Research on Energy Efficiency of 4G Cellular Networks with Co-channel Interference

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Outline

- Introduction
- System Model
- Spatial Distribution of Traffic Load
- Spatial Distribution of Power Consumption
- Energy Efficiency of PVT Cellular Networks
- Conclusion
- A list of deliverables
Introduction(1)

Energy efficiency issues in cellular networks (*static analysis*):
The energy consumption of Mobile operator can be as high as 10 MW

In EU:

- Over 80% of the power is consumed in RAN (at ChinaMobile)
- Base Station consumption 0.5 – 2.7 kW
- BSs consume most energy in RAN
Introduction(2)

• Energy efficiency issues in cellular networks (*dynamic*):

- Temporal and spatial variations of traffic load in cellular networks
- Lasting exponential data traffic growth for at next five years, and more complicated behaviors that are shown to be self-similar and bursty

In a dynamic cellular network, an energy efficiency model relating to traffic load variations is significant for dynamic energy-efficient BS planning, management, and operation.
Introduction(3)

• Importance of space in wireless networks, esp., energy consumption problems:
  – TX-RX distance
  – interference
  – traffic load variations in space

→ What about the impact of the spatial heterogeneity (hotspots) and randomness of traffic load towards energy efficiency in the interfering cellular networks?

<table>
<thead>
<tr>
<th>Resource Type</th>
<th>Time (division)</th>
<th>Frequency (division)</th>
<th>Space (division)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TXs &amp; RXs (spilling)</td>
<td>collocated</td>
<td>Collocated</td>
<td>not collocated</td>
</tr>
<tr>
<td>Power falloff (interference)</td>
<td>To zero at turn-off</td>
<td>&gt;=100dB/decade</td>
<td>20-40dB/decade</td>
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</tbody>
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Introduction(4)

• Summary of current research in cellular energy efficiency

Traffic-adaptive power management
– e.g.: Shutdown or sleep strategy, Macro- / micro- / femtocells overlaying, Adaptive traffic coalescing (ATC)
– neglect complex physical transmission processes, esp. under wireless channel effects and interference

Energy-efficient transmission
– e.g.: energy-efficient power control / like adaption, MIMO/SIMO transmission mode switch
– limited in the link level of cellular networks

⇒ To enable dynamic analysis, network level energy efficiency should be discussed by considering wireless channel effects, interference and traffic load characteristics.
- **Poisson-Voronoi Tessellation Cellular Networks:**
  BSs: $\prod_B = y_{Bk} : k = 0,1,2,\cdots \sim$ Poisson Point Process $\text{PPP}(\lambda_B)$,
  MSs: $\prod_M = x_{Mi} : i = 0,1,2,\cdots \sim$ $\text{PPP}(\lambda_M)$;
  An MS is served by the nearest BS in range, which would suffer the least path loss during wireless transmission.
  $\Rightarrow$ The typical cell $C_0$ (Palm theory)

- **Channel model:** the channel gain of the link between BS$_k$ and its $i$-th user is
  $$L_{ki}(r,\xi,\zeta) = P_{rx}/P_{tx} = K \cdot e^{c\sigma\xi} \cdot \zeta^2 / r^\beta$$
  where $\xi \sim \text{Gaussian}(0,1)$ and the constant $c = \ln 10 / 10$; the term $\zeta^2$ is exponentially distributed with mean 1 in Rayleigh fading environments.
System Model(2)

Fig. 1 Illustration of PVT cellular structure; real lines depict cell boundaries inside which a polygon corresponds a cell coverage; dashed lines, which are perpendicularly bisected by corresponding cell boundaries, demonstrate how to build tessellations through the “Delaunay Triangulation” method.
System Model (3)

- Problem formulation via the additive functional:
  \[ \Omega_w^{def} = \sum_{x_i \in \Pi_M} w \cdot x_i \cdot 1 \quad x_i \in C_0 \]

  where \( w x : \mathbb{R}^2 \rightarrow \mathbb{R}_+ \) is a given non-negative function (either deterministic or random), \( 1 \ldots \) is an indicator function, and \( C_0 \) is a typical cell.

- Aggregate traffic load \( \mathcal{T}_{C_0} \) in \( C_0 : w(x) = \rho(x) \) is the spatial traffic density.

- BS transmission power \( \mathcal{P}_{C_0} \) in \( C_0 : w x = \varepsilon(x, I_o, \rho) \), which is the power consumption (the “energy cost”) of a typical point-to-point fading wireless link; \( I_o \) represents other-cell interference and \( \rho \) is the traffic density.


Empirical traffic characterization and modeling results provide us a basis.

Modeling work is needed.
Spatial Distribution of Traffic Load (1)

- The **aggregate traffic load** in a typical cell $C_0$ is defined as:

\[
\mathcal{I}_{C_0}^{\text{def}} = \sum_{x_{Mi} \in \Pi_M} \rho(x_{Mi}) 1 \quad x_{Mi} \in C_0
\]

where $\rho(x)$ is the traffic intensity on each user, with PDF

\[
f_{\rho}(x) = \frac{\theta \rho_{\min}^\theta}{x^{\theta+1}}, \quad x \geq \rho_{\min} > 0
\]

and $\theta \in 1, 2$ reflects the “heaviness” of the distribution tail.

- The characteristic function of $\mathcal{I}_{C_0}$

\[
\phi_{\mathcal{I}_{C_0}}(j\omega) = \left[1 + \frac{\lambda_M}{b\lambda_B} - \frac{\lambda_M}{b\lambda_B} \theta(-j\rho_{\min}\omega)^\theta \Gamma(-\theta, -j\rho_{\min}\omega)\right]^{-\sigma}
\]

with $\Gamma(-\theta, -j\rho_{\min}\omega) = \int_{-j\rho_{\min}\omega}^{+\infty} t^{-\theta-1} e^{-t} dt$
Spatial Distribution of Traffic Load (2)

Performance analysis of traffic load model

The probability mass (which can be depicted as the area under the PDF curve) would shift to the right with the increase of $\frac{\lambda_M}{\lambda_B}$, indicating an increase in the average aggregate traffic load at BS.

Fig. 2. Aggregate traffic load in a typical PVT cell with respect to the intensity ratio of MSs and BSs.
Spatial Distribution of Traffic Load (3)

• Performance analysis of traffic load model

The minimum traffic rate and heaviness index have inverse impacts on the aggregate traffic load in a typical PVT cell.

Fig. 3 Impact of heaviness index and minimum traffic rate on the aggregate traffic load in a typical PVT cell.
Interference and power control model:
The instantaneous SIR of $MS_0$ is given by
\[
\gamma = \frac{S_0}{I_{agg}} = \frac{S_0}{\sum_{k \in I_{BS}} S_k \cdot \frac{L(r_{k0}, \xi_{k0}, \zeta_{k0})}{L(r_{kk}, \xi_{kk}, \zeta_{kk})} \cdot 1_D(L_{k0}/L_{kk})}
\]
with $1_D(L_{k0}/L_{kk}) = 1_D\{r_{kk}/r_{k0} \leq 1\}$, where $I_{agg}$ is the aggregate interference seen at $MS_0$, $I_{BS}$ is the index set of interfering BSs, and the indicator function $1_D(L_{k0}/L_{kk})$ is a constraint on MS distance distributions under the closest association rule in PVT cellular networks.

Fig. 4. Wireless downlinks of a PVT cellular network. An example of interfering BS is illustrated at $IBS_k$ with detailed channel parameters.
Spatial Distribution of Power Consumptions (2)

The required total transmission power in a typical PVT cell $C_0$ with perfect power control:

$$\mathcal{P}_{C_0\text{-req}} = \sum_{x_{Mj} \in \Pi_M} \frac{\|x_{Mj} - y_{B0}\|^2}{k} U \cdot 1 \quad x_{Mj} \in C_0$$

where $U = S_0 \cdot V$, $V = e^{-c_0 \xi}/\zeta^2$. The characteristic function of $P_i$ is:

$$\phi_{\mathcal{P}_{C_0\text{-req}}} (\omega) = \exp \left\{ -\frac{\lambda_M}{\lambda_B} \left[ 1 - E \left( \frac{\pi \lambda_B}{G(\omega) V^{\frac{2}{\beta}} \gamma^{\beta} + \pi \lambda_B} \right) \right] \right\}$$

with

$$G(\omega) = G(\omega) = \delta |\omega|^{\frac{2}{\beta}} \left[ 1 - j \cdot \text{sign}(\omega) \cdot \tan \frac{\pi}{\beta} \right]$$

$$\delta = \frac{\lambda_{\text{inf}}}{4 \lambda_B} \Gamma \{1 - \frac{2}{\beta}\} E(S_k^{2/\beta}) E(Q_k^{2/\beta})$$

$$E(Q_k^{2/\beta}) = \frac{2\pi}{\beta \sin(2\pi / \beta)} \exp \frac{4c^2 \sigma^2}{\beta^2}$$
Spatial Distribution of Power Consumption(3)

- The practical total transmission power of the typical BS limited to maximal power $P_{\text{max}}$, can be derived by “truncating” $P_{C0\_req}$ in the interval $0, P_{\text{max}}$,

$$f_{P_{C0\_pra}}(x) = \begin{cases} \frac{f_{P_{C0\_req}}(x)}{F_{P_{C0\_req}}(P_{\text{max}})}, & x \leq P_{\text{max}}; \\ 0, & x > P_{\text{max}}; \end{cases}$$

- A linear average BS power consumption model is built as follows

$$E(P_{BS}) = E(P_{C0\_pra})/\eta_{RF} + P_{\text{Circuit}}$$

$$= \frac{\int_0^{P_{\text{max}}} x f_{P_{C0\_req}}(x)dx}{\eta_{RF} \cdot \int_0^{P_{\text{max}}} f_{P_{C0\_req}}(x)dx} + P_{\text{Circuit}}$$

where $\eta_{RF}$ is the average efficiency of RF transmission circuits and the circuit power $P_{\text{Circuit}}$ is fixed as a constant.
Spatial Distribution of Power Consumption (4)

- Performance analysis of BS power consumption

With the decrease of heaviness index, indicating more bursty traffic load at MSs, the probability mass of required total BS transmission power remains rather stable except for the increasingly “heavier” tail that decays slower.

Fig. 5. Required total BS transmission power with respect to heaviness index
Spatial Distribution of Power Consumptions (5)

Performance analysis of BS power consumption

Fig. 6. Required total BS transmission power with respect to the intensity ratio of MSs and BSs

Fig. 7. Required total BS transmission power with respect to interfering link intensities
Energy Efficiency of PVT Cellular Networks (1)

- Energy efficiency modeling:
  - Energy efficiency metric:
    \[
    \eta_{EE} = \frac{E(T_C) \cdot (1 - p_{out})}{E(P_{BS})}
    \]
    \[
    = \frac{\lambda_M \theta \rho_{min}}{\lambda_B (\theta - 1)} \cdot \frac{\frac{1}{\eta_{RF}} \int_0^{P_{max}} xf_{\phi_{C0\_req}}(x)dx}{\int_0^{P_{max}} f_{\phi_{C0\_req}}(x)dx} \cdot \left( \int_0^{P_{max}} f_{\phi_{C0\_req}}(x)dx \right)^2
    \]
  - QoS constraints:
    - Minimum data (traffic) rate \( x_0 \)
    - BER target \( p_b \Rightarrow \) SIR gap \( \Delta \)
    - Maximal transmission power
Energy Efficiency of PVT Cellular Networks (2)

Numerical results and discussions

\[ \eta_{EE,\text{max}} = 0.55, 0.45, 0.29, 0.26 \text{ bits/Hz/Joule} \]

\[ \frac{\lambda_M}{\lambda_B^{\text{opt}}} \approx 110, 80, 130, 90 \]

The burstiness of traffic load causes the energy efficiency of PVT cellular networks to fluctuate over a wide range.

Fig. 8. Energy efficiency of PVT cellular networks with respect to the intensity ratio of MSs and BSs considering the heaviness index and the minimum traffic rate.
Energy Efficiency of PVT Cellular Networks (3)

Numerical results and discussions

\[ \eta_{\text{EE, max}} = 0.39, 0.29, 0.23 \text{ bits/Hz/Joule} \]

\[ \frac{\lambda_{\text{Inf}}}{\lambda_{\text{opt}}} \approx 170, 130, 100 \]

Fig. 9. Energy efficiency of PVT cellular networks with respect to the intensity ratio of MSs and BSs considering the interfering link intensity.
Energy Efficiency of PVT Cellular Networks (4)

Numerical results and discussions

\[ \eta_{\text{EE,max}} = 0.17, 0.29, 0.46 \text{ bits/Hz/Joule} \]

\[ \frac{\lambda_M}{\lambda_B^{\text{opt}}} \approx 80, 130, 190 \]

To optimize energy efficiency, a tradeoff between the fixed and the dynamic BS power consumption in accordance with traffic load variations should be considered.

Fig. 10. Energy efficiency of PVT cellular networks with respect to the intensity ratio of MSs and BSs considering the path loss exponent.
Conclusion

• An energy efficiency model for Poisson-Voronoi tessellation (PVT) cellular networks is proposed by considering spatial distributions of traffic load and power consumption.

• Simulation results have shown that there is a maximal limit of energy efficiency in PVT cellular networks considering a tradeoff between the traffic load and BS power consumption.

• Moreover, wireless channel conditions have great impact on the energy efficiency of PVT cellular networks.

• Our analysis indicates that interference reduction or interference coordination can effectively improve the energy efficiency of PVT cellular networks, especially in scenarios with high intensity ratio of MSs and BSs.
A. Publications


B. Joint Projects


C. Research Platform

Green International Collaboration Research Base
—— Green bRoadband wirEless mobilE communicatioN (GREEN) Lab

Granted by Hubei Provincial Science and Technology Department
Thank You!