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

Prof. Xiaohu Ge & Prof. Cheng-Xiang Wang

Huazhong University of Science and Technology Heriot-Watt University

Outline

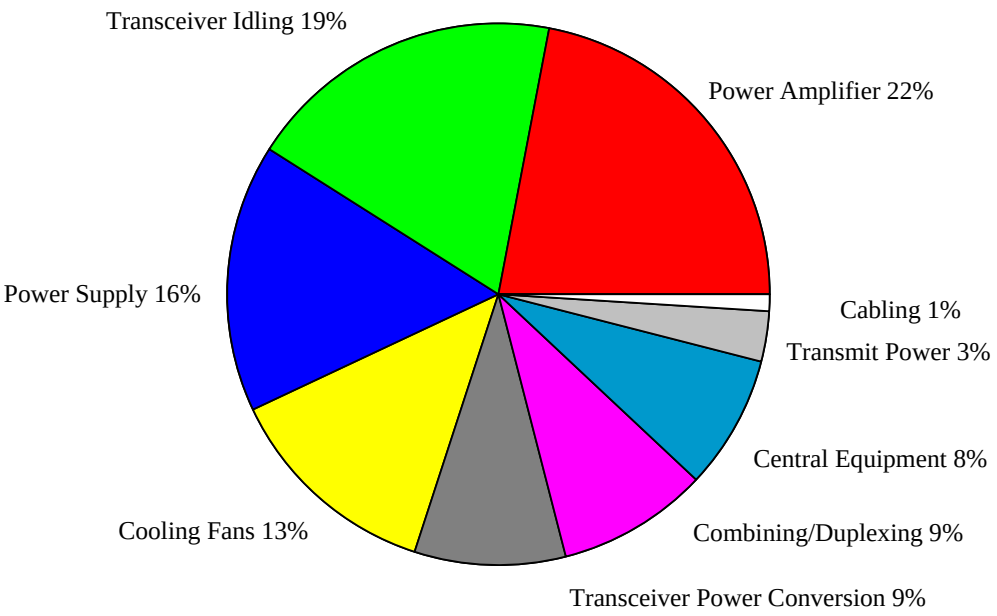
- Introduction
- System Model
- Spatial Distribution of Traffic Load
- Spatial Distribution of Power Consumption
- Energy Efficiency of PVT Cellular Networks
- Conclusion
- A list of deliverables

Introduction(1)

Energy efficiency issues in cellular networks (*static analysis*):

The energy consumption of Mobile operator can be as high as 10 MW

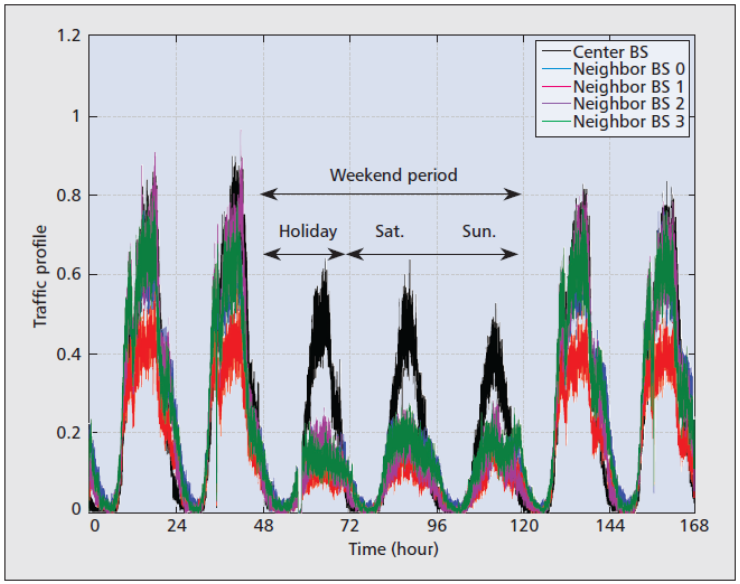
In EU:

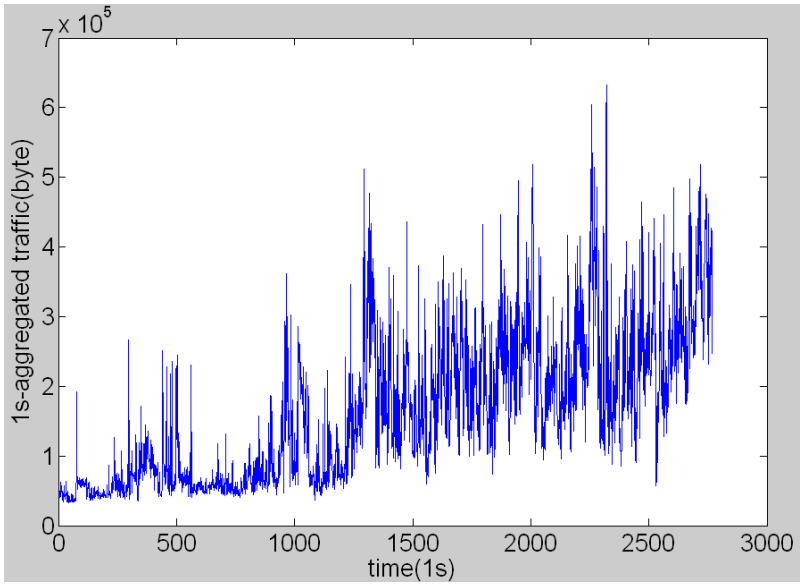


- Over 80% of the power is consumed in RAN (at ChinaMobile)
- Base Station consumption 0.5 – 2.7 kW
- BSs consume most energy in RAN

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?

Tab. 1. Comparisons of time/frequency/space resources

Resource Type	Time (division)	Frequency (division)	Space (division)
TXs & RXs (spilling)	collocated	Collocated	not collocated
Power falloff (interference)	To zero at turn-off	>=100dB/decade	20-40dB/decade

➢J.G. Andrews, R.K. Ganti, M. Haenggi, etc. "A Primer on Spatial Modeling and Analysis in Wireless Networks," *IEEE Communication Magazine*, vol. 48, pp. 156-163, Nov. 2010.

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.

System Model(1)

- **Poisson-Voronoi Tessellation Cellular Networks**:

  BSs: $\prod_B = y_{Bk} : k = 0,1,2,\cdots$ ~Poisson Point Process PPP(λ_B),

  MSs: $\prod_M = x_{Mi} : i = 0,1,2,\cdots$ ~ PPP(λ_M);

  An MS is served by the nearest BS in range, which would suffer the least path loss during wireless transmission.

  ➔The typical cell $\mathcal{C}_0$ (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 $\xi \sim Gaussian(0,1)$ and the constant $c = \ln 10/10$; the term ζ^2 is exponentially distributed with mean 1 in Rayleigh fading environments.

System Model(2)

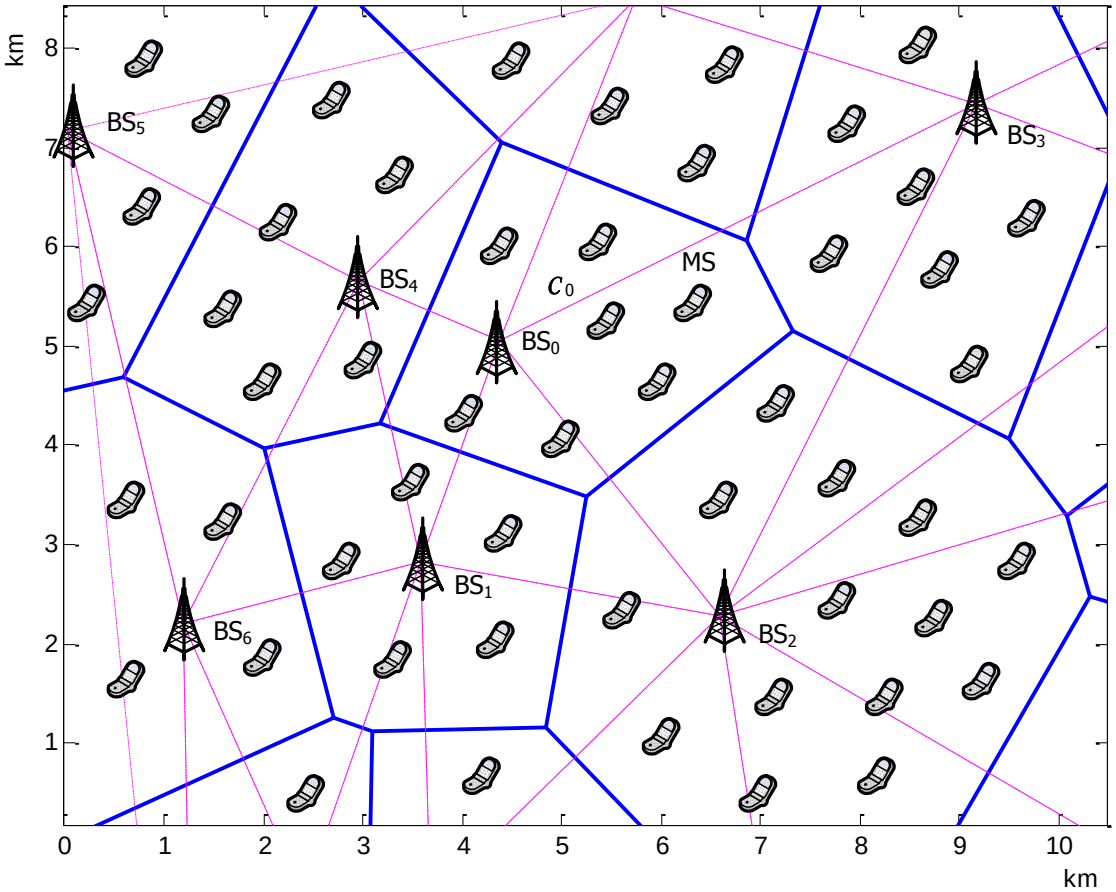


Fig. 1 Illustration of PVT cellular structure; real lines depict cell boundaries inside which a polygon corresponds a cell coverage; dashed lines, which are perpendicularly bisected by corresponding cell boundaries, demonstrate how to build tessellations through the "Delaunay Triangulation" method.

System Model(3)

- **Problem formulation via the additive functional:**

$$\Omega_w \overset{def}{=} \sum_{x_i \in \Pi_M} w\ x_i\ \mathbf{1}\ x_i \in \mathcal{C}_0$$

where $w\ x : \mathbb{R}^2 \to \mathbb{R}_+$ is a given non-negative function (either deterministic or random), $\mathbf{1}\ \ldots$ is an indicator function, and $\mathcal{C}_0$ is a typical cell.

Empirical traffic characterization and modeling results provide us a basis.

- Aggregate traffic load $\mathcal{T}_{\mathcal{C}0}$ in $\mathcal{C}_0$: $w(x) = \rho(x)$ is the spatial traffic density.
- BS tranmission power $\mathcal{P}_{\mathcal{C}0}$ in $\mathcal{C}_0$: $w\ x = \varepsilon(x, I_o, \rho)$, which is the power consumption (the "energy cost") of a typical point-to-point fading wireless link; I_o represents other-cell interference and ρ is the traffic density.

Modeling work is needed.

➢S.G. Foss, and S.A. Zuyev, "On a Voronoi aggregative process related to a bivariate Poisson process," *Advances in Applied Probability*, vol. 28, no. 4, pp. 965-981, Dec. 1996.
➢F. Baccelli, M. Klein, M. Lebourges, and S. Zuyev, "Stochastic geometry and architecture of communication networks," *Telecommunication Systems*, vol. 7, no. 1, pp. 209-227, 1997.

Spatial Distribution of Traffic Load(1)

- The **aggregate traffic load** in a typical cell $\mathcal{C}_0$ is defined as:

$$\mathcal{T}_{\mathcal{C}0} \overset{def}{=} \sum_{x_{Mi} \in \Pi_M} \rho(x_{Mi}) \mathbf{1} \quad x_{Mi} \in \mathcal{C}_0$$

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

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

Empirical measurement results have demonstrate that the traffic load in both wired and wireless networks, including cellular networks, is self-similar and bursty, which can be modeled by Pareto distributions with infinite variance.

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

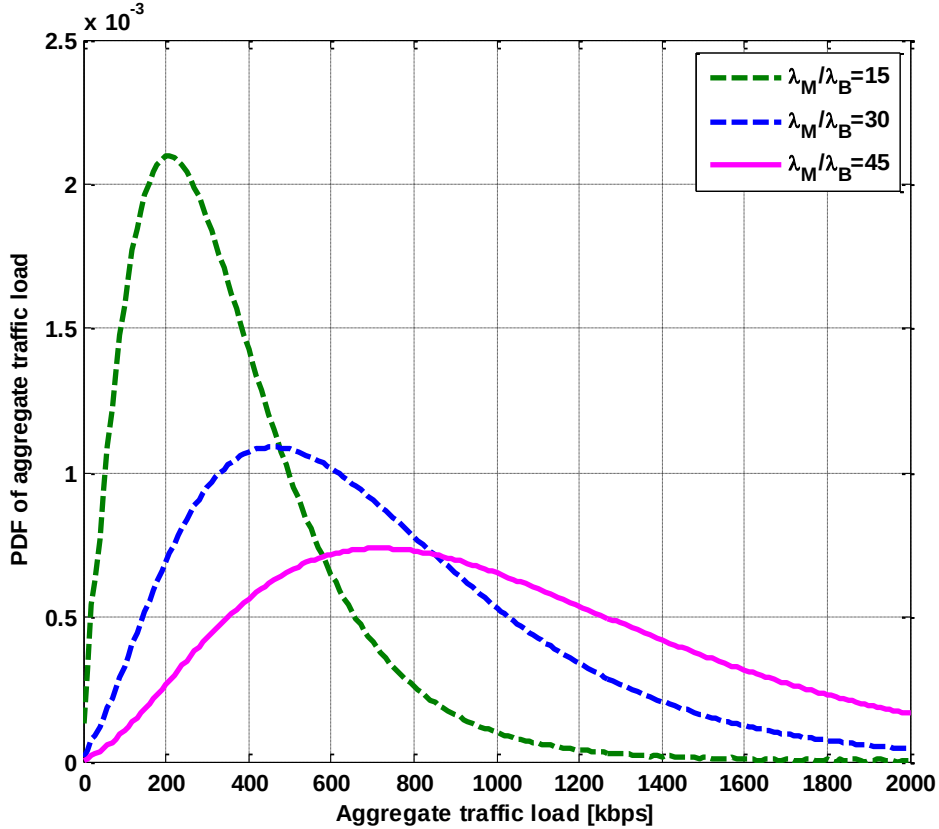
- **The characteristic function of** $\mathcal{T}_{\mathcal{C}0}$

$$\phi_{\mathcal{T}_{\mathcal{C}0}} \; j\omega = \left[1 + \frac{\lambda_M}{b\lambda_B} - \frac{\lambda_M}{b\lambda_B} \theta (-j\rho_{\min}\omega)^{\theta} \Gamma(-\theta, -j\rho_{\min}\omega) \right]^{-a}$$

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**

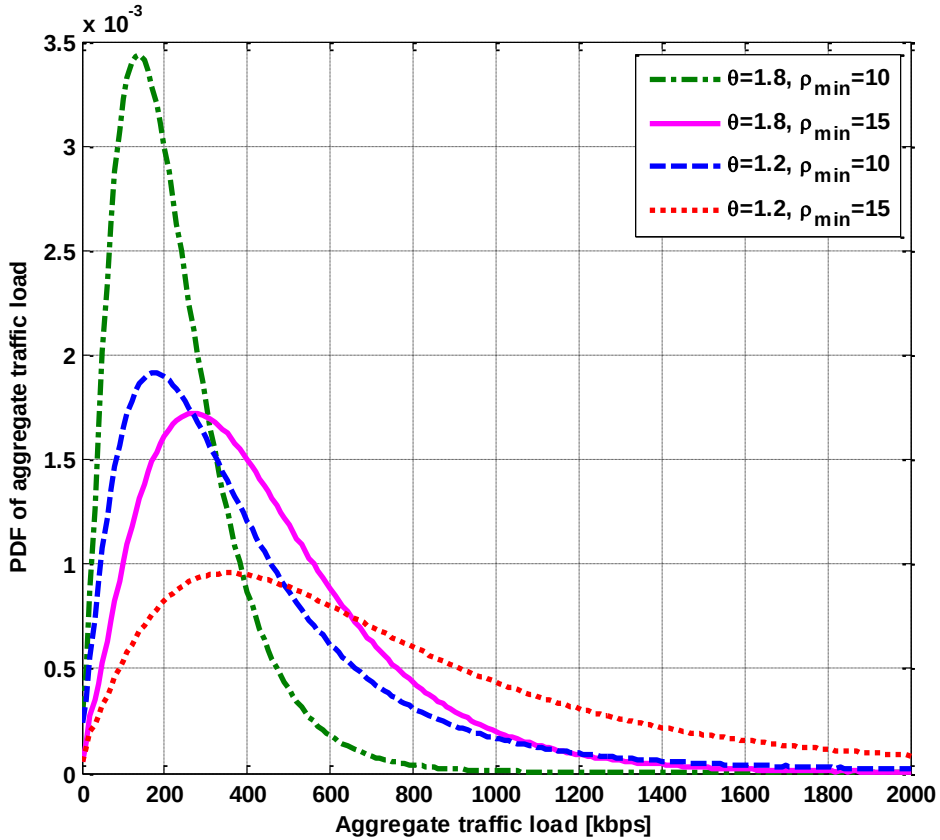


The probability mass (which can be depicted as the area under the PDF curve) would shift to the right with the increase of λ_M / λ_B, indicating an increase in the average aggregate traffic load at BS

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.

Spatial Distribution of Power Consumptions (1)

- **Interference and power control model:**

The instantaneous SIR of MS_0 is given by

$$\gamma = \frac{S_0}{I_{\text{agg}}} = \frac{S_0}{\sum_{k \in \Phi_{\text{BS}}} S_k \cdot \frac{L(r_{k0}, \xi_{k0}, \zeta_{k0})}{L(r_{kk}, \xi_{kk}, \zeta_{kk})} \cdot \mathbf{1}_D(L_{k0}/L_{kk})}$$

with $\mathbf{1}_D(L_{k0}/L_{kk}) = \mathbf{1}_D\{r_{kk}/r_{k0} \le 1\}$, where I_{agg} is the aggregate interference seen at MS_0, Φ_{BS} is the index set of interfering BSs, and the indicator function $\mathbf{1}_D(L_{k0}/L_{kk})$ is a constraint on MS distance distributions under the closest association rule in PVT cellular networks.

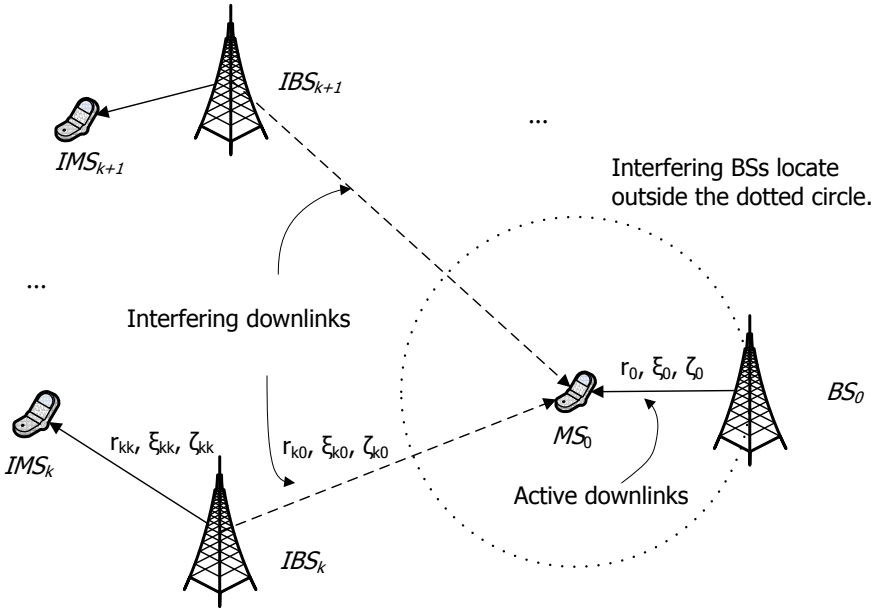


Fig. 4. Wireless downlinks of a PVT cellular network. An example of interfering BS is illustrated at IBS_k with detailed channel parameters.

Spatial Distribution of Power Consumptions (2)

- **The required total transmission power** in a typical PVT cell $\mathcal{C}_0$ with perfect power control:

$$\mathcal{P}_{\mathcal{C}0\_\text{req}} = \sum_{x_{Mj} \in \Pi_M} \frac{\left\| x_{Mj} - y_{B0} \right\|^{\beta}}{K} U \cdot \mathbf{1} \quad x_{Mj} \in \mathcal{C}_0$$

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

$$\phi_{\mathcal{P}_{\mathcal{C}0\_\text{req}}}(\omega) = \exp\left\{ -\frac{\lambda_M}{\lambda_B} \left[1 - \mathbf{E}\left(\frac{\pi \lambda_B}{G(\frac{\omega}{K}) V^{\frac{2}{\beta}} \gamma^{\frac{2}{\beta}} + \pi \lambda_B} \right) \right] \right\}$$

with

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

$$\delta = \frac{\lambda_{\text{Inf}}}{4\lambda_B} \Gamma(1 - \tfrac{2}{\beta}) \cos(\tfrac{\pi}{\beta}) \mathbf{E}(S_k^{2/\beta}) \mathbf{E}(Q_k^{2/\beta}) \quad , \quad \mathbf{E}(Q_k^{2/\beta}) = \frac{2\pi}{\beta \sin(2\pi / \beta)} \exp \frac{4c^2\sigma^2}{\beta^2}$$

Spatial Distribution of Power Consumption(3)

- **The practical total transmission power** of the typical BS limited to maximal power $P_{\max}$, can be derived by "truncating" $\mathcal{P}_{\mathcal{C}0\_\mathrm{req}}$ in the interval $0, P_{\max}$,

$$f_{\mathcal{P}_{\mathcal{C}0\_\mathrm{pra}}}(x) = \begin{cases} f_{\mathcal{P}_{\mathcal{C}0\_\mathrm{req}}}(x) / F_{\mathcal{P}_{\mathcal{C}0\_\mathrm{req}}}(P_{\max}), & x \le P_{\max}; \\ 0, & x > P_{\max}; \end{cases}$$

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

$$\mathbf{E}(P_{BS}) = \mathbf{E}(\mathcal{P}_{\mathcal{C}0\_\mathrm{pra}}) / \eta_{\mathrm{RF}} + P_{\mathrm{Circuit}}$$

$$= \frac{\int_0^{P_{\max}} x f_{\mathcal{P}_{\mathcal{C}0\_\mathrm{req}}}(x) dx}{\eta_{\mathrm{RF}} \cdot \int_0^{P_{\max}} f_{\mathcal{P}_{\mathcal{C}0\_\mathrm{req}}}(x) dx} + P_{\mathrm{Circuit}}$$

where η_{RF} is the average efficiency of RF transmission circuits and the circuit power P_{Circuit} is fixed as a constant.

Spatial Distribution of Power Consumption(4)

- **Performance analysis of BS power consumption**

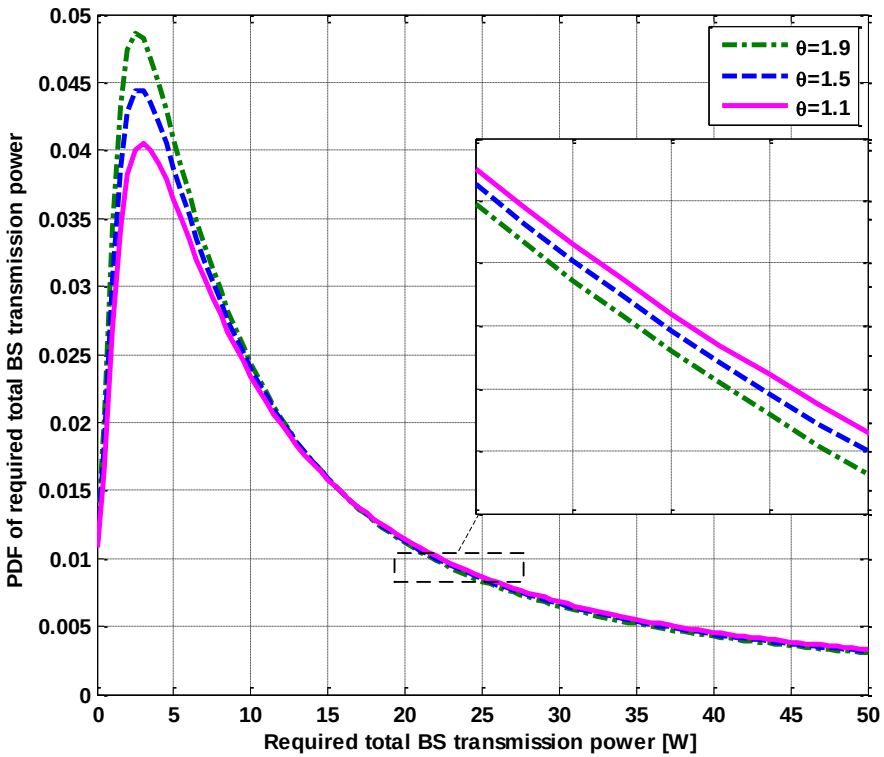


Fig. 5. Required total BS transmission power with respect to heaviness index

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.

Spatial Distribution of Power Consumptions (5)

Performance analysis of BS power consumption

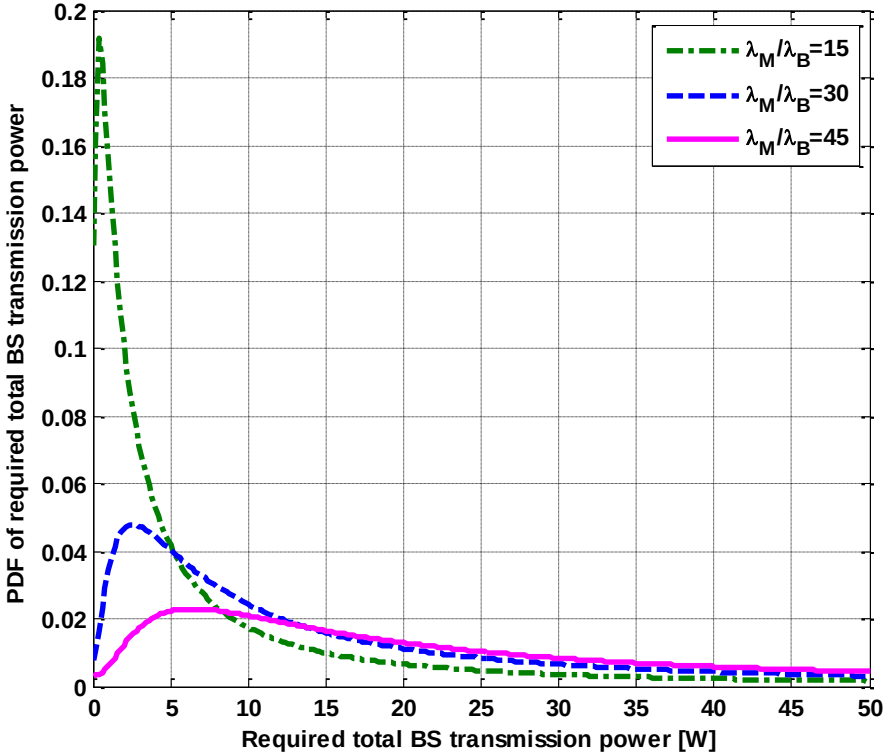


Fig. 6. Required total BS transmission power with respect to the intensity ratio of MSs and BSs

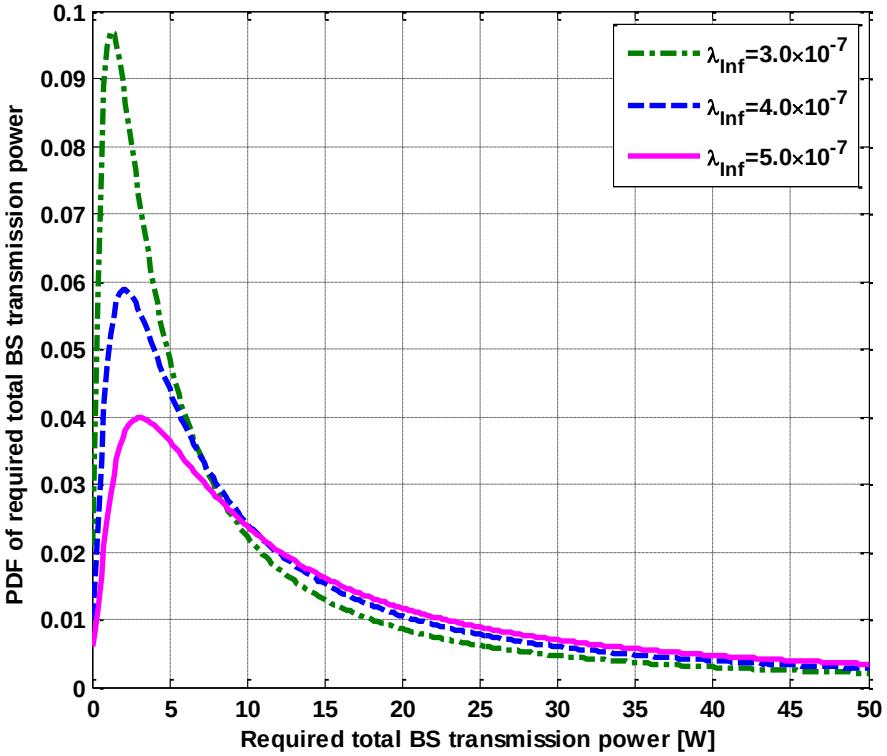


Fig. 7. Required total BS transmission power with respect to interfering link intensities

Energy Efficiency of PVT Cellular Networks (1)

- **Energy efficiency modeling:**
- **Energy efficiency metric:**

$$\eta_{\mathrm{EE}} = \frac{\mathbf{E}(\mathcal{T}_C)\cdot\ 1-p_{\mathrm{out}}}{\mathbf{E}(P_{BS})}$$

$$= \frac{\lambda_M \theta \rho_{\min}}{\lambda_B(\theta-1)} \cdot \frac{\left(\int_0^{P_{\max}} f_{\mathcal{P}_{C0\_\mathrm{req}}}(x)dx\right)^2}{\frac{1}{\eta_{\mathrm{RF}}}\int_0^{P_{\max}} x f_{\mathcal{P}_{C0\_\mathrm{req}}}(x)dx + P_{\mathrm{Circuit}}\cdot\int_0^{P_{\max}} f_{\mathcal{P}_{C0\_\mathrm{req}}}(x)dx}$$

- **QoS constraints:**

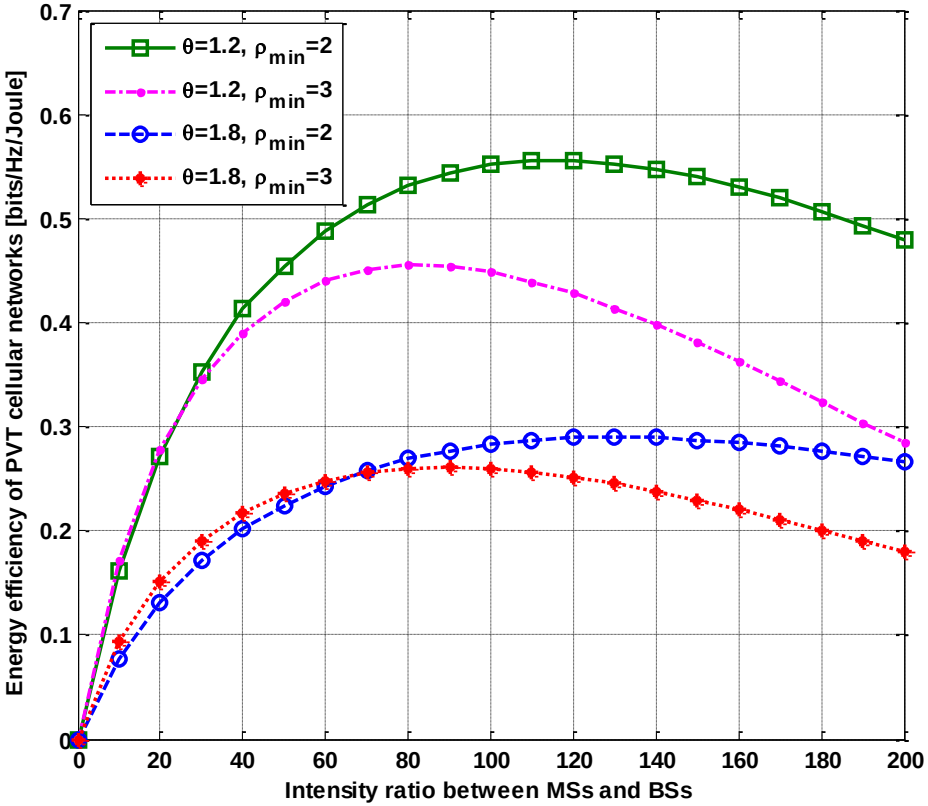
  - Minimum data (traffic) rate x_0
  - BER target $p_b \Rightarrow$ SIR gap Δ
  - Maximal transmission power

Energy Efficiency of PVT Cellular Networks (2)

Numerical results and discussions

$$\eta_{\mathrm{EE,max}} = 0.55,\ 0.45,\ 0.29,\ 0.26\ \mathrm{bits/Hz/Joule}$$

$$\left.\frac{\lambda_M}{\lambda_B}\right|_{\mathrm{opt}} \approx 110,\ 80,\ 130,\ 90$$



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

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

$$\left.\frac{\lambda_M}{\lambda_B}\right|_{\mathrm{opt}} \approx 170,\ 130,\ 100$$

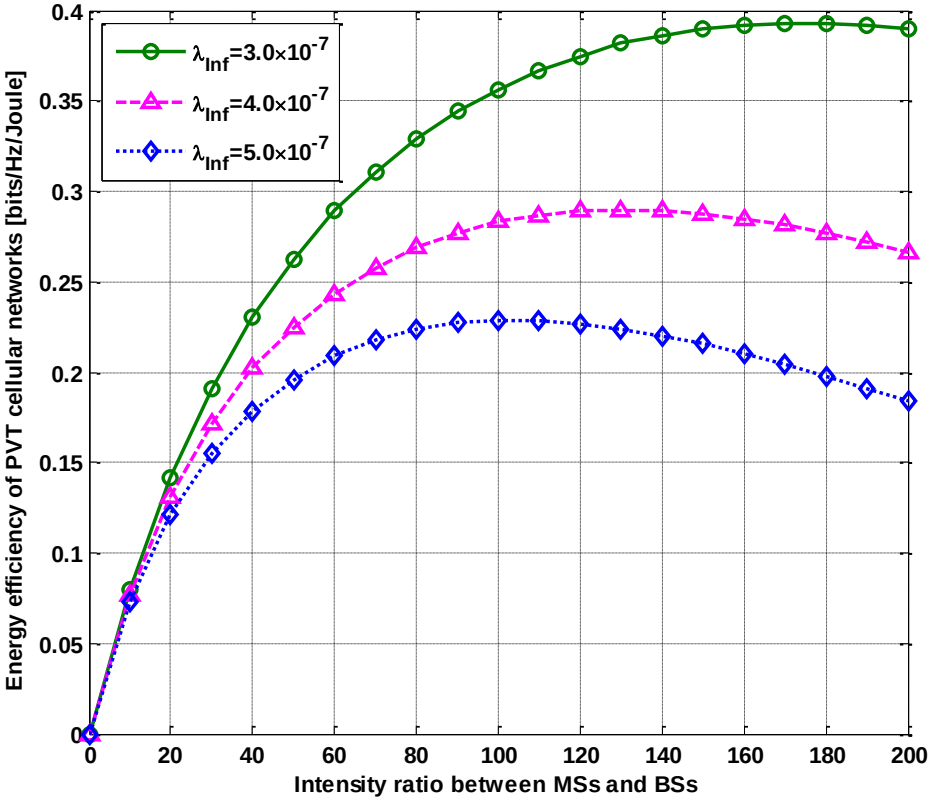
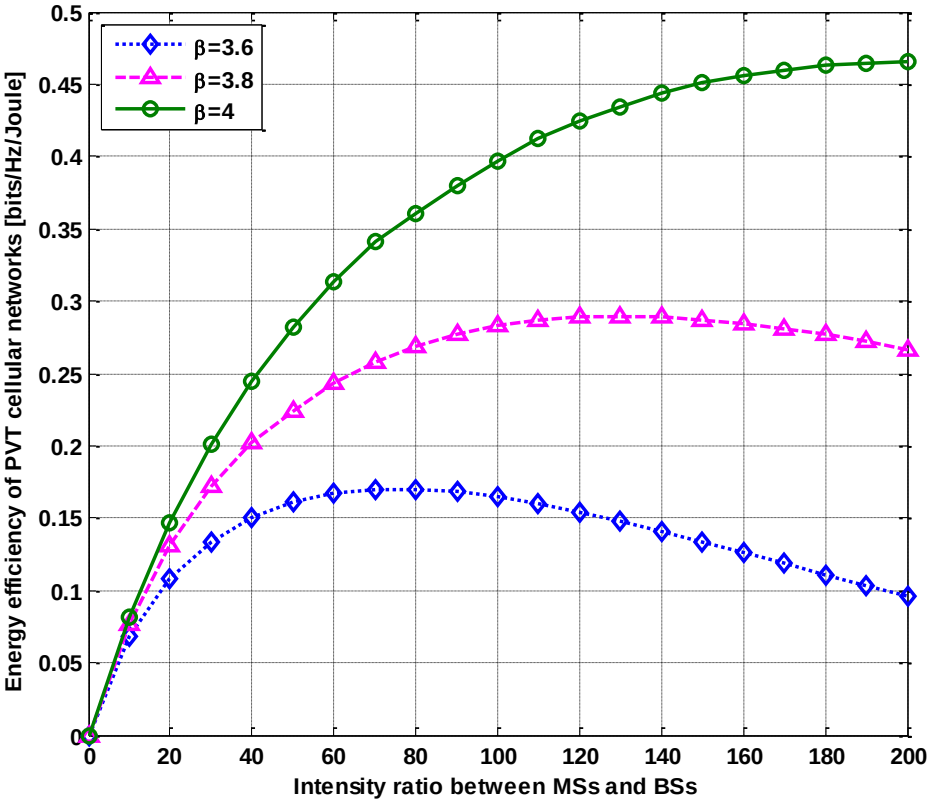


Fig. 9. Energy efficiency of PVT cellular networks with respect to the intensity ratio of MSs and BSs considering the interfering link intensity.

Energy Efficiency of PVT Cellular Networks (4)

Numerical results and discussions



$$\eta_{\mathrm{EE,max}} = 0.17,\ 0.29,\ 0.46\ \mathrm{bits/Hz/Joule}$$

$$\left.\frac{\lambda_M}{\lambda_B}\right|_{\mathrm{opt}} \approx 80,\ 130,\ 190$$

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 list of deliverables

A. Publications

[1] L. Xiang, **Xiaohu Ge (corresponding author), Cheng-Xiang Wang**, Frank Y. Li and Frank Reichert, "Energy Efficiency Evaluation of Cellular Networks Based on Spatial Distributions of Traffic Load and Power Consumption," ***IEEE Trans. On Wireless Commun.***, minor revision.

[2] **Xiaohu Ge**, K. Huang, **Cheng-Xiang Wang**, X. Hong, "Capacity Analysis of a Multi-Cell Multi-Antenna Cooperative Cellular Network with Co-Channel Interference," ***IEEE Trans. On Wireless Commun.***, vol. 10, no. 10, pp. 3298-3309, Oct. 2011.

[3] I. Humar, **Xiaohu Ge (corresponding author)**, L. Xiang, J. Ho, M. Chen, "Rethinking Energy‐Efficiency Models of Cellular Networks with Embodied Energy," ***IEEE Network Magazine***, Vol.25, No.3, pp.40-49, March, 2011.

[4] L. Xiang, **Xiaohu Ge**, C. Liu, L. Shu, **Cheng-Xiang Wang**, "A New Hybrid Network Traffic Prediction Method," *IEEE Proc. Conf. GlobeCom 2010*, Miami, USA, Dec. 2010. (**A Best Paper Award**)

[5] Z. Chen, **Cheng-Xiang Wang**, X. Hong, J. S. Thompson, S. A. Vorobyov, **Xiaohu Ge**, H. Xiao, and F. Zhao, "Aggregate interference modeling in cognitive radio networks with power and contention control," ***IEEE Trans. Commun.***, Vol.60, No.2, pp. 456-468, Feb., 2012.

[6] X. Hong, **Cheng-Xiang Wang**, J. S. Thompson, B. Allen, W. Q. Malik, and **Xiaohu Ge**, "On space-frequency correlation of UWB MIMO channels," ***IEEE Trans. on Vehicular Technology.***, vol. 59, no. 9, pp. 4201-4213, Nov. 2010.

[7] X. Hong, **Cheng-Xiang Wang**, M. Uysal, **Xiaohu Ge**, and S. Ouyang "Capacity analysis of hybrid cognitive radio networks with distributed VAAs," ***IEEE Trans. Vehicular Technology***, vol. 59, no. 7, pp. 3510-3523, Sept. 2010.

[8] **Cheng-Xiang Wang**, X. Hong, **Xiaohu Ge**, X. Cheng, G. Zhang, and J. S. Thompson, "Cooperative MIMO channel models: a survey," *IEEE Communications Magazine*, vol. 48, no. 2, pp. 80-87, Feb. 2010.

[9] **Xiaohu Ge**, J. hu, Cheng-Xiang Wang, J. Zhang and X. Yang "Energy Efficiency Analysis of MISO-OFDM Communication Systems Considering Power and Capacity Constraints," *ACM Mobile Networks and Applications*, Vol.17, No.1, pp.29-35, Feb. 2012.

[10] **Xiaohu Ge**, **Cheng-Xiang Wang**, Y. Yang, L. Shu, C. Liu, and L. Xiang, "AFSO: an adaptive frame size optimization mechanism for IEEE 802.11 wireless networks," *KSII Trans. on Internet and Information Systems*, vol. 4, no. 3, pp. 205-223, June 2010.

[11] **Xiaohu Ge**, Y. Yang, **Cheng-Xiang Wang**, Y.-Z. Liu, C. Liu, and L. Xiang, "Characteristics analysis and modeling of frame traffic in 802.11 wireless networks," *Wireless Communications and Mobile Computing*, John Wiley & Sons, vol. 10, no. 4, pp. 584-592, Apr. 2010.

[12] Z. Chen, **C.-X. Wang**, X. Hong, J. S. Thompson, S. Vorobyov, F. Zhao, and **Xiaohu Ge**, "Interference mitigation for cognitive radio MIMO systems based on practical precoding," **Invited Paper**, *Elsevier Physical Communication*, accepted for publication.

[13] F. S. Haider, **Cheng-Xiang Wang**, H. Haas, E. Hepsaydir, and **Xiaohu Ge**, "Energy-efficient subcarrier-and-bit allocation in multi-user OFDMA systems," in *Proc. IEEE VTC'12-Spring*, Yokohama, Japan, May 2012.

[14] Y. Yuan, X. Cheng, **Cheng-Xiang Wang**, D. I. Laurenson, **Xiaohu Ge**, and F. Zhao, "Space-time correlation properties of a 3D two-sphere model for non-isotropic MIMO mobile-to-mobile channels", *Proc. IEEE Globecom'10*, Miami, USA, Dec. 2010.

[15] X. Cheng, **Cheng-Xiang Wang**, Y. Yuan, D. I. Laurenson, and **Xiaohu Ge**, "A novel 3D regular-shaped geometry-based stochastic model for non-isotropic MIMO mobile-to-mobile channels", **invited paper**, *Proc. IEEE VTC'10-Fall*, Ottawa, Canada, 6-9 Sept. 2010.

[16] Z. Chen, **Cheng-Xiang Wang**, X. Hong, J. S. Thompson, S. A. Vorobyov, and **Xiaohu Ge**, "Interference modeling for cognitive radio networks with power and contention control," *Proc. IEEE WCNC 2010*, Sydney, Australia, 18-21 Apr. 2010.

[17]A. Ghazal, **Cheng-Xiang Wang**, H. Haas, M. Beach, X. Lu, D. Yuan, and **Xiaohu Ge**, "A Non-Stationary MIMO Channel Model for High-Speed Train Communication Systems," *Proc. IEEE VTC 2012-spring*, May 6-9, Yokohama, Japan.

B. Joint Projects

1. China Hubei Provincial Science and Technology Department, “Joint Research on Key Technologies of Next Generation Green Broadband Mobile Communications,” Principal Investigator: Xiaohu Ge, Foreign Partner: Cheng-Xiang Wang, Research Period: 2011~2013, Budget: 100,000 RMB (10,000GBP)
2. 2012 NSFC (National Natural Science Foundation China) Major International Joint Research Project, “Research on Theory and Key Technologies of Information Spatial Cooperation Optimization in Green Communication Networks,” Joint submitted by Xiaohu Ge and Cheng-Xiang Wang.

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 !