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

Introduction

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Energy Harvesting Wireless Communication: A Brief Overview

- 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:**
  \[
  C_1 = \pi \Delta_+ \\
  \Delta_+ \square \sum_{i=1}^{N} [\delta_i]^+ \text{ with } [x]^+ = \max(x, 0)
  \]
  - Total energy purchased from the grid:
  - Price for BSs to purchase one unit of energy from the grid: \( \pi \)

- **Inefficient renewable energy utilization:**
  - In total \( \Delta_- \square -\sum_{j=1}^{N} [\delta_j]^- \geq 0 \) 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 and 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
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:
  
  $$
  C_2 = \begin{cases} 
  \pi_{\text{buy}}\Delta_+ - \pi_{\text{sell}}\Delta_-, & \text{if } \Delta_+ \leq \Delta_- \\
  \pi_{\text{buy}}\Delta_- - \pi_{\text{sell}}\Delta_+ + \pi(\Delta_+ - \Delta_-), & \text{if } \Delta_+ > \Delta_- 
  \end{cases}
  $$
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:
  $$C_3 = \begin{cases} 
  \bar{C}, & \text{if } \Delta_+ \leq \Delta_- \\
  \pi(\Delta_+ - \Delta_-) + \bar{C}, & \text{if } \Delta_+ > \Delta_- 
  \end{cases}$$
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: $\tilde{C} = 0.1$
## Performance Comparison

<table>
<thead>
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<th>BS 1’s renewable energy supply</th>
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- 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
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
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

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.
Cost-Aware 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 grid
  - Different from conventional traffic offloading, which shifts the traffic of heavily loaded BSs to more lightly loaded BSs for load balancing

User association **before** traffic offloading

User association **after** traffic offloading
Cost-Aware 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

Approach II: Communication Cooperation on Demand Side

Bandwidth allocation before spectrum sharing

Bandwidth allocation after spectrum sharing
Cost-Aware 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

Approach II: Communication Cooperation on Demand Side

Downlink transmission without CoMP

Downlink transmission with CoMP
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

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Renewable energy supplies remain unchanged

Energy demands are rescheduled via communication cooperation

Communication cooperation saves energy cost
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- Approach I: Energy Cooperation on Supply Side

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- Approach III: Joint Energy and Communication Cooperation on Both Supply and Demand Sides

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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
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

A Case Study [8]
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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]
References