How densely should Traffic BSs be deployed in Hyper Cellular Networks?

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Summary of Talk #1

• **What’s 5G?**
  – 5G should be a *paradigm shift* of cellular architecture for **Green** and **Smart**

• **Major approaches towards 5G**
  – Reduce Energy Waste by Adapting to Real-traffic Dynamics (*REWARD*)
  – Traffic-Aware Network Planning and Green Operation (*TANGO*)
  – Collaborative and Harmonized Open Radio Ubiquitous Systems (*CHORUS*)

• **A novel Hyper Cellular architecture for 5G**
  – Decoupling signaling functions from data services to make cellular more adaptive and intelligent
  – Always-on hyper cells for coverage guarantee and on-demand data cells

• **Enabling technologies for 5G**
  – Separation of control and data coverage
  – Resource/network virtualization and network dimensioning
  – Traffic adaptation technologies, including cell zooming, BS sleeping, coverage extension, ……
  – Energy-delay tradeoff can help to shift the peak and therefore save energy
Traffic BSs in Hyper Cellular Networks

- Deployment of TBSs is typically random
- Operation of TBSs can also be dynamic
How should TBSs be Deployed?

- How densely should TBSs be deployed?
- Which and when should TBSs go to sleep?
- How long should a TBS sleep (when to wake up a TBS)?
- How to guarantee coverage & QoS when TBSs are sleeping?
- How to associate a user to the best TBS?

All these answers depend on TRAFFIC dynamics
Non-Uniformity of Mobile Traffic

• Mobile traffic is highly dynamic \((\text{non-uniform})\) in both temporal and spatial domains

• Mobile traffic is getting more and more diverse in content \((\text{voice, data, video, IM, M2M, \ldots})\)

• Mobile traffic also shows group behavior in applications
Mobile Traffic Dynamics – Time Domain

• **Highly dynamic in time domain**
  – day and night, weekday and weekend (*large- and small-scale*)

Mobile Traffic Dynamics: Spatial Domain

Mobile Traffic Dynamics: Our Measurement

Spatial Dynamics

- Real Measurement, Chengdu, China, 1500 3G BSs, 2012.7, One week

(Rural) Outside 3rd Ring Road

(Urban) (2nd ~ 3rd Ring Road)

(Dense urban) (Inside 1st Ring Road)

More smooth

More burst

Close to **PPP**

*(Poisson Point Process)*
Two-step Modeling – BS Distribution

• GSM/TD-SCDMA network in a city of Zhejiang, China
  – 20 MSCs, 15000 BSs, 3000 km2, 7 million users
  – 5 billion records within Feb.-Mar., 2012
Two-step Modeling – BS Density

PPP (Poisson Point Process) approximation is not always appropriate. Better approximated by Power-Law distribution (non-uniformity).

Two-step Modeling - Traffic Distribution

Traffic volume in a cell in every one hour

Weibull distribution or Log-normal mixture have the best fits
Two-step Modeling - Peak Traffic Density

- Log-normal distribution is the best

\[
\text{Peak traffic density} = \frac{\text{Uplink peak traffic volume (byte)}}{\text{Voronoi cell area (km}^2\text{)}}
\]

Two-step Modeling - Peak Traffic Density

- Coherence distance of Traffic Density
  - the distance where auto-correlation reduced to half

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Two-step Modeling - Peak Traffic Density

- Long-range dependence (fractal) of Peak Traffic Density

![Image of traffic density maps](image)

Macro Cells  Small Cells

Two-step Modeling - Signaling Traffic \((\text{indirectly})\)

- Arrived customers in an unit area

\[
p_a(k) = \begin{cases} 
1 - e^{-\lambda k} & \text{ exponential} \\
\frac{k^{-\alpha}}{\Gamma(\alpha)} & \text{ power-law} \\
\frac{2^{\frac{\alpha}{2}} \Gamma\left(\frac{\alpha+1}{2}\right)}{\Gamma\left(\frac{\alpha}{2}\right)} k^{-\alpha} & \text{ log-normal} \\
\frac{2^{\frac{\alpha}{2}} \Gamma\left(\frac{\alpha+1}{2}\right)}{\Gamma\left(\frac{\alpha}{2}\right)} k^{-\alpha} & \text{ weibull} \\
\frac{\sqrt{2 \pi} \Gamma\left(\frac{\alpha+1}{2}\right)}{\Gamma\left(\frac{\alpha}{2}\right)} k^{-\alpha} & \text{ rayleigh} \\
\end{cases}
\]

Power law is also the best approximation \((\text{non-uniformity})\)

Two-step Modeling - Signaling Traffic (indirectly)

Call Inter-Arrival Time (Power-law Distribution)

Call Dwell Time (Power-law Distribution)

Two-step Modeling – IM Traffic (WeChat)

Two-step Modeling – IM Traffic (WeChat)

- **Modeling IM traffic by joint ON-OFF model**
  - OFF-period and ON-period of IM traffic are *strongly correlated*: there must be an ON-period of length $l_m$ after an OFF-period of length $t_{KA}$ (Keep Alive)

\[
f(t_m, \frac{l_m}{r}) = \begin{cases} 
\alpha \cdot \delta(t_m - t_{KA}); & t_m = t_{KA}, l_m = l_{KA} \\
(1 - \alpha) \cdot f_i(t_m) \cdot g_u(l_m); & t_m < t_{KA} \\
0; & t_m > t_{KA}
\end{cases}
\]

- $\alpha$: Ratio of KA messages
- $g_u$: Power-Law Dist.
- $r$: transmission rate

Two-step Modeling – Traffic Content Correlation

- Average Traffic Volume of 133 cells within one week

Traffic contents show some correlation and hence predictable to some extent.
Performance of the Prediction

- **Train** the prediction algorithm by randomly selecting 800 TV drama videos from YouKu
- **Predict** 800 TV dramas randomly selected from TuDou
- **Compared with the real hitting performance**
  - Average prob of over-prediction = 14.83%
  - Average prob of under-prediction = 17.9%

More than 82% hot TV dramas can be predicted with quite low complexity

Does Traffic Burstiness (Non-uniformity) Harms System Performance?

- **Traffic-Aware Dynamic BS Sleeping**
  - 10x10 hexagon cells
  - Cell Radius 200m
  - Binary BS power
  - Link parameters according to ITU micro-cell test environment
  - Traffic:
    - 3 hotspots in the network – space
      - Hotspot center traffic $\lambda_h(t)$, 1st tier traffic $\alpha_1 \lambda_h(t)$, 2nd tier traffic $\alpha_2 \lambda_h(t)$ others $\alpha_3 \lambda_h(t)$, $0 \leq \alpha_3 \leq \alpha_2 \leq \alpha_1 \leq 1$
    - Average intensity varies - time

Traffic-Aware Dynamic BS Sleeping

- Compare with uniform sleeping algorithm [Marsan’09]

DP algorithm being more energy saving gain as traffic non-uniformity increases
**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)

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Optimal BS Density for Green
(Regular Deployment Case)

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

Deploying more smaller BSs can save energy!!!

Optimal BS Density for Green

*(Heterogeneous & Stochastic Deployment Case)*

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

Weighted Poisson-Voronoi Tessellation:

\[ f(A) \text{ follows } \Gamma\text{-distribution with density} \]

\[
\overline{A}_M = \mathbb{E}\{A_M\} = \frac{c}{c\rho_M + \rho_m}
\]

\[
\overline{A}_m = \mathbb{E}\{A_m\} = \frac{1}{c\rho_M + \rho_m}
\]

where:

\[ c = \left( \frac{P_M}{P_m} \right)^{\frac{2}{\alpha}} \]

Verification of PPP Models

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

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

Verification of PPP Models

Rural

Dense Urban

Distribution of BSs in a Square Area of a Chinese Operator

PDF

No. of BSs

PDF

No. of BSs

Real measurement
Poisson distribution

\[ P_A(n) = \frac{(\lambda A)^n}{n!} \exp(-\lambda A). \]
Verification of Gamma Distribution

Distribution of Cell Areas of a Chinese Operator

\[ f_{M}(x) = x^{K_{M}-1} \frac{\exp\left(-\frac{c\rho_{M} + \rho_{m}}{c} K_{M} x\right)}{\left(\frac{1}{c\rho_{M} + \rho_{m}} K_{M}\right)^{K_{M}} \Gamma(K_{M})} \]

\[ f_{m}(x) = x^{K_{m}-1} \frac{\exp\left(-\frac{c\rho_{M} + \rho_{m}}{1} K_{m} x\right)}{\left(\frac{1}{c\rho_{M} + \rho_{m}} K_{m}\right)^{K_{m}} \Gamma(K_{m})} \]
QoS Metrics

• **Coverage Probability**

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

If \( \alpha=4 \),

\[
\Pr(\text{SINR} \geq T) = \frac{1}{1 + \sqrt{T}(\pi/2 - \arctan(1/\sqrt{T}))}
\]

■ **Service Outage Probability**

\[
\mathbb{E}_{\{N, A\}} \left\{ \Pr \left( \frac{W}{N} \log_2(1 + \text{SINR}) < u \mid N, A \right) \right\}
\]

\[
= \mathbb{E}_A \mathbb{E}_{n \mid A} \left\{ \Pr \left( \frac{W}{n + 1} \log_2(1 + \text{SINR}) < u \mid n, A \right) \right\}
\]

\[
= \int_0^\infty \sum_{n=0}^\infty \Pr \left( \text{SINR} < 2^{\frac{(n+1)u}{W}} - 1 \mid n, A \right) P_A(n) f(A) dA.
\]
Optimal BS Density - Formulation
(Homogeneous Case)

\[
\begin{align*}
\min \quad & \rho \\
\text{s.t.} \quad & \int_0^\infty \sum_{n=0}^\infty \frac{1}{1 + (2(n+1) \frac{u}{W} - 1)^{\frac{2}{\alpha}}} \int_0^\infty \frac{1}{1 + x^{\alpha/2}} \, dx \\
& \frac{(\lambda A)^n}{n!} \exp(-\lambda A) \frac{K^K}{\Gamma(K)} A^{K-1} \exp(-K \rho A) \, dA \\
& \geq 1 - \eta.
\end{align*}
\]

(8)

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

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

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

\[
\bar{\rho} \triangleq \frac{\lambda}{W_u \log_2 \left( \frac{\alpha - 2 + 4 - \alpha}{2} \frac{1 - \eta}{1 - \eta} \right) - 1} \tag{10}
\]

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

\[
\lim_{\frac{u}{W} \to 0} \frac{\hat{\rho}}{\rho^*} = 1.
\]
Theorem 3. The optimal BS density in the interference-limited homogeneous cellular network (8) has a lower bound $\tilde{\rho}$, which satisfies the following expression:

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

(14)

$\alpha=4$, $u=1\text{Mbps}$, and $W=20\text{MHz}$

$\alpha = 4$ and $\eta = 0.3$. 

The ratio of user data threshold over network bandwidth ($u/W$)
Optimal BS Density and Tx Power
(Homogeneous Case)

Table: Optimal BS density with transmit power adaption (EARTH model)

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Rural</th>
<th>Suburban</th>
<th>Dense urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed full transmit power</td>
<td>$\rho^* = 0.1384 \text{ BSs/Km}^2$</td>
<td>$\rho^* = 0.9424 \text{ BSs/Km}^2$</td>
<td>$\rho^* = 1.2713 \text{ BSs/Km}^2$</td>
</tr>
<tr>
<td></td>
<td>$P_M = 20W$</td>
<td>$P_M = 20W$</td>
<td>$P_M = 20W$</td>
</tr>
<tr>
<td>Optimal transmit power adaption</td>
<td>$\rho^* = 0.1604 \text{ BSs/Km}^2$</td>
<td>$\rho^* = 1.0699 \text{ BSs/Km}^2$</td>
<td>$\rho^* = 1.4121 \text{ BSs/Km}^2$</td>
</tr>
<tr>
<td></td>
<td>$P^*_M = 12.2W$</td>
<td>$P^*_M = 3.8W$</td>
<td>$P^*_M = 3.1W$</td>
</tr>
</tbody>
</table>

Conclusion: Joint BS density adjustment and transmit power adaption can help to save more energy!

Optimal BS Density - Performance
(Homogeneous Case)

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

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>optimal BS density with noise</th>
<th>optimal BS density without noise</th>
<th>upper bound in Theorem 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural</td>
<td>0.1384</td>
<td>0.0542</td>
<td>0.0551</td>
</tr>
<tr>
<td>Suburban</td>
<td>0.9424</td>
<td>0.9017</td>
<td>0.9177</td>
</tr>
<tr>
<td>Dense urban</td>
<td>1.2713</td>
<td>1.2390</td>
<td>1.2610</td>
</tr>
</tbody>
</table>

Conclusion: Noiseless assumption is acceptable for suburban and dense urban scenarios, but not in rural scenario.
Optimal BS Density - Formulation
(Heterogeneous Case)

$$\min C_M \rho_M + C_m \rho_m$$

s.t. $$G_M = \mathbb{E}_{\{N_M, A_M\}} \left\{ \Pr \left( \frac{W}{N_M} \log_2(1 + \text{SINR}) < u \mid N_M, A_M \right) \right\} < \eta,$$

$$G_m = \mathbb{E}_{\{N_m, A_m\}} \left\{ \Pr \left( \frac{W}{N_m} \log_2(1 + \text{SINR}) < u \mid N_m, A_m \right) \right\} < \eta,$$

Coverage guarantee

$$\varnothing_0 \leq \rho_M \leq \rho_2,$$

$$\rho_1 \leq \rho_m \leq \rho_3.$$  

where \(\{C_M, C_m\}\) are deployment (energy) cost of macro and micro BSs, respectively and

\[ T \triangleq \frac{\rho_m}{\rho_M} \]

Optimal BS Density – Near-optimal Solution
(Heterogeneous Case)

\[ \rho_M = \frac{1 - 2^{-\frac{u}{\bar{w}}}}{c + \tau \cdot K_M \left\{ [2^{-\frac{u}{\bar{w}}} (1 - \eta)]^{-\frac{1}{K_M}} - 1 \right\}} \lambda, \]

\[ \tau^* = \begin{cases} 
\min\{\tau_0, \tau_3\}, & 0 \leq \xi < \frac{1}{c}; \\
\max\{\tau_1, \tau_2\}, & \frac{1}{c} < \xi \leq 1.
\end{cases} \]

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

\[ \tau_0 \approx \frac{1 - 2^{-\frac{u}{\bar{w}}}}{\rho_0 \log\left(\frac{1}{2^{-\frac{u}{\bar{w}}} (1-\eta)}\right)} c \lambda - c, \quad \tau_1 \approx \frac{1}{\rho_1 \log\left(\frac{1}{2^{-\frac{u}{\bar{w}}} (1-\eta)}\right)} \lambda - \frac{1}{c}, \]

\[ \tau_2 \approx \frac{1 - 2^{-\frac{u}{\bar{w}}}}{\rho_2 \log\left(\frac{1}{2^{-\frac{u}{\bar{w}}} (1-\eta)}\right)} c \lambda - c, \quad \tau_3 \approx \frac{1}{\rho_3 \log\left(\frac{1}{2^{-\frac{u}{\bar{w}}} (1-\eta)}\right)} \lambda - \frac{1}{c}. \]
Optimal BS Density – Performance
(Heterogeneous Case)

\[ \xi = \frac{C_m}{C_M} \]

Deployment energy cost ratio of micro- over Macro-BSs

\[ C = \left( \frac{P_M}{P_m} \right)^{\frac{2}{\alpha}} \]

Approximation

Optimal

Network Energy Consumption

\[ \rho_M^{+\xi_d}_M \]
Optimal BS Density – Optimal Policy
(Heterogeneous Case)

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

$$\xi = \frac{C_m}{C_M} ; \quad C = \left(\frac{P_M}{P_m}\right)^\frac{2}{\alpha}$$
Optimal BS Density – Performance
(Heterogeneous Case)

- **Dynamic BS Sleeping in Dense Urban Scenario** (EARTH Model)
  - $C_M = 780 + 28.2P_M$, $C_m = 112 + 5.2P_m$
  - $P_M = 20W$, $P_m = 2.42W \rightarrow \zeta = 0.0927 < c^{-1} = 0.3162$
  - Reference model: macro-only homogeneous network with no BS sleeping:
    total energy consumption = 3.26 KW/Km$^2$

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

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 $\beta = W_m/W_M$?

Lemma 1. In the heterogeneous cellular network model with the $\beta$-PSR scheme, the user SINR distribution follows:

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

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

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

$$G_M(\beta^*) = G_m(\beta^*).$$  \hspace{1cm} (15)
Optimal $\beta^*$ in PSR

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

\[
\lim_{\frac{u}{W} \to 0} \beta^* = \frac{u_m}{u_M} \frac{c\rho_M + \rho_m + \lambda_m}{c\rho_M + \rho_m + c\lambda_M}
\]

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

\[
e = \frac{C_m}{C_M}; \quad c = \left(\frac{P_M}{P_m}\right)^{\frac{2}{\alpha}}
\]
Energy Saving Gain by PSR

PSR scheme can save up to 50% of network energy consumption
Application to Network Planning – Capacity Extension
(EARTH Model: Dense Urban, Peak Traffic increases up to 74.3/Km²)

\[ \rho_M = 1 \text{ BS/km}^2 \ (\frac{3}{4} \text{ used for coverage}), \ EC = 5.9 \text{kW/km}^2 \]

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

Adding macro BSs: \( \rho_M \rightarrow 1.75 \text{ BS/km}^2 \)
EC \( \rightarrow 3.56 \text{ kW/km}^2 \) (40% saving)

Adding micro-BSs: \( \rho_m \rightarrow 4.25/\text{Km}^2 \)
EC \( \rightarrow 1.87 \text{ kW/km}^2 \) (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 up to 50% (37/Km²)

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

Traffic load down to 20% (15/Km²)

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

- **Modeling of traffic dynamics and traffic-aware network planning and operation**
  - Mobil traffic is highly dynamic in temporal, spatial, and content domains
  - Signaling and IM traffic are non-uniform either
  - Mobile Internet traffic and mobile video show strong group behavior and therefore should be served more intelligently by pushing and multicasting

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