskiFouladgarSimeone-TCOM2013]

- Practical SWIPT receivers and rate-energy tradeoff : [ZhangHo-TWC2013],[ZhouZhangHo-TCOM2013]

- MIMO transmit optimization and resource allocation in multiuser SWIPT
  - Broadcast channel: [XuLiuZhang-TSP2014], [HuangLarsson-TSP2014], [NgLoSchober-TWC2013]
  - Relay channel: [KrikidisTimotheouSasaki-CommLett2012],[NasirZhouDurraniKennedy-TWC2013]
  - Interference channel: [ParkClerckx-TWC2013],[LeeLiuZhang-TWC2015]

- Joint energy and communication optimization in WPCN: [JuZhang-TWC2014], [HuangLau-TWC2014], [JuZhang-TCOM2014], [LiuZhangChua-TCOM2014]

- Wireless power transfer under imperfect CSIT: [XuZhang-TSP2014], [ZengZhang-TCOM2015]

- Other topics
  - Secrecy communications in SWIPT: [LiuZhangChua-TSP2014], [NgLoSchober-TWC2014]
  - RF powered cognitive radio networks : [LeeZhangHuang-TWC2013]
  - Wireless information and power transfer coexisting : [XuBiZhang-CommLett2015]

Future Directions

- Information-theoretic limits and coding for WPCN/SWIPT
- Massive MIMO based WPT/WPCN/SWIPT
- Imperfect CSIT and practical feedback in WPT/WPCN/SWIPT
- Full-duplex WPCN/SWIPT
- New transceiver design for WPCN/SWIPT
- Many others (hardware development, safety/security/economic issues, MAC/network layer design, …….)

Recent Results

[1] S. Bi, C. K. Ho, and R. Zhang, "Wireless powered communication: opportunities and challenges," *IEEE Communications Magazine*, vol. 53, no. 4, pp. 117-125, April 2015.

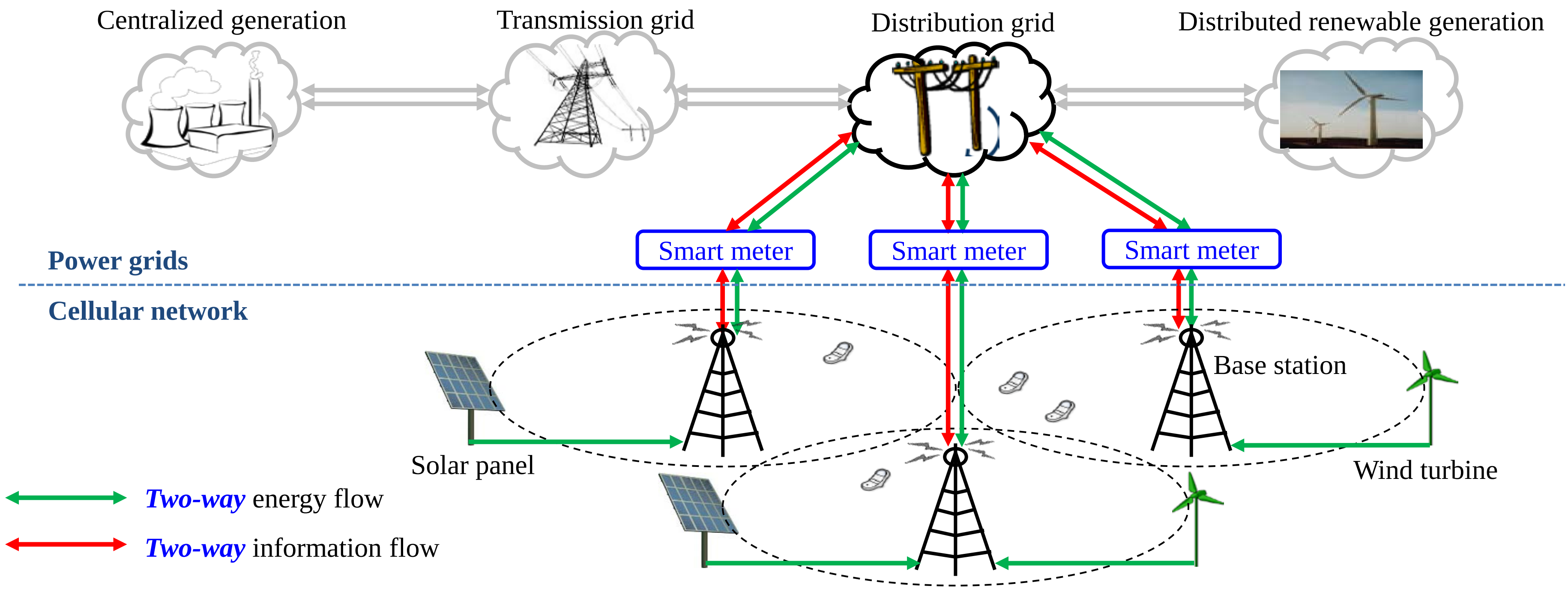
[2] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless Networks With RF Energy Harvesting: A Contemporary Survey," *IEEE Communications Surveys and Tutorials*, vol. 17, no. 2, pp.757-789, Second quarter 2015.

[3] I. Krikidis, S. Timotheou, S. Nikolaou, G. Zheng, D. W. K. Ng, and R. Schober, "Simultaneous wireless information and power transfer in modern communication systems", *IEEE Communications Magazine* , vol. 52, no. 11, pp. 104-110, Nov. 2014.

Outlines

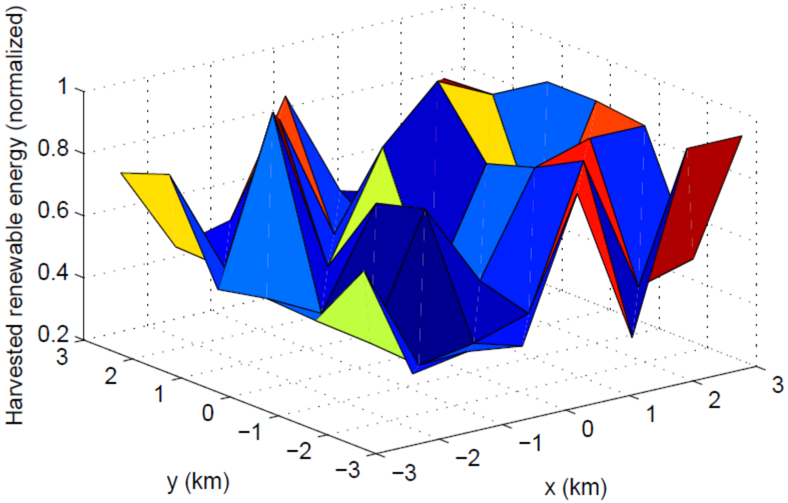
- ❑ Energy-Harvesting Communications
- ❑ Wireless-Powered Communications
- ❑ SmartGrid-Powered Communications

Smart Grid Powered Cellular Networks: A Generic Model

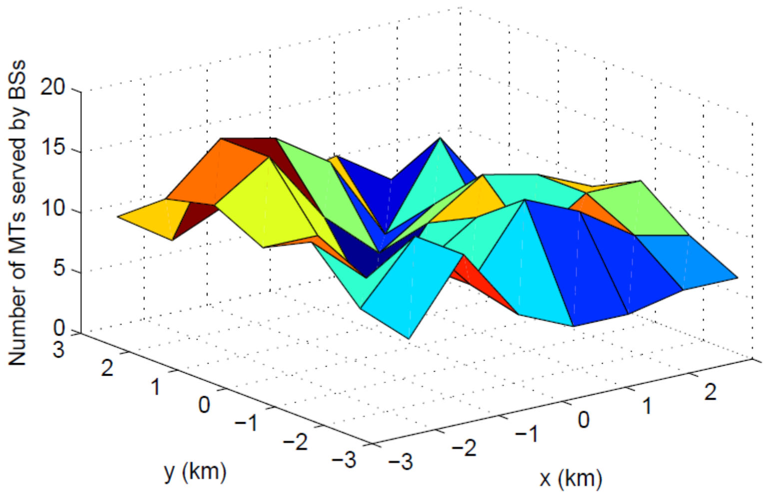


- ❑ Hybrid energy supply at cellular BSs
  - ➢ Renewable energy: cheap but intermittent (stochastically and spatially distributed)
  - ➢ On-grid power: reliable but expensive
- ❑ How to maximally utilize the cheap renewable energy to minimize the on-grid energy cost?

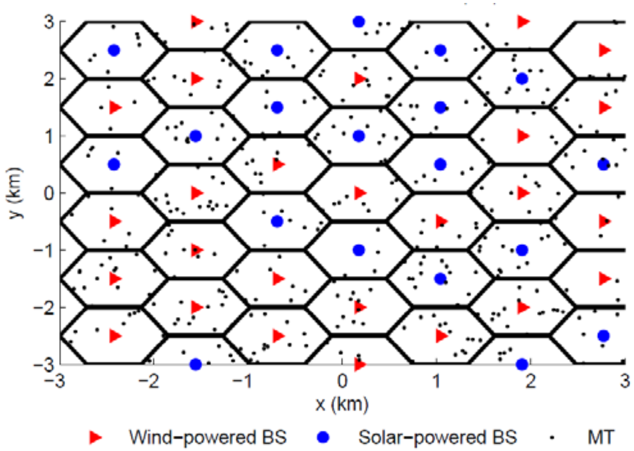
Renewable Energy Supply and Traffic Demand Dynamics



Spatially distributed harvested energy



Spatially distributed traffic load

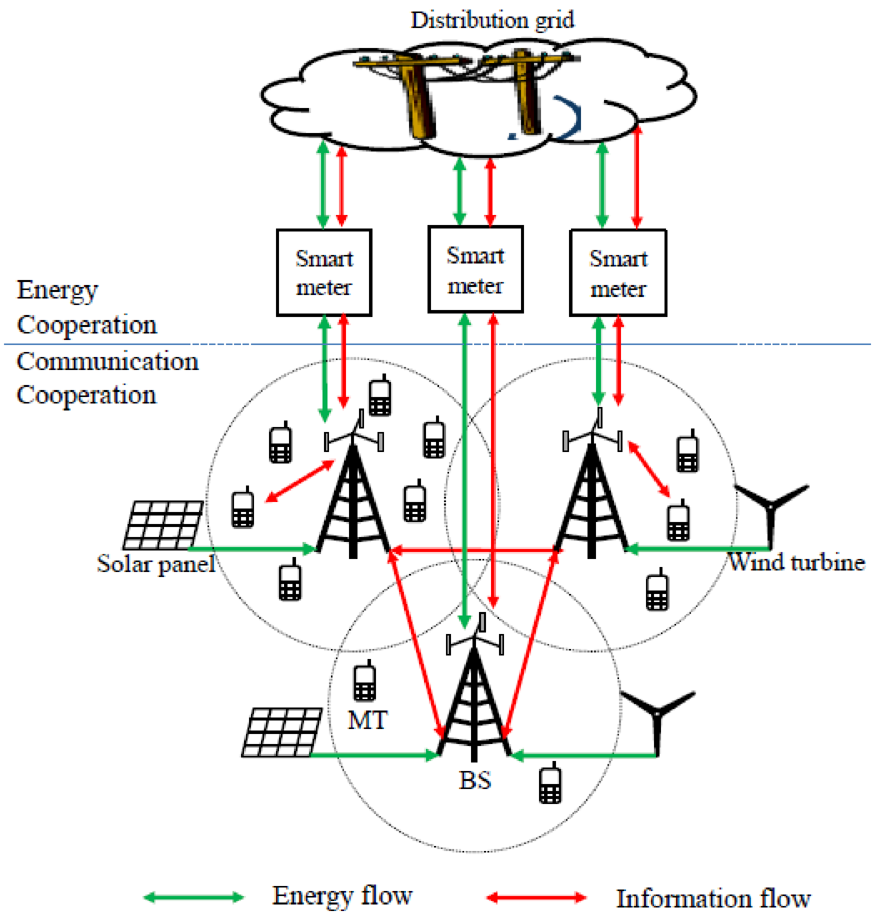


Cellular network with renewable powered BSs

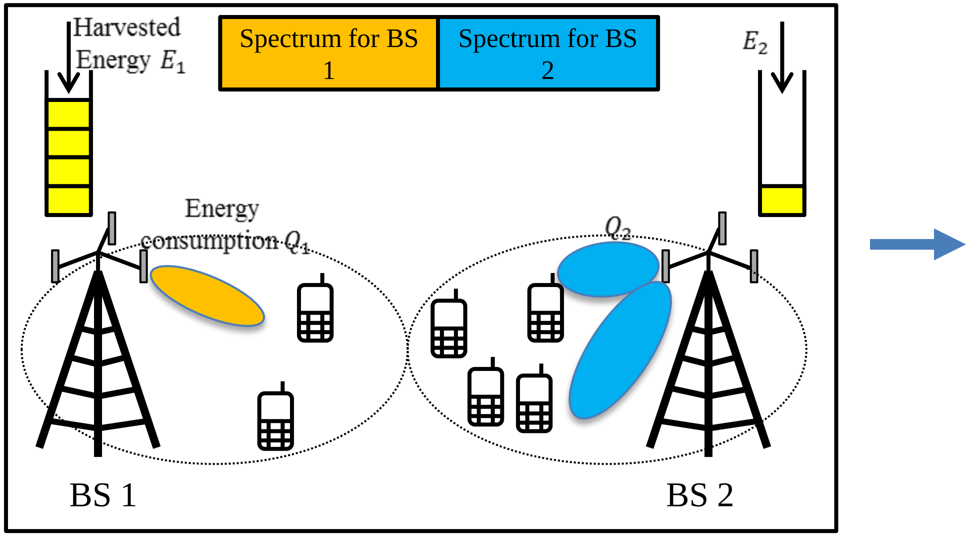
- ❑ Net load (power consumption offset by harvested renewable energy) at BSs
  - ➢Some BSs are renewable energy adequate
  - ➢Others are renewable energy deficit
  - ➢Both spatially and temporarily varying
- ❑ How to make more *balanced* use of renewable energy to reduce total energy cost?

Key Approaches

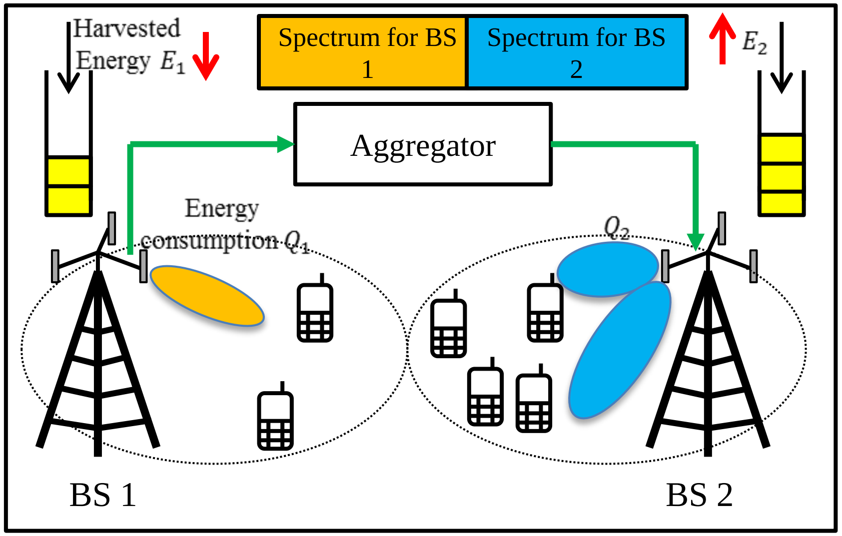
- Approach I: Energy Cooperation on Supply Side Only
  - BSs exploit two-way energy trading in smart grid for energy sharing
- Approach II: Communication Cooperation on Demand Side Only
  - BSs share wireless resources and reshape wireless loads to match individual renewable energy supplies
- Approach III: Joint Energy and Communication Cooperation on Both Supply an Demand Sides



Energy Cooperation



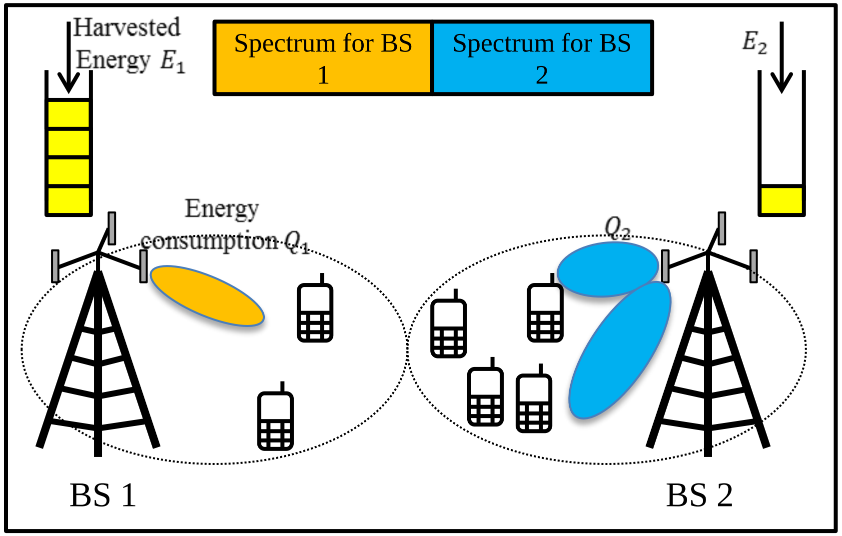
Without energy cooperation



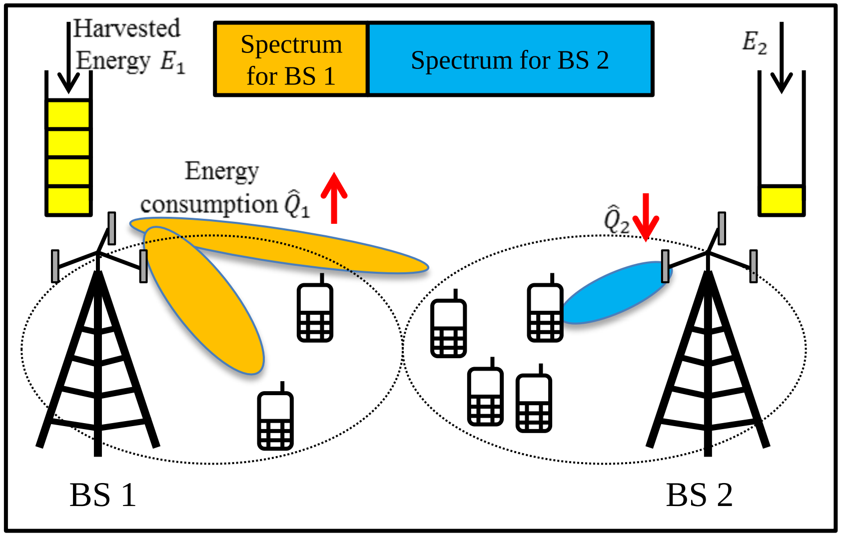
With energy cooperation

- BS 1 with excessive renewable energy (E_1>Q_1) shares energy to BS 2 in energy shortage (E_2<Q_2) via energy trading with the Aggregator
- E_1 decreases, and E_2 increases
- Total on-grid energy cost of two BSs is minimized

Energy Cost-aware Communication Cooperation



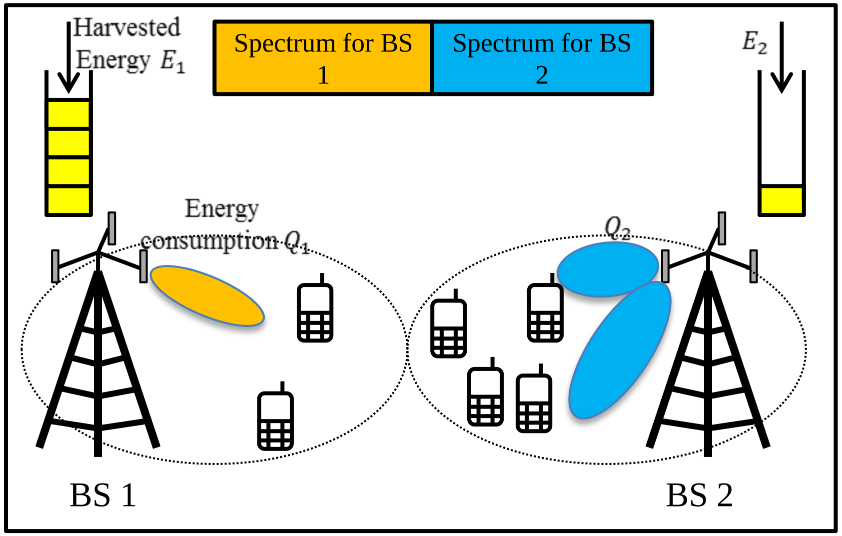
Without spectrum sharing



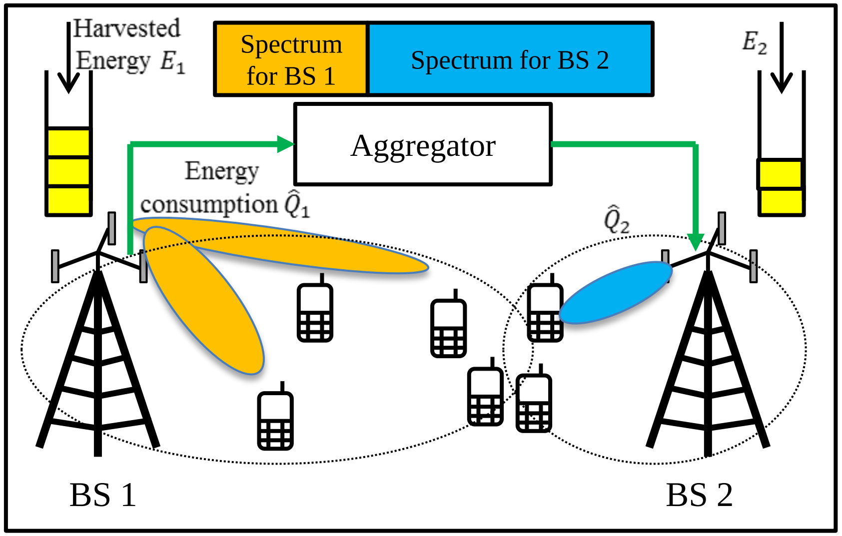
With spectrum sharing

- BS 1 with excessive renewable energy ($E_1>Q_1$) shares spectrum to BS 2 in energy shortage ($E_2<Q_2$)
- Q_1 increases, and Q_2 decreases; hence, total on-grid energy cost is minimized
- Other communication cooperation methods: traffic offloading, CoMP, etc.

Joint Energy and Communication Cooperation



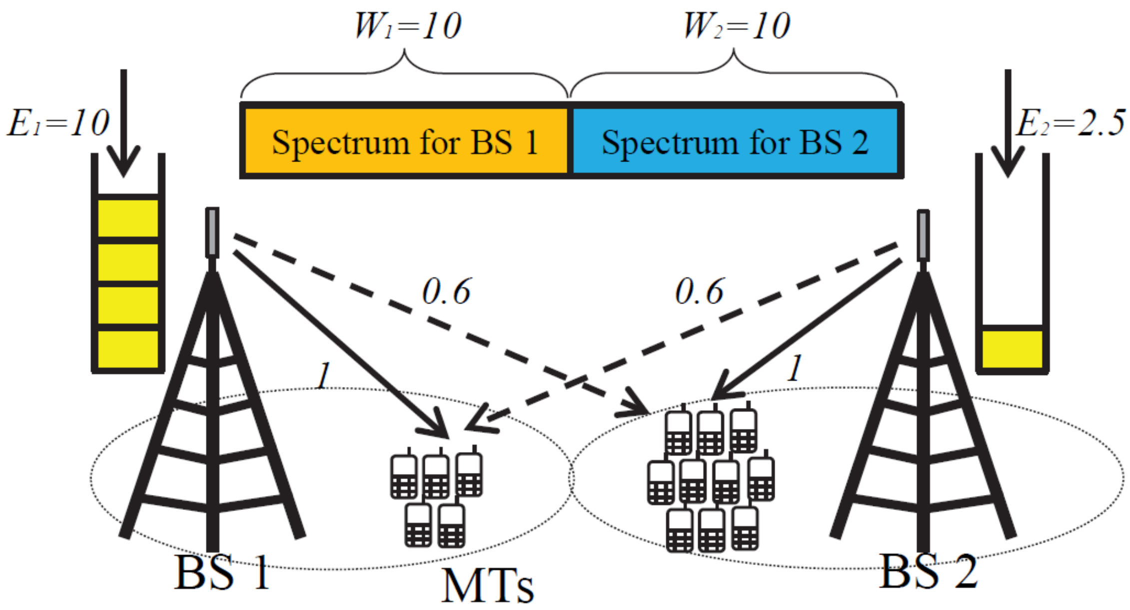
Without energy/communication cooperation



With joint energy and communication cooperation

- Joint energy and communication cooperation
  - BSs jointly optimize energy sharing and communication cooperation (e.g., spectrum sharing, traffic offloading, and CoMP)
  - Achieve maximum energy cost reduction

Case Study



- Schemes for comparison
  - Conventional design without energy or communication cooperation
  - Approach I: energy cooperation via energy trading
  - Approach II: communication cooperation via spectrum sharing
  - Approach III: joint energy trading and CoMP

	BS1's renewable energy supply	BS2's renewable energy supply	BS1's renewable energy consumption	BS2's renewable energy consumption	Total energy cost
Conventional design w/o energy or communication cooperation	10	2.5	4.14	18.28	15.78
Energy cooperation via energy trading	4.14	8.36	4.14	18.28	10.51
Communication cooperation via spectrum sharing	10	2.5	10	14.04	11.54
Joint energy trading and CoMP	6.87	5.62	6.87	5.77	0.46

Renewable energy supplies are modified via energy cooperation

Energy demands are rescheduled via communication cooperation

Joint energy and communication cooperation saves the most energy cost

Selected Publications

- Energy cooperation in smart grids: [SaadHanPoorBasar-SPM2012]
- Energy cooperation in cellular networks: [ChiaSunZhang-TWC2014]
- Joint energy and communication cooperation in cellular networks
  - Energy sharing/trading with CoMP: [XuZhang-TVT2015a], [XuZhang-TVT2015b]
  - Joint energy and spectrum cooperation: [GuoXuDuanZhang-TCOM2014]
- Energy management in cellular networks with renewable supplies: [HanAnsari-TWC2013], [ZhengPawelczakStanczakYu-CL2013], [GongThompsonZhouNiu-TCOM2014]
- Joint management of cellular networks and smart grids: [BuYuCaiLiu-TWC2012], [HongZhu-SmartGridCom2014]

Future Directions

- Multi-time-scale implementation of joint energy and communication cooperation under practical constraints
  - Energy harvesting rates in general change much slowly as compared to wireless channel and traffic load variations
- Cooperation between self-interested system operators with incomplete and private information sharing constraints
  - Incentive mechanisms design to motivate different systems to cooperate with "win-win" and fair cost reductions
- Energy and communication cooperation in heterogeneous networks
  - Need to address both heterogeneous communication demands and heterogeneous energy supplies
- Joint spatial and temporal energy/communication cooperation with energy storage management
  - Exploiting both time and space energy diversity

Recent Results

[1] J. Xu, L. Duan, and R. Zhang, "Cost-aware green cellular networks with energy and communication cooperation," *IEEE Communications Magazine*, vol. 53, no. 5, pp. 257-263, May 2015.

[2] T. Han and N. Ansari, "Powering mobile networks with green energy," *IEEE Wireless Communications*, vol. 21, no. 1, pp. 90-96, February 2014.

Conclusions

Staircase/directional water-filling

Energy harvesting cooperative communication

Energy diversity

Energy full/half duplex

Offline vs. Online energy control

Energy beamforming

Joint communication and energy transfer scheduling & design

Doubly near-far problem

Rate-energy tradeoff

Separated vs. Integrated receiver for SWIPT

Hybrid powered base stations (BSs)

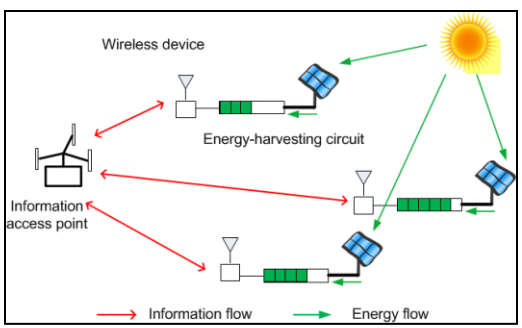
Energy cooperation

Two-way energy trading

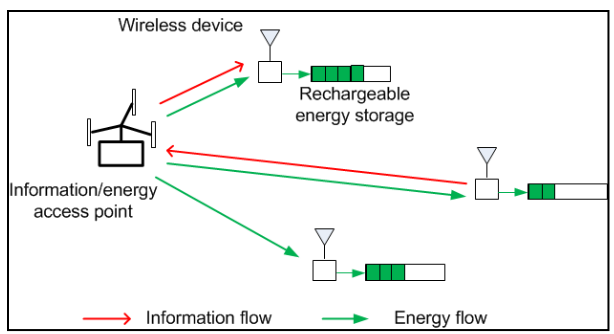
Energy cost-aware resource allocation & optimization

Joint energy/communication cooperation design

Energy-harvesting Communications



Wireless-powered communications



SmartGrid-powered communications