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Downlink CoMP in HetNets with Imperfect Overhead Messaging: Adaptation and Robustness

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OUTLINE

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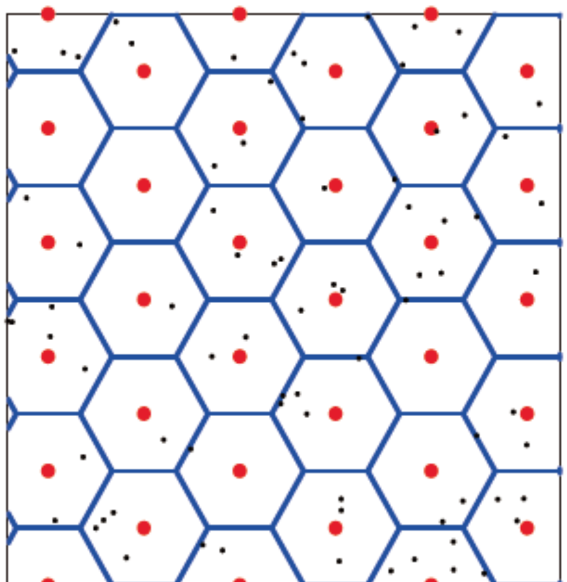
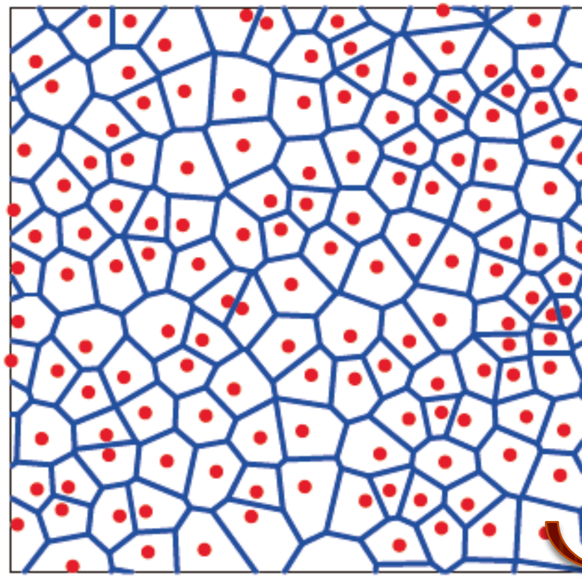
  - **K-tier HetNet Model**
  - **CoMP in HetNet**
- **Imperfect Overhead Messaging**
  - **Assumptions of Overhead Messaging**
  - **Lifetime Model of Overhead Messages**
- **Coordinated States under Overhead Messaging Delay**
  - **Coordination Model in CoMP and Throughput**
  - **Coordination Model in Adaptable CoMP and Throughput**
- **Simulation Results**
- **Summary**

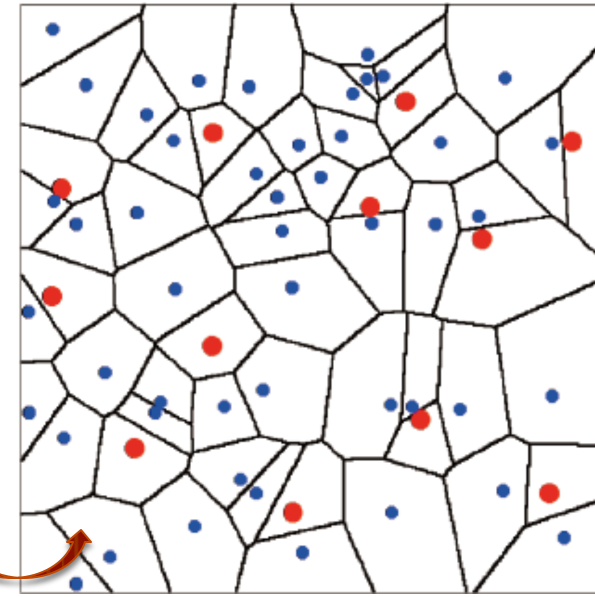
What is a Cellular Model Migrating to?



Textbook's grid model



Actual 4G macrocell today



Marcocells to Femtocells

- **Deterministic models (e.g. grids) are increasingly detached from reality, and not scalable to a HetNet.**
- **Results based on such models are thus pretty questionable, and not easy to be calculated.**

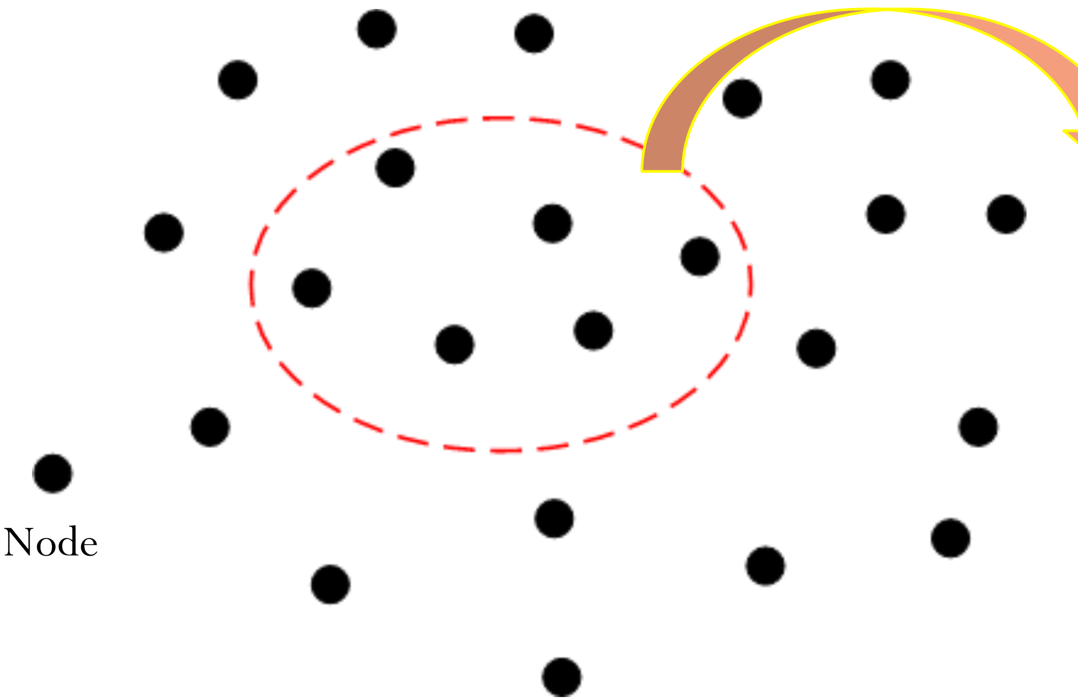
(Any tractable model for analyzing HetNets?)

Stochastic Geometry for HetNet Modeling

- **Review of one-dimensional Poisson Distribution : Suppose X is a Poisson random variable with parameter μ. Its distribution can be written as**

$$\mathbf{P}[X = k] = \frac{\mu^k}{k!} e^{-\mu}, \quad k = 1, 2, \ldots \quad (\mathbb{E}[X] = \mu)$$

- **Poisson Point Process (PPP) of density λ**



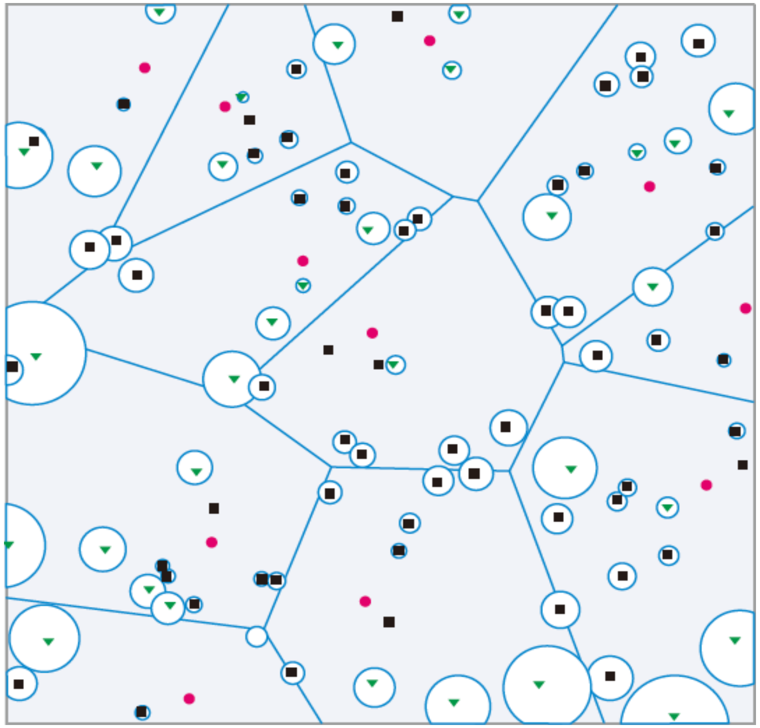
All nodes are randomly and independently scattered.

For a fixed region with area A, the number N of nodes within it is a Poisson Random Variable with mean λA , i.e.

$$\mathbb{P}[N = k] = \frac{(\lambda A)^k}{k!} e^{-\lambda A}$$

PPP-Baed *K*-tier HetNet Modeling

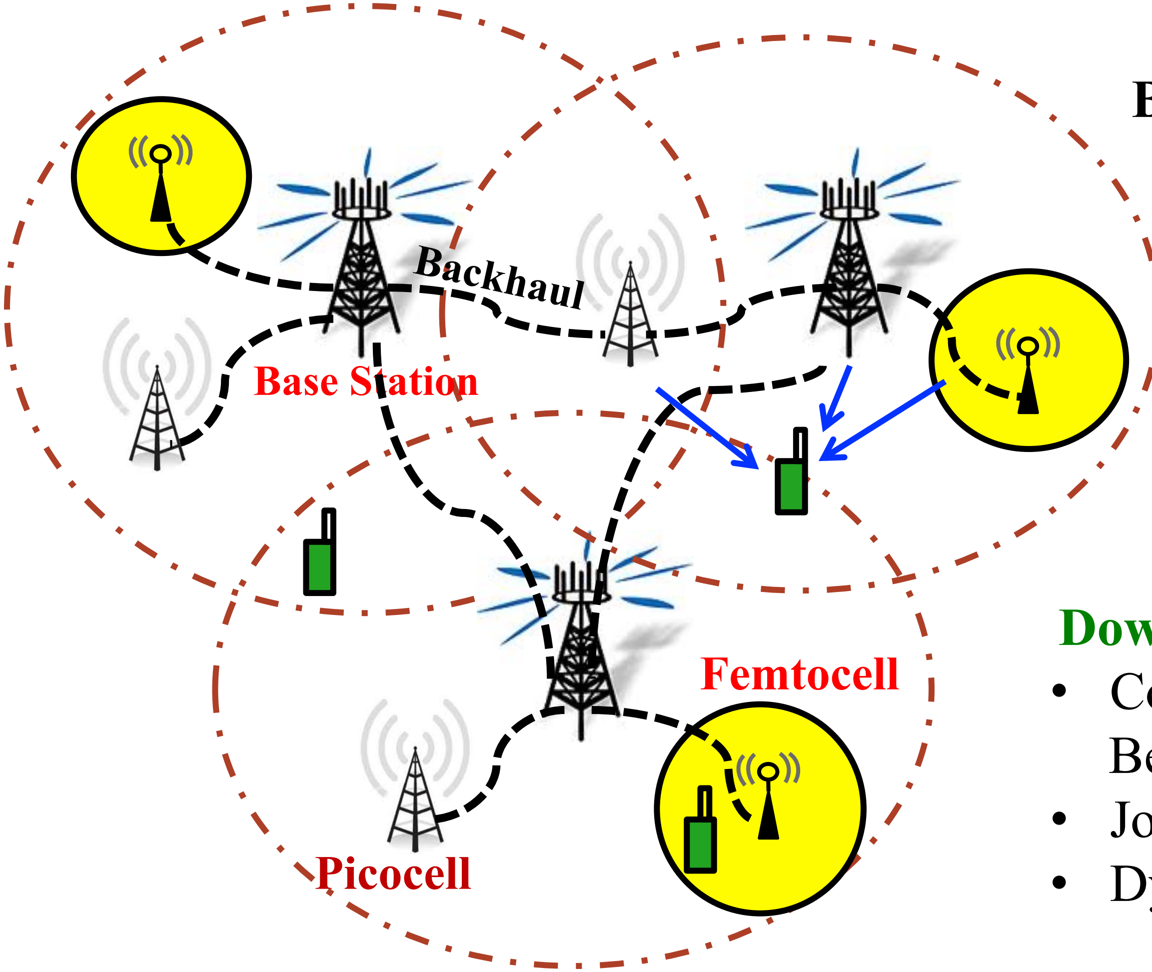
- **K-tiers of base stations, locations taken from independent PPPs**
  - Base Station Density: λ_k BSs/area
  - Transmit Power: P_k Watts
  - Can also include per-tier SIR target β_k , path loss exponent α_k, etc.



(Max SINR downlink coverage regions in a 3-tier network with macrocells (red), picocells (green), and femtocells (black).)

- **Typical Reactions to the Model**
  - Macrocells not "random": carefully planned. In fact, PPP is about as good as grid for a typical macrocell network, in some cases better (JAFBRG11)
  - Picocells might be clustered,or target hotspots. Note that PPP realizations often allow for this
  - Seems "about right" for femtocells

Coordinated Multi-Point (CoMP) Transmission



BSs are connected by (high speed) backhaul cables.

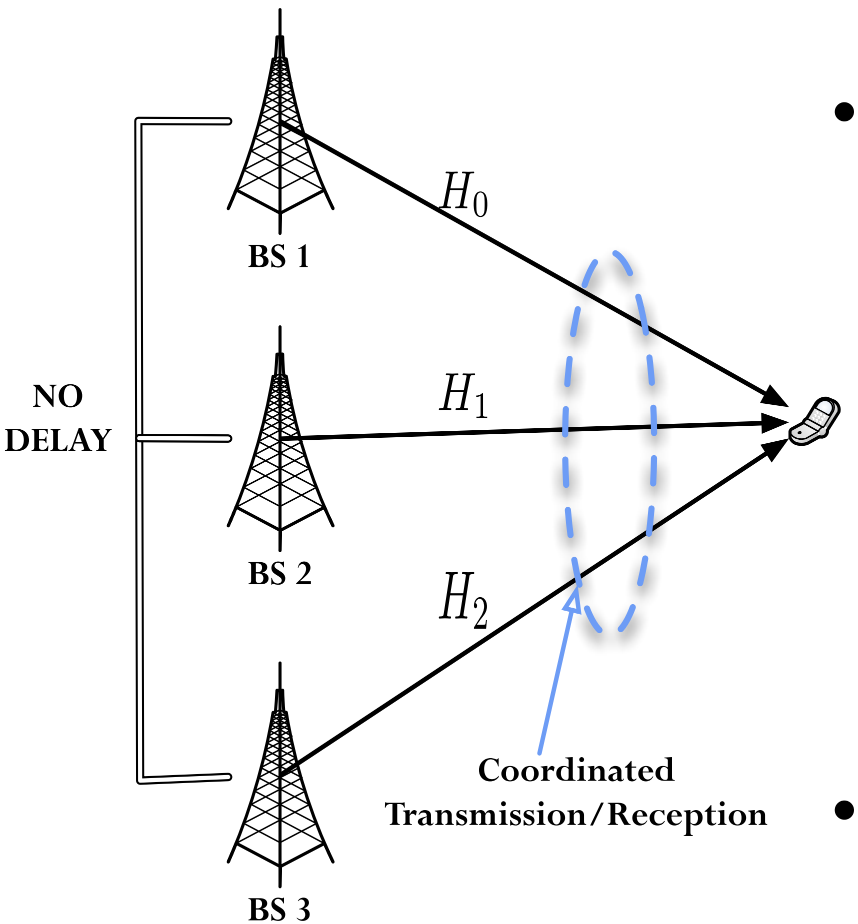
Downlink CoMP Techniques

- Coordinated Scheduling/ Beamforming
- Joint Transmission
- Dynamic Point Selection

Why CoMP?

- **Inter-cell coordination is necessary and could bring numerous gains**
  - Handoffs and mobility management : fewer dropped calls
  - Enhancements like networked MIMO : Higher spectral efficiency
- **Large theoretical gains do not translate to real systems. An example: downlink joint processing CoMP in macrocells**
  - Multi-fold downlink throughput gain in theory [D. Gesbert et. al. 10]
  - Barely any gain at all, according to NTT, Qualcomm, Vodafone, Motorola/NSN [AnnBarGeiMalGor10, R. Irmer et al 11]
  - **Major limiting factors are unsatisfactory interference distribution and inter-cell overhead sharing burden**
- **For HetNets, the interference model has been developed, but appropriate models for inter-cell overhead sharing are still missing.** [AndBacGan10, DhiGanAnd11, JoShaXiaAnd 11]

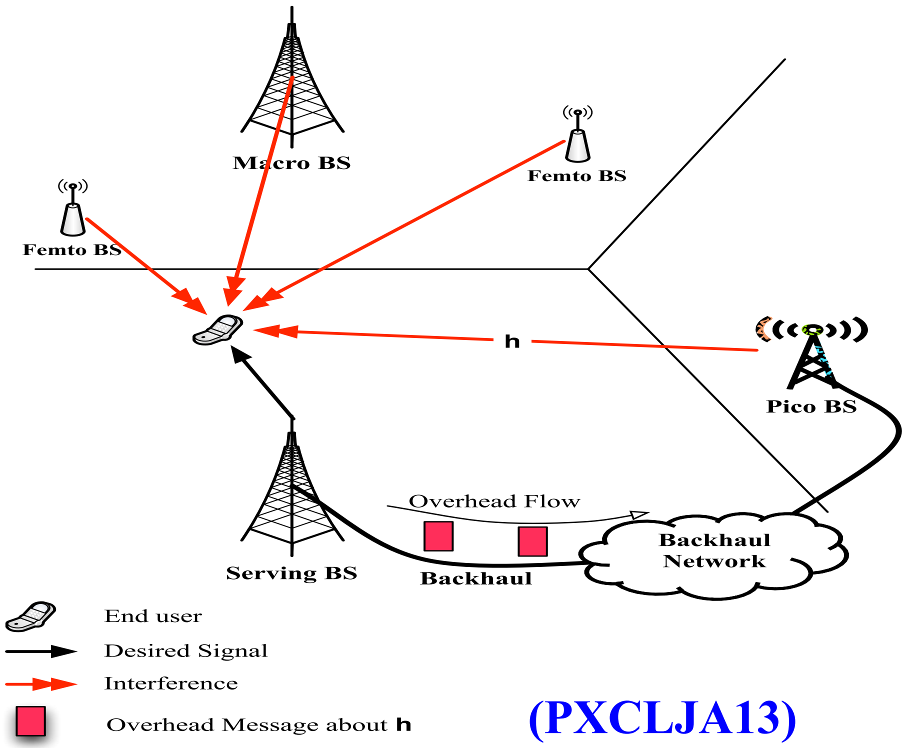
Main Hurdle of Studying CoMP



- The success of coordination depends heavily on **overhead rate and delay**
- If overhead issues are not addressed properly
  - **(CoMP Techniques)** typically less than *30% gain* in LTE Rev 11 [3GPP11CoMP]
  - (**CoMP JT, 1 tier**) only *20% gain* unless equipped with 1 Gb/s Ethernet backhaul [Qcom10, Vodafone et al 11]
  - (**CoMP CS/CB, 2 tiers**) *negative gain* compared with semi-static ICIC [Qcom12]
- BUT…….. **the impact of overhead however is hard to quantify and thus often ignored** [Gesbert et. al. 10]

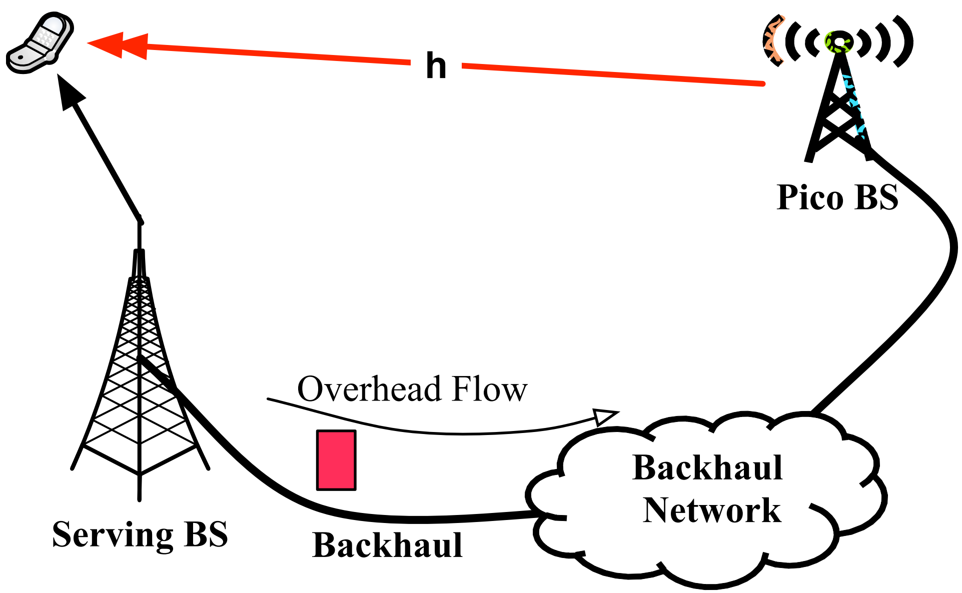
Downlink CoMP in a *K*-tier HetNet

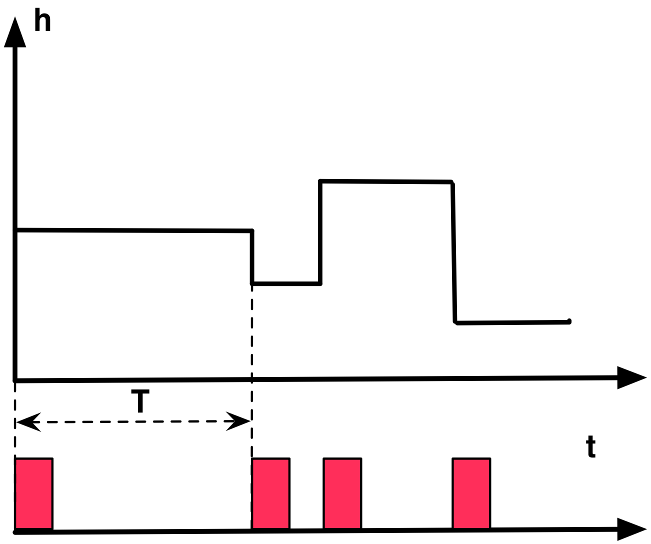
- **Downlink CoMP in a PPP-based HetNet with K tiers**
  - Base Station Density: λ_k BSs/ area
  - Transmit Power: P_k Watts
  - Per-tier SIR target β_k , path loss exponent α_k .
  - # of Antennas of BS in the k-th tier, n_k .



(PXCLJA13)

Overhead Messaging in CoMP



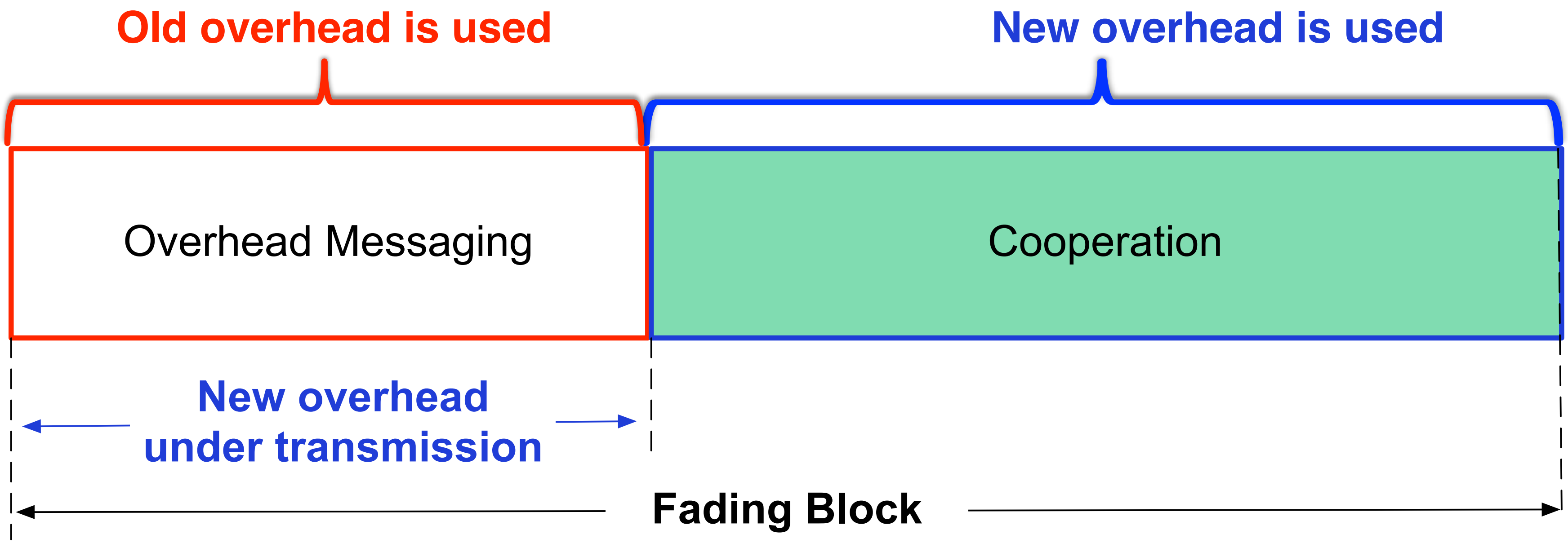


- **AS1 (discrete-time i.i.d. model)**: fading state h keeps constant for a block time T; fading states in different blocks are i.i.d.
- **AS2**: Once the fading state changes, an updating overhead will be generated and sent without re-transmission
- An overhead then has a lifetime (the time length of the fading block)

$$L_{i,k} \sim \Gamma\left(m, \frac{1}{m\mu_{i,k}}\right)$$

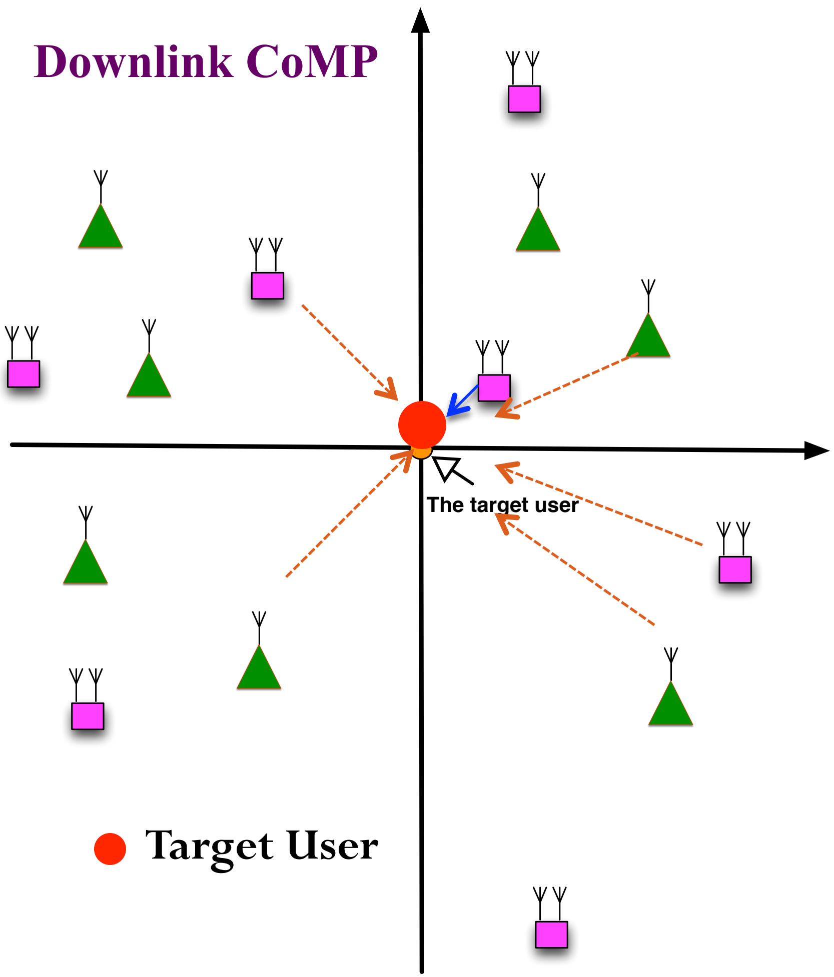
(PXCLJA13)

Simple Model for Overhead Delay Impact



- **Two possible states of a coordinated BS in every fading block**
  - **Overhead Messaging state**: New overhead is not received; No information about channel → ***No interference cancellation***
  - **Cooperation state**: New overhead is received; Accurate information about channel (minus quantization error) → ***Maximum interference cancellation***

User's SIR in CoMP ZFBF



- **SIR for the target user receiving signals from BS B_{i,k_*} is given by**

Fading Channel Gain

TX Power **Path Loss**

$$\gamma_{1,k_*} = \frac{p_{k_*} G_{1,k_*} |B_{1,k_*}|^{-\alpha_{k_*}}}{\sum_{B_{i,k} \in \bigcup_{k=1}^{K} \Phi_k \setminus B_{1,k_*}} p_k G_{i,k} |B_{i,k}|^{-\alpha_k}}$$

where

$$k_* = \arg \max_{k=1,2,\ldots K} \{p_k |B_{1,k}|^{-\alpha_k}\}$$

(User's best serving BS, B_{i,k_*})

SIR in Downlink CoMP ZFBF

$$\gamma_{1,k_*} = \frac{p_{k_*} G_{1,k_*} |B_{1,k_*}|^{-\alpha_{k_*}}}{\sum_{B_{i,k} \in \bigcup_{k=1}^{K} \Phi_k \setminus B_{1,k_*}} p_k G_{i,k} |B_{i,k}|^{-\alpha_k}}$$

Notation	Description
subscript i,k	Index for i^{th} nearest BS in tier k
$X_{i,k}$	location of $\mathrm{BS}_{i,k}$
$\mathbf{h}_{i,k}$	unit power Rayleigh fading of channel between $\mathrm{BS}_{i,k}$ and the end-user
$\mathbf{f}_{i,k}$	unit power precoder of $\mathrm{BS}_{i,k}$
$b_{i,k}$	overhead quantization bits

- For the serving BS

  $$G_{1,K_*} = |\mathbf{f}_{1,k_*} \mathbf{h}_{1,k_*}|^2 \sim \chi^2_{2n_{k_*} - 2|\mathcal{S}_{1,k_*}|}$$

- For non-coordinated BSs

  $$G_{i,k} = |\mathbf{f}_{i,k} \mathbf{h}_{i,k}|^2 \sim \exp(1)$$

- For coordinated BSs, with RVQ overhead codebook

  $$G_{i,k} = |\mathbf{f}_{i,k} \mathbf{h}_{i,k}|^2 \sim \rho_{i,k} \exp(1)$$

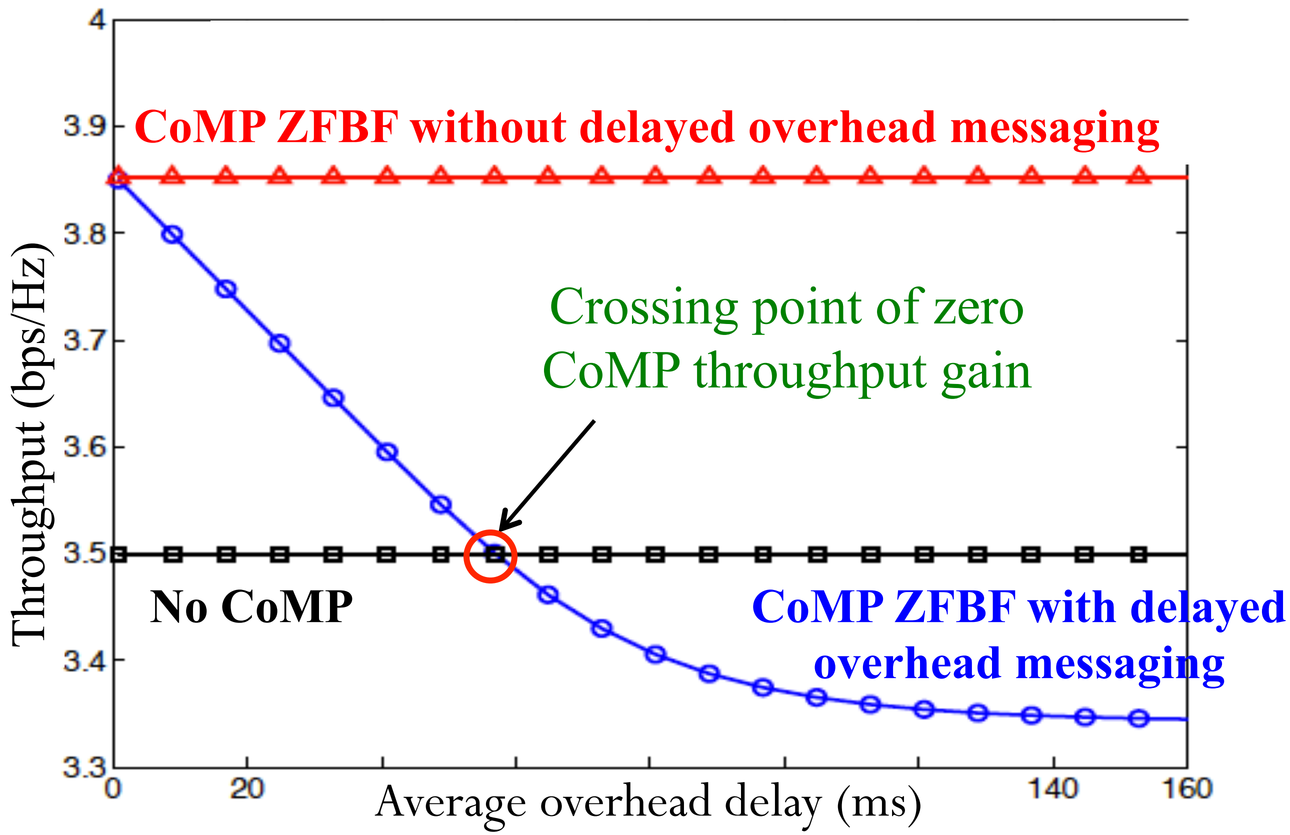
  - in overhead messaging state

    $$\rho_{i,k} = 1$$

  - in cooperation state

    $$\rho_{i,k} = 2^{-\frac{b_{i,k}}{N_k - 1}}$$

CoMP ZFBF Throughput vs. Delay



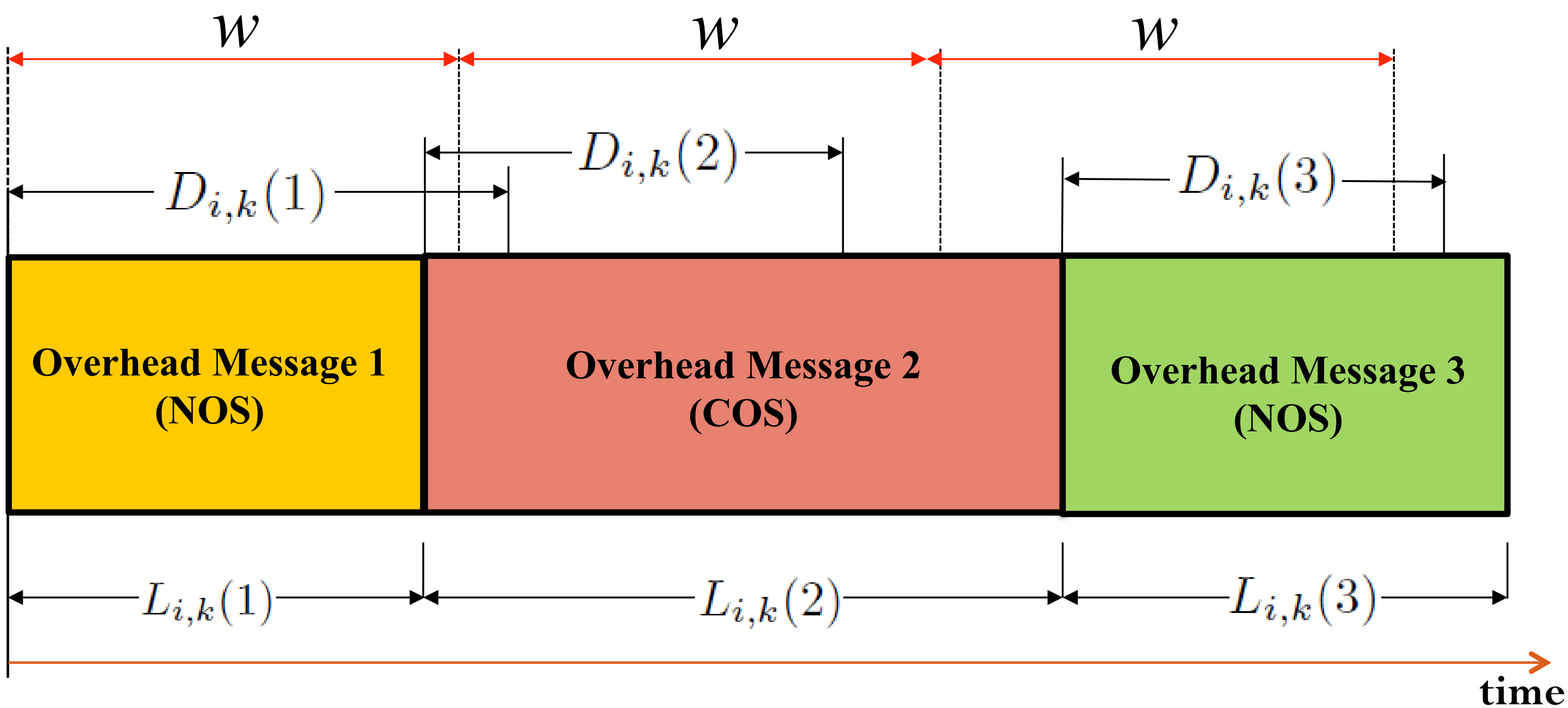
Notation	Description	Sim. Value
L	Fading coherence time	Fixed, 100 ms
$\lvert \mathcal{S}_{1,k_*} \rvert$	# of coordinated cells	1
$\rho_{i,k}$	Portion of residual interference	12.5%

Now, we know the delayed overhead messages have a significant impact on the throughput performance of CoMP.

Is there any method to mitigate this imperfect messaging problem ?

The key is to let the coordinated BSs realize whether themselves could be really helpful for coordination.

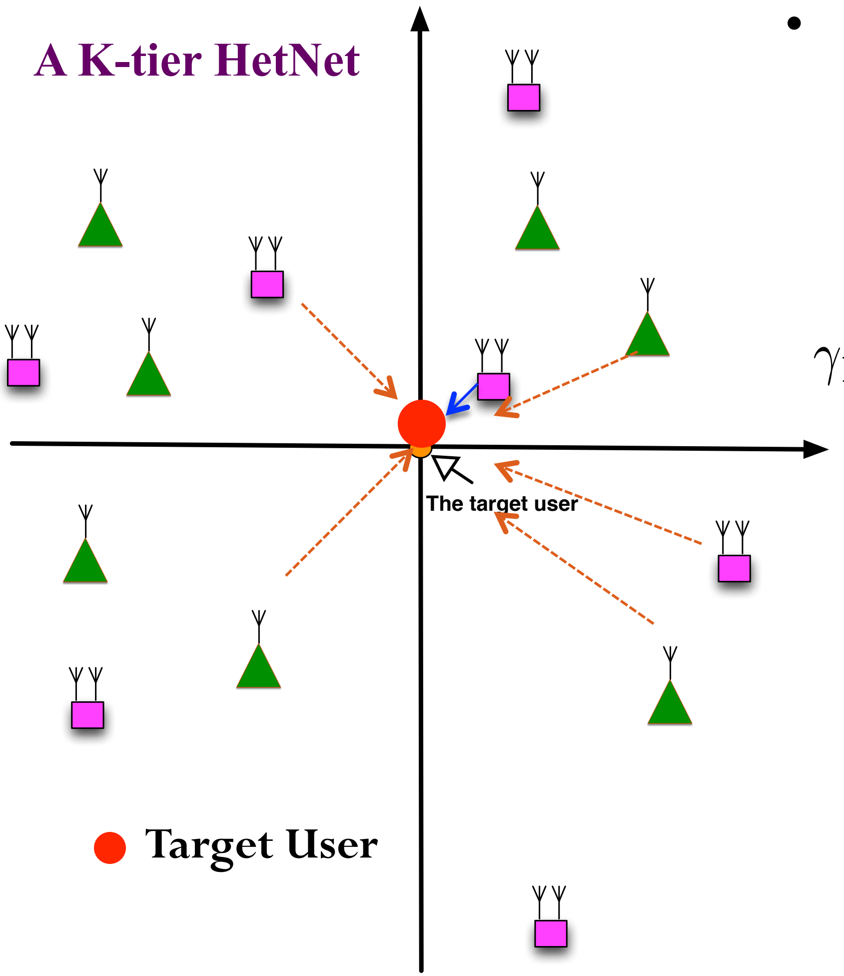
Adaptable CoMP: Coordinated States with Time Window



- **Non-coordinated Overhead State (NOS)**
  - **Overhead Message 1: It is not received within the waiting time window (w)**
  - **Overhead Message 3: The time window is too short!**
- **Coordinated Overhead State (COS)**
  - **Overhead Message 2: It is received within the waiting time window (w)**

Adaptable CoMP: Only BSs with COS are coordinated to transmit!

User's SIR in Adaptable CoMP ZFBF



- SIR for the target user receiving signals from BS B_{1,k_*} is given by

Channel Gain

TX Power

Path Loss

$$\gamma_{1,k_*} = \frac{p_{k_*} G_{1,k_*} |B_{1,k_*}|^{-\alpha_{k_*}}}{\sum_{B_{i,k} \in \bigcup_{k=1}^{K} \Phi_k \setminus B_{1,k_*}} \delta_{i,k} p_k G_{i,k} |B_{i,k}|^{-\alpha_k}}$$

Coor. index factor

where

$$\delta_{i,k} = \mathbb{1}(\mathrm{B}_{i,k} \notin \mathcal{S}_{1,k_*}) + 0 \cdot \mathbb{1}(\{\mathrm{B}_{i,k} \in \mathcal{S}_{1,k_*}\} \cap \{w < D_{i,k}\})$$
$$+ 2^{-\frac{b_{i,k}}{n_k - 1}} \mathbb{1}(\{\mathrm{B}_{i,k} \in \mathcal{S}_{1,k_*}\} \cap \{\min\{L_{i,k}, w\} \geq D_{i,k}\})$$
$$+ \mathbb{1}(\{\mathrm{B}_{i,k} \in \mathcal{S}_{1,k_*}\} \cap \{w \geq D_{i,k} \geq L_{i,k}\}),$$

$$G_{1,k_*} \triangleq |\mathbf{f}_{1,k_*} \mathbf{H}_{1,k_*}|^2 \sim \chi^2(2n_{k_*} - 2|\mathcal{S}_{1,k_*}|)$$

$$G_{i,k} \triangleq |\mathbf{f}_{1,k} \mathbf{H}_{1,k}|^2 \sim \chi^2_2$$

CCDF of SIR in Adaptable CoMP ZFBF

***Proposition 1* (CHL14) : Suppose the coordinated set $\mathcal{S}_{1,k_*}$ of BS B_{1,k_*} is given and the number of the BSs with a COS in $\mathcal{S}_{1,k_*}$ is *m*. The bounds on the CCDF of the user's SIR parameterized by *m* are given by**

$$F^c_{\gamma_{1,k_*}}(\beta;m)\begin{cases}\geq 1-\frac{\beta\Gamma\left(1+\frac{\alpha_{k_*}}{2}\right)}{n_{k_*}-|\mathcal{S}_{1,k_*}|-1}\left[\sum_{i=2}^{\infty}\mathbb{E}[\delta_{i,k_*}]\frac{(i-1)!}{\Gamma\left(i+\frac{\alpha_{k_*}}{2}\right)}+\sum_{\substack{k=1\\k\neq k_*}}^{K}\frac{P_k}{P_{k_*}}\sum_{i=1}^{\infty}\mathbb{E}[\delta_{i,k}]\frac{(\lambda_{k_*}\pi)^{-\frac{\alpha_{k_*}}{2}}(i-1)!}{(\lambda_k\pi)^{\frac{-\alpha_k}{2}}\Gamma\left(i+\frac{\alpha_k}{2}\right)}\right]\\ \leq \exp\left[-\left(\pi\tilde{\lambda}_*\right)^{1-\frac{\alpha_{k_*}}{\alpha_{\max}}}\Gamma\left(1+\frac{2}{\alpha_{\max}}\right)\left(\frac{\beta[3^{-\alpha_{\max}}\delta_{k_*}]+(2m+3)^{-\alpha_{\max}}(1-\delta_{k_*})]}{(n_{k_*}-|\mathcal{S}_{1,k_*}|)\Gamma\left(1-\frac{\alpha_{k_*}}{2}\right)}\right)^{\frac{2}{\alpha_{\max}}}\right]\end{cases}$$

where $\tilde{\lambda}_*=\sum_{k=1}^{K}\lambda_k\left(p_k/p_{k_*}\right)^{\frac{2}{\alpha_k}}$ **,** $\alpha_{\max}\triangleq\max\{\alpha_1,\ldots,\alpha_K\}$**,** $\delta_k\triangleq\min_i\mathbb{E}[\delta_{i,k}]$ **,** $|\mathcal{S}_{1,k_*}|<n_{k_*}$ **is the cardinality of** $\mathcal{S}_{1,k_*}$ **, and**

$$\begin{aligned}\mathbb{E}[\delta_{i,k}]=&\mathbb{1}[\mathsf{B}_{i,k}\notin\mathcal{S}_{1,k_*}]+2^{-\frac{b_{i,k}}{n_k-1}}\mathbb{1}[\mathsf{B}_{i,k}\in\mathcal{S}_{1,k_*}]\cdot\\&\left\{F^c_{L_{i,k}}(w)F_{D_{i,k}}(w)+F_{L_{i,k}}(w)-\mathbb{E}[F_{L_{i,k}}(D_{i,k})]\right\}\\&+\mathbb{1}[\mathsf{B}_{i,k}\in\mathcal{S}_{1,k_*}]\left\{F_{D_{i,k}}(w)-\mathbb{E}[F_{D_{i,k}}(L_{i,k})]\right\}.\end{aligned}$$

We need to reduce it to increase the CCDF of SIR !

Time Fraction of COS

***Proposition 2* (CHL14): The time fraction of the COS for a BS $\mathtt{B}_{i,k} \in \mathcal{S}_{1,k_*}$ performing adaptable CoMP ZFBF is**

$$\eta_{i,k} = \mu_{i,k}\Bigg\{\int_0^w F^c_{L_{i,k}}(x)dx - F^c_{L_{i,k}}(w)\left(wF_{D_{i,k}}(w) - \int_0^w F_{D_{i,k}}(x)dx\right) + F_{L_{i,k}}(w)\mathbb{E}\left[L_{i,k}F_{D_{i,k}}(L_{i,k}) - \int_0^{L_{i,k}} F_{D_{i,k}}(x)dx\right]\Bigg\}$$

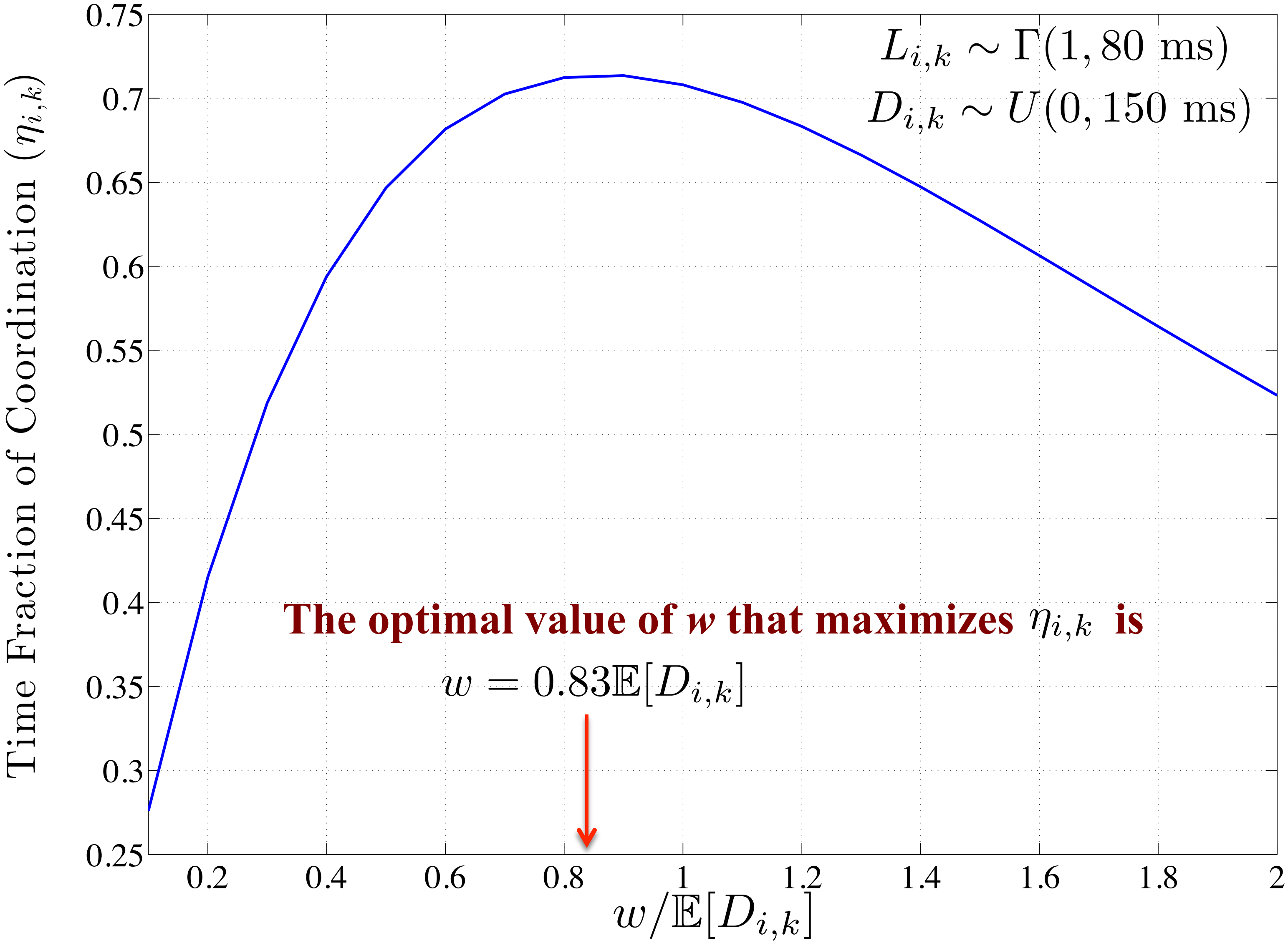
where $F_Z(\cdot)$ and $F^c_Z(\cdot)$ are the CDF and CCDF of random variable *Z*, respectively.

- **Time Fraction of COS depends on *w*, the distributions of $L_{i,k}$ and $D_{i,k}$.**
- **For example, if $D_{i,k} \sim U(0,1)$ then $\eta_{i,k}$ reduces to**

$$\eta_{i,k} = \mu_{i,k}\left[\int_0^w F^c_{L_{i,k}}(x)dx + \frac{1}{2}\left(\frac{(m-1)}{\mu_{i,k}} + w^2\right)F_{L_{i,k}}(w) - \frac{1}{2}w^2\right]$$

(We can show that $\eta_{i,k}$ is a concave function of *w*)

Simulation of Time Fraction of COS



User's Average Throughput

***Proposition 3* (CHL14): For adaptable CoMP ZFBF without user data sharing, the average throughput per unit bandwidth of the reference user in a *K*-tier HetNet is**

$$\mathcal{T}_{1,k_*} = \sum_{v=0}^{|\mathcal{S}_{1,k_*}|} \eta_{i,k_*}^{v}(1-\eta_{i,k_*})^{|\mathcal{S}_{1,k_*}|-v} \int_0^{\infty} \frac{F^c_{\gamma_{1,k_*}(v)}(x;m)}{(\ln 2)(x+1)} dx.$$

***Proof*:**

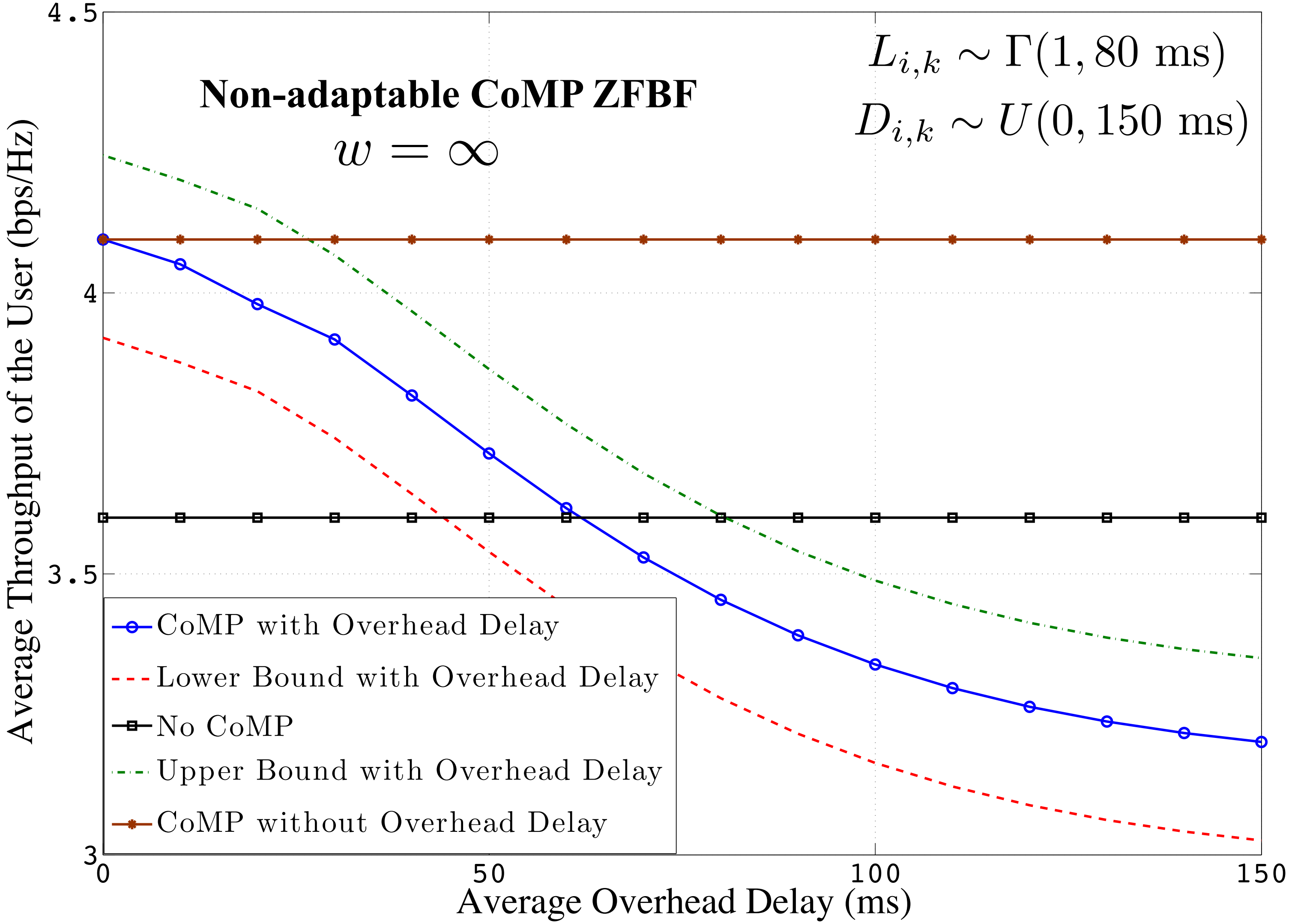
Let V be the random number of the BSs in $\mathcal{S}_{i,k_*}$ that are in COS. Since we know that each BS in $\mathcal{S}_{1,k_*}$ is either in NCS or in COS, *M* is a binomial random variable, i.e.

$$\mathbb{P}[V=v] = \eta_{i,k_*}^{v}(1-\eta_{i,k_*})^{|\mathcal{S}_{1,k_*}|-v}.$$

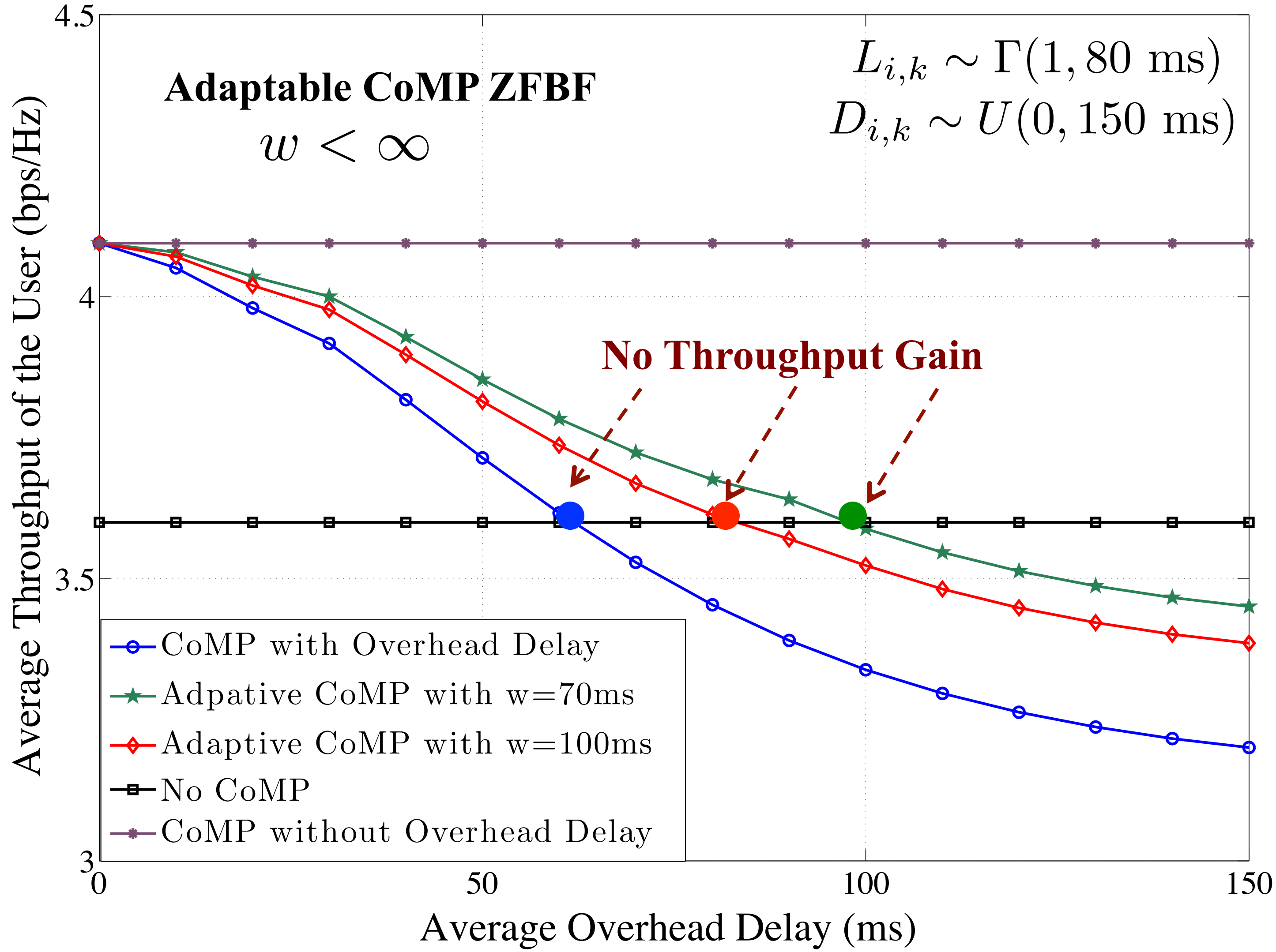
Therefore, the average throughput of a user can be expressed as

$$\begin{aligned}\mathcal{T}_{1,k_*} &= \sum_{v=0}^{|\mathcal{S}_{1,k_*}|} \mathbb{P}[V=v]\mathbb{E}[\log_2(1+\gamma_{1,k_*})] \\ &= \sum_{v=0}^{|\mathcal{S}_{1,k_*}|} \eta_{1,k_*}^{v}(1-\eta_{1,k_*})^{|\mathcal{S}_{1,k_*}|-v} \int_0^{\infty} \frac{\mathbb{P}[\gamma_{1,k_*}(v)\geq x]}{(\ln 2)(x+1)} dx.\end{aligned}$$

Simulation of Average Throughput (II)



Simulation of Average Throughput (I)



Summary

- **Introduce Downlink CoMP in a HetNet**
- **Propose Overhead Delay Model for CoMP**
- **Characterize the coordination states of BSs.**
- **Propose Adaptable CoMP with Delay Time Window**
- **Downlink Adaptable CoMP ZFBF: SINR characterization**
  - **Upper and lower bounds on SIR are derived**
  - **Optimal time window size for SIR maximization can be found. (Not presented)**
- **Downlink Adaptable CoMP ZFBF: Throughput Analysis**
  - **Throughput gain of CoMP can be more robust to imperfect overhead if the time window of coordination is properly chosen.**

Thank You