The Value of BS Flexibility for QoS-Aware Sleep Modes in Cellular Access Networks

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What is the value of sleep modes for mobile network operators?

• SM essential for achieving network energy proportionality
  – theoretical savings of up to 40-60%

• Practical issues:
  – Legacy BS: slow dynamics
  – SM shorten their average lifetime
  – Flexible BS: Switching up speed vs standby energy tradeoff erodes gains
  – Uncertainty in traffic demand forecast

• What is the optimal ratio of BS which should be replaced with flexible BS?
System Model

Users, BS ~ Homogeneous PPP
- Density is a function of time
- Forecasted user density: Gaussian, with known mean

Time is divided into **periods** and **slots** (within a period)

Two types of base stations:
- **Static**: They can only be on or off;
- **Flexible**: They also access a low power standby state.

A BS can transition from/to the off state only at the beginning of each period (**slow sleep modes**)
The transition from (to) the standby state can happen at the beginning of each slot (**fast sleep modes**)

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**Period**: No off->on transitions

**Slots**: Flexible BSs can sleep/wake up
A method for the derivation of the energy optimal BS density

- QoS parameter: expected per-bit delay

\[
\bar{\tau}(\lambda_b, \lambda_u) = \int_0^\infty \left( \int_0^\infty \int_0^{2\pi} e^{-\lambda_b A(r, x, \theta)} \lambda_u x \, d\theta \, dx \right) \frac{e^{-\lambda_b \pi r^2} \lambda_b 2\pi r}{C(r)} \, dr
\]

- The energy consumed by a BS with utilization \( U \) is

\[ p_{on} + q_{on} U. \]

- The energy optimal BS density is obtained by solving

\[
\begin{align*}
\text{minimize} & \quad \lambda_b \left( p_{on} + q_{on} \frac{\bar{\tau}(\lambda_b, \lambda_u)}{\bar{\tau}_0} \right) \\
\text{subject to} & \quad \bar{\tau}(\lambda_b, \lambda_u) \leq \bar{\tau}_0
\end{align*}
\]
Derivation of the optimal coordinated sleep modes strategy

• We assume BSs are turned on/off independently
  – Sleep mode univocally identified by BS density

• **At each period**: we compute the energy optimal total density of BS satisfying the QoS constraints, with a probability $p_{th}$
  – For the peak user density, this corresponds to the max total $n$ of BS
  – All BS in excess are turned off, starting from legacy BSs.

• **In each slot**: we determine the optimal density of flexible BS, based on the value taken by user density in that slot
  – All flexible BS in excess are put into standby mode.
Numerical evaluation

- Duration of each period: 3h
  - Max consumed power: 1500 W
  - Idle power consumption: 60% of max
  - Standby power consumption: 30% of max
  - $\tau_0 = 10^{-5}$, $p_{th} = 2\%$
Flexibility allows reducing the energy costs of uncertainty in traffic forecasts.

- Uncertainty affects also the total number of active BS.
Combining slow and fast sleep modes enables the highest energy gains

- Fast sleep modes increase EE by at most 12%
Combining slow and fast sleep modes enables the highest energy gains.

- Need of an accurate evaluation of impact of slow sleep modes on capex and opex to determine the most efficient solution.
No need to speed up «slow» sleep modes

- Modest increase in energy efficiency
- Capex/Opex of networks with slow sleep modes increase with frequency of power on/off events
No need to speed up «slow» sleep modes

- Majority of BS are turned off once per day: modest impact of on off costs
Conclusions

• We provide a tool for estimating maximum achievable energy savings for a given % of flexible BS
  – Assuming a given QoS target is always met
• We estimate the cost of uncertainty in traffic predictions
• Our results enable CAPEX/OPEX analysis to determine optimal deployment strategies.
Future work

Evaluate the impact of

• different energy models

• different traffic mix, with different requirements
  – Project with predicted evolution of wireless traffic

Capex/Opex study

• (include maintenance costs, projected energy costs, renewables, etc)
Thanks!