Stochastic analysis of energy savings in cellular networks

(GreenTouch project)

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17/12/2012
Outline

- Introduction
  - BCG\textsuperscript{2} project (Beyond Cellular Green Generation)
  - GTT project (Green Transmission Technologies)

- Publications
  - Stochastic Analysis of Energy Savings with Sleep Mode in OFDMA Wireless Networks (accepted at INFOCOM’13)
  - Spectral and Energy Efficiency Trade-Off with Joint Power-Bandwidth Allocation in Wireless Networks (to be submitted)

- Ongoing work
  - Distributed optimization of energy efficiency by local decisions - Markov Random Field (MRF)
  - Virtual cells (main topic for 2\textsuperscript{nd} year)
BCG² main idea

• Traditional cellular architecture

• Limitations
  • Continuous and full coverage for data access
  • Limited flexibility for energy management
  • High energy consumption also at low traffic load
Full coverage limitation
• Separation of signaling and data functions:
  • Full Coverage and always available connectivity ensured by signaling base stations only
  • Data access capacity provided by data base stations on demand
  • Adaptive network capacity and high energy efficiency
BCG\(^2\) gains

- From base station power consumption profile to network profile
GTT project

• Motivation

The objective of GTT project is to answer the question of what EE we can achieve in the best case given the fundamental tradeoffs and to find the step by step ways towards that goal with the design insights obtained from analyzing the tradeoffs relations.
GTT objectives

- SE - EE trade-off
- Study scenarios: Single cell / Multi-cell -> HetNet

**Insight from Shannon**
- Larger bandwidth $\rightarrow$ Lower transmit power (for same rate)

**Approaches**
- Bandwidth expansion
- Advanced technologies to better use bandwidth
1. **Stochastic Analysis of Energy Savings with Sleep Mode in OFDMA Wireless Networks** (BCG²)

**Facts**
- Explosion of data traffic and need for growing network infrastructure leads to increased energy consumption
- ICT industry currently responsible for almost the 2~2.5% of global CO²
- Almost 80% of the energy consumed by BSs in cellular networks
- Current networks optimized for capacity

**Challenges**
- Allow the BSs to enter a low-power sleep mode by monitoring the traffic demands
- Impact on other performance indicators, especially related to coverage issues
Contribution

- Theoretical framework in order to evaluate the potential EE gains with sleep mode

- Reference scenario for BCG²: no separate signaling BS layer to handle possible coverage holes when some BSs are switched off

- Impact on other performance indicators?

- Number of active cells is reduced in a way that:
  - Outage probability remains the same in the area of study
  - Network energy efficiency is maximized
Stochastic Model

- BSs distributed as a Poisson point process
- Very popular among other stochastic models due to its well known properties
- Comparison to an actual network
  - Tractable expressions of outage probability / SINR for a randomly located user
  - Natural inclusion of various cell shapes and sizes
  - Lack of edge effects (network extends indefinitely)
  - In some cases BSs are located close to each other (repulsion models available)
- Average behavior, expected over a given area and over all possible cell topologies
• Mathematical model
  • BSs distributed as a 2D homogeneous PPP with density $\lambda$
  • Outage probability: $P\left(SINR \leq t\right)$
  • SINR expression
    • $p$ Tx power
    • $h$ fading
    • pathloss model
    • $r$ distance between user and BS
    • $N$ noise power
    • $b$ serving BS
    • $i$ interfering BS

$$SINR_u = \frac{p_b h_b l(r_b)}{N + \sum_{i \neq b} p_i h_i l(r_i)}$$
Subject to PPP stochastic nature

• The Poisson point process allows an analytical calculation of the outage probability
Outage probability

• Assumptions
  • Mobile users served by their nearest active base station
  • Power law pathloss model: \( l(r) = (kr)^{-a} \)
  • Rayleigh fading with \( E[h] = 1/\tau \)

• Theoretical analysis
  • Distance to the closest point of a PPP
    \[
    P\left[r_b \leq x\right] = 1 - \exp\left(-\pi \lambda x^2\right)
    \]
  • Final expression
    \[
    P\left[SINR \leq t\right] = 1 - 2\pi \lambda \int_0^\infty P\left[h > \frac{t(N+I)}{p_b(r_b)}\right] \exp\left(-\pi \lambda r_b^2\right) r_b \, dr_b
    \]
    \[
    = 1 - \pi \int_0^\infty \exp\left\{-\frac{\tau tNk^a}{p} \left(\frac{x}{\lambda}\right)^{a/2} - \pi x \left(1 + \int_1^\infty \frac{t}{t + z^{a/2}} \, dz\right)\right\} \, dx
    \]
    \[\text{SNR term} \quad \text{SIR term} \]
Sleep mode

- PPP thinning property
  - A BS is kept active with probability $\beta$ or
  - $\beta$ BSs are in active mode and $1-\beta$ in sleep mode
  - New PPP with density $\lambda\beta$

- Outage probability
  \[
P\left(\text{SINR} \leq t \mid \lambda\beta\right) = 1 - \pi \int_0^\infty \exp\left\{-\frac{\tau t N k^a}{p} \left(\frac{x}{\lambda\beta}\right)^{a/2} - \pi x \left(1 + \int_1^\infty \frac{t}{t + z^{a/2}} \, dz\right)\right\} \, dx
  \]

- In order to keep the outage probability unchanged
  \[
p_{\text{new}} = p \cdot \frac{1}{\beta^{a/2}}
  \]

- The same analysis for other models (pathloss, fading) is possible, even if the above simplified formula for $p_{\text{new}}$ is not in close-form anymore
Energy savings

- **Linear BS power consumption model:**
  \[ P_{tot} = \begin{cases} 
  P_0 + \gamma \cdot P_{out}, & P_{out} \leq P_{out}^{\text{Max}} \quad \text{Active mode} \\
  P_{\text{Sleep}} & \text{Sleep mode} 
  \end{cases} \]

- **Achieved EE gains**
  - **EE Metric:** Area power consumption (W/m²)
    \[
    G @ \frac{EE_{\text{Initial}}}{EE_{\text{Sleep}}} = \frac{\lambda (P_0 + \gamma P_{out})}{\lambda \beta \left[ P_0 + \gamma P_{out} \beta^{-a/2} \right] + \lambda (1 - \beta) P_{\text{Sleep}}} 
    \]

- **Optimization problem**
  \[
  \text{find } \beta_{opt} = \arg \max_{\beta} (G) \\
  \text{s.t. i. } P_{out} \leq \beta_{opt}^{a/2} P_{out}^{\text{Max}} \\
  \text{ii. } 0 \leq \beta_{opt} \leq 1 
  \]
Numerical results

- Parametric studies for different values of the BS power model

- Non-monotonic shape
  - EE gain from less active BSs
  - Increased Tx power from remaining ones

- Curves for different pathloss exponent
  - First find optimal $\beta$
  - Then evaluate achieved EE gains
2. Spectral and Energy Efficiency Trade-Off with Joint Power-Bandwidth Allocation in Wireless Networks (GTT)

- **Facts**
  - EE - SE usually inter-related and conflicting
  - Limited work in the literature for multi-cell scenario

- **Contributions**
  - **Single cell scenario**
    - Optimal BW-PW allocation
    - Special case for low SNR regime approximation
  - **Multi-cell scenario**
    - Extension based on the previous model of stochastic geometry
    - Evaluation of performance shifts with some interference reduction techniques

![Graph showing EE vs SE]
Single cell

- Optimization problem
  - Given the traffic demand $T_u$ and pathloss $l_u$ for each user $u$
  - Allocate power & bandwidth $(w_u, p_u)$
  - In order to maximize $EE$:
    \[
    \max_{(w_u, p_u)} EE = \frac{\sum_u T_u P[C_u \geq T_u]}{\sum_u p_u}
    \]
    
    st. 1. $\sum_u p_u \leq P_{tot}$
    2. $\sum_u w_u \leq W_{tot}$

- Solution by introducing Lagrange function
  - Lagrange multiplier $\lambda$ found numerically with bisection method in a well defined interval
  - $(w_u, p_u)$ then given by straightforward equations
Findings

- For the set of users experiencing the same pathloss:
  - BW proportional to traffic \( \frac{w_u}{T_u} = \frac{\ln 2}{1 + W_0 \left( \frac{1}{e} \left( \frac{\lambda u}{N_0} - 1 \right) \right)} \)
  - Same power spectral density \( \frac{p_u}{w_u} = \frac{N_0}{I_u} \exp \left\{ W_0 \left( \frac{1}{e} \left( \frac{\lambda u}{N_0} - 1 \right) \right) \right\} \)

- Insight: Users can be grouped by class of pathloss

- Analytical approach:
  - Group users by class of pathloss
  - Find the optimal allocation \( (W_k, P_k) \) for each class \( k \)
  - For the per user allocation in a class \( k \), we find that:
    \[
    w_u = T_u \frac{W_k}{T_k}, \quad p_u = w_u \frac{P_k}{W_k}, \text{ where } T_k = \sum_u T_u
    \]

- EE upper bound for low SNR linear approximation
  \[
  C_u = w_u \log_2 \left( 1 + SNR_u \right) \approx \frac{1}{\ln 2} w_u SNR_u \quad \implies \quad EE = \frac{T_{tot}}{N_0 \ln 2 \sum_u \frac{T_u}{I_u}}
  \]
Multi-cell

- Previous stochastic model for BS location - PPP

- Initial approach
  - Allocation of resources to one randomly selected BS
  - Other BSs at full load
  - No interference coordination

- Example of SINR curves
  - Best curve for an intermediate value of $\alpha$
    - Opposing behavior of SIR/SNR wrt to $\alpha$
    - High $\alpha$: worse received signal
    - Low $\alpha$: higher received interference
Numerical results

• Single cell
  • Higher EE for smaller cells and lower $a$
  • SE-EE no longer monotonically related if circuit power proportional to BW is introduced
  • SE-EE tradeoff curves converge fast w.r.t. the number of user groups

• Multi-cell
  • Interference strongly degrades EE
  • Higher EE for smaller cells and intermediate $a$
  • Beamforming is very efficient in terms of EE
  • By only applying frequency reuse, EE is not increased
Ongoing work

1. Distributed optimization of energy efficiency ($BCG^2$)

- **Scenario**
  - Dense cellular networks
  - Arbitrary deployments
  - Distributed auto-configuration

- **Objective**
  - Throughput, fairness
  - Energy minimization by introducing sleep mode

- **Approach**
  - Markov Random Field
  - Heuristic Algorithms (Gibbs, SA,...)
Synopsis

• Topology
  • Undirected graph, set of nodes
  • Nodes $u \in U$, (BSs, users, ...)
  • State of node $s_u$: decision variable out of finite set
    (channel, Ptx, users association, precoding matrix, ...)
  • Edges between nodes
    • Reflect local interaction
    • Neighborhood $N_u$
  • Clique $\mu$, complete sub-graph where all nodes are neighbors
General description

- **Objective**
  - Define nodes and edges
  - Define clique’s potential function $V_\mu(s_u), u \in \mu$ so that the total cost function (energy) is additive over cliques’ potentials: $\epsilon = \sum_\mu V_\mu$

- **Result**
  - Local energy of $u$ depends only on the state of the neighbors $\epsilon_u = \sum_{\mu: u \in \mu} V_\mu$

- **Algorithm**
  - **Gibbs sampling**
    - $\forall u \in U$, evaluate $\epsilon_u$ for all possible states $s_u$ and select one randomly, according to a probability distribution that favors states with low local energy
    $$P(X_u = s_u) \propto \exp(-\epsilon_u)$$
  - **Simulated Annealing**
    - $\forall u \in U$, select a state $s_u$ randomly. If it leads to lower $\epsilon_u$, always accept it, otherwise accept it with a probability that reduces over iterations in order to initially escape from local optimum and then converge
Formulation

- Nodes of the graph are the users
- Node state: DL Tx power and user association binary variable \( q_{u,b} = \begin{cases} 1, & \text{if } b = b_u \\ 0, & \text{else} \end{cases} \)
- A BS without users is set to sleep mode
- Cost function to be minimized:
  \[
  \varepsilon = \sum_u \frac{1}{SINR_u} + \lambda_1 \left( \sum_b \left[ 1\left( \sum_u q_{u,b} > 0 \right) P_{0,b} \right] + \gamma \sum_u P_{tx,u} \right)
  \]
- According to the found local energy, for the second term, a user prefers:
  - BSs of many users
  - Especially BSs with small power \( P_0 \)
- A user needs to know limited information from every BS \( b \) that can serve him:
  - The current number of active users in that BS
  - The power consumption \( P_0 \) of the BS
Scenario

- Macro BSs and randomly deployed smaller BSs
- Daily traffic profile
- Comparison with centralized optimization
Ongoing work

2. Virtual cells ($BCG^2$)

- Scenario
  - Dense cellular networks
  - Low activity (night traffic)

- Idea
  - A virtual cell is centered on the user
  - The cell Id follows the mobile, so that a user seamlessly moves through the network

- Advantages
  - Allows to manage ON/OFF states of BSs
  - Allows to reduce signaling and handover traffic
Scenario 1: One user

- Several BSs, one moving user
- Virtual cell: the set of BSs in user’s range
- ‘virtual cell’ algorithm
  - 1) Initial state: a BS b is active and manages the mobile m, with a broadcasted cell Id #i
  - 2) MU moves, sends its data and signaling information
  - 3) Network selects the active BSs among those in ON state
  - 4) The selected BS sends the broadcast cell id #i, thus takes the identity of the cell serving the mobile, and transmit data.
  - 5) Network decides to switch on/off some BSs in the virtual cell (possible delay & E. cost)
  - 6) Switch back to step 2.

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Extensions

- **Proposed exploration:**
  - Consider a delay for switching BSs ON/OFF (Activ. is possible only if BS is ON)
  - Add an energy cost for switching BSs ON/OFF (to enforce stable solutions)
  - Consider uncertainties in path loss and shadowing
  - Adapt to different traffic models such as burst traffic or continuous traffic

- **Additional features**
  - Use of COMP (multi-BSs transmission) to reduce radiated energy.
  - Distributed algorithm : X2 Links may allow BSs to switch on/off their neighbors.
  - Comparison with centralized processing and distributed antennas
Scenario 2 : more users

• Objective:
  - How can the network manage for example two mobiles in the same vicinity?

• Two approaches:
  - Orthogonal approach : the BSs aim at building orthogonal cells
  - Collapse approach : the BSs build a unique common cell with ‘classical’ resource sharing
Questions?

Thank you!