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Artificial Interference Aided Physical Layer Security in Cache-enabled Heterogeneous Networks

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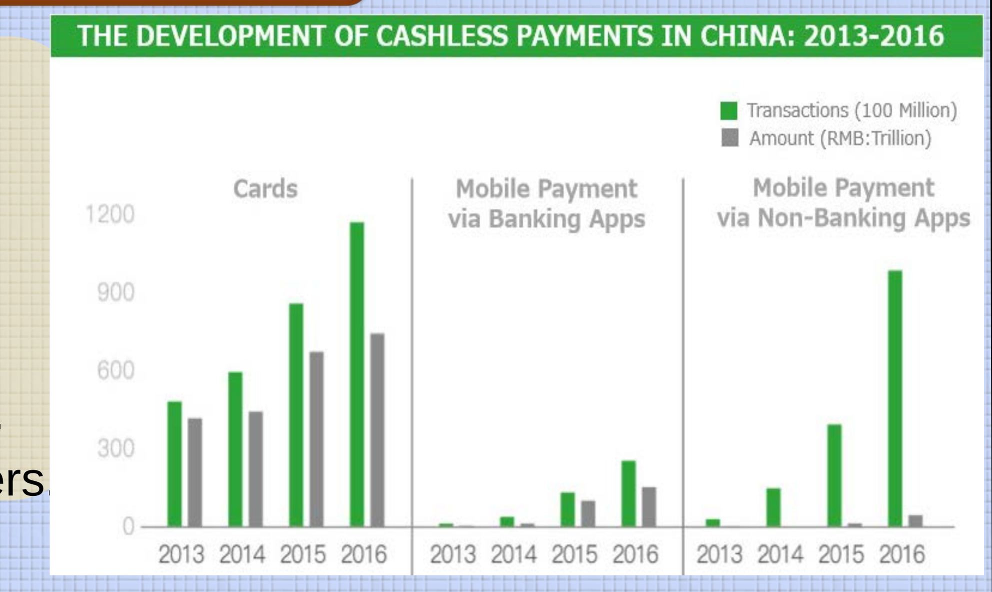
1 Background

- **Challenges:**
  - Increasing Security Rank
    - Mobile payment
    - Internet of things
  - Complex Network topology.
    - Heterogeneous BS deployment.
    - Randomly located Eavesdroppers



Physical Layer Solutions:
- Artificial noise
- Cooperative relays

Caching:
- Improve signal strength
- Cancel received interference

- **Questions:**
  How to utilize cache ability to improve transmission secrecy ?
  How to measure cache ability in secrecy improving?

2 System Model

- **Network and Caching Model**
  - A cache-enabled 3-tier HetNet : BSs Φ_b , users Φ_u, and Eves Φ_e.
  - A database: N files with equal length, $\boldsymbol{F}=\{f_1, f_2, \dots, f_N\}$.
    - Request probability: p_i, Zipf distribution.
  - BSs can access all the files in $\boldsymbol{F}$ without counting costs.
  - Only $\boldsymbol{\alpha}$ part of users have cached the files $\boldsymbol{M}=\{f_1, f_2, \dots, f_M\}$ from $\boldsymbol{F}$.
    - Cache hit ratio $\boldsymbol{\delta}=\sum_{i=1}^{M} p_i$.

- **File Access Protocol**
  - **Self-offloading: Cache-enabled user** u_o requests content from $\boldsymbol{M}$ which can be served by their local storage.
  - **Secure-transmission: Cache-enabled user** u_o requests content from $\boldsymbol{F}/\boldsymbol{M}$ which is served by the nearest BS in secure-transmission.

    Requested file ! $t_i=\sqrt{\boldsymbol{\theta} P}x_i+\sqrt{(1-\boldsymbol{\theta})P}x_m$ Cached file !
    - BSs served in this state are denoted as $\Phi_{b_1}(\lambda_{b_1})$
  - **Normal-transmission: Cache-untenabled user** u_o requests content from $\boldsymbol{F}$ which is served by the nearest BS in normal-transmission.

    $t_i=\sqrt{P}x_i$
    - BSs served in this state are divided by $x_i \in/\notin M$ as $\Phi_{b_2}(\lambda_{b_2})$, $\Phi_{b_3}(\lambda_{b_3})$

3 Transmission Scheme Analysis

- **Normal Transmission (NT)**
  - Consider a non-colluding wiretap scenario where each Eve individually overhears the data transmission from u_o to b_o.
  - The received SINR of u_o and an arbitrary Eve e_j can be write as (i=u_o, e_j)

$$\mathrm{SINR}_i=\frac{P\left|h_{i,b_0}\right|^2 d_{i,b_0}^{-\beta}}{\sum_{k\in\Phi_b\setminus\{b_0\}} P\left|h_{i,b_k}\right|^2 d_{i,b_k}^{-\beta}+\sigma^2}$$

Note that interference come from Φ_{b_1}, Φ_{b_2} and Φ_{b_3}.

- **Secure Transmission (ST)**
  - Since the pre-cached signal x_m is known perfectly at u_o. And assume that the perfect channel state information is fully available at cache-enabled users. The received SINR of u_o is

$$\mathrm{SINR}_{u_o}=\frac{\theta P\left|h_{u_0,b_0}\right|^2 d_{u_0,b_0}^{-\beta}}{\theta\sum_{k\in\Phi_{b_1}\setminus\{b_0\}} P\left|h_{u_0,b_k}\right|^2 d_{u_0,b_k}^{-\beta}+\sum_{k\in\Phi_{b_3}} P\left|h_{u_0,b_k}\right|^2 d_{u_0,b_k}^{-\beta}+\sigma^2}$$

The (1−θ) part of interference from Φ_{b_1} can be cancelled. ← Cached files M → The fully interference from Φ_{b_2} can be cancelled.

The transmitted signal x_m can introduce an extra interference to greatly restrict the e_j. The received SINR of an arbitrary Eve $e_j\in\Phi_e$ can be write as

$$\mathrm{SINR}_{e_j}=\frac{\theta P\left|h_{e_j,b_0}\right|^2 d_{e_j,b_0}^{-\beta}}{(1-\theta)P\left|h_{e_j,b_0}\right|^2 d_{e_j,b_0}^{-\beta}+\sum_{k\in\Phi_b\setminus\{b_0\}}\left|h_{e_j,b_k}\right|^2 d_{e_j,b_k}^{-\beta}+\sigma^2}$$

It has the form of $\frac{\theta X}{C+(1-\theta)X}$ → Upper bound !

- **Average Secrecy Rate**
  - The average secrecy rate is defined as $\mathbb{C}=[max\{C_u-C_e\},0]$.
  - When $\sigma^2\to 0$(interference−limited), the average secrecy rate of NT and ST are

$$C_{NT}=\frac{1}{ln2}\int_0^{\infty}\frac{e^{-\lambda_e/\left[\lambda_b\Gamma\left(1+\frac{2}{\beta}\right)\Gamma\left(1-\frac{2}{\beta}\right)\gamma_{th}^{\frac{2}{\beta}}\right]}}{(1+\gamma_{th})[Z(\gamma_{th})+1]}d\gamma_{th}$$

→ Only depend on the ratio of $\frac{\lambda_e}{\lambda_b}$!

$$C_{ST}=\frac{1}{ln2}\int_0^{\gamma_{th_0}}\frac{\lambda_b e^{-\lambda_e/\left[\lambda_b\Gamma\left(1+\frac{2}{\beta}\right)\Gamma\left(1-\frac{2}{\beta}\right)\left[\frac{\gamma_{th}}{\theta-(1-\theta)\gamma_{th}}\right]^{\frac{2}{\beta}}\right]}}{(1+\gamma_{th})[\lambda_{b_1}Z(\gamma_{th})+\lambda_{b_3}Z(\gamma_{th})+\lambda_b]}d\gamma_{th}+\frac{1}{ln2}\int_{\gamma_{th_0}}^{\infty}\frac{\lambda_b d\gamma_{th}}{(1+\gamma_{th})[\lambda_{b_1}Z(\gamma_{th})+\lambda_{b_3}Z(\gamma_{th})+\lambda_b]}$$

→ Depend on θ, the ratio of $\frac{\lambda_e}{\lambda_b}$ and $\left(\frac{\lambda_{b_1}}{\lambda_b},\frac{\lambda_{b_3}}{\lambda_b}\right)$ which are related to α and δ !

where $Z(\gamma_{th})\triangleq\frac{2\gamma_{th}}{\beta-2}\,{}_2F_1\left(1,1-\frac{2}{\beta},2-\frac{2}{\beta},-\gamma_{th}\right)$, ${}_2F_1[\cdot]$ is the Gauss hypergeometric function and $\Gamma[\cdot]$ is the Gamma function.

- **Secrecy Coverage Probability**
  - The secrecy coverage probability is defined as $\mathrm{P}=P_r(\mathbb{C}>R_S)$.
  - When $\sigma^2\to 0$, the secrecy coverage probability of NT and ST are

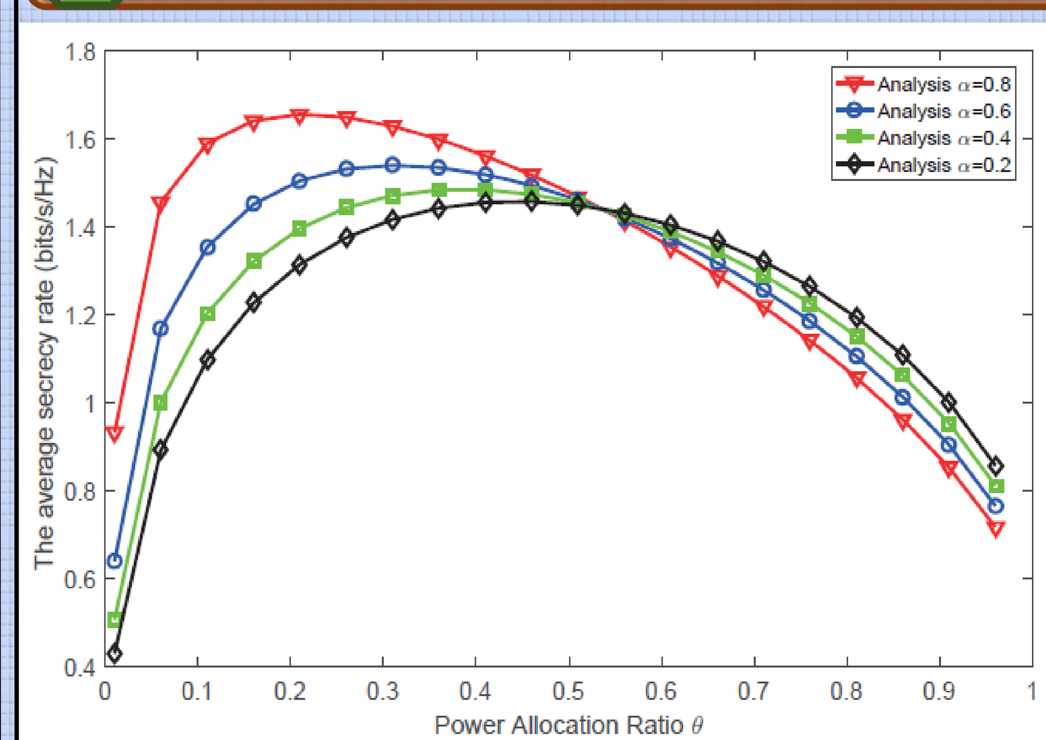
$$P_{NT}=\int_0^{\infty}\frac{2\lambda_e\gamma_{th}^{-\frac{\beta+2}{\beta}}e^{-\lambda_e/\left[\lambda_b\Gamma\left(1+\frac{2}{\beta}\right)\Gamma\left(1-\frac{2}{\beta}\right)\gamma_{th}^{\frac{2}{\beta}}\right]}d\gamma_{th}}{\beta\lambda_b[G(R_S)+1]\Gamma\left(1+\frac{2}{\beta}\right)\Gamma\left(1-\frac{2}{\beta}\right)}$$

→ Depend on θ, the ratio of $\frac{\lambda_e}{\lambda_b}$ and $\left(\frac{\lambda_{b_1}}{\lambda_b},\frac{\lambda_{b_3}}{\lambda_b}\right)$

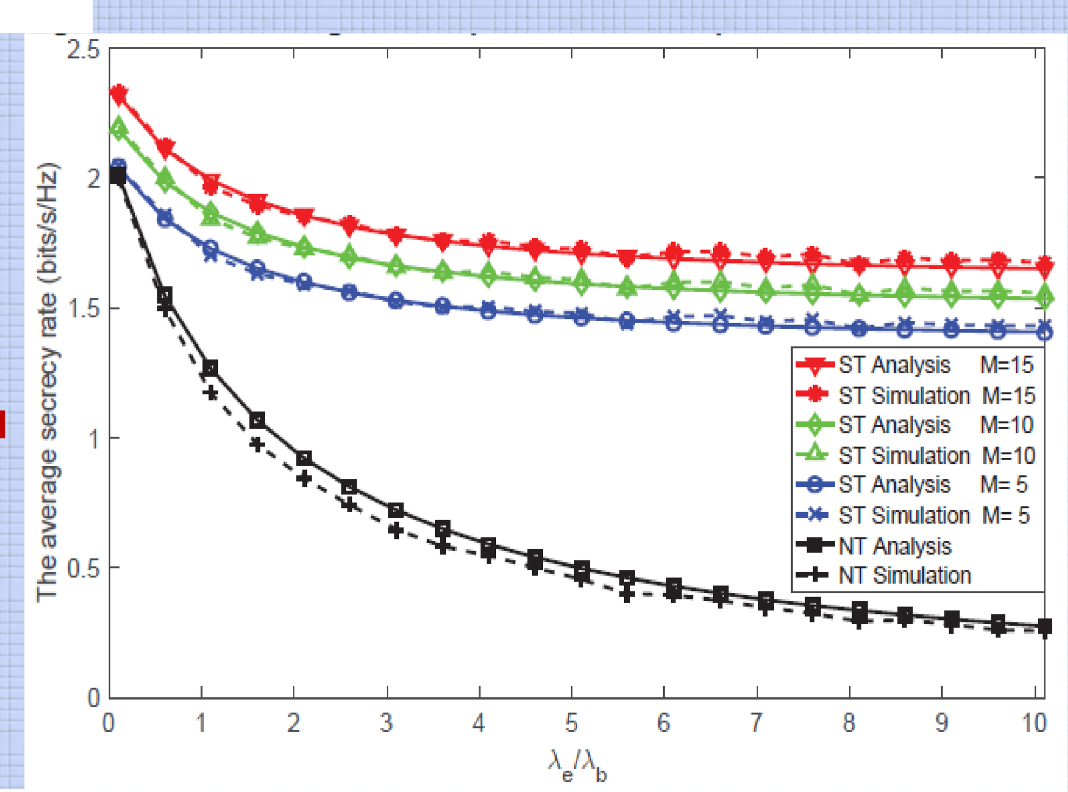
$$P_{ST}=\int_0^{\gamma_{th_0}}\frac{2\theta\lambda_e\gamma_{th}^{-\frac{\beta+2}{\beta}}e^{-\lambda_e/\left[\lambda_b\Gamma\left(1+\frac{2}{\beta}\right)\Gamma\left(1-\frac{2}{\beta}\right)\left[\frac{\gamma_{th}}{\theta-(1-\theta)\gamma_{th}}\right]^{\frac{2}{\beta}}\right]}d\gamma_{th}}{\beta(1+\gamma_{th})[\lambda_{b_1}G(R_S)+\lambda_{b_3}G(R_S)+\lambda_b]\Gamma\left(1+\frac{2}{\beta}\right)\Gamma\left(1-\frac{2}{\beta}\right)\left[\frac{\gamma_{th}}{\theta-(1-\theta)\gamma_{th}}\right]^{\frac{\beta-2}{\beta}}}$$

where $G(R_S)\triangleq Z(2^{R_S}-1)$

4 Simulation & Numerical Results

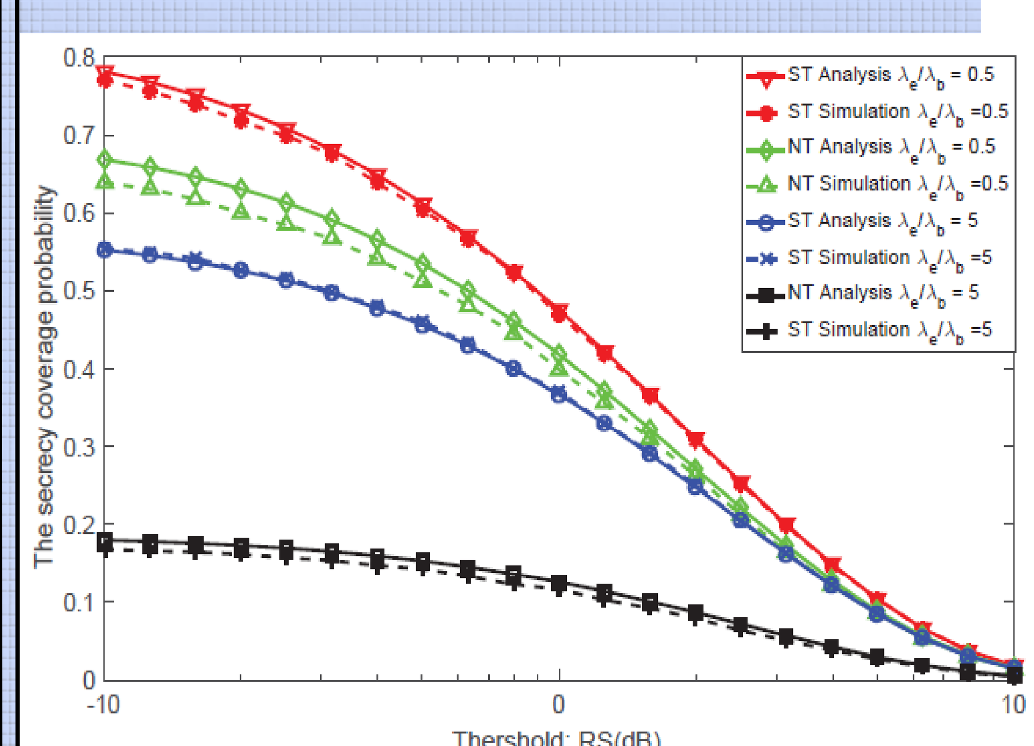


C_{ST} under different α and θ
It shows that there exists an optimal power allocation θ^* to achieve the maximal C_{ST} for a given cache user ratio α.



Compare of C_{ST} and C_{NT}
It shows that ST outperforms than NT in both Eve-dense scenario and Eve-sparse scenario.

It also shows that larger cache size achieves better secrecy rate.



Compare of P_{ST} and P_{NT}
It shows that ST outperforms than NT with larger secrecy coverage probability in both scenarios.

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