# Cost-Aware Green Cellular Networks with Energy and Communication Cooperation

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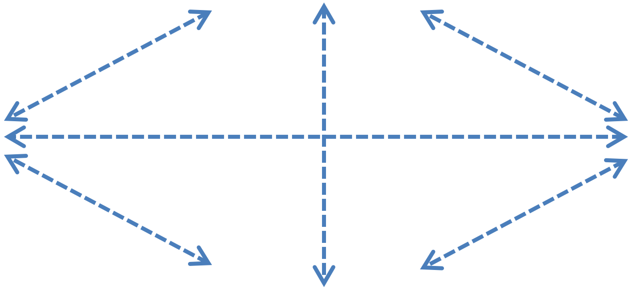
# Wireless Communications in the Age of "Energism"

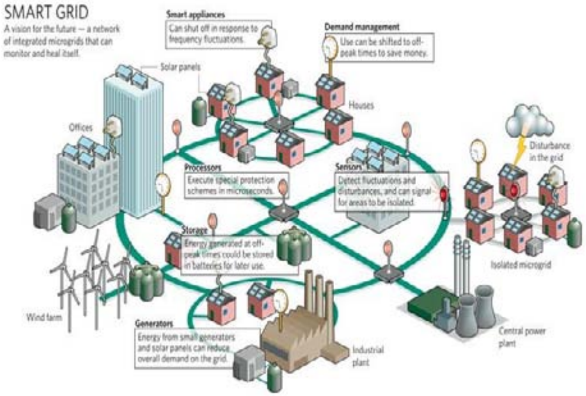

Wireless power transfer

Green communications

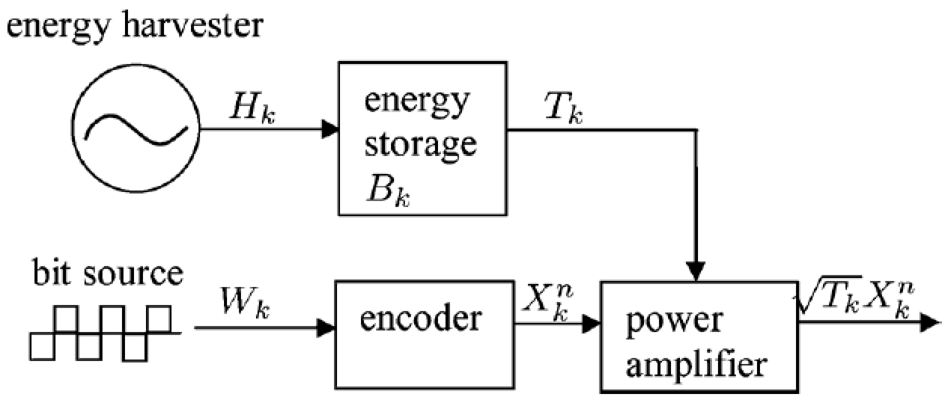



Energy harvesting

Smart grid



# Energy Harvesting Wireless Communication: A Brief Overview

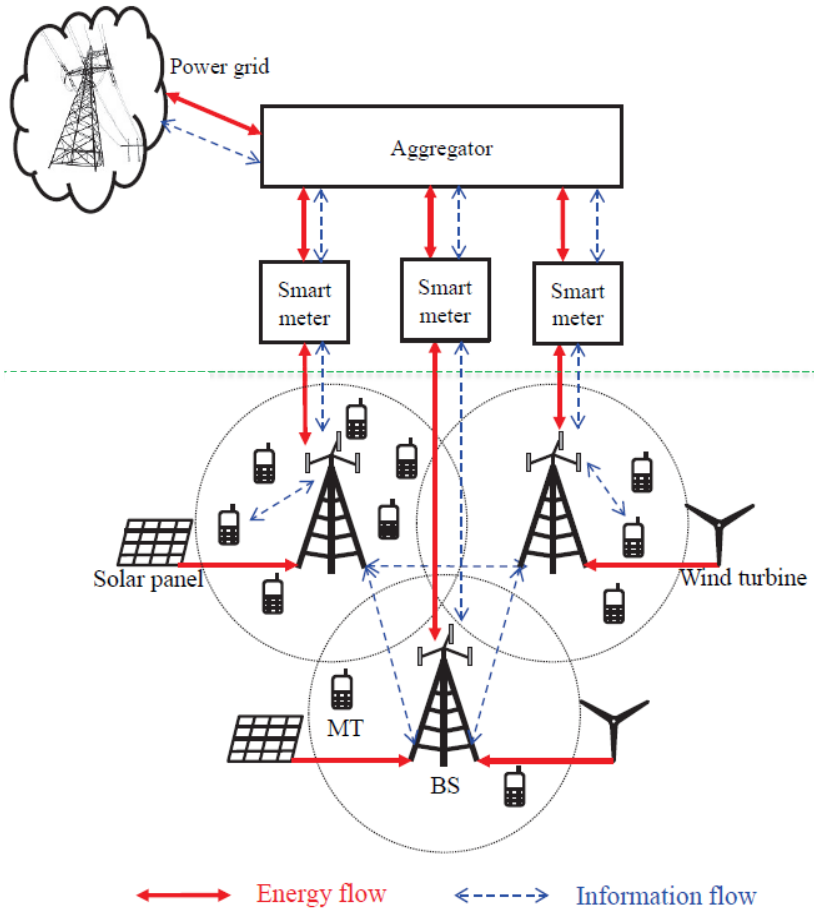



Wireless transmitter powered by an energy harvester

- Point-to-point link with an energy harvesting transmitter
  - Throughput maximization: Staircase/directional water-filling power allocation [1,2]
  - Outage probability minimization [3]
- Practical considerations
  - Imperfect energy storage [4], half-duplex energy harvesting constraint [5], circuit power [6], …
- Other setups
  - Relay channel [7], broadcast channel, multiple-access channel, …

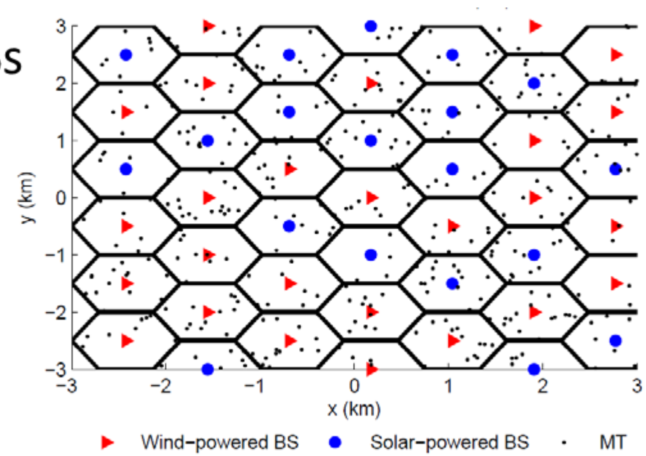
# New Challenge: Cellular Networks with Energy Harvesting and Smart Grid Powered Base Stations (BSs)

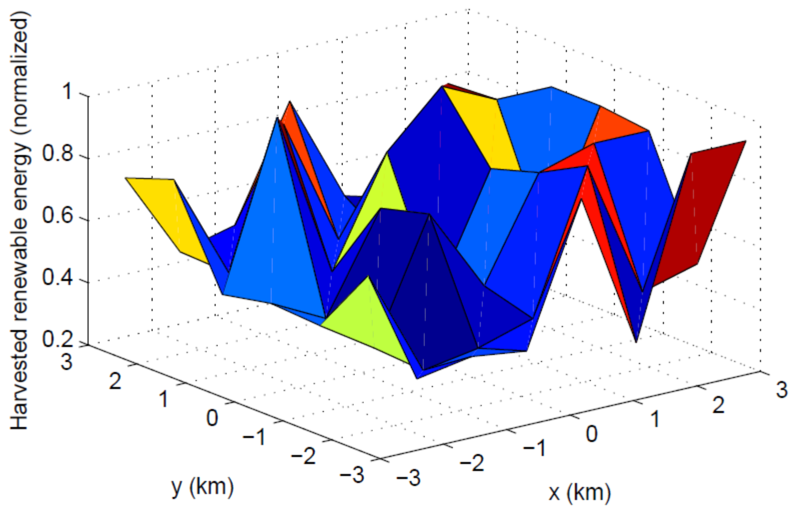
- ❑ Hybrid Energy Supply
  - ➢ **Renewable Energy**: cheap but intermittent; unevenly distributed over both time and space
  - ➢ **Smart grid power**: reliable but expensive; time-varying energy prices; two-way energy flow
- ❑ BSs' Energy Demand
  - ➢ To meet the quality of service (QoS) requirements of mobile terminals (MTs)
  - ➢ Time- and space-varying traffic loads due to mobility of MTs
- ❑ Challenge
  - ➢ How to use the stochastically and spatially distributed renewable energy at cellular BSs to reliably support time- and space-varying wireless traffic cost-effectively?



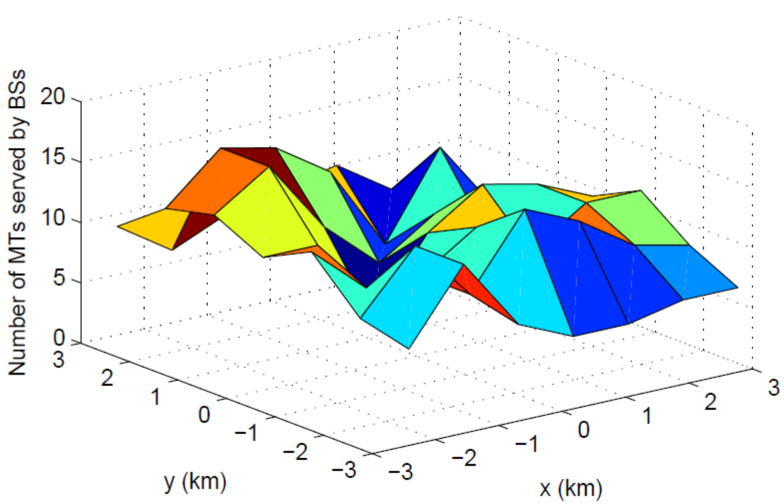
# Energy Supply and Demand Models for Cellular Networks

- Consider one single cellular system with $N > 1$ BSs
- Renewable energy harvested by BS $i : E_i \geq 0$
- Power consumption of BS $i : Q_i \geq 0$
- Net load at BS $i : \delta_i = Q_i - E_i$
  - $\delta_i < 0$ : Renewable energy adequate
  - $\delta_i > 0$ : Renewable energy deficit
  - $\delta_i$'s are geographically diverse and time-varying




Spatially distributed harvested energy




Spatially distributed traffic load

# Energy Cost by Directly Employing Renewable Energy at BSs

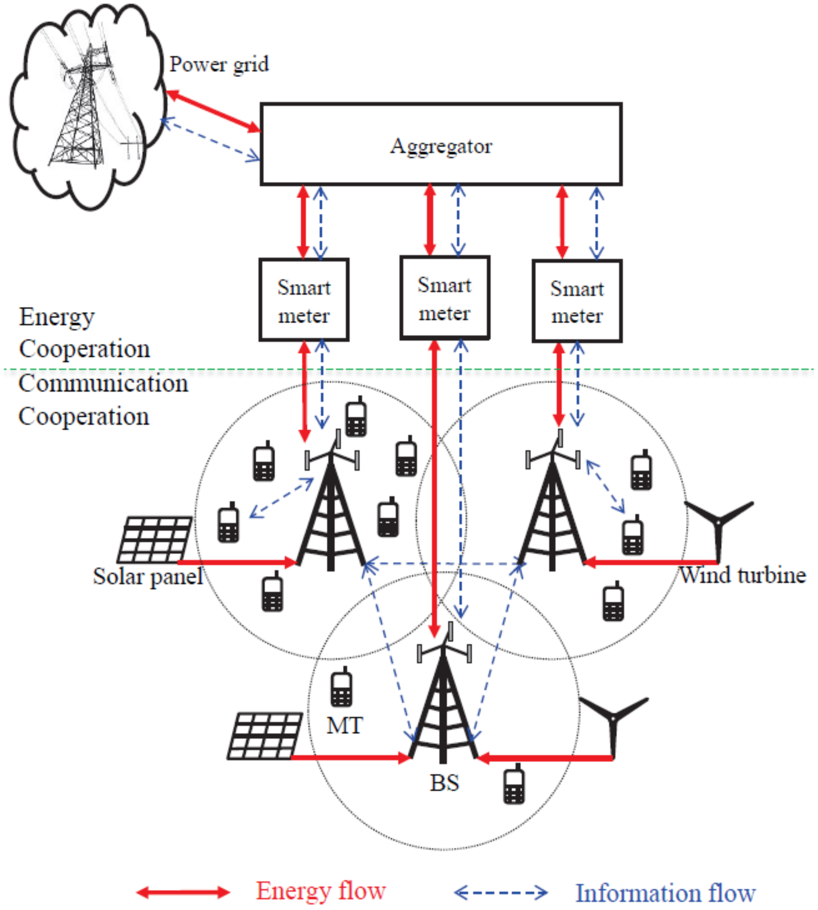
- Renewable energy deficit BS $i$ with $\delta_i > 0$
  - Purchase $\delta_i$ unit of energy from the grid
- Renewable energy adequate BS $j$ with $\delta_j < 0$
  - Waste $-\delta_j$ unit of renewable energy (if not selling back to the grid or stored for future use)
- Total energy cost of the $N$ BSs:

$$\boxed{C_1 = \pi \, \Delta_+}$$

  - Total energy purchased from the grid: $\Delta_+ \triangleq \sum_{i=1}^{N} [\delta_i]^+$ with $[x]^+ = \max(x, 0)$
  - Price for BSs to purchase one unit of energy from the grid: $\pi$
- Inefficient renewable energy utilization:
  - In total $\Delta_- \triangleq -\sum_{j=1}^{N} \left[\delta_j\right]^- \geq 0$ unit of energy wasted, where $[x]^- = \min(x, 0)$

# Energy Cost Saving for Cellular Networks by Energy and/or Communication Cooperation

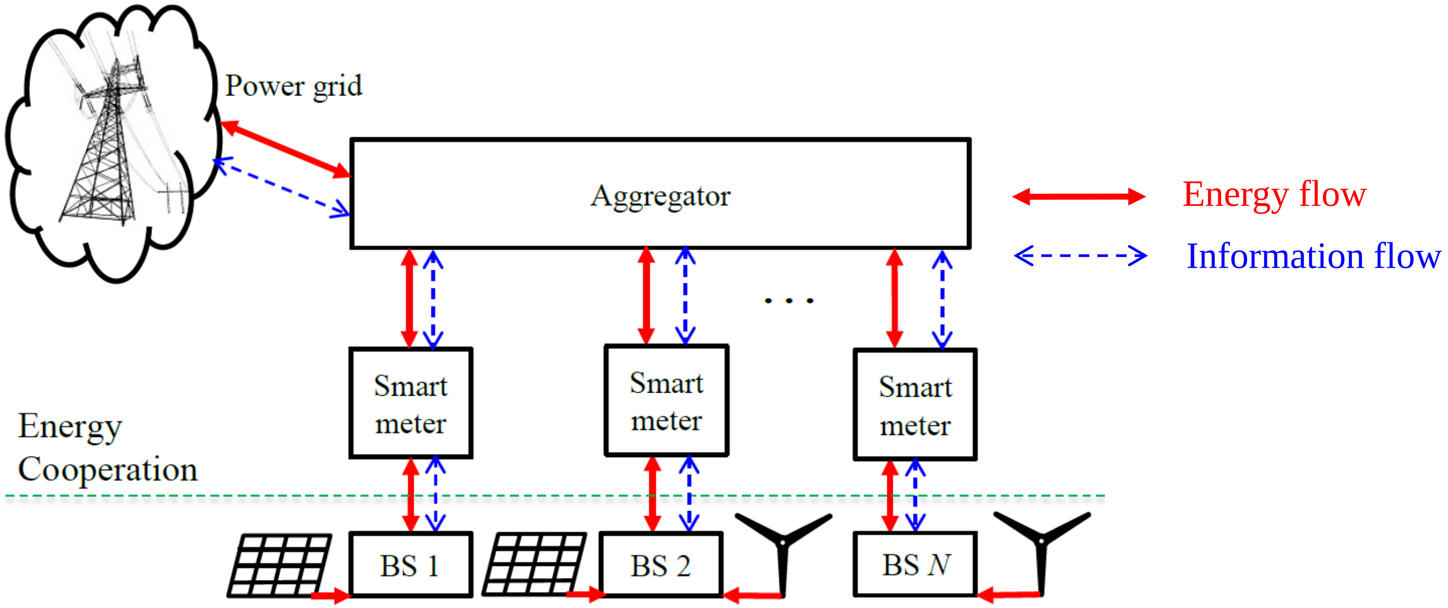
- **Approach I:** Energy Cooperation on Supply Side
  - BSs exploit two-way energy flow in smart grid to share their renewable energy supply $E_i$'s to match the wireless traffic loads
- **Approach II:** Communication Cooperation on Demand Side
  - BSs share wireless resources and reshape wireless loads $Q_i$'s to match their renewable energy supplies
- **Approach III:** Joint Energy and Communication Cooperation on Both Supply an Demand Sides



# Agenda

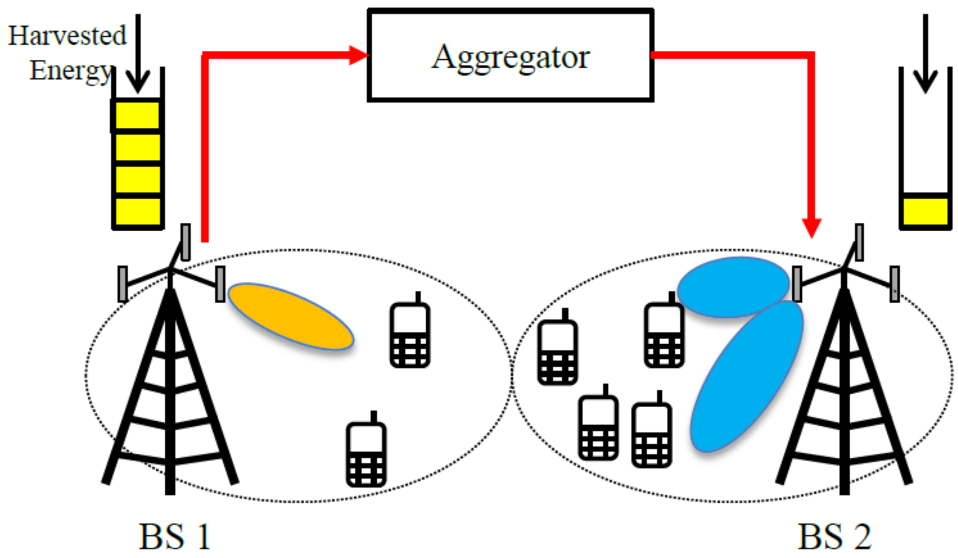
- ❑ Approach I: Energy Cooperation on Supply Side
- ❑ Approach II: Communication Cooperation on Demand Side
- ❑ Approach III: Joint Energy and Communication Cooperation on Both Supply and Demand Sides
- ❑ Conclusion and Future Work Direction

# Energy Cooperation Among BSs




- Exploiting the two-way energy flow between cellular BSs and smart grid
  - To better utilize the otherwise wasted renewable energy surplus ( $\Delta\_$ ) at BSs
- Practical implementation
  - Aggregator serves as an intermediary party to control a group of BSs for energy sharing via the grid
  - Smart meters enable the two-way energy and information flows between the grid and BSs

# Energy Cooperation Based on Different Energy Harvesting Rates




BS 1 injects excessive harvested energy to Aggregator, and BS 2 draws extra energy from Aggregator, to reduce the total energy cost

- Two schemes
  - Aggregator-assisted energy trading with BSs
  - Aggregator-assisted energy sharing among BSs

# Aggregator-Assisted Energy Trading with BSs

- The aggregator trades energy with BSs at different selling and buying prices
  - $\pi_{\text{buy}} > 0$ and $\pi_{\text{sell}} > 0$ denote the unit energy prices for the BSs to buy and sell energy from/to the aggregator
  - $\pi_{\text{sell}} < \pi_{\text{buy}} < \pi$ : both prices are cheaper than the grid energy price so that the BSs and aggregator both benefit from the trading
- Energy trading at the BSs
  - The BSs with adequate renewable energy will sell their total $\Delta_-$ unit of surplus energy to the aggregator at the price $\pi_{\text{sell}}$
  - The BSs short of renewable energy will first purchase $\min(\Delta_+, \Delta_-)$ unit of energy from the aggregator at the price $\pi_{\text{buy}}$, (if not enough) then will buy $\Delta_+ - \min(\Delta_+, \Delta_-)$ additional energy from the grid at the price $\pi$
- Total energy cost of the $N$ BSs:

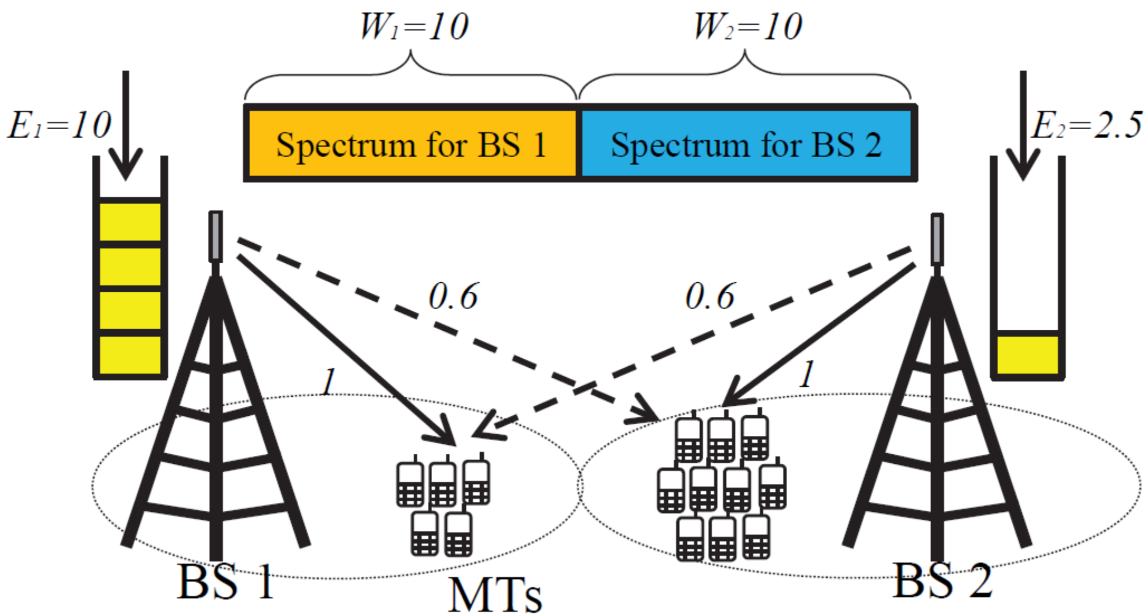
$$C_2 = \begin{cases} \pi_{\text{buy}}\Delta_+ - \pi_{\text{sell}}\Delta_-, & \text{if } \Delta_+ \le \Delta_- \\ \pi_{\text{buy}}\Delta_- - \pi_{\text{sell}}\Delta_- + \pi(\Delta_+ - \Delta_-), & \text{if } \Delta_+ > \Delta_- \end{cases}$$

# Aggregator-Assisted Energy Sharing Among BSs

- The BSs mutually negotiate and share renewable energy by simultaneously injecting or drawing energy to/from the aggregator
  - The group of BSs should sign a contract with the aggregator by paying a contract fee $\bar{C}$
- Energy sharing among the BSs
  - When $\Delta_+ \leq \Delta_-$ , the $N$ BSs can maintain their operation without purchasing any energy from the grid; otherwise, a total $\Delta_+ - \Delta_-$ amount of energy should be purchased from the grid at the price $\pi$
- Total energy cost of the $N$ BSs:

$$C_3 = \begin{cases} \bar{C}, & \text{if } \Delta_+ \leq \Delta_- \\ \pi\left(\Delta_+ - \Delta_-\right) + \bar{C}, & \text{if } \Delta_+ > \Delta_- \end{cases}$$

# A Case Study [8]




- Schemes for comparison
  - Conventional design without energy or communication cooperation
  - Approach I: energy cooperation via aggregator-assisted energy trading (without communication cooperation)
  - Approach I: energy cooperation via aggregator-assisted energy sharing (without communication cooperation)
- Parameters
  - Energy prices: $\pi = 1, \pi_{buy} = 0.5, \pi_{sell} = 0.4$; contract fee for the aggregator: $\bar{C} = 0.1$

# Performance Comparison

| | BS 1's renewable energy supply | BS 2 's renewable energy supply | BS 1's energy consumption | BS 2's energy consumption | Total energy cost |
|---|---|---|---|---|---|
| Conventional design without energy or communication cooperation | 10 | 2.5 | 4.14 | 18.28 | **15.78** |
| Approach I: energy cooperation via aggregator-assisted energy trading | 4.14 | 8.36 | 4.14 | 18.28 | **10.51** |
| Approach I: energy cooperation via aggregator-assisted energy sharing | 4.14 | 8.36 | 4.14 | 18.28 | **10.03** |

Renewable energy supplies are modified via energy cooperation

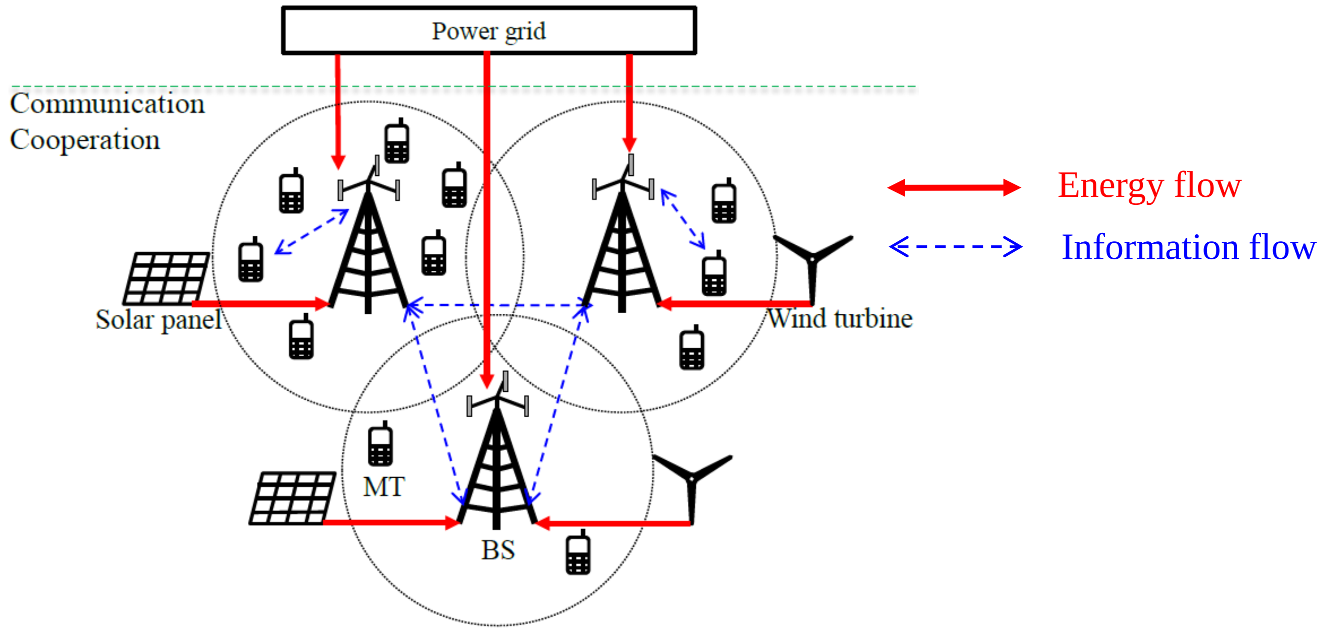
Energy demands remain unchanged

**Energy cooperation saves energy cost**

# Agenda

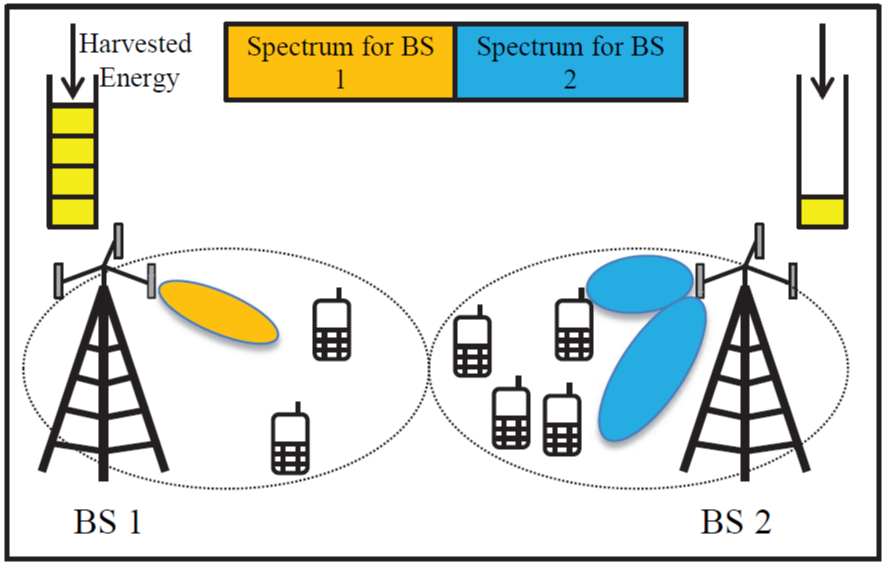
- ❑ Approach I: Energy Cooperation on Supply Side
- ❑ Approach II: Communication Cooperation on Demand Side
- ❑ Approach III: Joint Energy and Communication Cooperation on Both Supply and Demand Sides
- ❑ Conclusion and Future Work Direction

# Communication Cooperation on Demand Side




- Wireless resource sharing via communication cooperation
  - Reshape BSs' wireless load and energy consumption ( $Q_i$'s) to better match their individual renewable energy supply, thus minimizing the use of more expensive grid energy
- Practical implementation
  - Communication/energy information sharing among BSs through backhauls
  - Communication protocols need to be redesigned to be aware of "energy cost" saving

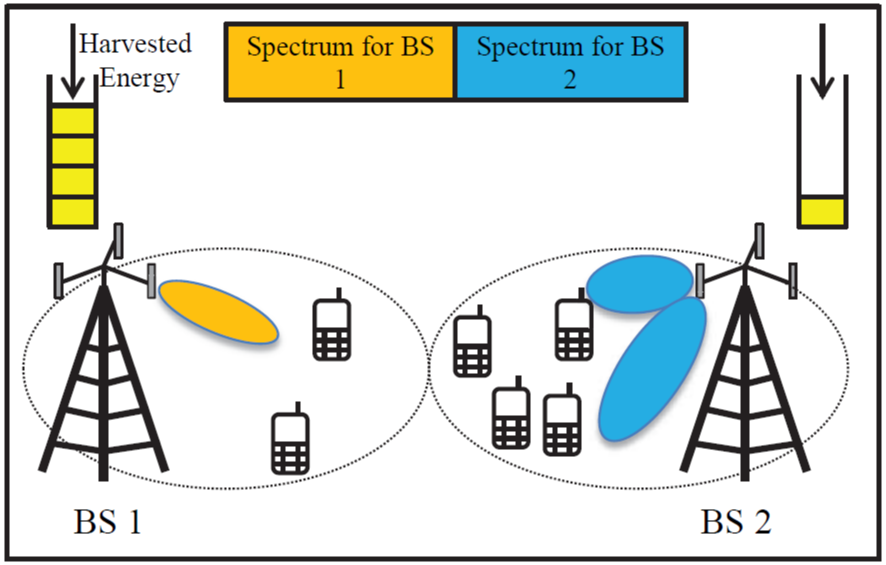
# Communication Cooperation Design with New Energy Cost Consideration



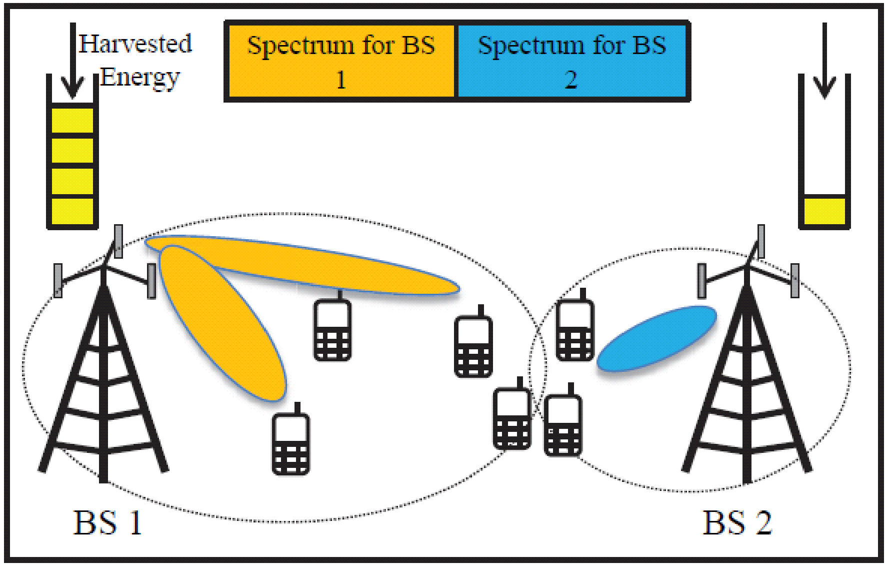

BS 1 shares wireless resource (e.g., spectrum) to BS 2, and/or BS 2 shifts wireless load to BS 1, to reduce BS 2's energy purchased from the grid.

- Three "energy cost"-aware communication cooperation schemes
  - Cost-aware traffic offloading
  - Cost-aware spectrum sharing
  - Cost-aware coordinated multi-point (CoMP) transmission
- Key difference from conventional communication cooperation
  - Need to consider the price differences of renewable and grid energy for cost minimization

# Cost-Aware Traffic Offloading



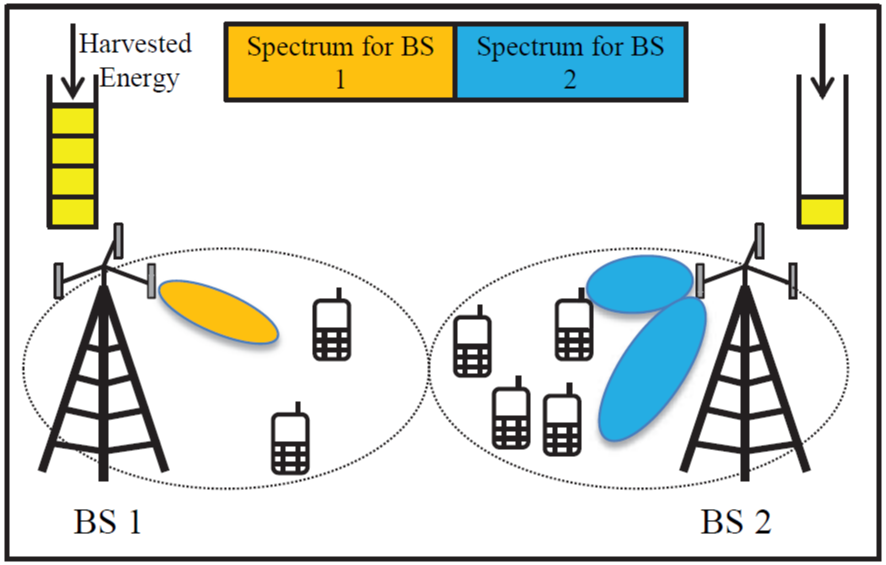

User association before traffic offloading



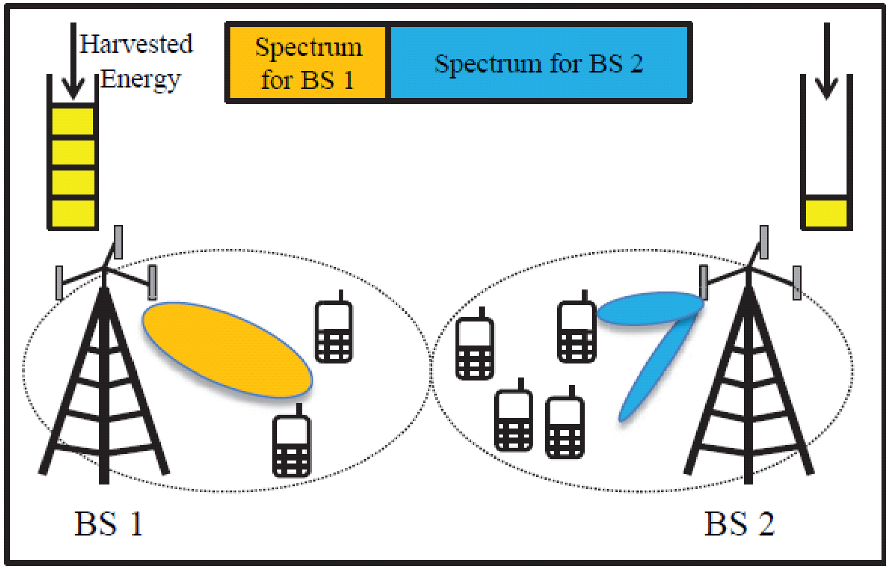

User association after traffic offloading

- Traffic offloading between BSs based on renewable energy availability
  - BSs short of renewable energy can offload their MTs to neighboring BSs with surplus renewable energy, thus reducing the energy drawn from the gird
  - Different from conventional traffic offloading, which shifts the traffic of heavily loaded BSs to more lightly loaded BSs for load balancing

# Cost-Aware Spectrum Sharing



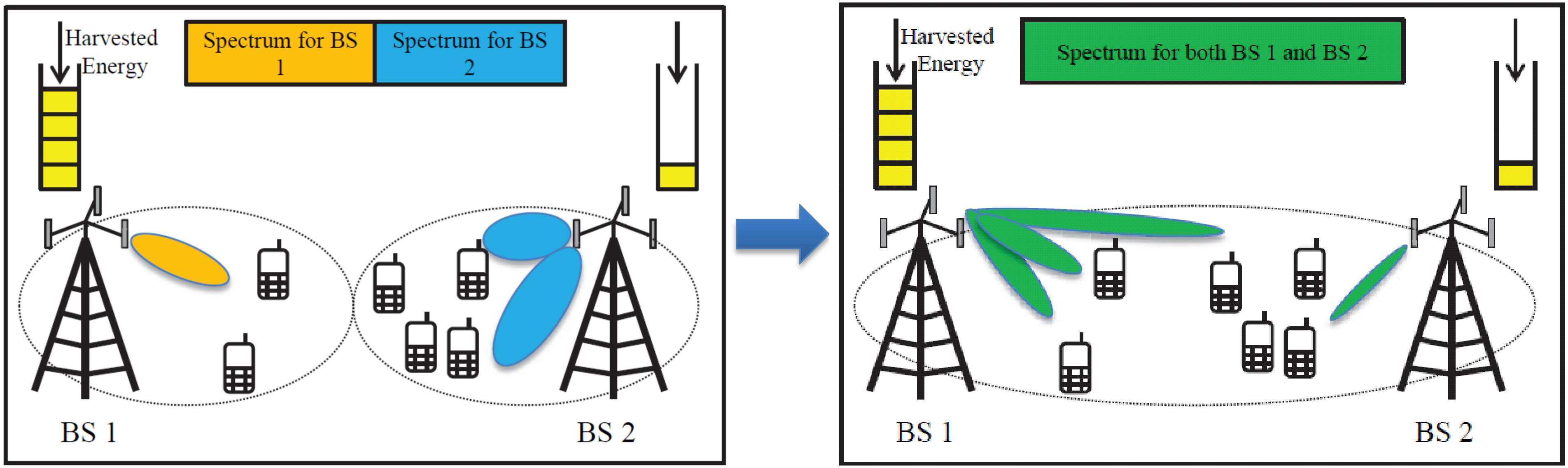
Bandwidth allocation before spectrum sharing



Bandwidth allocation after spectrum sharing

- Spectrum sharing between BSs based on renewable energy availability
  - Energy and spectrum can partially substitute each other to support the same wireless transmission QoS, thus sharing spectrum to a BS short of renewable energy can help reduce its transmit power and save the energy cost
  - Different from conventional spectrum sharing, which aims to improve the spectrum utilization efficiency

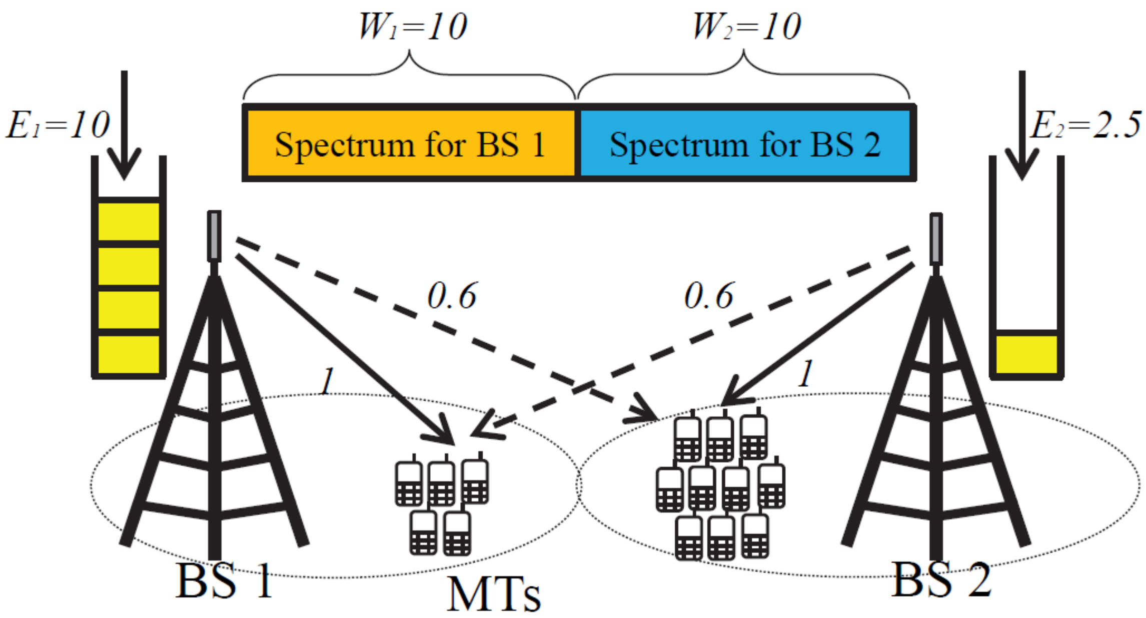
# Cost-Aware CoMP




Downlink transmission without CoMP    Downlink transmission with CoMP

- CoMP downlink transmission based on BSs' renewable energy availability
  - BSs adjust transmit power to match individually harvested energy, thus minimizing the total energy drawn from the grid while meeting MTs' QoS
  - Different from conventional CoMP, which aims to maximize the spectrum efficiency subject to BSs' given transmit power
- Need to implement at baseband signal level and require instantaneous channel state information (CSI) at BSs

# A Case Study [8]




- Schemes for comparison
  - Conventional design without energy or communication cooperation
  - Approach II: communication cooperation via spectrum sharing (without energy cooperation)
  - Approach II: communication cooperation via CoMP (without energy cooperation)

# Performance Comparison

| | BS 1's renewable energy supply | BS 2 's renewable energy supply | BS 1's energy consumption | BS 2's energy consumption | Total energy cost |
|---|---|---|---|---|---|
| Conventional design without energy or communication cooperation | 10 | 2.5 | 4.14 | 18.28 | **15.78** |
| Approach II: communication cooperation via spectrum sharing | 10 | 2.5 | 10.00 | 14.04 | **11.54** |
| Approach II: communication cooperation via CoMP | 10 | 2.5 | 10.00 | 3.75 | **1.25** |

Renewable energy supplies remain unchanged

Energy demands are rescheduled via communication cooperation

**Communication cooperation saves energy cost**

# Agenda

- ❑ Approach I: Energy Cooperation on Supply Side
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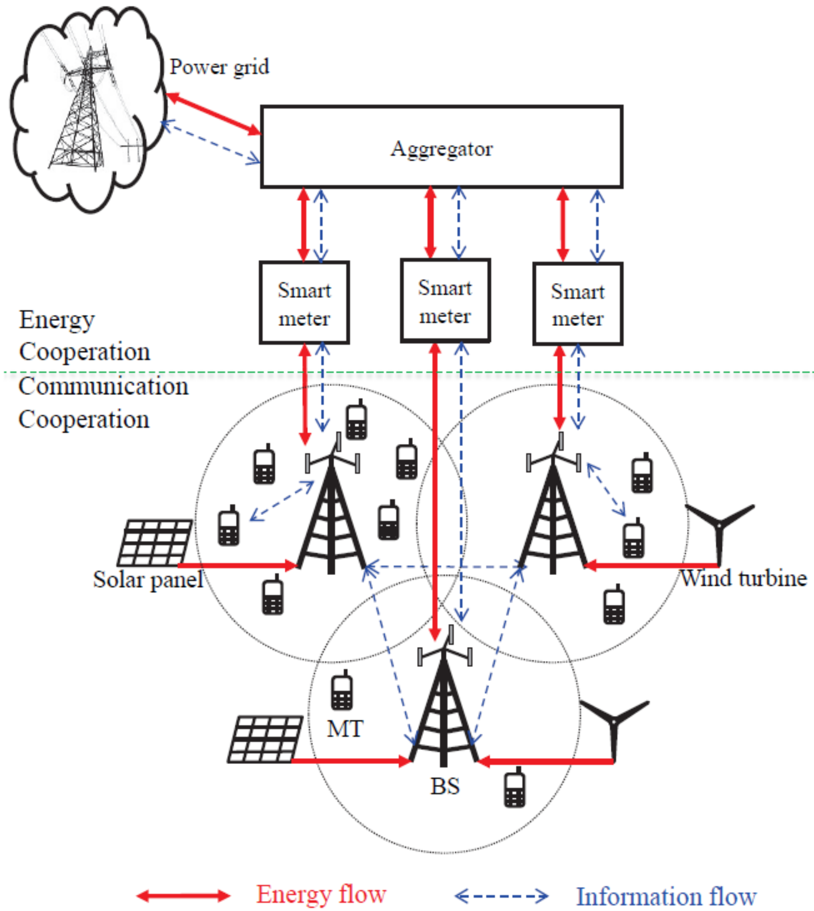
# Joint Energy and Communication Cooperation on Both Supply and Demand Sides

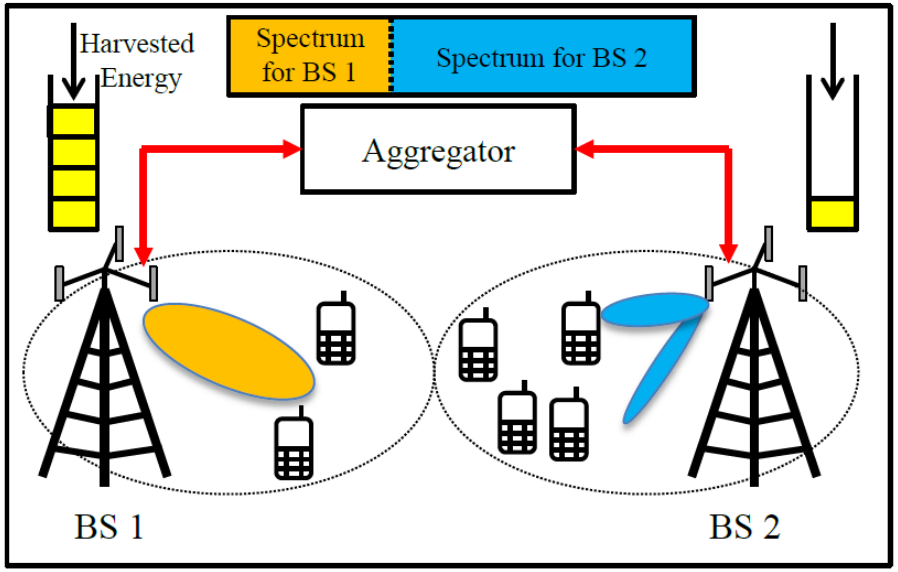
- Two schemes considered for energy cooperation on supply side
  - Aggregator-assisted energy trading with BSs
  - Aggregator-assisted energy sharing among BSs
- Three schemes considered for communication cooperation on demand side
  - Cost-aware traffic offloading
  - Cost-aware spectrum sharing
  - Cost-aware CoMP transmission
- Many combined solutions for joint energy and communication cooperation on both supply and demand sides with different complexity-performance trade-offs

# Joint Energy and Communication Cooperation on Both Supply and Demand Sides

- Practical implementation
  - Communication information sharing among BSs through backhauls
  - Energy information sharing among BSs through smart meters
- Three specific schemes to be considered
  - Joint energy and spectrum sharing [9]
  - Joint energy trading and CoMP [10]
  - Joint energy sharing and CoMP [11]

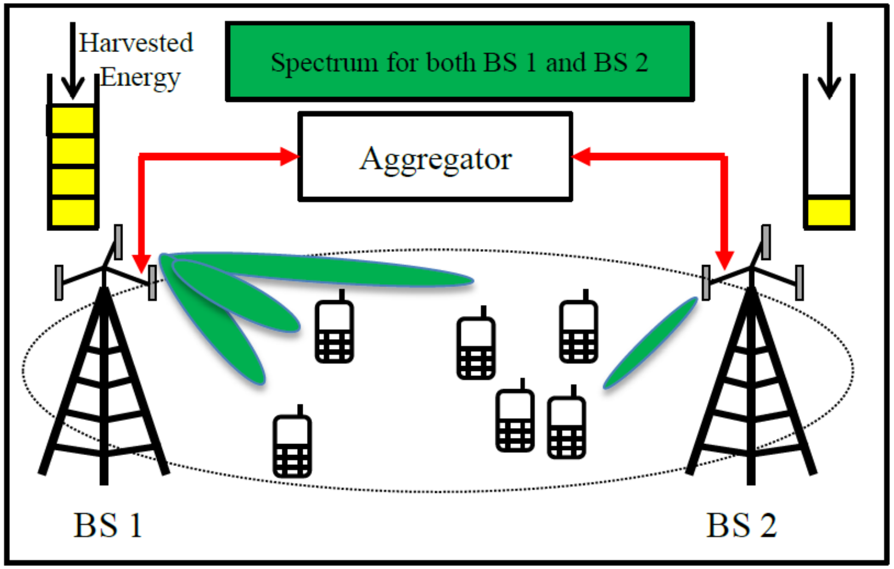


# Joint Energy and Spectrum Sharing



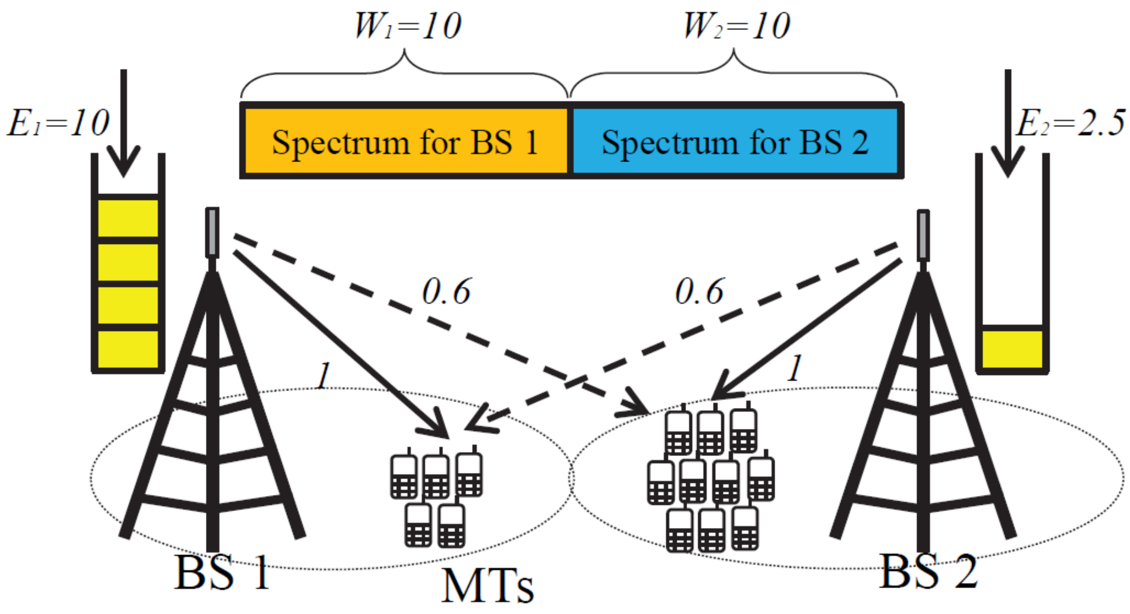

- Aggregator-assisted energy trading with BSs on supply side and communication spectrum sharing on demand side
  - BSs exchange energy and spectrum to take advantage of the resource complementarity
- Two scenarios
  - Unidirectional sharing: one BS adequate in energy and spectrum shares both resources to the other
  - Bidirectional sharing: one BS exchanges its energy for spectrum with the other

# Joint Energy Trading/Sharing and CoMP




- ❑ Aggregator-assisted energy trading/sharing with BSs on supply side and CoMP transmission on demand side
  - ➢ BSs jointly optimize the energy trading/sharing via the aggregator and their CoMP based cooperative transmission to minimize the total energy cost

# A Case Study [8]




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

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| Approach II: communication cooperation via spectrum sharing | 10 | 2.5 | 10.00 | 14.04 | **11.54** |
| Approach II: communication cooperation via CoMP | 10 | 2.5 | 10.00 | 3.75 | **1.25** |
| Approach III: joint energy and spectrum sharing | 5.00 | 7.50 | 5.00 | 15.00 | **7.60** |
| Approach III: joint aggregator-assisted energy trading and CoMP | 6.87 | 5.62 | 6.87 | 5.77 | **0.46** |
| Approach III: joint aggregator-assisted energy sharing and CoMP | 5.47 | 7.03 | 5.47 | 7.03 | **0.10** |

Renewable energy supplies are modified via energy cooperation

Energy demands are rescheduled via communication cooperation

**Joint energy trading/sharing and CoMP save the most energy cost**

# Agenda

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# Conclusion

- Cellular Networks with Energy Harvesting and Smart Grid Powered BSs
  - Challenges and opportunities
    - ✓ Unevenly distributed energy harvesting rates over both time and space
    - ✓ Cost differences between harvested energy versus smart grid power
    - ✓ Time-varying buying/selling energy prices for the smart grid power
    - ✓ Time- and space-varying traffic loads and energy demands
  - Energy and/or communication cooperation
    - ✓ Energy cooperation on supply side: BSs exploit two-way energy flow in smart grid to share their renewable energy to match the given wireless traffic load
    - ✓ Communication cooperation on demand side: BSs share wireless resources and reshape wireless loads to match the given renewable energy supplies
    - ✓ Joint energy and communication cooperation on both supply and demand sides: BSs jointly optimize the energy and communication cooperation to exploit both benefits

# Future Work Direction

- Multi-time-scale implementation of joint energy and communication cooperation under practical constraints
  - Energy harvesting rates in general change slowly as compared to wireless channel and traffic load variations [13]
- 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 [9]
- 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
  - Exploit both time and space energy diversity [12]

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[13] H. Li, J. Xu, R. Zhang, and S. Cui, "A general utility optimization framework for energy harvesting based wireless communications," submitted to *IEEE Communications Magazine.*