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Energy-Delay Tradeoff in Hyper-Cellular Networks with Base Station Sleeping Control


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[Appreciation to: Jian Wu, Xueying Guo, Jianan Zhang, Sheng Zhou, P. R. Kumar]
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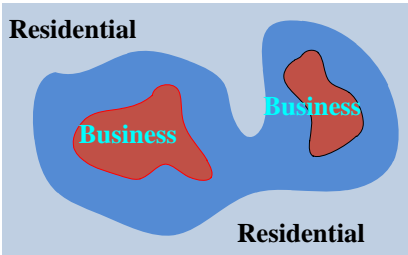
Feb.4, 2014 @ ICNC2014



Energy Waste in Cellular Networks



- All BSs are ON (*active*) all the time (in order to keep coverage), although traffic is almost zero in many areas
- Each BS almost transmits in *peak* power, although peak traffic only lasts for a very short time in most cells
- Multi-BSs (*small cells, HetNet*) are *densely* deployed in many areas without any collaboration (*work almost independently*)
- As cell size is getting *smaller* AND traffic dynamics more *bursty*, energy waste is getting more serious

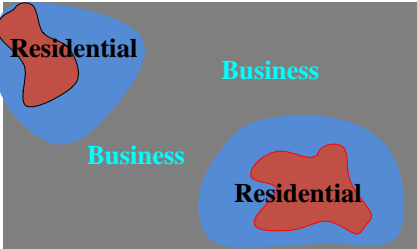


Residential

Business

Business

Residential



Residential

Business

Business

Residential

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Daytime
Nighttime
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Ways to Reduce Energy Waste

- ❖ **Exploiting traffic dynamics** (*reduce energy consumption when traffic is low*)
 - Targeting **THROUGHPUT** rather than **CAPACITY** per joule
- ❖ **Exploit energy model** (*much energy is consumed at BB/PA/AC rather than RF, therefore **BS sleeping** is the most efficient way for energy saving*)
 - Targeting **TOTAL ENERGY** rather than **RF power reduction only**
- ❖ **Exploit cell collaboration** (*cell densification and HetNet make cell collaboration possible, helping to turn more BSs off*)
 - Targeting **NETWORK** rather than **LINK/CELL** performance
- ❖ **GREEN: Globally Resource-optimized & Energy-Efficient Networks**
 - **GREEN** should be a *holistic* approach with *paradigm shift*
 - Cellular networks should be more *flexible* and *smart*

Key idea: *Reduce Energy Waste by Adapting to Real-traffic Dynamics (REWARD)*

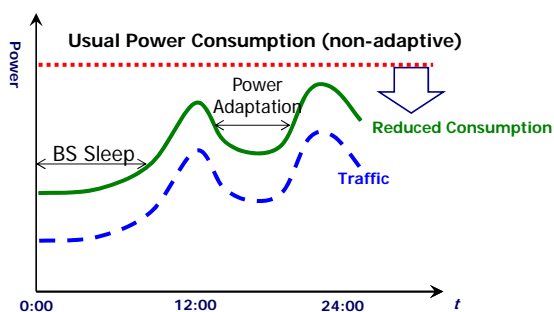
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Paradigm Shift (1): Adapt to Traffic Dynamics

(Traffic dynamics can provide opportunities for energy saving)

- ◆ **Tango: Traffic-aware network planning & green operation**
 - Adapted to traffic distribution (*temporally and spatially non-uniform*)
 - Adapted to traffic characteristics (*unicast, multicast, broadcast*)
 - Adapted to QoS requirements (*realtime, nonrealtime*)



Key challenge: How to guarantee the **coverage** and **QoS**?
How to **model** and predict traffic dynamics?


Z. Niu, "TANGO: Traffic-Aware Network Planning and Green Operation",
IEEE Wireless Commun., Oct.2011 (invited article)

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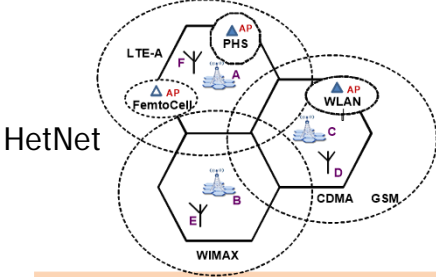
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Paradigm Shift (2): Adapt to Environment

(BS collaboration can provide opportunities for energy saving)




- **CHORUS: Collaborative & Harmonized Open Radio Ubiquitous System**
 - **Open Radio:** *spectrum in HetNet are shared by multi-modal terminals (software defined radio)*
 - **Globally optimized:** *cross-layer → cross-node → cross-network/system (software defined network)*



HetNet

cross-layer → cross-node design

cross-network system design




Challenges: 1) How to detect the NSI? (*information explosion and incompleteness?*)
 2) How to virtualize the network resources? (*self-optimizing networks*)

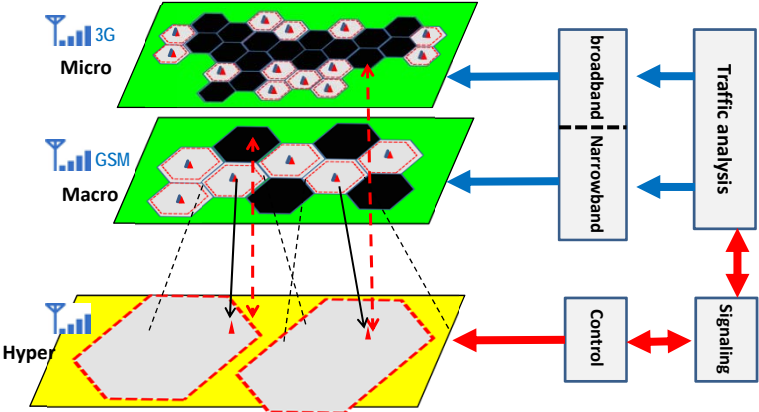
[1] S. Zhou, **Z. Niu**, S. Tanabe, "CHORUS: Collaborative and Harmonized Open Radio Ubiquitous Systems", *4th Intl. Conf. Commun. Sys. & Nets. (COMSNETS)*, Bangalore, India, Jan. 2012 (invited)
 [2] S. Zhou, Z. Niu, S. Tanabe, and P. Yang, "CHORUS: Framework for Scalable Collaboration in Heterogeneous Networks with Cognitive Synergy," *IEEE Wireless Commun. Mag.*, accepted, 2012

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A Novel Cellular Architecture: Hyper-Cellular

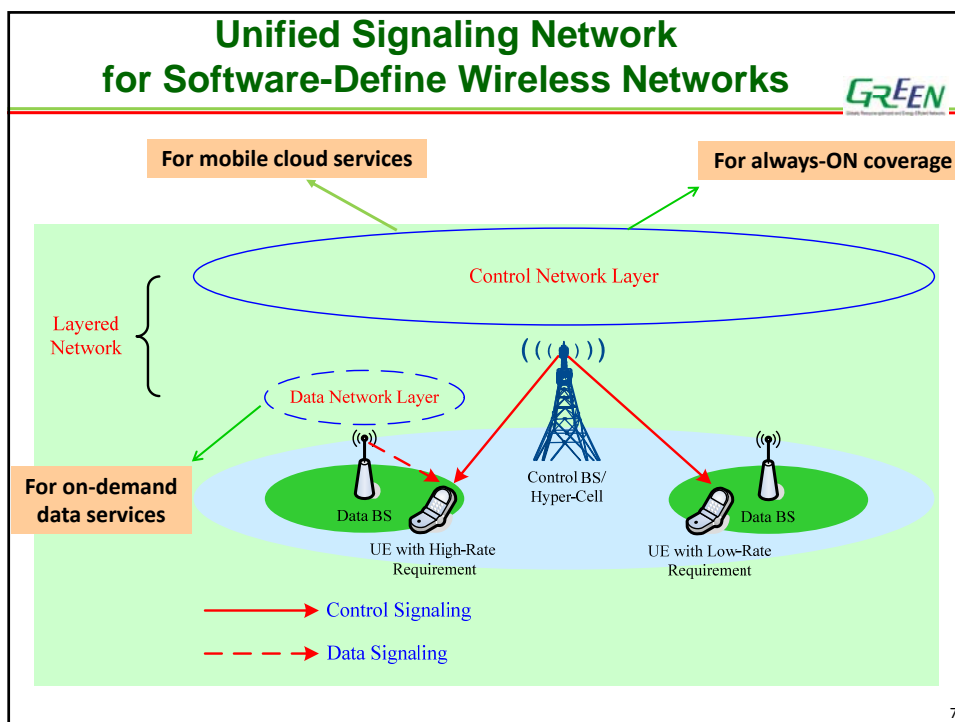


- **Hyper-Cellular Networks:** *Decouple signaling and data coverage so that data cells could be more adaptive to traffic and network state, and also friendly to global resource optimization*



Z. Niu, S. Zhou, S. Zhou, X. Zhong, J. Wang, "A Hyper-Cellular Paradigm for Globally Resource-optimized and Energy-Efficient Networks (GREEN)", *Science in China*, Sep. 2012 (in Chinese)

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Energy-Delay Tradeoff in GREEN Communications

GREEN

- **Background: Both TANGO and CHORUS approaches will bring more delays (i.e., trade delay for energy)**
 - Cell Zooming, BS Sleep, BS Cooperation, Relaying, Power control, ...
- **Question: How much energy can be traded off by a tolerable delay? (Guideline for incentive design and tariff mechanism)**
 - Encourage users to **shift the peaks** to create more opportunities for sleeping
- **Challenge #1: Both energy and delay concepts need to be extended**
 - Energy = transmitting power + **circuit** (processing) power + **basic** power
= power x **time**
 - Delay = transmitting delay + **queueing** delay + **sleeping** period
= average + **delay variation**
- **Challenge #2: Energy-Delay-Tradeoff should be evaluated in the whole network wide**
 - EDT on link-level → **single-cell** level → **multi-cell** level

Energy-Delay Tradeoff is getting much more complicated

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Ex: Transmit Power vs Transmit Delay



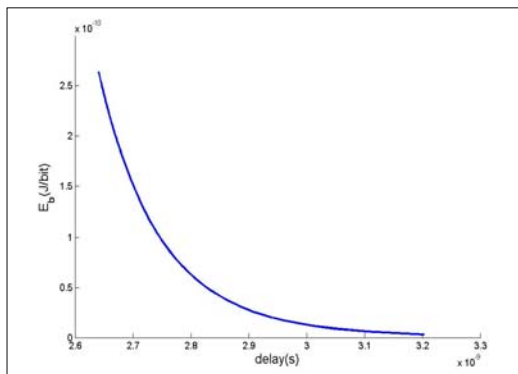
❖ AWGN Channel

- Upper limit of transmit rate

$$R = W \log_2 \left(1 + \frac{P}{WN_0} \right)$$
- Delay per bit

$$t_b = 1 / R$$
- Energy per bit

$$E_b = WN_0 t_b (2^{1/t_b W} - 1)$$



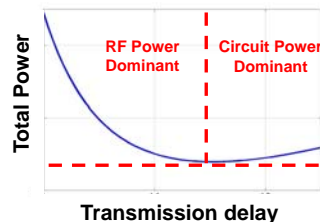
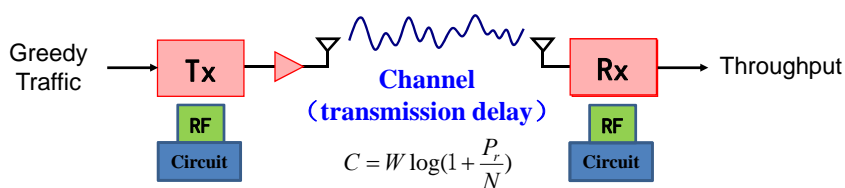
Power can be traded off by delay!

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Ex: Total Power vs Transmission Delay



Energy and Delay is not always a tradeoff!
But, traffic dynamics was not considered (no queueing delay, etc)

G. Miao, G. Y. Li, "Cross-Layer Energy-Efficient Wireless Communications: A survey," *Wireless Com & Mobile Comp*, 2009

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Ex: Impact of Queueing Delay on EDT

Exp ($s\mu$)

M/M/1(0) – realtime service system

$P_B^{(1)} = \rho_1 / (1 + \rho_1)$

where $\rho_1 = \lambda / s\mu$

Exp (μ)

M/M/1(k) – non realtime service system

$P_B^{(2)} = \rho_2^{k+1} (1 - \rho_2) / (1 - \rho_2^{k+2})$

where $\rho_2 = \lambda / \mu$

$P_B^{(1)} = P_B^{(2)}$

$s = \lceil (1 - \rho_2^{k+1}) / [(1 - \rho_2) \rho_2^k] \rceil$

For $k=2$ and $\rho_2=0.5$, then $s=7$, while $W_2 = 1.7\mu_2^{-1}$

For $k=8$ and $\rho_2=0.5$, then $s=511$, while $W_2 = 1.9\mu_2^{-1}$

Considering $C = W \log(1 + \frac{P}{N})$, we know a small delay can trade for a great amount of energy savings

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Characterizing EDT need to combine IT and QT

- Information Theory (IT) focuses mainly on **link capacity** (i.e., capability) over *noisy* channels, but not *traffic dynamics*
- Queueing Theory (QT) focuses mainly on *traffic dynamics* and **system performance**, but not channel *unreliability*

A. Ephremides, B. Hajek, "Information Theory and Communication Networks: an Unconsummated Union", IEEE Trans. IT, Oct. 1998

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Optimal Condition of a Queueing System

- For a given traffic load, what's the best service rate?
 - Higher service rate (capacity) \rightarrow lower queueing delay W_q (higher throughput)
 - Lower service rate (capacity) \rightarrow higher server utilization ρ (less energy waste)
- Considering a queue as a *blackbox* with *equivalent* service rate $\mu' = 1/(W_q + 1/\mu)$, maximize $\rho\mu'$ – *effective power*
 - For M/G/1, $\rho\mu' = 2\mu q\rho(1-\rho)/[\rho\mu^2 b_2 + 2(1-\rho)]$, which leads to

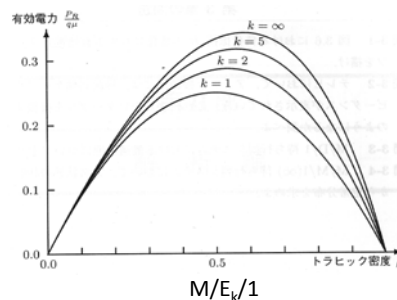
$$\rho_{opt} = 1/[1 + \text{sqrt}(\mu^2 b_2/2)]$$

$$W_q^{opt} = \text{sqrt}(b_2/2)$$

$$W^{opt} = \text{sqrt}(b_2/2) + 1/\mu$$

$$L_q^{opt} = \rho_{opt} \text{sqrt}(\mu^2 b_2/2)$$

$$L^{opt} = \rho_{opt} [\text{sqrt}(\mu^2 b_2/2) + 1] = 1 (!)$$

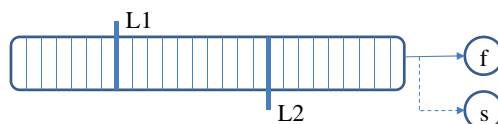


How does sleep operation change this EDT? (When and how long should the BS sleep?)

Y. Yoshioka, "on the Optimization of Queueing Systems", IEICE Trans. Commun., Aug. 1977. (in Japanese)
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Dynamic Control of a Queue

- Considers a $M^{[x]}/M/2$ queue. The **faster server** is always on, but the **slower server** is only used when the queue length exceeds a certain level and switched off when it completes a service.
- Activating the slower server involves **fixed set-up costs**. Also there are **linear operating costs** and **linear holding costs**.
- **Conclusion:** the **two-level hysteretic switching rule** that turns the slower server on when the number of jobs in the system exceeds some pre-specified upper level and turns the slower server off when upon service completion by the slower server the number of jobs left behind is below some pre-specified lower level.



Rein D. Nobel and Henk C. Tijms, "Optimal Control of a Queueing System with Heterogeneous Servers and Setup Costs", *IEEE Trans. Automatic Control*, April 2000

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How does sleep operation change the tradeoff?



- For a typical server under *dynamic* load, where entering and leaving sleeping mode incurs an energy and a response time penalty, the *optimal sleeping* policy has a simple *hysteretic* structure
 - When asleep, the server stay in OFF mode until the queue builds up to the point where the *ON threshold* is met
 - After waking up, the server stays awake until all jobs in the queue are processed and then is turned OFF
- Compared with a baseline policy that never puts the server to sleep, it was shown that
 - low utilization can result in almost **87%** energy saved
 - high utilization results in only **7.4%** energy saved

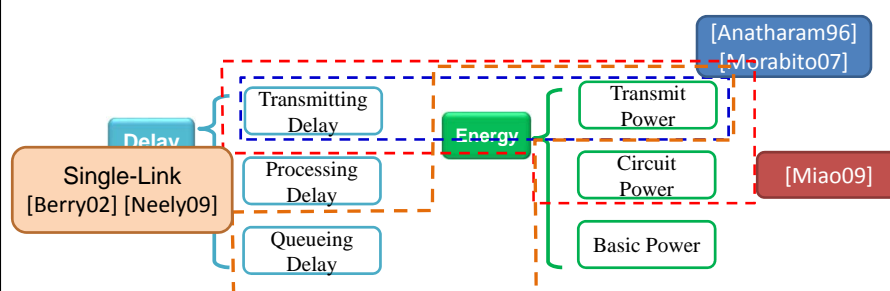
Ioannis Kamitsos, Lachlan Andrew, Hongseok Kim, Mung Chiang, “Optimal Sleep Patterns for Serving Delay-Tolerant Jobs”, Proceedings of the 1st International Conference on Energy-Efficient Computing and Networking, pp.31-40, 2010

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Other Related Work



[Berry02] R. A. Berry, R. G. Gallager, “Communication over Fading Channels with Delay Constraints”, IEEE Trans. IT, May. 2002

[Neely09] M.J. Neely, “ Intelligent Packet Dropping for Optimal Energy-Delay Tradeoffs in Wireless Downlinks”, IEEE Trans. Automatic Control, March 2009

[Chen11] Y. Chen , G. Y. Li, et al, “Fundamental trade-offs on green wireless networks”, IEEE Comm. Mag., June 2011

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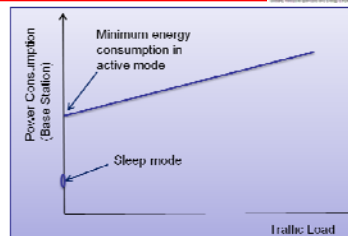
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M/G/1 Vacation queue with setup and close-down time

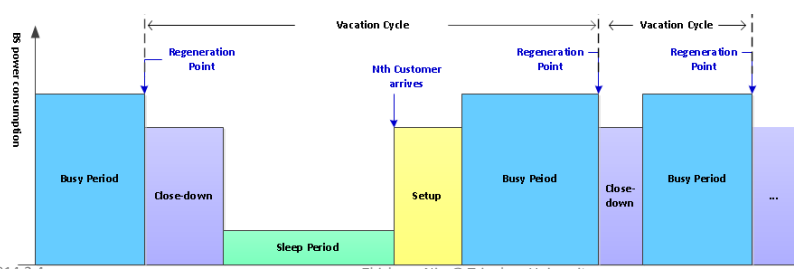
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• Rationale of single-server queue

- Consider whole BS as a single server, which is either serving customers (busy) or idling (close-down, idle, setup)



$$P_{in} = \begin{cases} P_o + \Delta_P \cdot P_{out} & \text{active} \\ P_{sleep} & \text{sleep.} \end{cases}$$



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Some Preliminary Studies

GREEN

1. Z. NIU and Y. TAKAHASHI, "A Finite-Capacity Queue with Exhaustive vacation/close-down/setup times and Markovian Arrival Processes", *QUESTA*, vol.31, no.1, pp.1-23, 1999.
2. Z. Niu, T. Shu, Y. Takahashi, "A Vacation Queue with Setup and Close-down Times and Batch Markovian Arrival Processes", *Performance Evaluation*, vol. 54, pp.225-248, 2003.
3. F. Zhu, Y. Wu and Z. Niu, "Delay analysis for sleep-based power saving mechanisms with downlink and uplink traffic," *IEEE Com Lett*, 2009.
4. F. Zhu, Z. Niu, "Queueing Delay and Energy Efficiency Analyses of Sleep Based Power Saving Mechanism", *IEICE Tran Com*, 2010.4

Z. Niu, Jianan Zhang, Xueying Guo, Sheng Zhou, "On the Energy-Delay Tradeoff in Base State Sleep Mode Operation", *The 13th International Conference on Communication Systems*, Singapore, 21-23 Nov., 2012 (invited)

Xueying Guo, Sheng Zhou, P. R. Kumar, Zhisheng Niu, "Optimal Wake-up Mechanism for Single Base Station with Sleep Mode", *25th International Teletraffic Congress (ITC25)*, Shanghai, China, Sep. 2013. (Best Student Paper Award)

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EDT in terms of Close-down Time



• M/G/1 N-policy vacation queue with setup and close-down time

– Impact of *close-down* time

Mean Sojourn Time

$$E[T] = E[B] + \frac{\lambda E[B^2]}{2(1-\rho)} + \frac{\tilde{D}(\lambda)[N(N-1) + 2N\lambda E[S] + \lambda^2 E[S^2]]}{2\lambda[\tilde{D}(\lambda)(N + \lambda E[S]) + 1 - \tilde{D}(\lambda)]}$$

Average Power

$$E[P] = \frac{1}{E[C]} \left[\frac{1 - \tilde{D}(\lambda)}{\lambda} (P_{CD} - P_{SL}) + \tilde{D}(\lambda) E[S] (P_{ST} - P_{SL}) + (1 - \rho) P_{SL} + \rho P_{ON} \right]$$

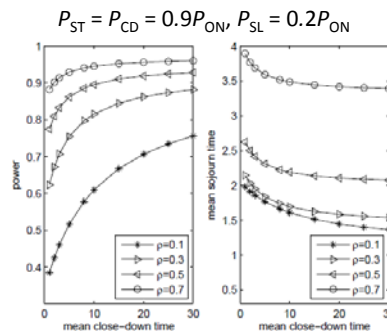


Fig. 1. Mean sojourn time (normalized by $1/\mu$) and mean power (normalized by P_{ON}) vs. mean close-down time (normalized by $1/\mu$) in an 1-policy M/M/1 queue with exponentially distributed close-down time and deterministic setup time. $E[S] = 1/\mu$.

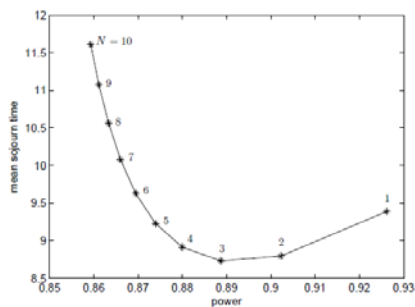
Sleep mode brings more benefits on energy saving when traffic load is light

EDT in terms of Close-down Time and N



Power –Delay Tradeoff

$$E[P] = \rho P_{ON} + (1 - \rho) P_{CD} + (1 - \rho) \frac{2\lambda[E[T] - E[B] - E[B^2]\lambda/2(1-\rho)]}{E[S^2]\lambda^2 + 2NE[S]\lambda + N(N-1)} \times [E[S]\lambda(P_{ST} - P_{SL}) - (N + E[S]\lambda)(P_{CD} - P_{SL})]$$



$$E[S] = 1/\mu, \lambda E[S] = 0.8, C_S^2 = 25$$

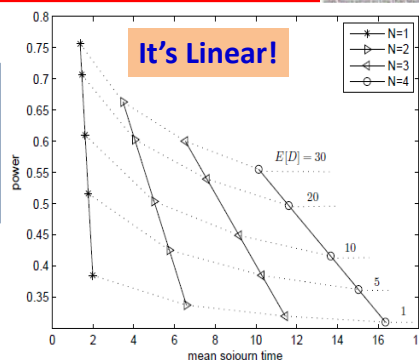


Fig. 2. Mean sojourn time (normalized by $1/\mu$) vs. mean power (normalized by P_{ON}) in an N-policy M/M/1 queue with exponentially distributed close-down time and deterministic setup time (changing the close-down time). $\rho = 0.1, E[S] = 1/\mu$.

Without sleep operation, EDT always exists
With sleep operation, energy can be further reduced by $(1 - \rho)(P_{id} - P_{sl})/(\lambda L_{data})$ with same delay

EDT in terms of N and Setup Time



- **Impact of N** (for simplicity, assume *close-down time* equals to zero)

$$E[P] = \rho P_{ON} + (1 - \rho) P_{SL} + \frac{\lambda(1 - \rho)E[S]}{N + \lambda E[S]} (P_{ST} - P_{SL})$$

$$E[T] = E[B] + \frac{\lambda E[B^2]}{2(1 - \rho)} + \frac{N(N - 1) + 2N\lambda E[S] + \lambda^2 E[S^2]}{2\lambda(N + \lambda E[S])}$$

If we generalize N to real numbers, in condition that $\sqrt{C_S^2 + 1/(\lambda E[S])} > 1$, there exists an $N_{\text{delay optimal}}$ that minimizes $E[T]$, i.e.,

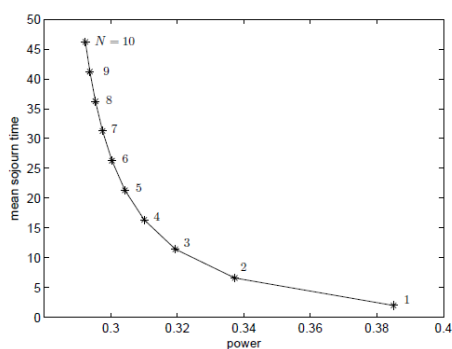
$$N_{\text{delay optimal}} = \lambda E[S] (\sqrt{C_S^2 + 1/(\lambda E[S])} - 1)$$

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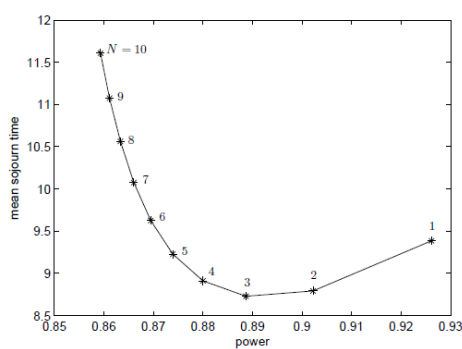
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Optimization of N



$$E[S] = 1/\mu, \lambda E[S] = \hat{0}.1, C_S^2 = 0$$

Monotone if setup time is fixed and therefore $N=1$ is optimal



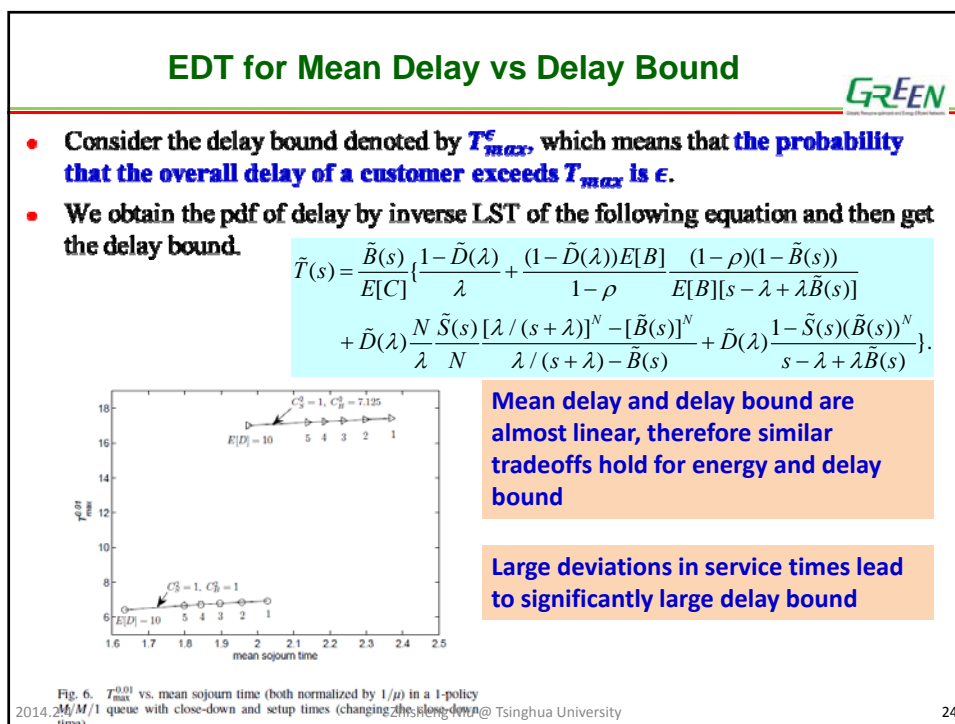
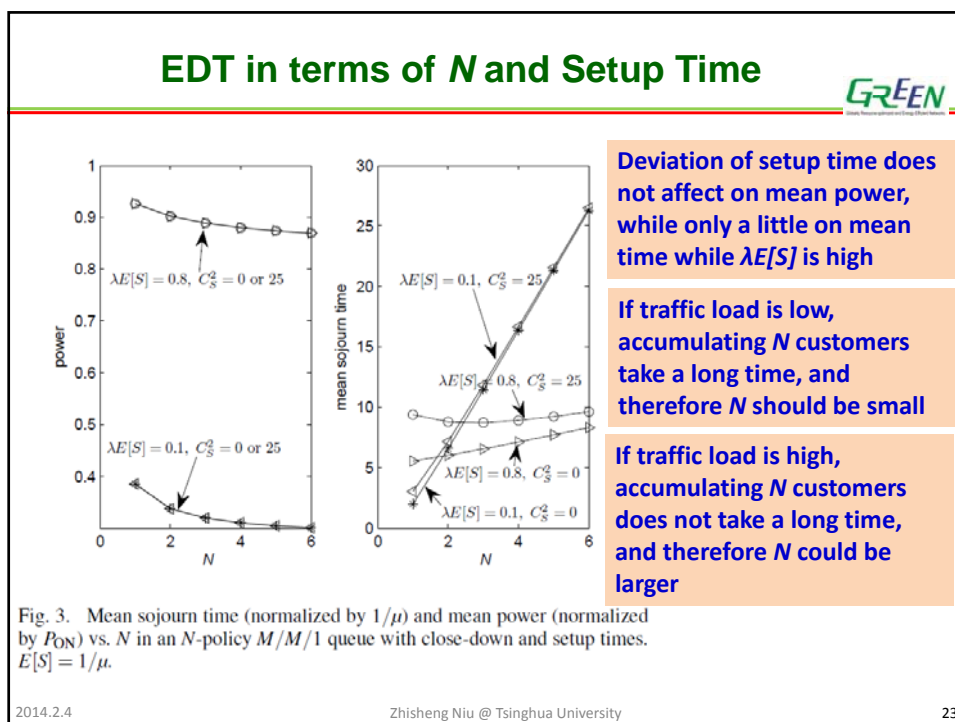
$$E[S] = 1/\mu, \lambda E[S] = \hat{0}.8, C_S^2 = 25$$

Convex if setup time is bursty and therefore there is an optimal $N > 1$

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Traffic-aware **Dynamic** Sleeping Control and Power Adaptation in GREEN Communication

J. Wu, Z. Niu, S. Zhou, "Traffic-Aware Base Station Sleeping Control and Power Matching for Energy-Delay Tradeoffs in Green Cellular Networks", *IEEE Trans. Wireless Commun.*, Vol.12, no.8, Aug. 2013

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Dynamic Power Adaptation without Sleep

• System Modeling

– Single Cell with n users, Processor-sharing model^[1]

– Traffic dynamics:

✓ Large-scale: *load-aware*

✓ Small-scale: *queue-aware*

– Optimization **delay** **power**

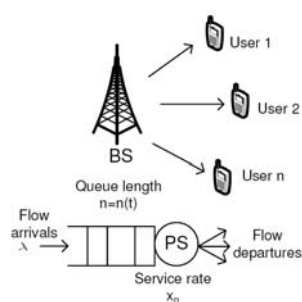
$$z(\mathbf{x}) = \sum_{n=1}^{\infty} \underbrace{q_n(\mathbf{x})}_{\text{delay}} [n] + \underbrace{P(x_n)}_{\text{power}} / \beta$$

✓ where $x_n = w \log_2(1 + \gamma P_t(n))$, $\gamma = g/N_0u$.

– Lambert function: $W(z)$

$$W(z)e^{W(z)} = z, z \in \mathbb{C} \quad W_0: \mathcal{D}_{W_0} = [-e^{-1}, +\infty) \mapsto [-1, +\infty)$$

[1] S.C. Borst, "User-level performance of channel-aware scheduling algorithms in wireless data networks". *Proc. Infocom 2003 Conference*.



Dynamic Power Adaptation without Sleep



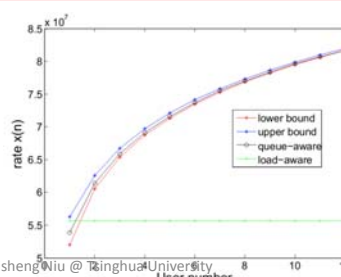
• Upper and lower bounds

$$\mathbf{W}\left(\frac{1}{\alpha e} \left(\frac{x_s^*}{x_s^* - \lambda l}\right)^2 - \frac{1}{e}\right) = \frac{\ln 2}{w} x_s^* - 1.$$

Upper bound:
$$x_n^* \leq \min \left\{ w \log_2 \left(\frac{1}{\alpha} \left(\frac{n + \alpha 2^{\frac{M}{w}} (e^{1+R(n)} - 1)}{1 + R(n)} + \frac{\frac{M \ln 2}{w}}{(1 + R(n))^2} \right) \right), \right.$$

$$\left. w \log_2 \left(\frac{1}{\alpha \ln 2} \left(\frac{n + \alpha 2^{\frac{M}{w}} (2^{t^*} - 1)}{t^*} + \frac{\frac{M}{w}}{t^{*2}} \right) \right) \right\}$$

Lower bound:
$$x_n^* \geq \left(\mathbf{W} \left(\left(\frac{n - z_s^*}{\alpha} + 1 \right) e^{-\left(\frac{M \ln 2}{w} + 1 \right)} \right) + 1 \right) \frac{w}{\ln 2} + \lambda l$$



$$\lambda = 0.5, \quad l = 2MB$$

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Dynamic Power Adaptation with Sleep



• Objective function: *weighted sum of energy consumption and mean delay*

$$P^{tot} = p^{active} (P_o + \Delta P \cdot P_{out}) + p^{sleep} P_{sleep} + 2E_{sw} / \mathbb{E}(T_c)$$

where $T_c = T_a + T_s$ represents the cycle time and E_{sw} is the switching energy

$$P_{in} = \begin{cases} P_o + \Delta P \cdot P_{out} & \text{active} \\ P_{sleep} & \text{sleep.} \end{cases}$$

• Sleeping mechanism

- **N-based**: go to sleep whenever queue becomes empty and wake up if N requests accumulated during sleeping period
- **V-based**: go to sleep whenever queue becomes empty and wake up if V time expires

But, setup and close-down times and their impact on energy consumption not considered

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M/G/1 Processor Sharing Modeling

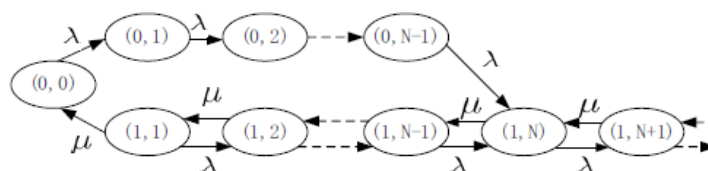


Fig. 1. The 2-D state transition diagram for the N -based sleep strategy.

$$P = \begin{cases} P_o + \Delta_P \tilde{P}_t(\rho), & \text{active mode,} \\ P_{sleep}, & \text{sleep mode.} \end{cases}$$

$$P_{N,x}^{tot} = \frac{\lambda l}{x} \left[P_o + \frac{\Delta_P}{\gamma} (2^{\frac{x}{B}} - 1) \right] + \left(1 - \frac{\lambda l}{x} \right) \left[P_{sleep} + \frac{2\lambda E_s}{N} \right]$$

$$D_{N,x} = \frac{l}{x - \lambda l} + \frac{N-1}{2\lambda}$$

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N -Policy: With or Without Sleep



Proposition 1: Compared with the power-matching without sleep control, using the N -based sleep scheme incorporated with power-matching

- i) has $\frac{N-1}{2\lambda}$ longer residence time in the average delay performance;
- ii) brings energy saving gain in the average total power consumption only when

$$\lambda < \frac{(P_o - P_{sleep})N}{2E_s}. \quad (14)$$

Sleep operation can only help to save energy when traffic load is lower than a specific value

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N-Policy: Region for EDT

Proposition 2: For the N -based sleep scheme, with varying service rate x ,

1. $P_{N,x}^{tot}$ is a monotonously decreasing function of $D_{N,x}$, when either one of the following conditions is satisfied.

$$i) \quad \lambda < \frac{(P_o - P_{sleep})N}{2E_s},$$

$$l \geq \frac{B}{\lambda \ln 2} \left[\mathbf{W} \left[\frac{\gamma}{\Delta P e} \left(P_o - P_{sleep} - \frac{2\lambda E_s}{N} \right) - \frac{1}{e} \right] + 1 \right].$$

$$ii) \quad \lambda \geq \frac{(P_o - P_{sleep})N}{2E_s}.$$

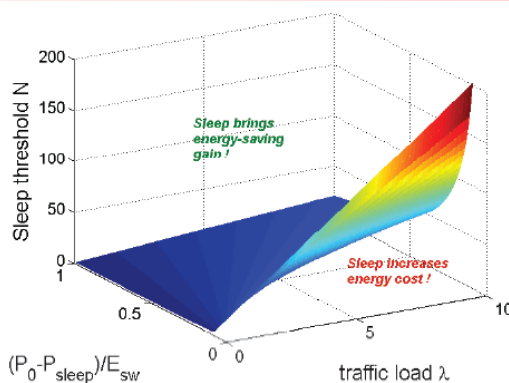
Energy can only be traded off by delay if traffic load is higher than a specific value in N -policy sleeping operation

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N-Policy: Region for Energy Saving Gain



Sleeping control helps to save energy only when

- 1) Traffic load is light,
- 2) $(P_o - P_{sleep})/E_{sw}$ is large, or
- 3) N is small

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N-Policy: Optimality of x^* and Lower Bound of P_{total}



2. For $P_{N,x}^{\text{tot}}[D_{N,x}]$, there exists the sole energy-optimal rate x_{en}^* when the following condition is satisfied,

$$\lambda < \frac{(P_o - P_{\text{sleep}})N}{2E_s},$$

If traffic load is further lower than a specific value (?), EDT doesn't exist all the time

$$l < \frac{B}{\lambda \ln 2} \left[\mathbf{W} \left[\frac{\gamma}{\Delta P e} \left(P_o - P_{\text{sleep}} - \frac{2\lambda E_s}{N} \right) - \frac{1}{e} \right] + 1 \right].$$

And the the energy-optimal rate is

$$x_{\text{en}}^* = \frac{B}{\ln 2} \left[\mathbf{W} \left[\frac{\gamma}{\Delta P e} \left(P_o - P_{\text{sleep}} - \frac{2\lambda E_s}{N} \right) - \frac{1}{e} \right] + 1 \right].$$

3. In both of the upper two cases, as delay goes to infinity, the total power consumption is bounded by $P_o + \frac{\Delta P}{\gamma} (2^{\frac{\lambda}{B}} - 1)$.

x_{en}^* is an increasing function of γ , so transmitting faster when channels are good indeed saves energy. In addition, fast transmission is beneficial when $P_o - P_{\text{sleep}}$ is larger

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Proposition 3: For the optimum power/delay curve $P_{N,x}^{\text{tot}*}[D_{N,x}]$, we have the following properties:

1. Given the tradeoff parameter β , in the optimal control pair (N^*, x^*) , x^* is the sole solution of the following equation

$$\mathbf{W} \left[\frac{\gamma}{\Delta P e} \left[\frac{\beta x^2}{\lambda(x - \lambda)^2} + P_o - P_{\text{sleep}} - \frac{2\lambda E_s}{N} - \frac{\Delta P}{\gamma} \right] \right] = \frac{\ln 2}{B} x - 1.$$

and the optimal threshold N^* is

$$N^* = 2\lambda \left[\frac{E_s}{\beta} \left(1 - \frac{\lambda l}{x} \right) \right]^{1/2}$$

N^* is related to the switching cost in a square root form!

2. For the limiting case, $P_{N,x}^{\text{tot}*}[D_{N,x}]$ is lower bounded by P_{lb}^* where

i) for $\rho \geq \frac{B}{\ln 2} \left[\mathbf{W} \left[\frac{\gamma(P_o - P_{\text{sleep}})}{\Delta P e} - \frac{1}{e} \right] + 1 \right]$,

$$P_{\text{lb}}^* = P_{N \rightarrow \infty, x \rightarrow \lambda l}^{\text{tot}} = P_o + \frac{\Delta P}{\gamma} (2^{\frac{\lambda}{B}} - 1). \quad (17)$$

ii) for $\rho < \frac{B}{\ln 2} \left[\mathbf{W} \left[\frac{\gamma(P_o - P_{\text{sleep}})}{\Delta P e} - \frac{1}{e} \right] + 1 \right]$,

$$P_{\text{lb}}^* = P_{N,x}^{\text{tot}} \left\{ N \rightarrow \infty, x = \frac{B}{\ln 2} \left[\mathbf{W} \left[\frac{\gamma(P_o - P_{\text{sleep}})}{\Delta P e} - \frac{1}{e} \right] + 1 \right] \right\}. \quad (18)$$

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N-Policy: Pareto-Optimal (N*, X*)

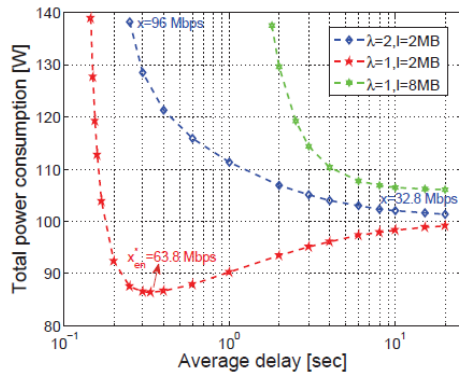


Fig. 3. Example of Proposition 2 with $N = 1$: the relationship of $P_{N,x}^{tot}$ and $D_{N,x}$. $P_o = 100W, P_{sleep} = 30W, E_s = 25J, \Delta p = 7$ [15].

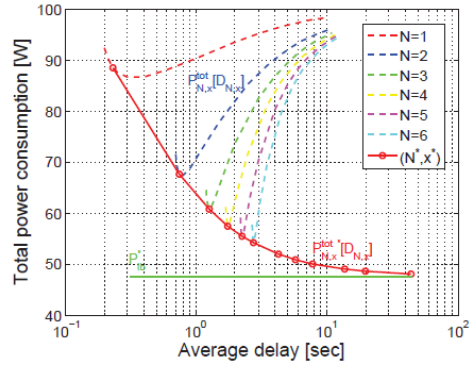


Fig. 4. The energy-delay tradeoff of N -based strategy with optimized threshold and transmit rate. $\lambda = 1, l = 2MB$.

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V-Policy: EDT with Different Weight



Proposition 4: Compared with the power-matching without sleep control, using the V -based sleep scheme incorporated with power-matching

i) has $\frac{\lambda v^2}{2(\lambda v + e^{-\lambda v})}$ longer residence time in the average delay performance;

ii) brings energy saving gain in the average total power consumption only when

$$P_o - P_{sleep} - \frac{2E_s}{v} > \frac{\Delta p(2^{\frac{x}{B}} - 1)}{\gamma e^{\lambda v}} \left[\frac{1 - e^{-\lambda v}}{\lambda v} - \frac{\lambda l}{x} \right]. \quad (25)$$

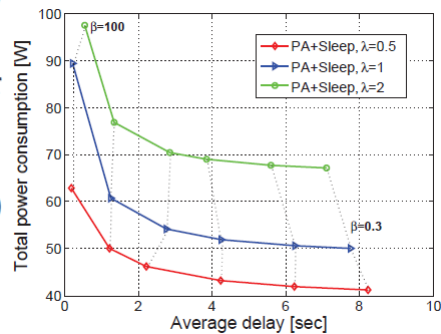
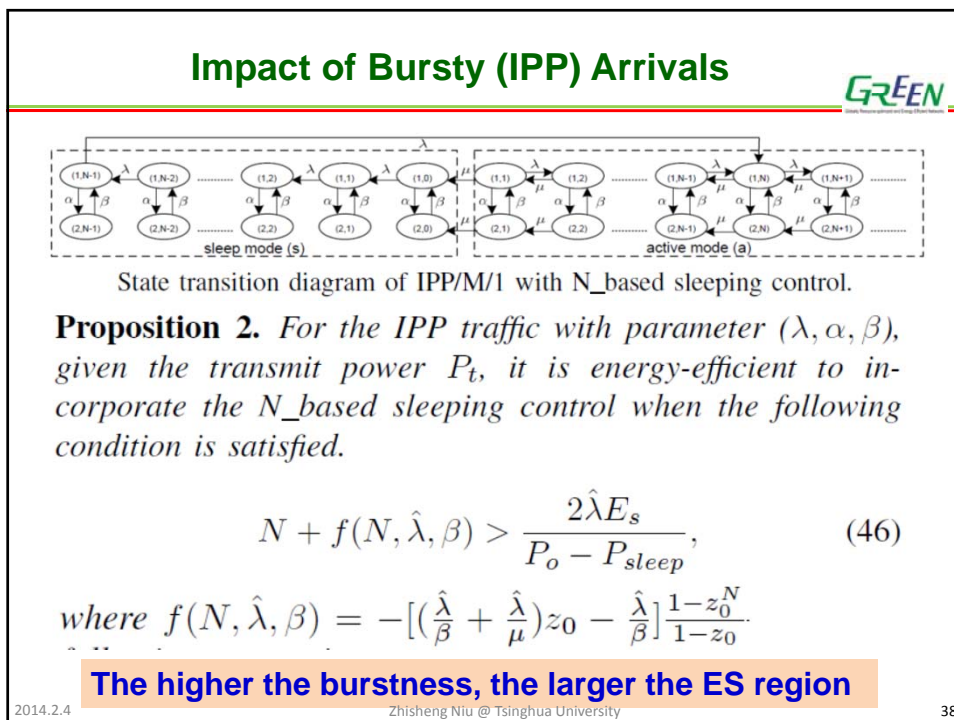
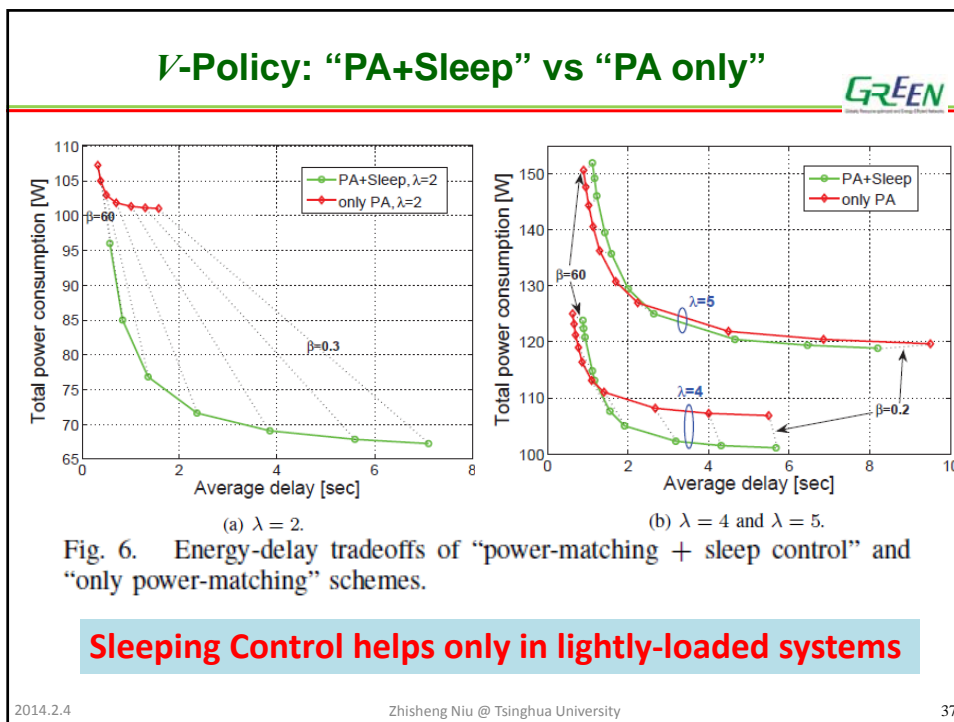


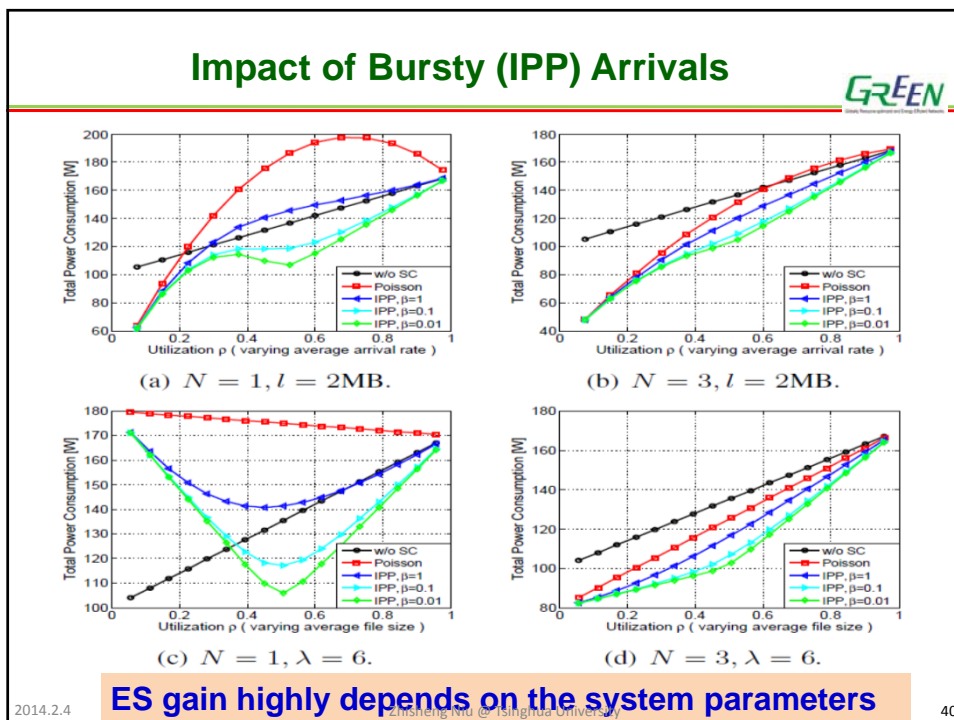
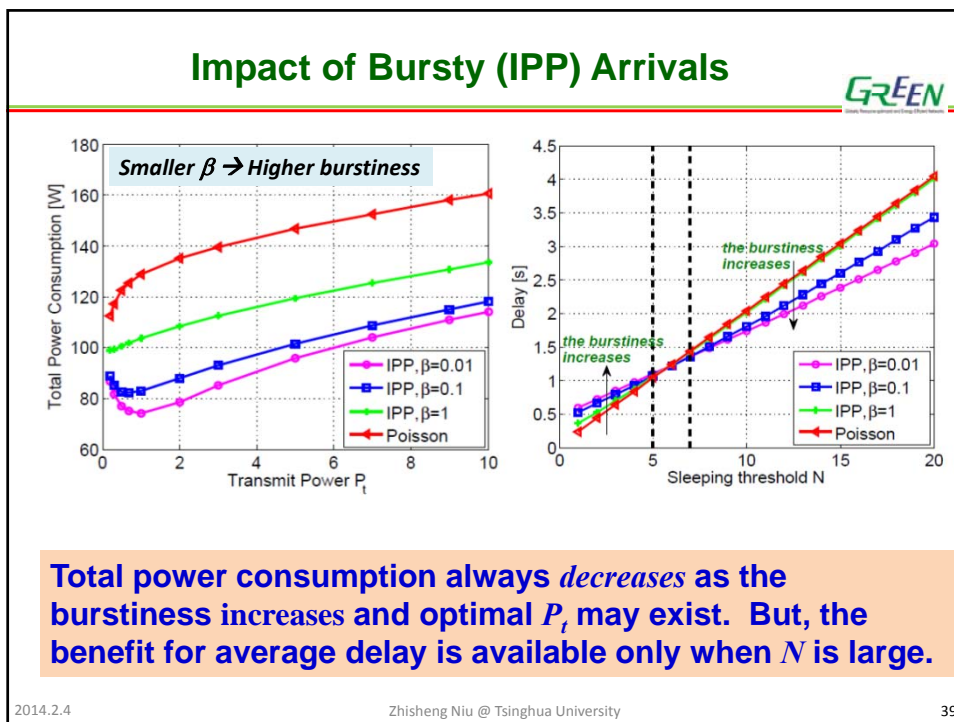
Fig. 5. The optimal energy-delay tradeoffs with “power-matching + sleep control” with different arrival rates.

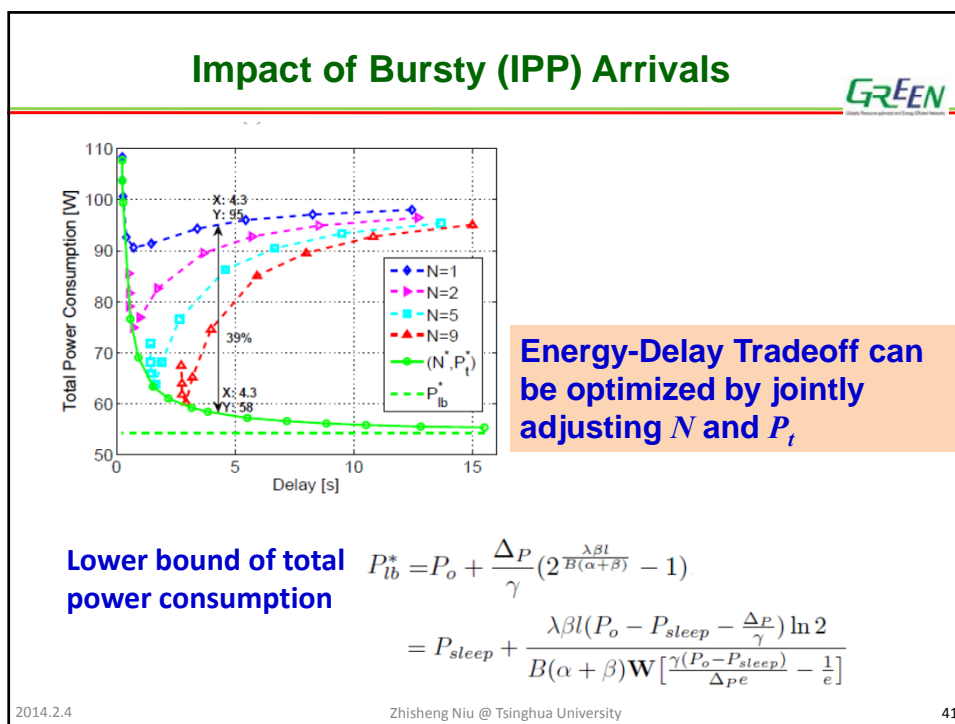
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Summary



- **What's GREEN?**
 - **GREEN:** Globally Resource-optimized and Energy-Efficient Networks
- **Paradigm Shift towards GREEN**
 - **TANGO:** Traffic-Aware Network planning and Green Operation
 - **CHORUS:** Collaborative and Harmonized Open Radio Ubiquitous Systems
- **Energy-Delay Tradeoff in GREEN Communications**
 - EDT is much complicated than before if considering BS sleep control
 - EDT in terms of close-down time is almost linear, while the deviation of setup time does not have any impact on energy consumption
 - If setup time is not fixed and traffic load is high, there exist an optimal $N > 1$ so that the system can achieve the best EDT
 - EDT is almost same for mean delay and maximum delay
 - Sleep operation does not bring benefits all the time
 - Sleeping operation should jointly be optimized with power allocation
 - Burstiness of arrival process has great impact on EDT

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Concluding Remark



- from *World-Wide-Web* to *World-Wide-Wireless*
- for *World-Wide-Watch* & *World-Wide-Wisdom*
- ❖ but definitely should not *World-Wide-Wait*
and *World-Wide-Waste!*



Energy-Delay Tradeoff!



GREEN

Globally Resource-optimized and Energy-Efficient Networks

For more information on “973GREEN” and NiuLab,
please visit <http://network.ee.tsinghua.edu.cn>