清華大学 Tsinghua University

Sino-German Workshop 2014

How Densely should Data BSs be Deployed in Hyper Cellular Networks?

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Nature Land is Continuously Evolving *(Yardang)*

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So is Cellular

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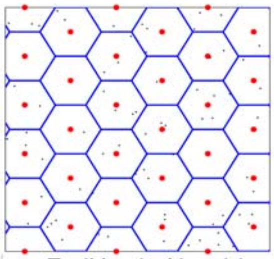
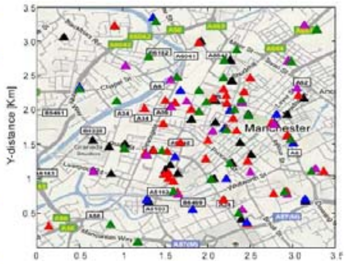
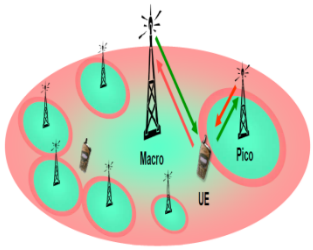


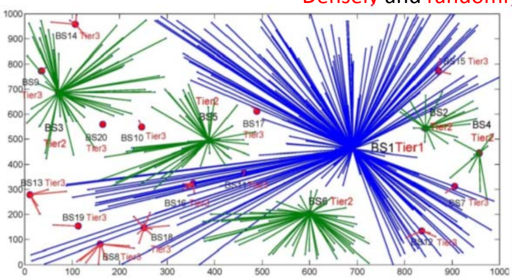
Traditional grid model



Densely and randomly deployed



2G/3G/4G Coexisting (HetNet)



Users are not necessarily connected to the nearest BSs (Traditional max SINR Association)

→ What's a Cell?

J. Andrews, "Seven Ways that HetNets are Cellular Paradigm Shift", IEEE ComMag, March 2013

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How should new cellular be designed?

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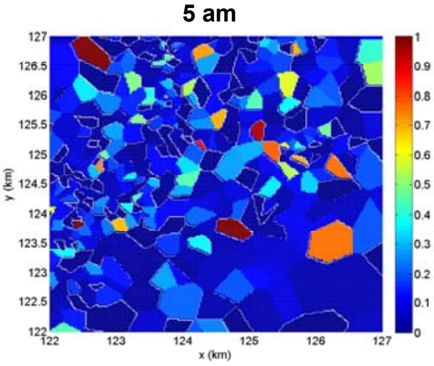
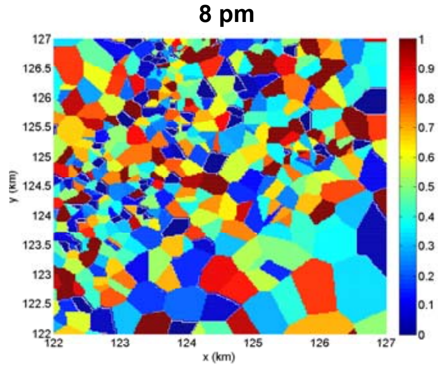
- **How densely should the BSs be deployed?**
- **Can lightly loaded BSs go to sleep *(in order to save energy)*?**
- **How long should BSs sleep? How to guarantee coverage?**
- **How to associate a user to the best BS?**
- **……**

5 am



8 pm



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Dynamic deployment/operation may help to save energy

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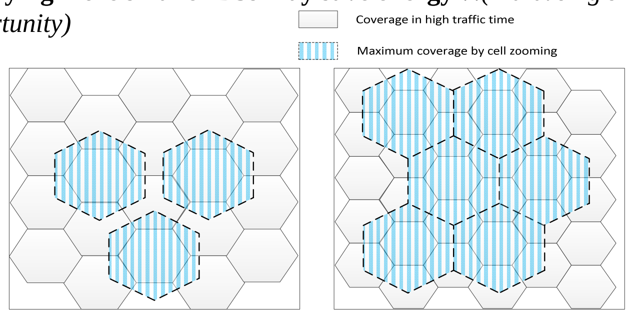
- **Problem:** ***For given QoS, how densely should BSs be deployed and how should the spectrum be allocated?***
  - BS density should adapt to traffic dynamics (e.g., cell zooming, BS sleeping)
  - **Deploying more smaller BSs may save energy** ?!*(increasing sleeping opportunity)*



Traditional planning
Insufficient Zooming

Deploying smaller but
more cells

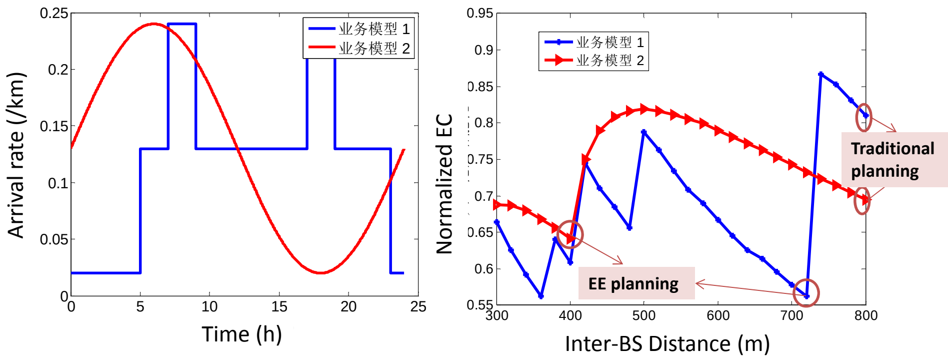
[1] Z. Niu, Y. Wu, J. Gong, Z. Yang, "**Cell zooming for Green cellular networks**", ***IEEE Com Mag***, Nov. 2010
[2] X. Weng, D. Cao, Z. Niu, "**Energy-Efficient Cellular Network Planning under Insufficient Cell Zooming**", ***IEEE VTC2011-spring***, Budapest, Hungary, May 2011

Optimal BS Density for Green

(Regular Deployment Case)

GREEN

- **Normalized EC vs Inter-BS Distance** **(P_B<2%)**

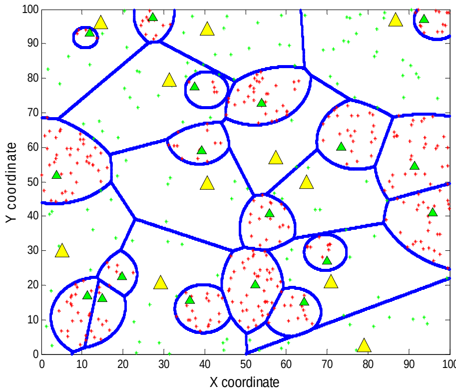


Deploying more smaller BSs can save energy!!!

1. Z. Niu, S. Zhou, Y. Hua, Q. Zhang, and D. Cao, "**Energy-aware network planning for wireless cellular systems with inter-cell cooperation**", ***IEEE TWC***., vol.11, no.4, pp.1412-1423, 2012
2. Y. Wu, Z. Niu, "**Energy Efficient Base Station Deployment in Green Cellular Networks with Traffic Variations**", ***IEEE ICCC2012***, Beijing, China, Aug. 2012

Optimal BS Density for Green

*(**Heterogeneous & Stochastic** Deployment Case)*



Stochastic Geometry Modeling

1. Two-tier PPP models with BS density ρ_M and ρ_m
2. Always connect to the BS with highest SNR *(not necessarily the nearest)*

Weighted Poisson-Voronoi Tessellation:

f(A) follows Γ-distribution with density

$$\overline{A_M} = \mathbb{E}\{A_M\} = \frac{c}{c\rho_M + \rho_m}$$

$$\overline{A_m} = \mathbb{E}\{A_m\} = \frac{1}{c\rho_M + \rho_m}$$

where: $c \triangleq \left(\frac{P_M}{P_m}\right)^{\frac{2}{\alpha}}$

D. Cao, S. Zhou, Z. Niu, **"Optimal Combination of Base Station Densities for Cost-Efficient Two-tier Heterogeneous Cellular Networks"**, *IEEE TWireless*, Sep. 2013

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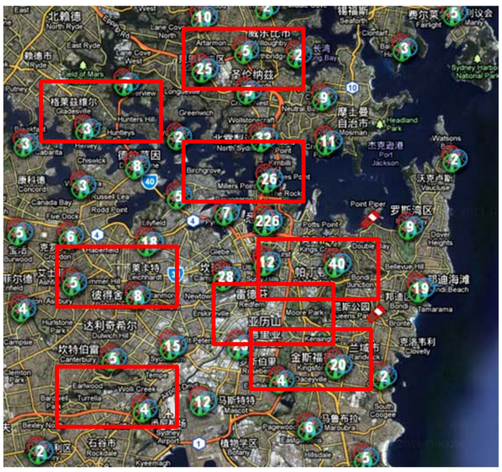
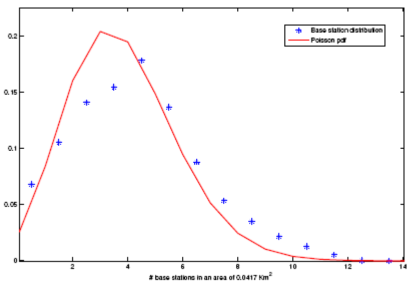
Verification of PPP Models



Australian Geographical Radio Frequency Map (http://spench.net/)

Bay area of Sydney, Australia.
Dense deployment: 81.64 per Km^2



B. Rengarajan, G. Rizzo, and M. A. Marsan, ``Bounds on QoS-Constrained Energy Savings in Cellular Access Networks with Sleep Modes'', *ITC 2011*, pp. 47-54, San Francisco, USA, Sep. 2011.

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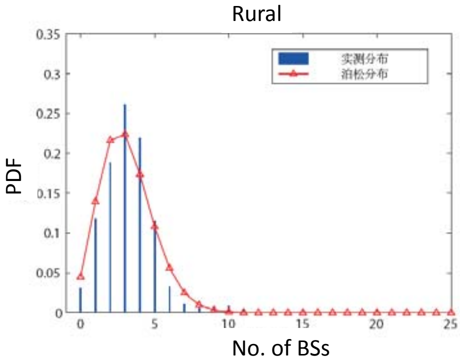
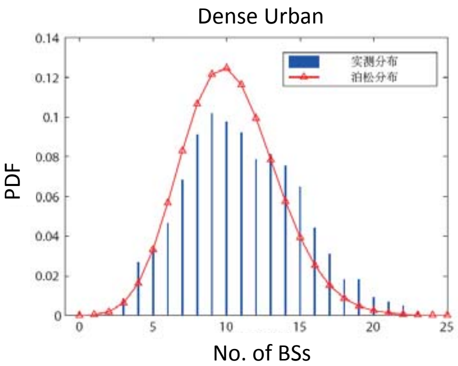
Verification of PPP Models





$$P_A(n) = \frac{(\lambda A)^n}{n!}\exp(-\lambda A).$$

Distribution of BSs in a Square Area of a Chinese Operator

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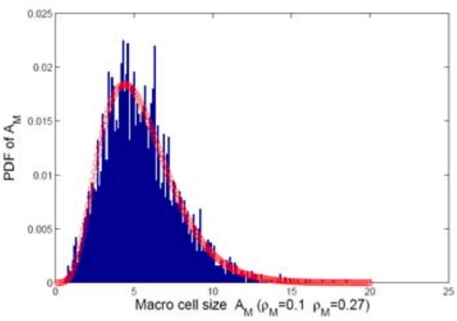
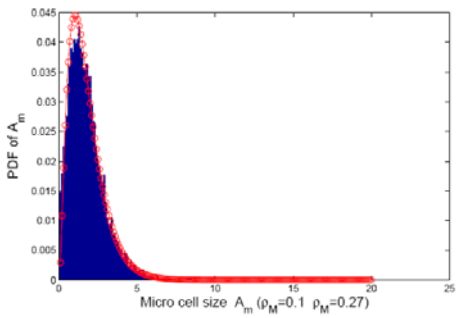
Verification of Gamma Distribution





$$f_M(x) = x^{K_M-1}\frac{\exp(-\frac{c\rho_M+\rho_m}{c}K_M x)}{(\frac{c}{c\rho_M+\rho_m}\frac{1}{K_M})^{K_M}\Gamma(K_M)}$$

$$f_m(x) = x^{K_m-1}\frac{\exp(-(c\rho_M+\rho_m)K_m x)}{(\frac{1}{c\rho_M+\rho_m}\frac{1}{K_m})^{K_m}\Gamma(K_m)}$$

Distribution of Cell Areas of a Chinese Operator

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QoS Metrics

- **Coverage Probability**

$$\Pr(\mathrm{SINR} \geq T) = \frac{1}{1 + T^{2/\alpha} \int_{T^{-2/\alpha}}^{\infty} \frac{1}{1+x^{\alpha/2}} dx}$$

If α=4,

$$\Pr(\mathrm{SINR} \geq T) = \frac{1}{1 + \sqrt{T}(\pi/2 - \arctan(1/\sqrt{T}))}$$

- **Service Outage Probability**

$$\mathbb{E}_{\{N,A\}} \left\{ \Pr\left(\frac{W}{N} \log_2(1 + \mathrm{SINR}) < u \middle| N, A \right) \right\}$$
$$= \mathbb{E}_A \mathbb{E}_{n|A} \left\{ \Pr\left(\frac{W}{n+1} \log_2(1 + \mathrm{SINR}) < u \middle| n, A \right) \right\}$$
$$= \int_0^{\infty} \sum_{n=0}^{\infty} \Pr\left(\mathrm{SINR} < 2^{\frac{(n+1)u}{W}} - 1 \middle| n, A \right) P_A(n) f(A) dA.$$

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Optimal BS Density - Formulation

(Homogeneous Case)

$$\min \quad \rho$$
$$s.t. \int_0^{\infty} \sum_{n=0}^{\infty} \frac{1}{1 + (2^{(n+1)\frac{u}{W}} - 1)^{\frac{2}{\alpha}} \int_{(2^{(n+1)\frac{u}{W}} - 1)^{-\frac{2}{\alpha}}}^{\infty} \frac{1}{1+x^{\alpha/2}} dx}$$
$$\frac{(\lambda A)^n}{n!} \exp(-\lambda A) \rho^K \frac{K^K}{\Gamma(K)} A^{K-1} \exp(-K\rho A) dA$$
$$\geq 1 - \eta. \quad (8)$$

Theorem 1. *The optimal BS density in the interference-limited homogeneous cellular network (8) is linear with the user density, i.e.,* $\rho^* \sim \lambda$.

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Optimal BS Density – Upper Bound

(Homogeneous Case)

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Theorem 2. *The optimal BS density in the interference-limited homogeneous cellular network (8) has an upper bound $\hat{\rho}$, which satisfies the following expression:*

$$\frac{\alpha-2}{2}2^{\frac{-u}{W}}\sum_{m=0}^{\infty}\left(\frac{4-\alpha}{2}2^{\frac{-u}{W}}\right)^{m}\left\{\frac{K\hat{\rho}}{(1-2^{(m+1)\frac{-u}{W}})\lambda+K\hat{\rho}}\right\}^{K} = 1-\eta. \qquad (9)$$

For the special case $\alpha = 4$, the upper bound has a closed-form expression:

$$\bar{\rho} \triangleq \frac{\lambda}{\frac{W}{u}\log_2\frac{\frac{\alpha-2}{2}+\frac{4-\alpha}{2}(1-\eta)}{1-\eta}-1} \qquad (10)$$

Further, the upper bound $\hat{\rho}$ has the following property as

$$\lim_{\frac{u}{W}\to 0}\frac{\hat{\rho}}{\rho^{*}} = 1.$$

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Optimal BS Density – Lower Bound

(Homogeneous Case)

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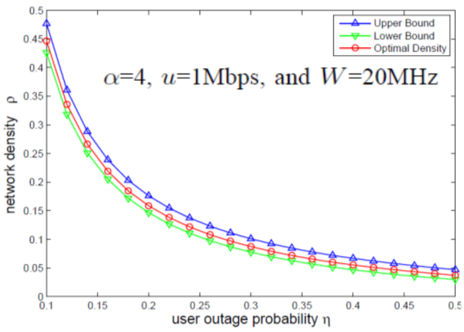
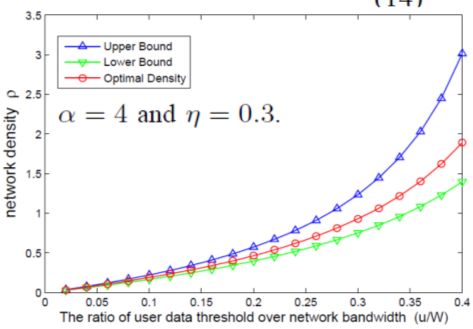
Theorem 3. *The optimal BS density in the interference-limited homogeneous cellular network (8) has a lower bound $\check{\rho}$, which satisfies the following expression:*

$$\frac{1}{2}\sum_{m=0}^{\infty}2^{-(\frac{3u}{4W}+1)m-\frac{u}{4W}}\left\{\frac{K\check{\rho}}{(1-2^{-\frac{3m+1}{4}\frac{u}{W}})\lambda+K\check{\rho}}\right\}^{K} = 1-\eta. \qquad (14)$$





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Optimal BS Density - Performance

(Homogeneous Case)

Table: Optimal BS density for 3 typical scenarios (in BSs/Km2, EARTH model)

Scenarios	optimal BS density with noise	optimal BS density without noise	upper bound in Theorem 2
Rural	0.1384	0.0542	0.0551
Suburban	0.9424	0.9017	0.9177
Dense urban	1.2713	1.2390	1.2610

Conclusion: noiseless assumption is acceptable for *suburban* and *dense urban* scenarios, but not in *rural* scenario

Table: Optimal BS density with transmit power adaption

Strategy	Rural	Suburban	Dense urban
Fixed full transmit power	ρ^*=0.1384 BSs/Km^2 P_M=20W	ρ^*=0.9424 BSs/Km^2 P_M=20W	ρ^*=1.2713 BSs/Km^2 P_M=20W
Optimal transmit power adaption	ρ^*=0.1604 BSs/Km^2 P_M^*=12.2W	ρ^*=1.0699 BSs/Km^2 P_M^*=3.8W	ρ^*=1.4121 BSs/Km^2 P_M^*=3.1W

Conclusion: transmit power adaption can help save more energy

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Optimal BS Density - Formulation

(Heterogeneous Case)

$$\begin{aligned}
\min \quad & C_M \rho_M + C_m \rho_m \\
s.t. \quad & G_M = \mathbb{E}_{\{N_M, A_M\}} \left\{ \Pr\left(\frac{W}{N_M} \log_2(1+\mathrm{SINR}) < u \middle| N_M, A_M \right) \right\} < \eta, \\
& G_m = \mathbb{E}_{\{N_m, A_m\}} \left\{ \Pr\left(\frac{W}{N_m} \log_2(1+\mathrm{SINR}) < u \middle| N_m, A_m \right) \right\} < \eta, \\
& \rho_0 \le \rho_M \le \rho_2, \\
& \rho_1 \le \rho_m \le \rho_3.
\end{aligned}$$

Coverage guarantee

where $\{C_M, C_m\}$ *are deployment (energy) cost of macro and micro BSs, respectively and* $\tau \triangleq \frac{\rho_m}{\rho_M}$

1. D. Cao, S. Zhou, Z. Niu, **"Optimal Combination of Base Station Densities for Cost-Efficient Two-tier Heterogeneous Cellular Networks"**, ***IEEE TWireless***, Sep. 2013
2. D. Cao, S. Zhou, Z. Niu, **"Improving the Energy Efficiency of Two-Tier Hetwrogeneous Cellular Networks through Partial Spectrum Reuse"**, ***IEEE TWireless***, Aug. 2013

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Optimal BS Density – Near-optimal Solution

(Heterogeneous Case)

$$\rho_M = \frac{1 - 2^{-\frac{u}{W}}}{\frac{c+\tau}{c} K_M \{[2^{\frac{u}{W}}(1-\eta)]^{-\frac{1}{K_M}} - 1\}} \lambda,$$

$$\tau^* = \begin{cases} \min\{\tau_0, \tau_3\}, & 0 \le \xi < \frac{1}{c}; \\ \max\{\tau_1, \tau_2\}, & \frac{1}{c} < \xi \le 1. \end{cases} \qquad \xi = \frac{C_m}{C_M};\ c = \left(\frac{P_M}{P_m}\right)^{\frac{2}{\alpha}}$$

$$\tau_0 \approx \frac{1 - 2^{-\frac{u}{W}}}{\rho_0 \log(\frac{1}{2^{\frac{u}{W}}(1-\eta)})} c\lambda - c, \quad \tau_1 \approx \frac{1}{\frac{1-2^{-\frac{u}{W}}}{\rho_1 \log(\frac{1}{2^{\frac{u}{W}}(1-\eta)})}\lambda - \frac{1}{c}},$$

$$\tau_2 \approx \frac{1 - 2^{-\frac{u}{W}}}{\rho_2 \log(\frac{1}{2^{\frac{u}{W}}(1-\eta)})} c\lambda - c, \quad \tau_3 \approx \frac{1}{\frac{1-2^{-\frac{u}{W}}}{\rho_3 \log(\frac{1}{2^{\frac{u}{W}}(1-\eta)})}\lambda - \frac{1}{c}}.$$

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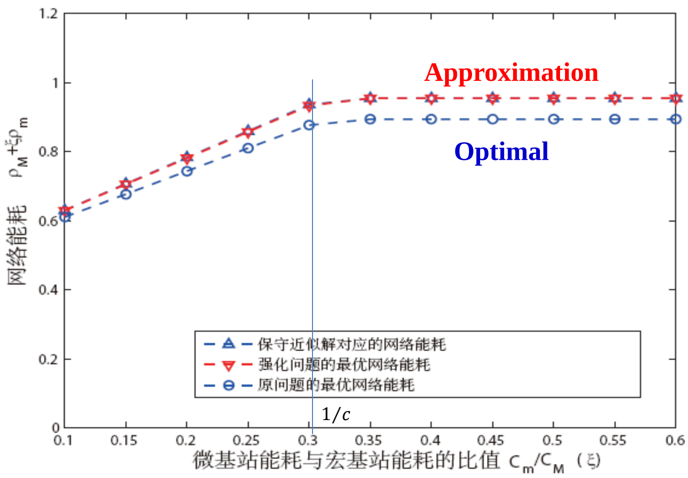
Optimal BS Density – Performance

(Heterogeneous Case)



$$\xi = \frac{C_m}{C_M};\ c = \left(\frac{P_M}{P_m}\right)^{\frac{2}{\alpha}}$$

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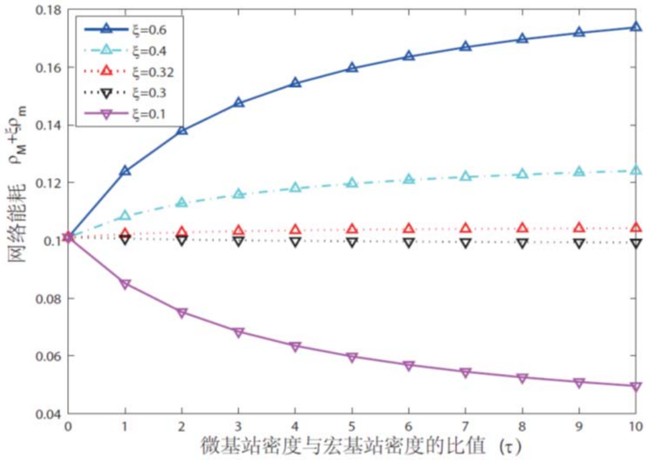
Optimal BS Density – Optimal Policy
(Heterogeneous Case)



$$\xi = \frac{C_m}{C_M};\ c = \left(\frac{P_M}{P_m}\right)^{\frac{2}{\alpha}}$$

If $\xi < 1/c$=0.3162, preferentially add micro BSs or sleep macro BSs
If $\xi > 1/c$=0.3162, preferentially add macro BSs or sleep micro BSs

Optimal BS Density – Performance
(Heterogeneous Case)

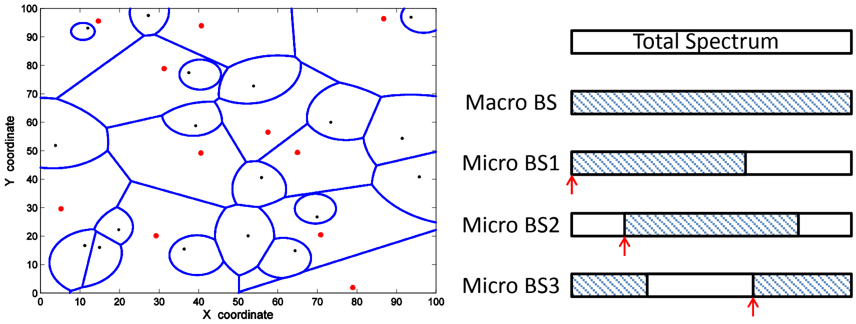
- **Dynamic BS Sleeping in Dense Urban Scenario** (EARTH Model)
  - $C_M = 780 + 28.2P_M$, $C_m = 112 + 5.2P_m$
  - P_M = 20W, P_m =2.42W → ζ = 0.0927 < c^{-1}=0.3162
  - **Reference model**: macro-only homogeneous network with no BS sleeping: total energy consumption=**3.26** KW/Km²

Time	normalized traffic to the peak	macro BS sleeping probability $\frac{\rho_2-\rho_M^*}{\rho_2-\rho_0}$	micro BS sleeping probability $\frac{\rho_3-\rho_m^*}{\rho_3}$	energy consumption (KW/Km^2)
09:00-11:00	90%	28.1%	0%	1.59
11:00-13:00	100%	0%	0%	1.91
13:00-15:00	70%	84.2%	0%	0.95
15:00-18:00	80%	56.2%	0%	1.27
18:00-23:00	55%	100%	15.5%	0.68
23:00-09:00	20%	100%	72.5%	0.36

0.82 (average)
(**75%** saving)

Heterogeneous Networks with PSR

- **PSR** *(Partial Spectrum Reuse)* **to reduce over-provisioning and potential interference** *(to macro BSs and among micro BSs)*



- **Optimization Problem:** $\min_{\beta} \quad \max\{G_M(\beta), G_m(\beta)\}$

What's the optimal $\beta = W_m/W_M$?

D. Cao, S. Zhou, Z. Niu, **"Improving the Energy Efficiency of Two-Tier Hetwrogeneous Cellular Networks through Partial Spectrum Reuse"**, *IEEE TWireless*, Aug. 2013

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Properties with PSR

Lemma 1. *In the heterogeneous cellular network model with the β-PSR scheme, the user SINR distribution follows:*

$$\Pr(\text{SINR} \geq T) = \frac{1}{1 + \frac{c\rho_M + \beta\rho_m}{c\rho_M + \rho_m} T^{2/\alpha} \int_{T^{-2/\alpha}}^{\infty} \frac{1}{1+x^{\alpha/2}} \mathrm{d}x}. \quad (11)$$

Lemma 2. *In the heterogeneous cellular network model with the β-PSR scheme, $G_M(\beta)$ is increasing, while $G_m(\beta)$ is decreasing with the PSR factor β.*

Lemma 3. *In the problem (3), the optimal PSR factor β^* is achieved if and only if,*

$$G_M(\beta^*) = G_m(\beta^*). \quad (15)$$

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Optimal *β* in PSR

Theorem 1. *In the heterogeneous cellular network model with the β-PSR scheme, the optimal PSR factor β^* of the problem (3) has the following property:*

$$\lim_{\frac{u}{W}\to 0} \beta^* = \frac{u_m}{u_M}\frac{c\rho_M + \rho_m + \lambda_m}{c\rho_M + \rho_m + c\lambda_M} \quad (19)$$

$$e = \frac{C_m}{C_M}; \quad c = \left(\frac{P_M}{P_m}\right)^{\frac{2}{\alpha}}$$

If $\beta<1$, allocate FULL spectrum to *macro* BSs and PARTIAL spectrum to *micro* BSs

If $\beta>1$, allocate PARTIAL spectrum to *macro* BSs and FULL spectrum to *micro* BSs

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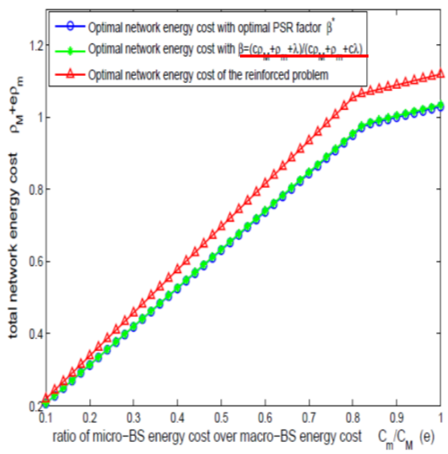
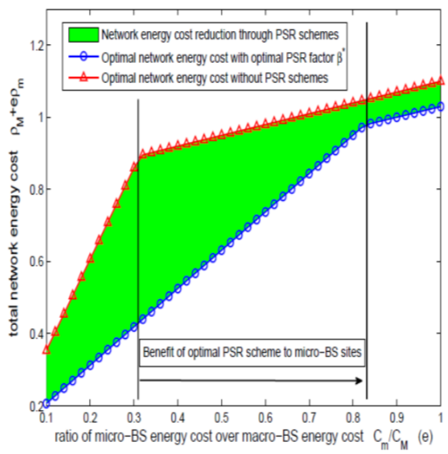
Energy Saving Gain by PSR





Approximate PSR achieves the near-optimal performance

PSR scheme can save up to 50% of network energy consumption

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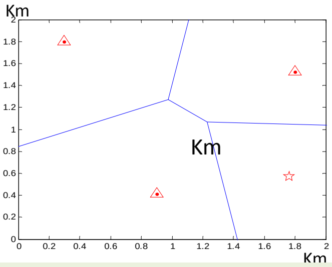
Application to Network Planning – Capacity Extension

(EARTH Model: Dense Urban, Peak Traffic increases up to 74.3/Km²)

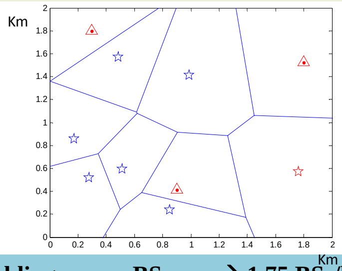


Network Topology before capacity extension

- Macro BSs for coverage guarantee
- Other macro BSs (could be switched off)
- Newly added BSs for capacity extension

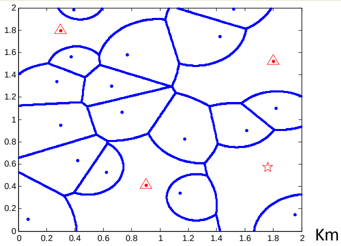
ρ_M=1 BS/km² (¾ used for coverage), EC=5.9kW/km2

Capacity extension by homogeneous BSs



Adding macro BSs: ρ_M → 1.75 BSs/km²
EC → 3.56 kW/km² (40% saving)

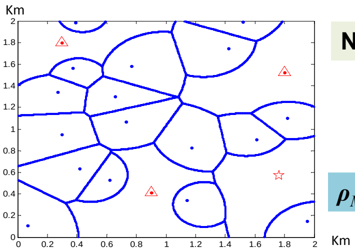
Capacity extension by heterogeneous BSs



Adding micro-BSs: ρ_m → 4.25/Km²
EC → 1.87 kW/km² (48% further savings)

Application to Energy Saving – BS Sleeping

(EARTH Model, Dense Urban)

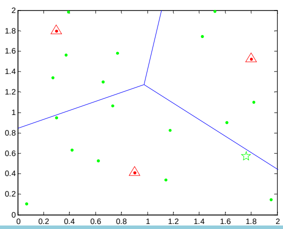


Network Topology during Peak Traffic (75/Km²)

- Macro BSs for coverage guarantee
- Other macro BSs (could be switched off)
- Micro BSs

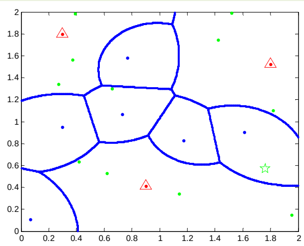
ρ_M=1 BS/km², ρ_m=4.25 BS/km², EC=1.87 KW/Km²

Traffic load down to 20% (15/Km²)



All unnecessary BSs going to sleep, ρ_M=0.75/km², EC=0.97KW/Km² (↓50%)

Traffic Load up to 50% (37/Km²)



Awake 35% micro BSs: ρ_m=1.5 /km², EC=1.18KW/Km2 (↓37%)

Summary

TeHL

- **Optimal BS density in heterogeneous networks**
  - **If *e* is lower than a threshold 1/*c*, deploying or switching on more *micro* BSs is more beneficial, and vice versa.**
  - **Heterogeneous cellular network with BS sleeping can reduce the total energy consumption by up to 75%**
  - **PSR scheme can save up to 50% of network energy consumption compared with no PSR schemes.**

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Globally Resource-optimized and Energy-Efficient Networks

For more information,
visit *http://network.ee.tsinghua.edu.cn/niulab/?category_name=publications*