Integrated mmWave Access and Backhaul in 5G: Bandwidth Partitioning and Downlink Analysis

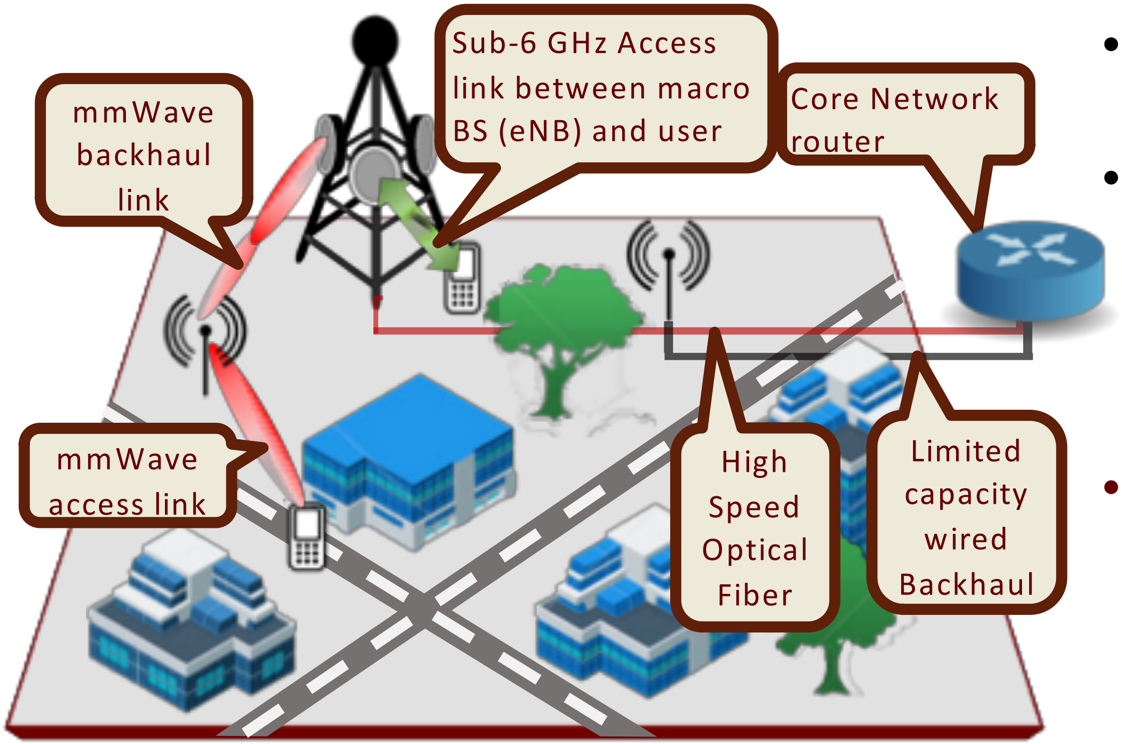
Chiranjib Saha and Harpreet S. Dhillon

Background and Key References

- **Wireless Backhaul**
  - H. S. Dhillon and G. Caire, "Wireless Backhaul Networks: Capacity Bound, Scalability Analysis and Design Guidelines", *IEEE Transactions on Wireless Communications*, vol. 14, no. 11, pp. 6043-6056, Nov. 2015.
- **Integrated Access and Backhaul**
  - C. Saha, M. Afshang and H. S. Dhillon, "Integrated mmWave Access and Backhaul in 5G: Bandwidth Partitioning and Downlink Analysis", in *Proc. IEEE ICC*, Kansas City, MO, May 2018.
  - C. Saha, M. Afshang, and H. S. Dhillon, "Bandwidth Partitioning and Downlink Analysis in Millimeter Wave Integrated Access and Backhaul for 5G", *IEEE Transactions on Wireless Communications*, vol. 17, no. 12, pp. 8195-8210, Dec. 2018.
  - C. Saha, H. S. Dhillon, "Load Balancing in 5G HetNets with Millimeter Wave Integrated Access and Backhaul", available online: https://arxiv.org/abs/1902.06300

Integrated Access and Backhaul in 5G

- 5G requires **Gbps backhaul** capacity, which requires new spectrum (e.g. mmWave) for both access and backhaul.
- **Integrated Access-and-Backhaul (IAB)**: when the access and the backhaul links **share the same wireless channel** [1-3].

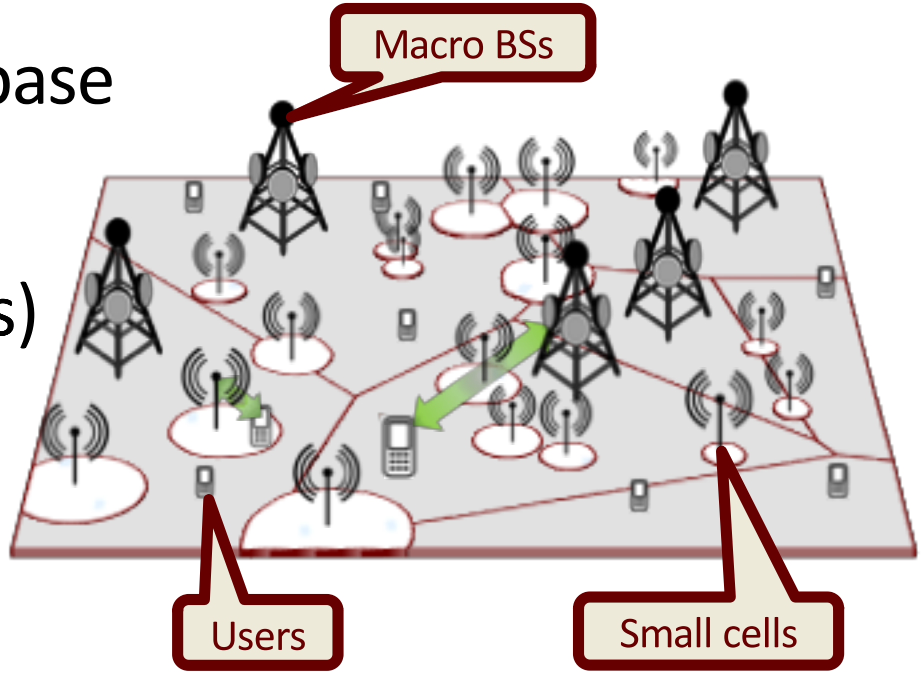


- Currently being considered by 3GPP[2].
- Self-backhaul will become a driving technology owing to more ubiquitous deployment of small cells, e.g. in vehicles, trains, lamp-posts etc.
- Need to develop analytical framework for IAB-enabled cellular network to gain key design insights.

[2] 3GPP TR 38.874, "NR; Study on integrated access and backhaul," Tech. Rep., 2017.

Stochastic Geometry Models Based on Poisson Point Process

- First comprehensive model assumed all wireless nodes (base stations and users) to be distributed as *independent* Poisson Point Processes (PPPs)
- *Roughly speaking, PPP places points uniformly at random independently of each other*
- This led to a highly tractable approach to cellular analysis

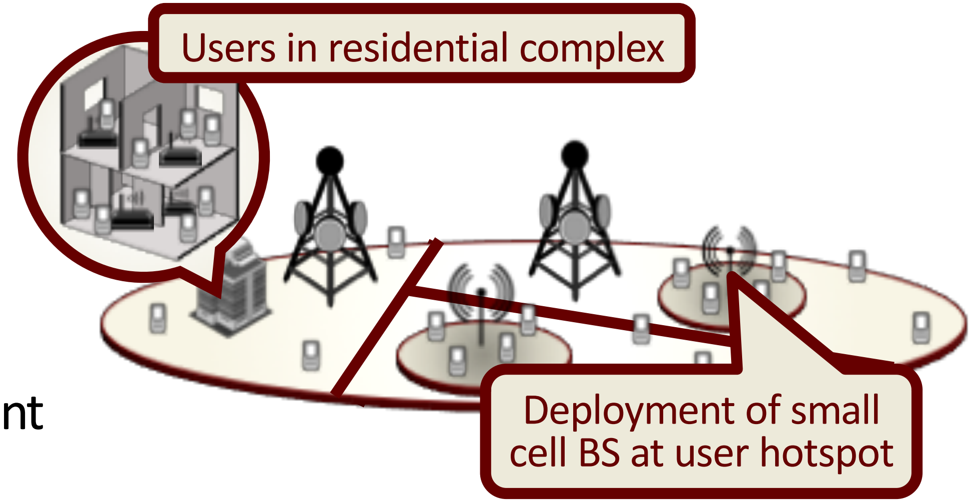


An illustration of the PPP-based cellular model

H. S. Dhillon, R. K. Ganti, F. Baccelli, and J. G. Andrews, "Modeling and analysis of K-tier downlink heterogeneous cellular networks," *IEEE Journal on Sel. Areas in Commun.*, 2012.

How Realistic is this Model?

- Key features missing in this PPP-based model:
- User hotspots
  - Very important to model hotspots *(areas of high user density)*
  - Modeling all users as an independent PPP is no longer realistic

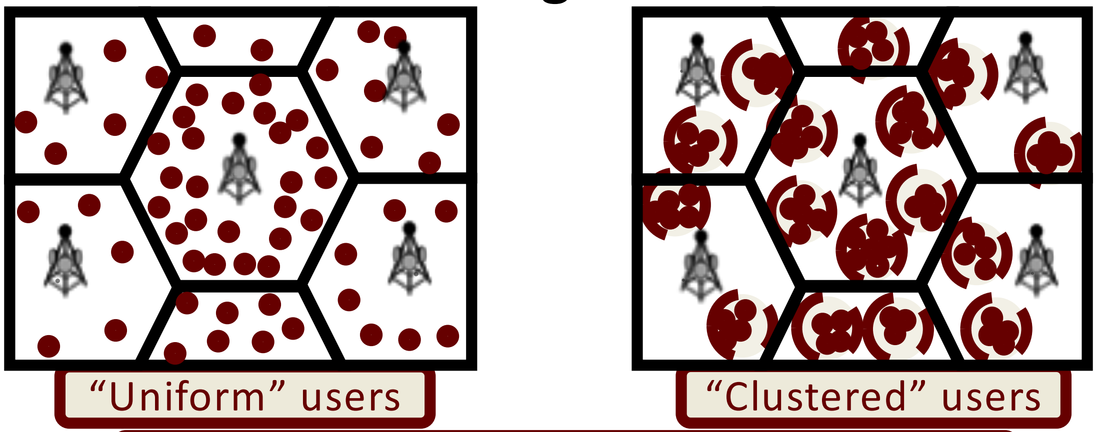


- Coupling between small cell BSs (SBSs) and user locations
  - Operators deploy SBSs (e.g., picocells) at the areas of high user density
- Inter and intra BS-tier dependence
  - BS locations are not necessarily independent
  - Site planning for deploying BSs introduces coupling in BS locations

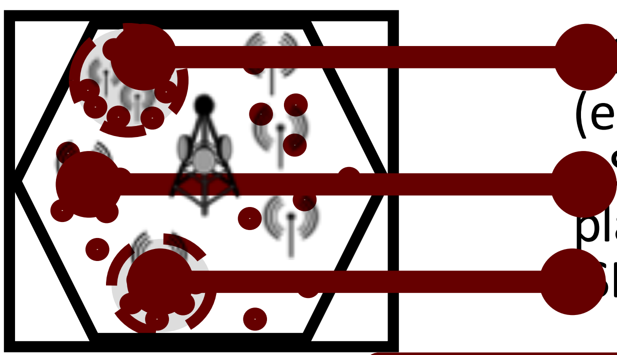
Takeaway: Although a huge step-up from the deterministic models, PPP-based models are unable to capture hotspot formation as well as coupling in the locations of wireless nodes

3GPP Cellular Models

- 3GPP considers different configurations of SBSs and users



User configurations in 3GPP cellular models

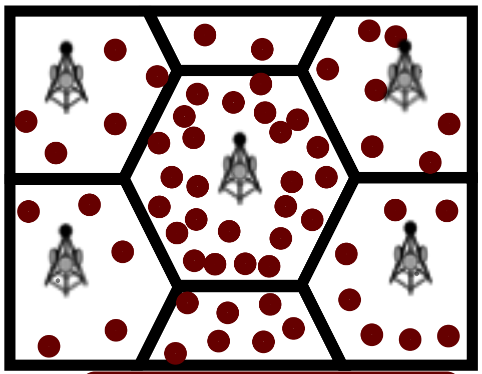


- SBSs deployed at higher density in certain areas (e.g., indoor models)
- SBSs deployed *randomly* or under some site planning
- SBSs deployed at the centers of user hotspots

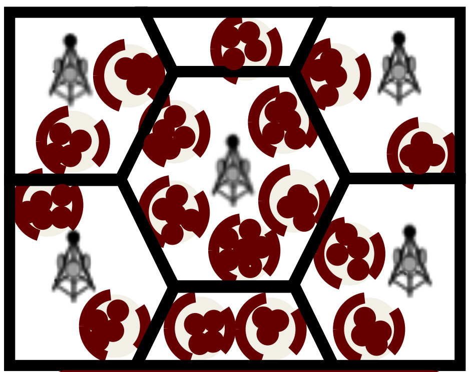
SBS configurations in 3GPP cellular models

3GPP TR 36.932 V13.0.0 , “3rd generation partnership project; technical specification group radio access network; scenarios and requirements for small cell enhancements for E-UTRA and E-UTRAN (release 13),” Tech. Rep., Dec. 2015

How does PPP Model Hold Up?

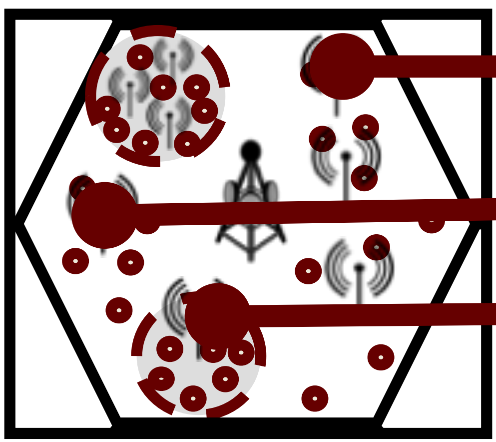


“Uniform” users



“Clustered” users

While PPP model is very useful, it is highly restrictive

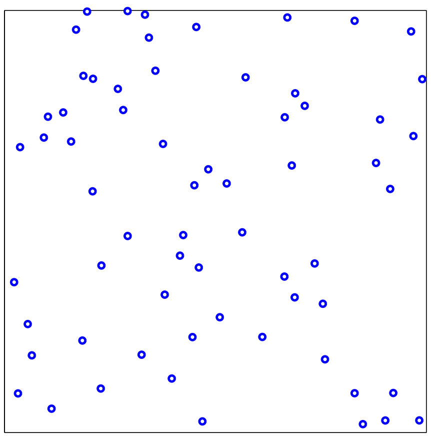


- SBSs deployed at higher density in certain areas (e.g., indoor models)
- SBSs deployed randomly or under some site planning
- SBSs deployed at the centers of user hotspots

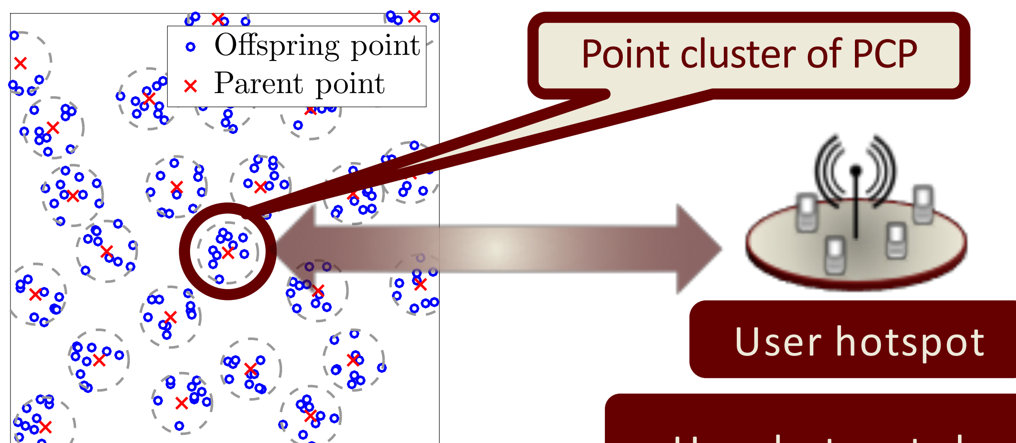
These deficiencies can be overcome by using a **Poisson Cluster Process** to model users

Poisson Cluster Process-based Models

- PCP exhibits **intra-point attraction**. The points of a PCP are *clustered* around the points of a parent PPP
- Points of PCP from the same cluster are spatially coupled!



Realization of a PPP



Realization of a PCP

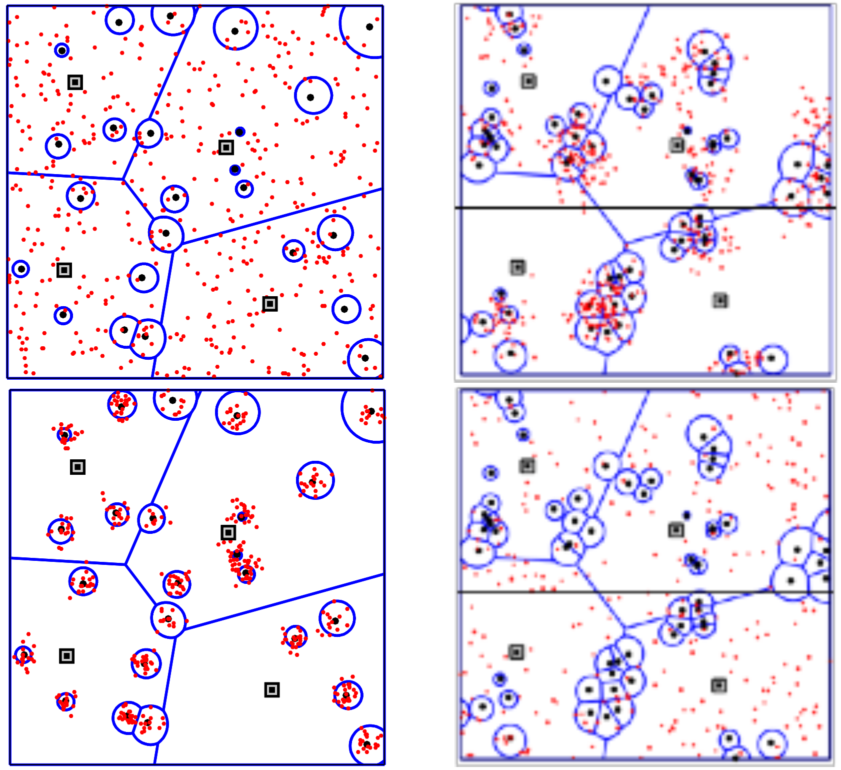
User hotspots have natural resemblance with clusters of PCP

New Canonical Cellular Models using PCP

- It is possible to capture spatial coupling with new models generated by combining PCPs with PPPs

Model 1: Users PPP, BSs PPP (Baseline)

Model 3: Users PCP, BSs PCP



Model 2: Users PCP, BSs PPP

Model 4: Users PPP, BSs PCP

Model 1: H. S. Dhillon, R. K. Ganti, F. Baccelli, and J. G. Andrews, "Modeling and analysis of K-tier downlink heterogeneous cellular networks," *IEEE JSAC,* 2012.

Model 2: C. Saha, M. Afshang, and H. S. Dhillon, "Enriched K-Tier HetNet Model to Enable the Analysis of User-Centric Small Cell Deployments", *IEEE Twireless,* 2017.

Model 3: M. Afshang, H. S. Dhillon, "Poisson Cluster Process Based Analysis of HetNets with Correlated User and Base Station Locations", submitted, 2017.

Unified: C. Saha, M. Afshang, H. Dhillon., "3GPP-inspired HetNet Model using Poisson Cluster Process: Sum-product Functionals and Downlink Coverage", submitted, 2017.

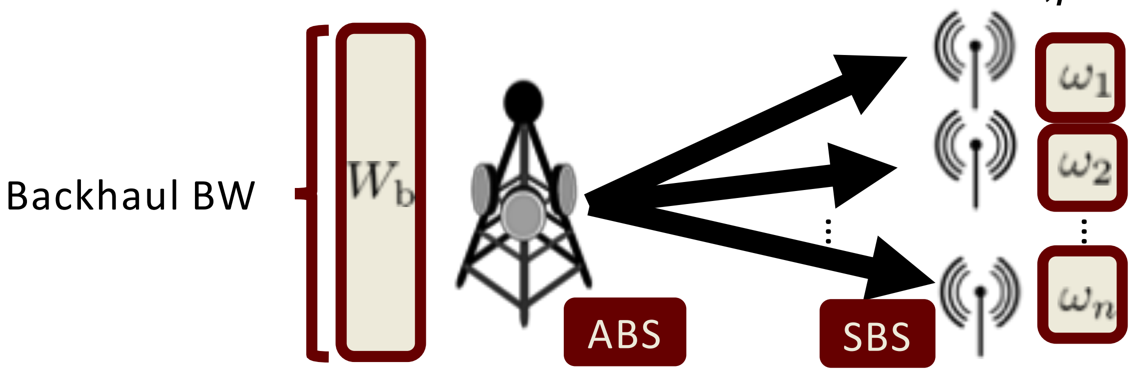
PCP-based HetNet Models

- So far..
  - We have characterized useful mathematical properties of of PCP, e.g., contact and nearest neighbor distance distributions, sum-product functionals.
  - Using these results, we have evaluated coverage probability for these HetNet models under max-power and max-SIR connectivity.
- What's next?
  - In all these models, one common assumption is **infinite backhaul capacity for all BSs**
  - Need to account for backhaul constrained smallcells which is the fundamental component in any IAB-enabled cellular network model.

Research Question: Resource Allocation

How to efficiently partition backhaul resources among different SBSs?

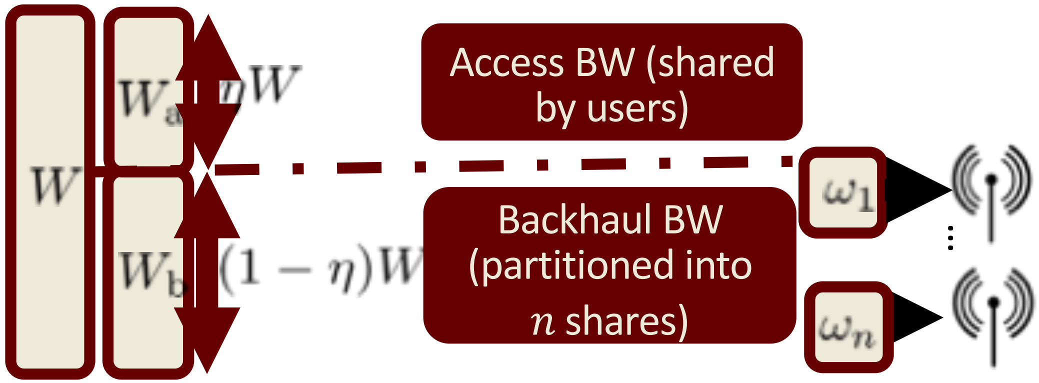
- Assume that the anchored BS (ABS, i.e., the BS connected to the core network by high speed fiber) has to provide wireless backhaul connectivity to n small cell BSs (SBSs).
- If W_b is the total backhaul bandwidth (BW), then the problem is to find the partition $\{\omega_1, \omega_2, \dots, \omega_n\}$ such that $\sum_i \omega_i = W_b$.
- What is the optimum partition that maximizes the number of users connected to small cells that achieve a predefined target downlink data rate ρ (denoted by $N_{u,\rho}^{SBS}$)?



$$\arg\max_{\{\omega_j\}} N_{u,\rho}^{SBS}$$

Research Question: Resource Allocation

How is bandwidth split between access and backhaul?



- Another problem is to determine the value of the partition fraction, η $(0 < \eta < 1)$ that maximizes the number of users (connected to MBS or SBS) receiving minimum downlink data-rate ρ, denoted by $N_{u,\rho}$.
- The optimization problem in the previous slide can be further enhanced to: $\boxed{\arg \max_{\{\eta,\omega_1,\ldots,\omega_n\}} N_{\mathrm{u},\rho}}$

Proposed System Model

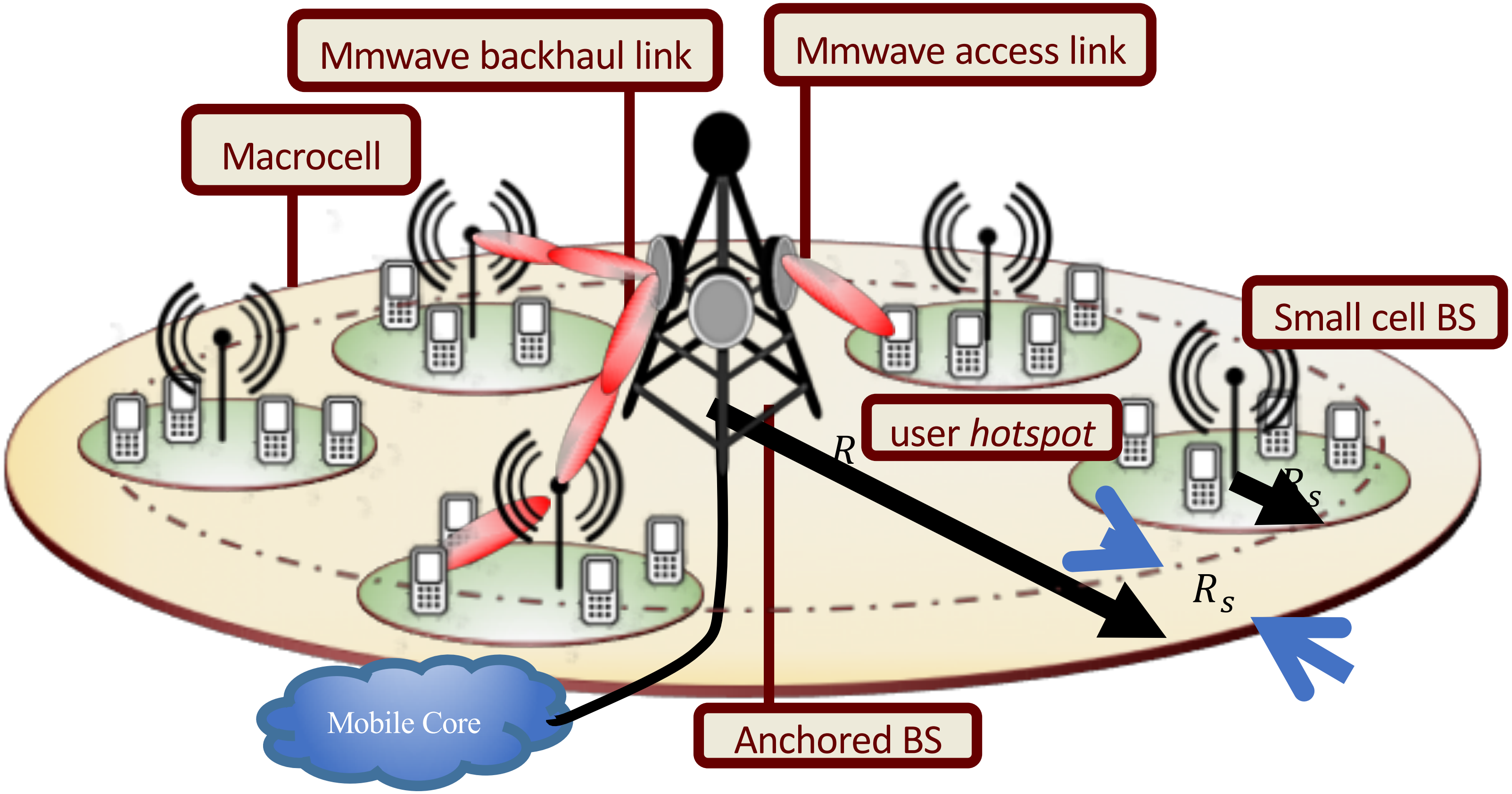
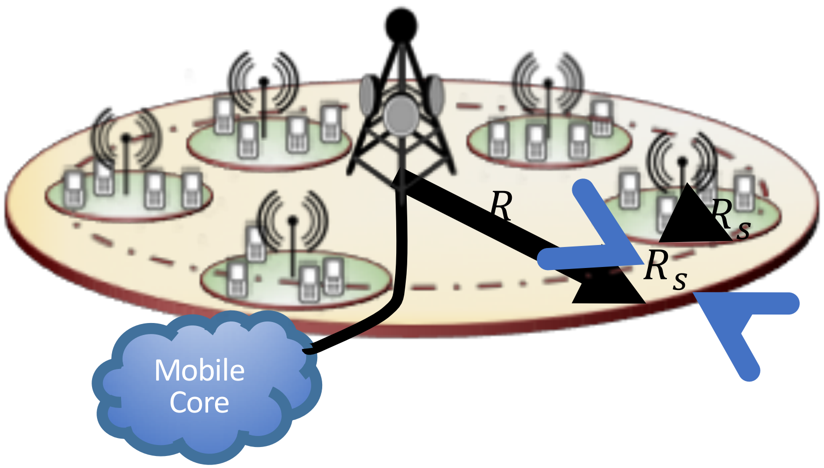


Illustration of proposed system model

Proposed System Model

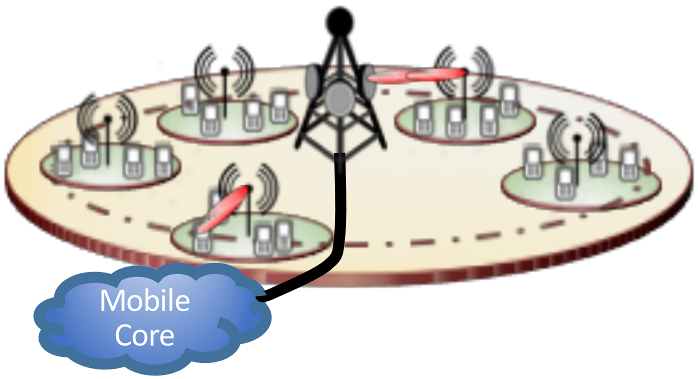
⁕ User and BS locations



- A circular macro cell of radius R.
- The macro (or anchored) BS is located at the center of the macro cell.
- n user hotspots (circles of radius R_s) located uniformly at random across the macro cell at locations $\{\boldsymbol{x}_1, \boldsymbol{x}_2, \ldots, \boldsymbol{x}_n\}$.
- Each hotspot has a SBS at center.
- m users located uniformly at random in each user hotspot.

Proposed System Model

⁕ Propagation assumptions



- All transmissions are in mmWave spectrum.
- Each BS transmits at a constant power spectral density $\frac{P}{W}$ over a system BW W ($P = P_m$ and P_s are the transmission powers of ABS and SBS.
- We assume noise-limited system, where N_0 is the noise PSD.

- SNR received for a link of BW $\widetilde{W}$ is proportional to $\frac{\frac{P}{W}W}{N_0 W} = \frac{P}{N_0 W}$.

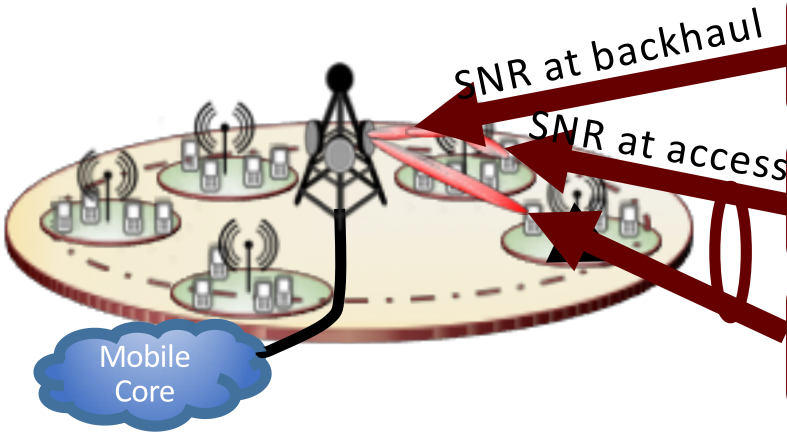
⁕ Blocking (Exponential blocking model)

- For mmWave, LOS and NLOS path-loss characteristics have to be explicitly considered.
- Each link of distance r is LOS or NLOS according to an independent Bernoulli random variable with LOS probability $p(r) = e^{-r/\mu}$, where μ is the LOS range constant.

* T.Bai and R.W.Heath, "Coverage and rate analysis for millimeter-wave cellular networks," *IEEE Trans. on Wireless Commun.*, vol. 14, no. 2, pp. 1100–1114, Feb. 2015.

User Association and Coverage

SNR Expressions



$$\mathrm{SNR_b}(\mathbf{x}) = \frac{\mathrm{P_m G^2 h_b L}(\mathbf{0}, \mathbf{x})^{-1}}{\mathrm{N_0 W}},$$

$$\mathrm{SNR_a^{SBS}}(\mathbf{x}+\mathbf{u}) = \frac{\mathrm{P_s G h_s L}(\mathbf{x}, \mathbf{x}+\mathbf{u})^{-1}}{\mathrm{N_0 W}},$$

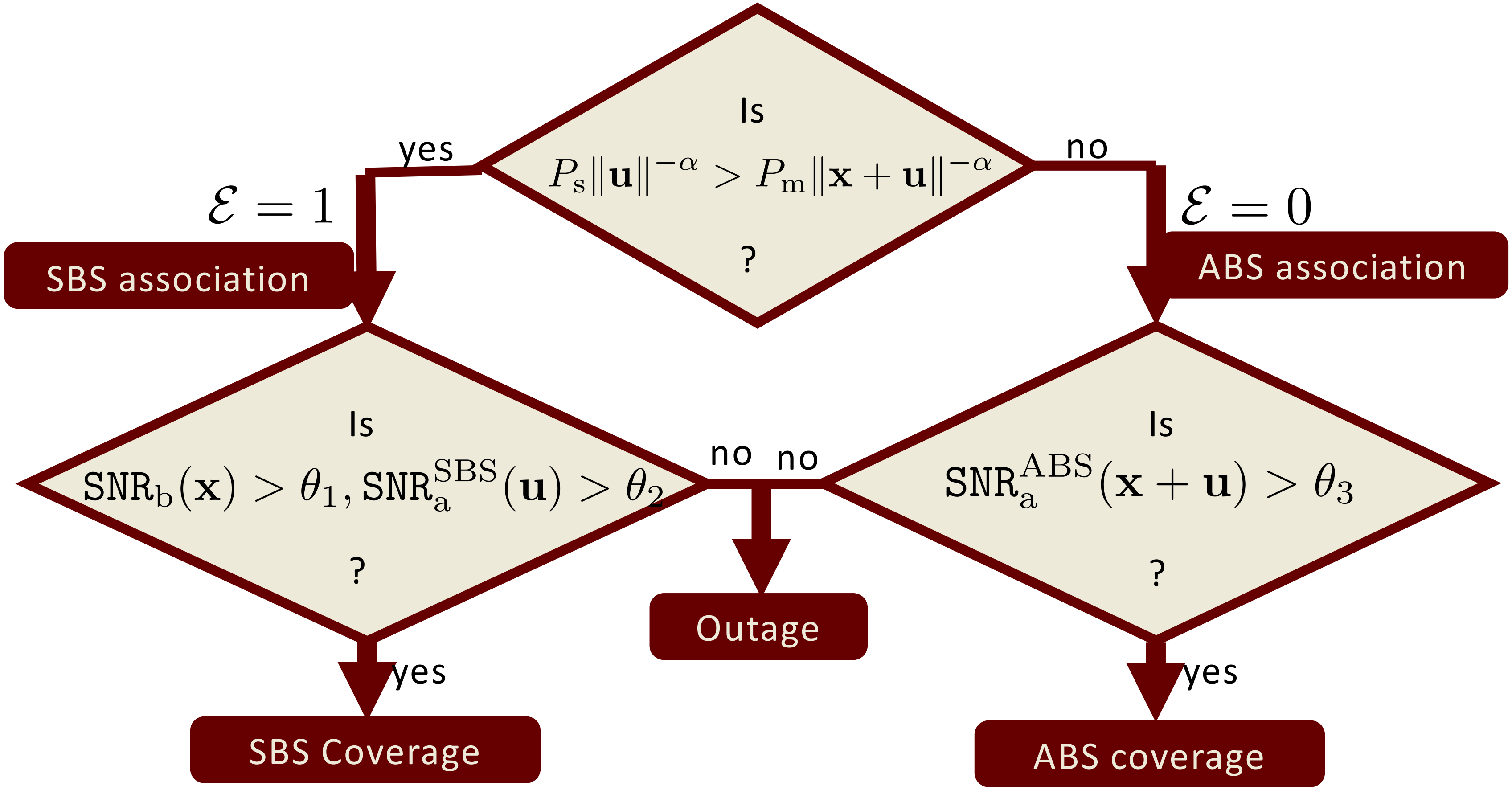
$$\mathrm{SNR_a^{ABS}}(\mathbf{x}+\mathbf{u}) = \frac{\mathrm{P_m G h_m L}(\mathbf{0}, \mathbf{x}+\mathbf{u})^{-1}}{\mathrm{N_0 W}}.$$

where $h_{\mathrm{b}}, h_{\mathrm{s}}, h_{\mathrm{m}} \overset{i.i.d.}{\sim} \texttt{Gamma}(m, m^{-1})$.

User Association

- *Closed access* SBSs: users in hotspot can only connect to the SBS at hotspot center, or the ABS.
- The user association is performed by signaling in sub-6 GHz which is analogous to the current LTE standard.

User Association and Coverage



- **Note:** Coverage event is a subset of the association event.
- The *general idea of our analysis* is to first condition on a SBS-user pair (located at $\boldsymbol{x} = \boldsymbol{x}_i$ ($i = 1$, without loss of generality) and $\boldsymbol{x} + \boldsymbol{u}$) and later decondition w.r.t. $\boldsymbol{u}$ and $\boldsymbol{x}$.

Resource Allocation

- The total mmWave downlink BW W is partitioned into two parts, $W_b = \eta W$ for backhaul and $W_a = (1-\eta)W$ for access.

$\eta \in [0,1) :=$ access-backhaul split.

Access BW ($W_{\rm a} = (1-\eta)W$)

Each BS employs a simple round robin scheduling policy for serving users, i.e., the total access BW is equally shared among its load on that particular BS.

Backhaul BW ($W_{\rm b} = \eta W$)

The backhaul BW is shared amongst n SBSs by the following strategies.

Equal Partition

$$W_s(\boldsymbol{x}) = \frac{\mathrm{W_b}}{\mathrm{n}}$$

Instantaneous Load-based Partition

$$W_s(\boldsymbol{x}) = \frac{N_{\mathbf{x}}^{\rm SBS}}{N_{\mathbf{x}}^{\rm SBS} + \sum_{i=1}^{n-1} N_{\mathbf{x}_i}^{\rm SBS}} \mathrm{W_b}$$

Average Load-based Partition

$$W_s(\boldsymbol{x}) = \frac{N_{\mathbf{x}}^{\rm SBS}}{N_{\mathbf{x}}^{\rm SBS} + \sum_{i=1}^{n-1} N_{\mathbf{x}_i}^{\rm SBS}} \mathrm{W_b}$$

$N_{\mathbf{x}}^{\rm SBS} :=$ Load on SBS at $\mathbf{x}$, $N_{\mathbf{x}}^{\rm SBS} = \mathbb{E}\bar{N}_{\mathbf{x}}^{\rm SBS}$.

Downlink Data-rate and Rate-coverage

- **Data-rate:** Assuming Shannon rate is achievable on each link,

Rate on backhaul link

$$\mathcal{R}_{\rm b}^{\rm ABS} = W_{\rm s}(\mathbf{x}) \log_2(1 + \mathtt{SNR}_{\rm b}(\mathbf{x}))$$

Rate on access link

From SBS to user

$$\mathcal{R}_{\rm a}^{\rm SBS} = \min\left(\frac{W_{\rm a}}{N_{\mathbf{x}}^{\rm SBS}} \log_2(1 + \mathtt{SNR}_{\rm a}^{\rm SBS}(\mathbf{u})), \frac{W_{\rm s}(\mathbf{x})}{N_{\mathbf{x}}^{\rm SBS}} \log_2(1 + \mathtt{SNR}_{\rm b}(\mathbf{x}))\right)$$

From ABS to user

$$\mathcal{R}_{\rm a}^{\rm ABS} = \frac{W_{\rm a}}{N_{\mathbf{x}}^{\rm ABS} + \sum_{i=1}^{n-1} N_{\mathbf{x}_i}^{\rm ABS}} \log_2(1 + \mathtt{SNR}_{\rm a}^{\rm ABS}(\mathbf{x} + \mathbf{u}))$$

- **Rate-coverage Probability:** For a link with $\widetilde{W}$, rate-coverage is:

$$\mathbb{P}(\tilde{W} \log_2(1 + \mathtt{SNR}) > \rho)$$
$$= \mathbb{P}(\mathtt{SNR} > 2^{\rho/\tilde{W}} - 1)$$

ρ := Rate threshold or target data-rate

This is nothing but coverage probability at a new coverage threshold.

Downlink data-rate and Rate-coverage

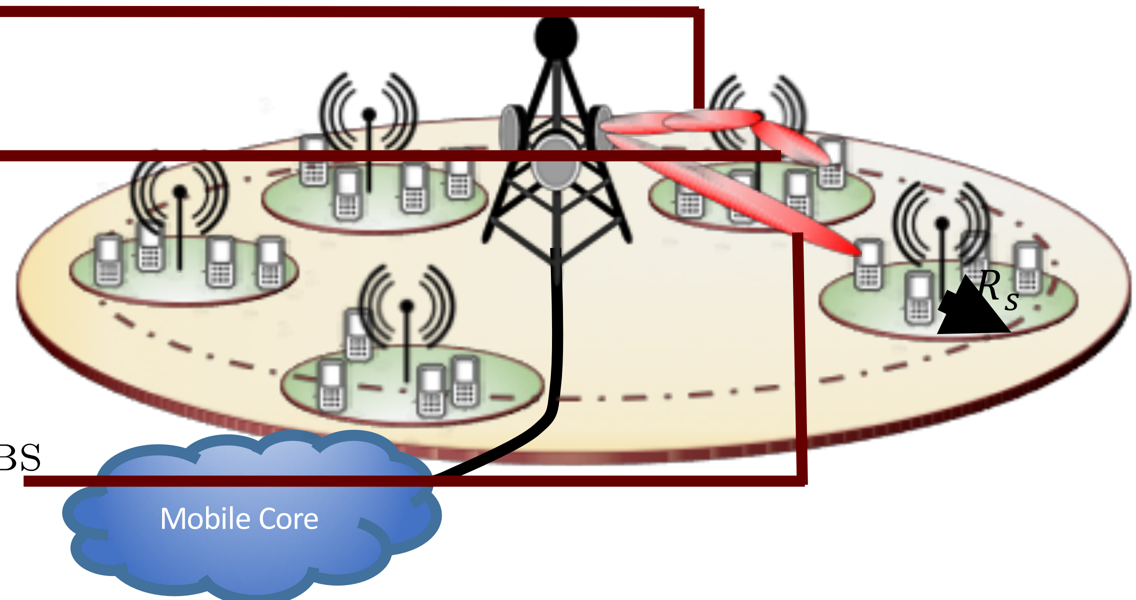
- **Data-rate:** Assuming Shannon rate is achievable on each link,

Rate on backhaul link $\mathcal{R}_{\mathrm{b}}^{\mathrm{ABS}}$

Rate on access link

From SBS to user $\mathcal{R}_{\mathrm{a}}^{\mathrm{SBS}}$

From ABS to user $\mathcal{R}_{\mathrm{a}}^{\mathrm{ABS}}$



- **Rate-coverage Probability:** For a link with $\widetilde{W}$, rate-coverage is:

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$$=\mathbb{P}(\mathtt{SNR}>2^{\rho/\tilde{W}}-1)$$

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This is nothing but coverage probability at a new coverage threshold.

Association and Coverage Probability

Lemma 1. Association Probability

Conditioned on the fact that the user belongs to the hotspot at $\mathbf{x}$, the association probability to SBS is given by:

$$\mathcal{A}_{\rm s}(\mathbf{x}) = \mathcal{A}_{\rm s}(\|\mathbf{x}\|) = \int_0^{2\pi} \frac{\left(\min\left(R_{\rm s}, x\frac{k_p\sqrt{(1-k_p^2.\sin^2\xi)}+k_p\cos\xi}{1-k_p^2}\right)\right)^2}{R_{\rm s}^2}{\rm d}\xi.$$

Here, $k_p = \left(\frac{P_{\rm s}}{P_{\rm m}}\right)^{1/\alpha}$.

Coverage probability can be written as follows.

$$\mathrm{P_c} = \int_0^{R-R_{\rm s}} \underbrace{\left(\overbrace{\boxed{\mathrm{P_{cs}}(\theta_1,\theta_2|x)}}^{\text{Conditional SBS Coverage}} + \overbrace{\boxed{\mathrm{P_{cm}}(\theta_3|x)}}^{\text{Conditional MBS Coverage}}\right)\boxed{f_X(x)}}_{\text{Deconditioned over } x\text{: distance of hotspot center from ABS}}{\rm d}x,$$

What else do we need for Rate Coverage?

- Remember that rate coverage is actually coverage but evaluated at a modified SNR threshold.
- Like coverage, rate coverage will also have two terms:

$$\mathrm{P_r} = \underbrace{\boxed{\mathrm{P_{rs}}}}_{\text{SBS rate Coverage}} + \underbrace{\boxed{\mathrm{P_{rm}}}}_{\text{MBS rate Coverage}}$$

- Let's focus on the second term (relatively easy)

$$\mathrm{P_{rm}} = \mathbb{P}(\mathcal{R}_{\mathrm{a}}^{\mathrm{ABS}} > \rho) = \mathbb{P}\left[\frac{W_{\mathrm{a}}}{N_{\mathbf{x}}^{\mathrm{ABS}} + N_{\mathrm{o}}^{\mathrm{ABS}}} \log_2(1 + \mathtt{SNR}_{\mathrm{a}}^{\mathrm{ABS}}(\mathbf{x}+\mathbf{u})) > \rho\right]$$

$N_{\mathbf{x}}^{\mathrm{ABS}}$:= Macro load from user hotspot $N_{\mathrm{o}}^{\mathrm{ABS}}$:= Macro load from other hotspots

We don't yet know, what are the distributions of $N_{\mathbf{x}}^{\mathrm{ABS}}$ and $N_{\mathrm{o}}^{\mathrm{ABS}}$

What else do we need for Rate Coverage?

- Now, we come to the first term. Note that, this term will depend on the choice of backhaul BW partition.
- For load-based backhaul partition.

$$\mathrm{P}_{\mathrm{rs}} = \mathbb{P}\left(\frac{W_b}{N_{\mathbf{x}}^{\mathrm{SBS}} + N_{\mathrm{o}}^{\mathrm{SBS}}} \log_2(1 + \mathtt{SNR}_{\mathrm{b}}^{\mathrm{SBS}}(\mathbf{x})) > \rho\right) \mathbb{P}\left(\frac{W_{\mathrm{a}}}{N_{\mathbf{x}}^{\mathrm{SBS}}} \log_2(1 + \mathtt{SNR}_{\mathrm{a}}(\mathbf{u})) > \rho\right)$$

- We can simplify this further, but we can observe two more random variables due to **SBS load** whose distributions are unknown.

$N_{\mathbf{x}}^{\mathrm{SBS}}$:= SBS load at the user hotspot

$N_{\mathbf{o}}^{\mathrm{SBS}}$:= Sum of total SBS loads on all other hotspots

We have developed a new approach of load modeling which is *directly applicable* to the 3GPP-inspired finite network models. In particular, we have characterized the probability mass function of $N_{\mathbf{x}}^{\mathrm{ABS}}$,$N_{\mathbf{o}}^{\mathrm{ABS}}$, $N_{\mathbf{x}}^{\mathrm{SBS}}$, and $N_{\mathbf{o}}^{\mathrm{SBS}}$.

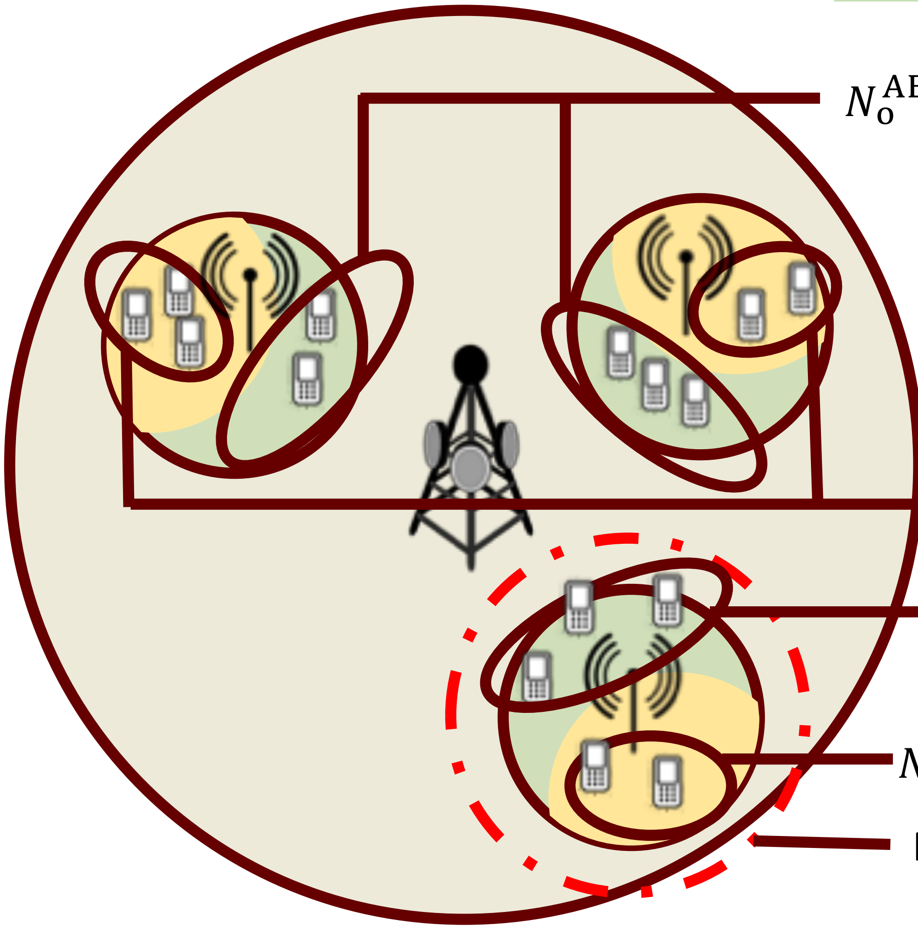
This cell load characterization is completely different than the well-known approaches for PPP-based networks*.

* S. Singh, M. N. Kulkarni, A. Ghosh, and J. G. Andrews, "Tractable model for rate in self-backhauled millimeter wave cellular networks," *IEEE Journal on Sel. Areas in Commun.*, vol. 33, no. 10, pp. 2196–2211, Oct. 2015.

Illustration of the load variables

SBS association region

ABS (macro) association region



N_o^{ABS}:= Sum of total macro loads from all other hotspots

N_o^{SBS}:= Sum of total SBS loads on all other hotspots

$N_{\mathbf{x}}^{\mathrm{ABS}}$:= macro load at the representative hotspot

$N_{\mathbf{x}}^{\mathrm{SBS}}$:= SBS load at the representative hotspot

Representative hotspot (centered at $\boldsymbol{x}$)

Load Distribution

Lemma 2. Distribution (exact) of $N_{\mathbf{x}}^{\mathrm{ABS}}$ and $N_{\mathbf{x}}^{\mathrm{SBS}}$

Given the fact that the typical user belongs to a hotspot at $\mathbf{x}$,

$$\mathbb{P}(N_{\mathbf{x}}^{\mathrm{ABS}} = k|\mathbf{x}) = \binom{\bar{m}-1}{k-1}\mathcal{A}_{\mathrm{m}}(x)^{k-1}\mathcal{A}_{\mathrm{s}}(x)^{\bar{m}-k},$$
$$\mathbb{P}(N_{\mathbf{x}}^{\mathrm{SBS}} = k|\mathbf{x}) = \binom{\bar{m}-1}{k-1}\mathcal{A}_{\mathrm{s}}(x)^{n-1}\mathcal{A}_{\mathrm{m}}(x)^{\bar{m}-k}.$$

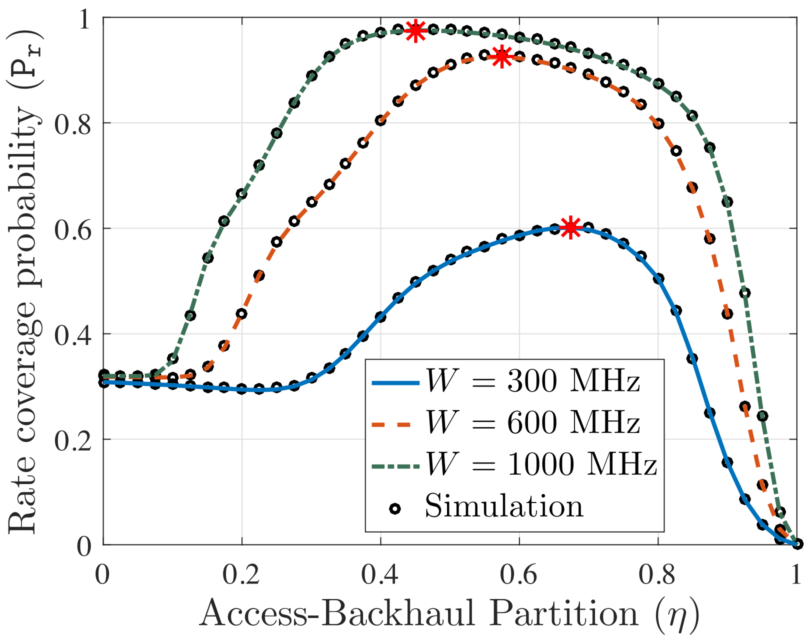
Lemma 3. Distribution (central limit theorem-based) of $N_{\mathrm{o}}^{\mathrm{ABS}}$ and $N_{\mathrm{o}}^{\mathrm{SBS}}$

Load on the ABS due to all other $n-1$ hotspots is distributed as:

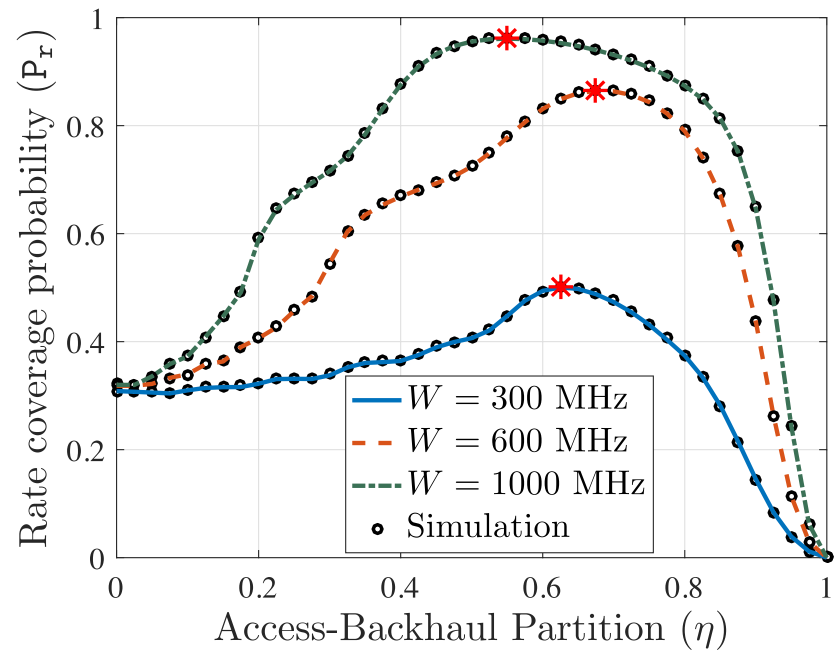
$$N_{\mathrm{o}}^{\mathrm{ABS}} \sim \mathcal{N}(\upsilon_{\mathrm{m}}, \sigma_{\mathrm{m}}^2), \text{ for large } n,$$
$$N_{\mathrm{o}}^{\mathrm{SBS}} \sim \mathcal{N}(\upsilon_{\mathrm{s}}, \sigma_{\mathrm{s}}^2), \text{ for large } n.$$

Here, $\upsilon_{\mathrm{m}} = (n-1)\bar{m}\mathbb{E}[\mathcal{A}_{\mathrm{m}}(X)], \upsilon_{\mathrm{s}} = (n-1)\bar{m}\mathbb{E}[\mathcal{A}_{\mathrm{s}}(X)]$, and
$$\sigma_{\mathrm{m}}^2 = (n-1)[\bar{m}\mathbb{E}[A_{\mathrm{m}}(X)A_{\mathrm{s}}(X)] + \bar{m}^2\mathrm{Var}[\mathcal{A}_{\mathrm{m}}(X)]] = \sigma_{\mathrm{s}}^2$$

Trend in Rate Coverage



Instantaneous Load-based partition

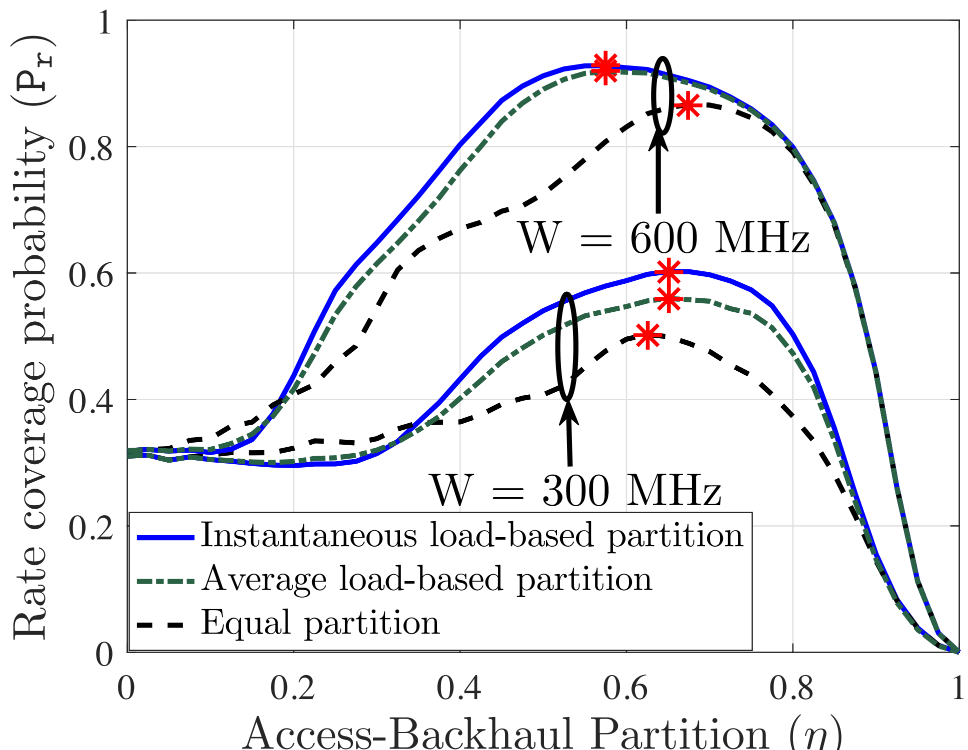


Equal partition

- For both cases, we observe optimum access-backhaul BW partition fraction for which rate coverage is maximized.
- Our CLT based approach is surprisingly exact even for $n = 10$.

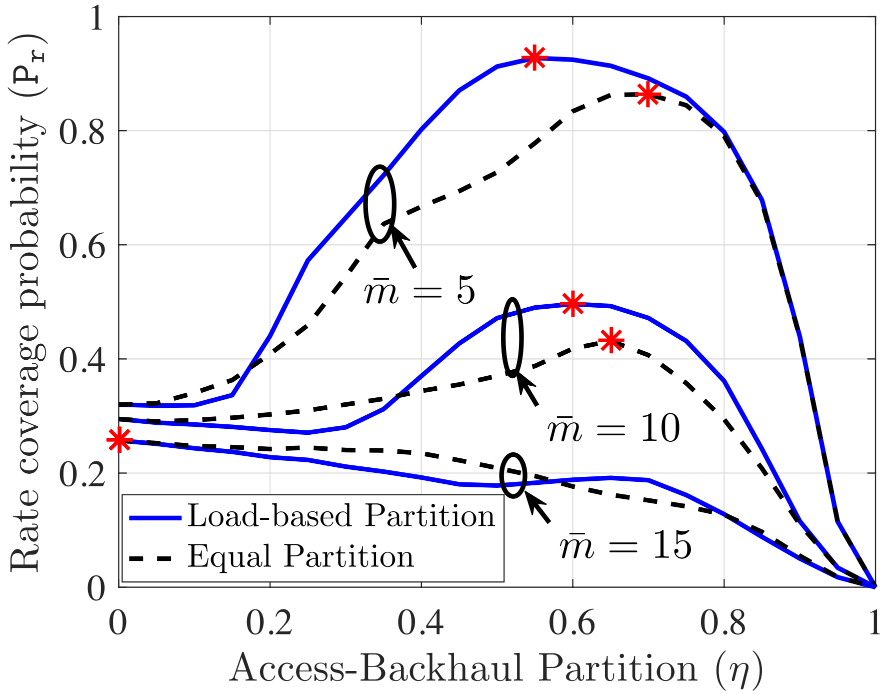
For all numerical results, $\rho = 50$ Mbps, n=10. In these figures, $m = 5$.

Which policy is better?



- In terms of optimal rate coverage,
  Instantaneous load-based partition>Average load-based partition>Equal partition
- In terms of signaling overhead,
  Instantaneous load-based partition<Average load-based partition<Equal partition
- So there exists a complexity performance trade-off for designing IAB networks.
- The performance gain becomes less prominent if system BW is increased.

How much load can IAB support?

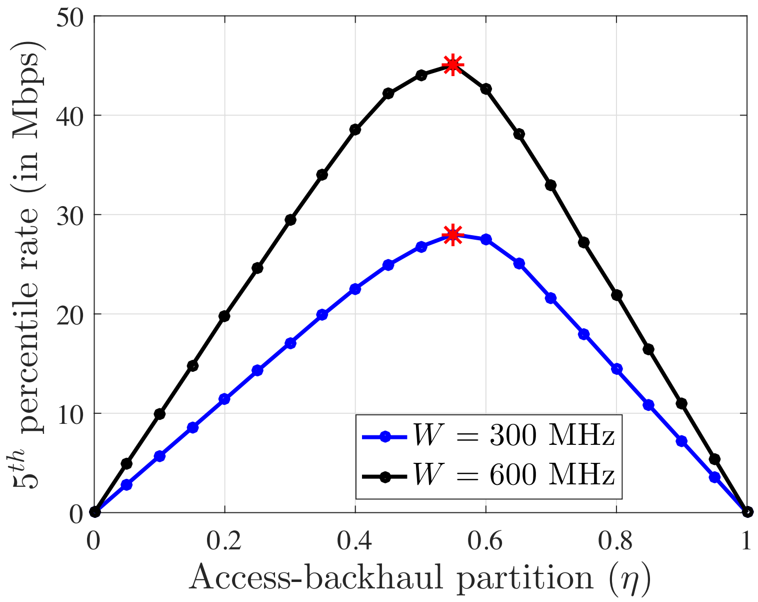


- In this plot, BW is fixed, but number of users per hotspot is varied.
- For $m = 15$, we see that the optimal partition has moved to $\eta = 0$, which means all BW should be assigned to the access links. This is equivalent to a single tier macro-only network.

There exists a critical cell load beyond which the gain of IAB completely diminishes.

What do we gain by analytical tractability?

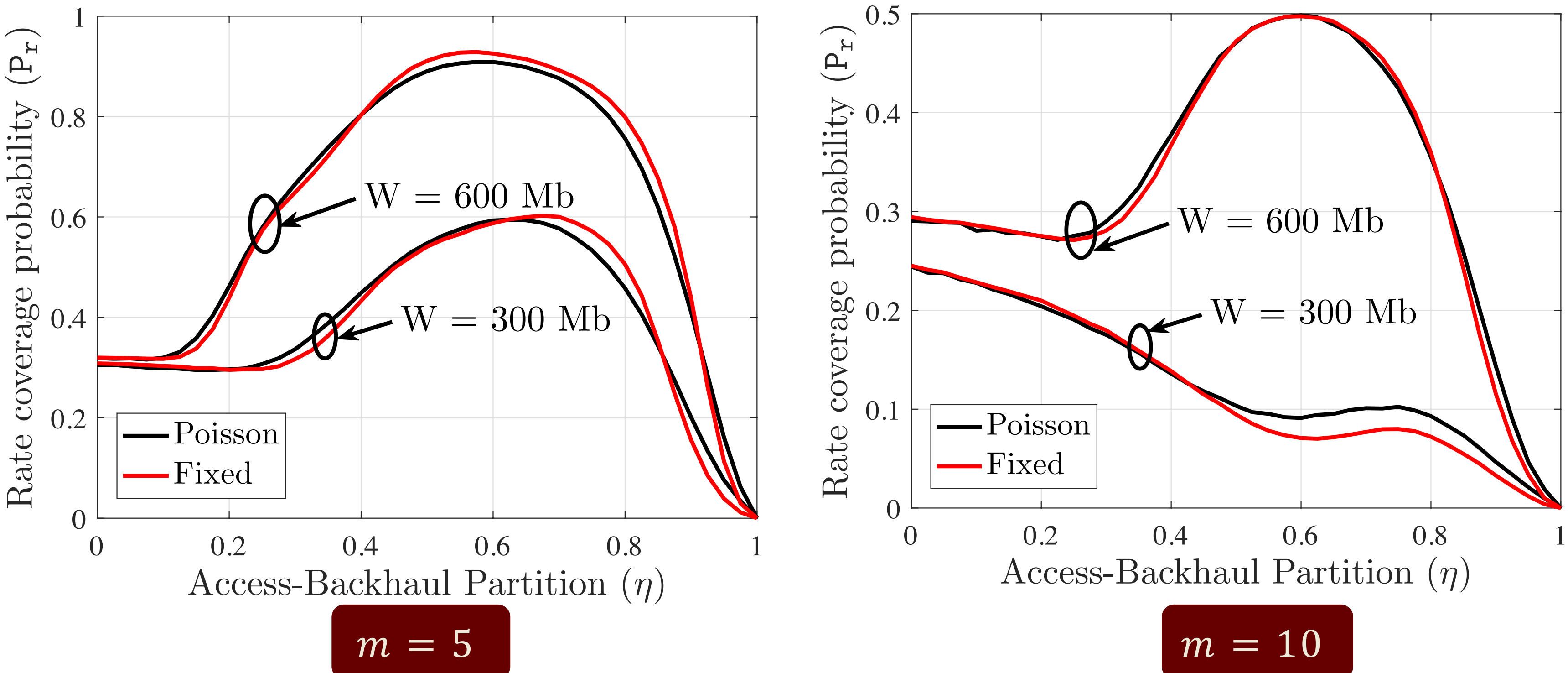
- The analytical expression of rate coverage probability, or the CCDF of rate is computationally efficient than evaluation through Monte Carlo simulations.
- It is possible to easily compute metrics like median rate or 5^{th} percentile rate by exhaustive search over the rate CCDF.



5^{th} percentile rate for instantaneous load-based partition (obtained by numerically solving $\mathrm{P_r}(\rho_{95}) = 0.95$).

- To compute ρ_{95} for a given η, it will take K Monte Carlo simulations if K is the number of function evaluations a numerical solver requires to converge to the solution. This is evidently a time-consuming process unless we have an easy-to-compute expression of rate coverage.

Is fixed number of users per hotspot a good assumption?



- We compare our results of fixed number of users (m) per hotspot with the case where number of users per hotspot is i.i.d. Poisson(m).
- The trends in rate coverage are very similar.
- Fixed number of users has computational efficiency, and the assumption is also not *unreasonable*.

Key Take-aways

Novelty

- Proposed the first 3GPP inspired stochastic geometry based analytical framework for IAB.

How to efficiently partition backhaul resources among different SBSs?

- Depending on the backhaul BW partition, there exists an optimum access-backhaul partition for which rate coverage is maximized.
- Load-based backhaul BW partition provides better rate coverage.

Is there a fundamental limit of IAB enabled networks?

- No additional performance gain is obtained from the IAB architecture compared to a traditional macro-only network beyond certain critical value of total network load.

Assumptions which may be sufficient (note for future studies)

- Fixed number of users per hotspot turns out to be a reasonably good assumption.

References

The results of this talk are the outcome of:

[1] C.Saha, M. Afshang, and Harpreet S. Dhillon, “Integrated mmWave access and backhaul in 5G: Bandwidth partitioning and Downlink analysis”, submitted. Available online: https://arxiv.org/abs/1710.06255.

3GPP’s technical report on IAB

[2] 3GPP TR 38.874, “NR; Study on integrated access and backhaul,” Tech. Rep., 2017.

[3] 3GPP RP-170831: “New SID Proposal: Study on Integrated Access and Backhaul for NR”, Source: AT&T, Qualcomm, Samsung.

Relevant prior art: stochastic geometry

[4] S. Singh, M. N. Kulkarni, A. Ghosh, and J. G. Andrews, “Tractable model for rate in self-backhauled millimeter wave cellular networks,” *IEEE Journal on Sel. Areas in Commun.*, vol. 33, no. 10, pp. 2196–2211, Oct. 2015.

[5] H. S. Dhillon and G. Caire, “Wireless backhaul networks: Capacity bound, scalability analysis and design guidelines,” *IEEE Trans. on Wireless Commun.*, vol. 14, no. 11, pp. 6043–6056, Nov. 2015.

Most Relevant Publications

- **C. Saha**, M. Afshang, H.S. Dhillon. "Integrated mmWave Access and Backhaul in 5G: Bandwidth Partitioning and Downlink Analysis". Submitted to ICC, 2017.
- **C. Saha**, M. Afshang, H. S. Dhillon, "Enriched K-Tier HetNet Model to Enable the Analysis of User-Centric Small Cell Deployments", *IEEE Trans. on Wireless Commun.*, 2017.
- **C.Saha**, Harpreet S. Dhillon, "Downlink coverage probability of K-tier HetNets with general non-uniform user distributions", in *Proc.* ICC, 2016.
- **C. Saha**, M. Afshang, and H. S. Dhillon, "Poisson Cluster Process: Bridging the Gap Between PPP and 3GPP HetNet Models", in *Proc. ITA,* Feb. 2017.
- **C. Saha**, M. Afshang, H. S. Dhillon, "3GPP-inspired HetNet Model using Poisson Cluster Process: Sum-product Functionals and Downlink Coverage", submitted to *IEEE Trans. on Commun.,* 2017.
- **C. Saha**, Harpreet S. Dhillon, "D2D underlaid cellular networks with user clusters: Load balancing and downlink rate analysis", ", in *Proc.* WCNC, 2017.
- M. Afshang, **C. Saha**, and H. S. Dhillon, "Nearest-Neighbor and Contact Distance Distributions for Thomas Cluster Process", *IEEE Wireless Commun. Letters*, 2017.
- M. Afshang, **C. Saha**, and H. S. Dhillon, "Nearest-Neighbor and Contact Distance Distributions for Matern Cluster Process", *IEEE Commun. Letters*, 2017.

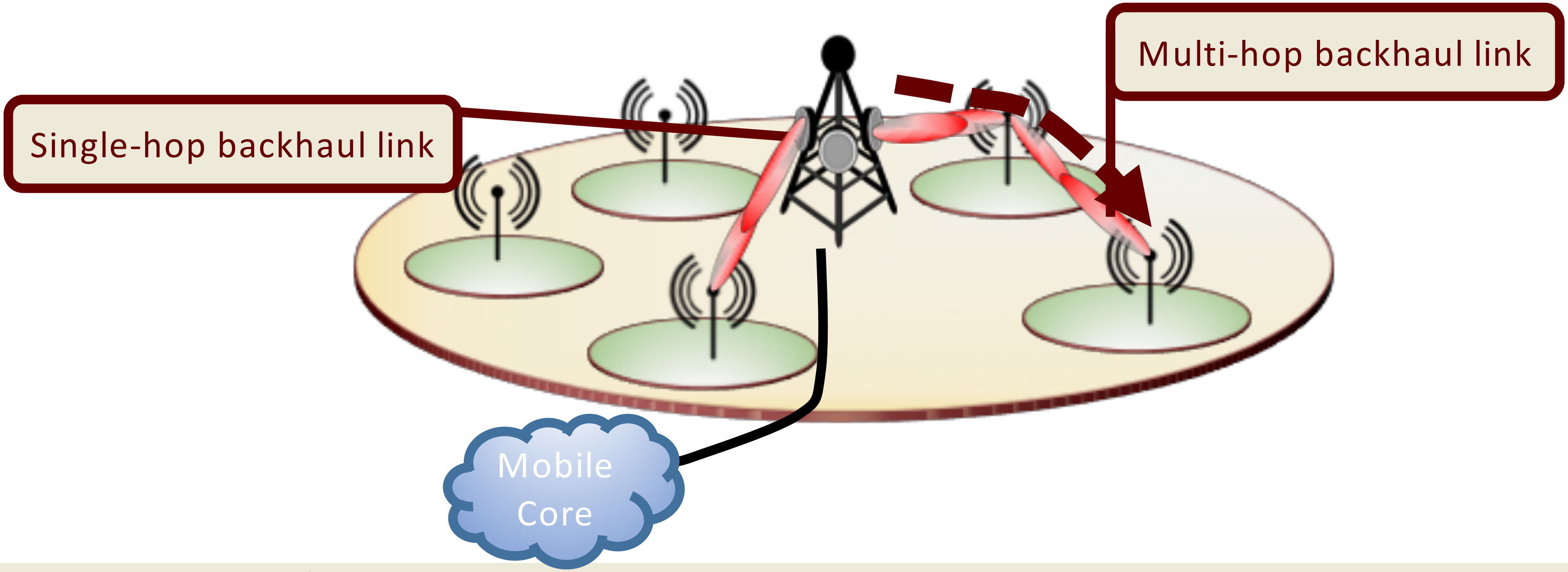
Thank you.

Questions ?

Backup Slides

Question 3: Multi-hop Backhaul

- If backhaul is done in mmWave, it is not reliable for long distance (SBSs at cell edge) due to blockages.
- This shortcoming can be overcome by Multihop backhauling, where the backhaul link between an anchored BS and SBS can be established through multiple SBSs acting as relay node.



Question 3: Multi-hop Backhaul

Immediate questions for multi-hop backhaul design:

- **Performance gain and optimal relay placement**: How much performance gain in terms of downlink rate coverage can be achieved by placing relay nodes? Where should the relays be placed?
- **Beam alignment errors**: How will the misalignment in antenna beams affect system performance? *Note that it is common to assume perfect beam alignment between anchored SB and SBSs in the literature.*
- **Control and user plane protocol design**:
  - Is it efficient to split the control and user plane?
  - How much additional overhead is incurred on RAN-2 due to multi-hop routing to guarantee QoS?

Question 2: Impact on RAN

What are the design considerations in RAN 2 for self backhauling?

- How much information exchange is required between the SBSs and the ABS?
  - The most efficient load-based resource partition requires continuous update of load/traffic information (which is highly time-varying in nature).
  - The *ideal* load-based partition is not possible due to high overhead, security concerns.
- **Equal partition** is always the **easiest** solution (however, will not guarantee proportional fairness of QoS across users).
  - SBS with high load will require more backhaul BW.
  - SBSs located far away from the ABS (cell edge SBSs) will require high backhaul BW for higher throughput.

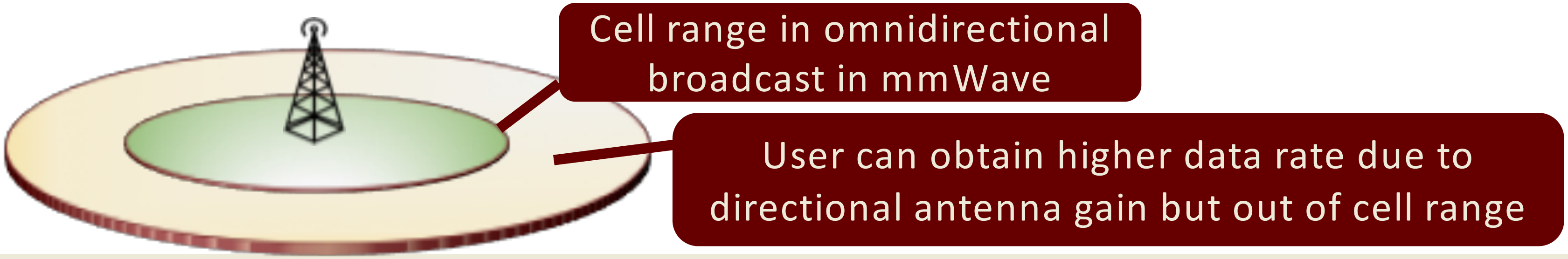
Question 2: Impact on RAN 2

How should the frame-structure be redesigned?

- Current LTE frames are divided into uplink (UL) and downlink (DL) sub-frames.
- For self-backhauled cellular network, four types of sub-frames are required.
  - **DL**: ABS to SBS, SBS/ABS to user
  - **UL**: SBS to ABS, user to SBS/ABS
- How is the total frame split between sub-frames?
  - Solution to Question 1 will provide necessary insights on splitting access and backhaul frames.
  - Static or dynamic time division duplex (TDD) can be used for dividing access and backhaul sub-frames into DL and UL.

Effects on Control Signalling

- Higher frequency bands (mmWave) are prone to suffer more propagation loss than the lower bands (sub-6 GHz) but offers capacity enhancement due to high bandwidth.
- *Cell Search/Discovery Problem:*
  - In the current setup, no beamforming or user-specific directional transmission is used for broadcasting paging signals.
  - Using omnidirectional pattern (by current LTE standards) in mmWave creates disparity between the range of cell detection (before beamforming) and the range at which high data rate is achieved (after beamforming)
  - *Is it useful to use more reliable sub 6 GHz band for paging and synchronization signaling while data traffic is carried in mmWave band?*



Small Cell Wireless Backhaul Solutions

So far:

- PtP links use licensed microwave or un-licensed frequencies.
- PmP and mesh wireless systems typically operate in the **un-licensed** 2.4GHz, 5.3GHz, 5.4GHz, and 5.8GHz bands.
- Some PmP wireless systems can operate in licensed UHF/VHF, 900MHz, 3.65GHz (WiMax), and 4.9GHz (public safety) frequency bands.

Some companies providing wireless backhaul solutions:

- PtP: Cabium Networks, BridgeWave, Alcatel-Lucent
  - Creating long range (upto 245 kms) links with directional beamforming.
  - Use mmWave frequencies (60, 80 GHz).
- PmP: Cambridge Broadband Networks, Ofcom, Exalt
  - Spatial multiplexing, efficient beam steering between small cells.
  - Intelligent resource partitioning depending on load requirements.

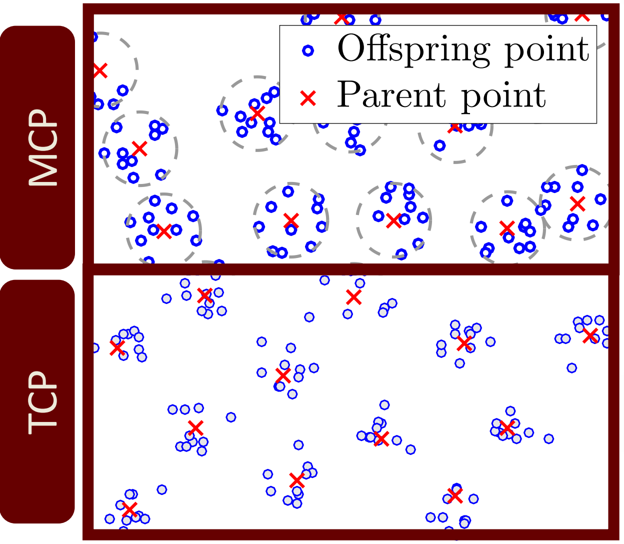
So Far in IAB

- In [4], authors proposed a Poisson point process (PPP)-based cellular network where a fraction (κ) of BSs are ABS and the rest are backhauled wirelessly.
- **Useful insight**: Performance gain can be obtained by densifying the network with non-anchored BSs.
- **Limitation:**
  - Not possible to answer the problems we discussed so far.
  - This model is far away from the spatial setup of BSs and users considered in 3GPP simulations.

[4] S. Singh, M. N. Kulkarni, A. Ghosh, and J. G. Andrews, "Tractable model for rate in self-backhauled millimeter wave cellular networks," *IEEE Journal on Sel. Areas in Commun.*, vol. 33, no. 10, pp. 2196–2211, Oct. 2015.

The Answer is Poisson Cluster Process

- **Poisson Cluster Process** (PCP) is more appropriate abstraction for user and BS distributions considered by 3GPP.



Examples of PCPs

Definition: Poisson Cluster Process (PCP)

A PCP is generated from a PPP $\Phi_{\rm p}$ called the **Parent PPP**, by replacing each point $\mathbf{z}_i$ by a finite offspring point process $\mathcal{B}_i$ where each point is independently and identically distributed around origin.

$$\Phi = \bigcup_{\mathbf{z}_i \in \Phi_{\rm p}} \mathbf{z}_i + \mathcal{B}_i.$$

Special cases

- $\#\mathcal{B}_i \sim \texttt{Poisson}(\bar{m})$
- Matern Cluster Process: Each point in $\mathcal{B}_i$ is **uniformly** distributed inside disc of radius $r_{\rm d}$ centered at origin.
- Thomas Cluster Process: Each point in $\mathcal{B}_i$ is **normally** distributed (with variance σ^2) around the origin.

Coverage Probability

Conditional SBS Coverage

Conditional MBS Coverage

$$\mathrm{P_c} = \int_0^{R-R_s} \underbrace{\left(\boxed{\mathrm{P_{cs}}(\theta_1, \theta_2 | x)} + \boxed{\mathrm{P_{cm}}(\theta_3 | x)} \right) \boxed{f_X(x)}}_{\text{Deconditioned over } x\text{: distance of hotspot center from ABS}} \mathrm{d}x,$$

- The derivation of coverage probability builds on the similar lines of Lemma 1.
- Remember that the coverage event was a subset of the association event.
- We expand the first term of the summation as follows.

$$\mathrm{P_{cs}}(\theta_1, \theta_2 | x) = \mathbb{P}(\mathtt{SNR}_\mathrm{a}^{\mathrm{SBS}}(u) > \theta_2, \mathtt{SNR}_\mathrm{b}(x) > \theta_1, \mathcal{E} = 1 | x)$$

$$= \mathbb{P}(\mathtt{SNR}_\mathrm{a}^{\mathrm{SBS}}(u) > \theta_2, \mathcal{E} = 1 | x) \mathbb{P}(\mathtt{SNR}_\mathrm{b}(x) > \theta_1 | x) = \left[\sum_{\mathrm{link} = \{LOS, NLOS\}} \mathbb{P}(\mathtt{SNR}_\mathrm{a}^{\mathrm{SBS}}(u) > \theta_2, \mathcal{E} = 1 | \mathrm{link}, x) p(\mathrm{link}) \right]$$

$$\times \left[\sum_{\mathrm{link} = \{LOS, NLOS\}} \mathbb{P}(\mathtt{SNR}_\mathrm{b}(x) > \theta_1 | x, \mathrm{link}) p(\mathrm{link}) \right]$$

- The last step is due to the fact that each link undergoes i.i.d. blocking. Remember that blocking is distance dependent, hence, $p(\mathrm{link})$ is function of x.

Load Distribution

Lemma 3.

Load on the ABS due to all other $n-1$ hotspots is distributed as:

$$N_{\rm o}^{\rm ABS} \sim \mathcal{N}(\upsilon_{\rm m}, \sigma_{\rm m}^2), \text{ for large } n,$$
$$N_{\rm o}^{\rm SBS} \sim \mathcal{N}(\upsilon_{\rm s}, \sigma_{\rm s}^2), \text{ for large } n.$$

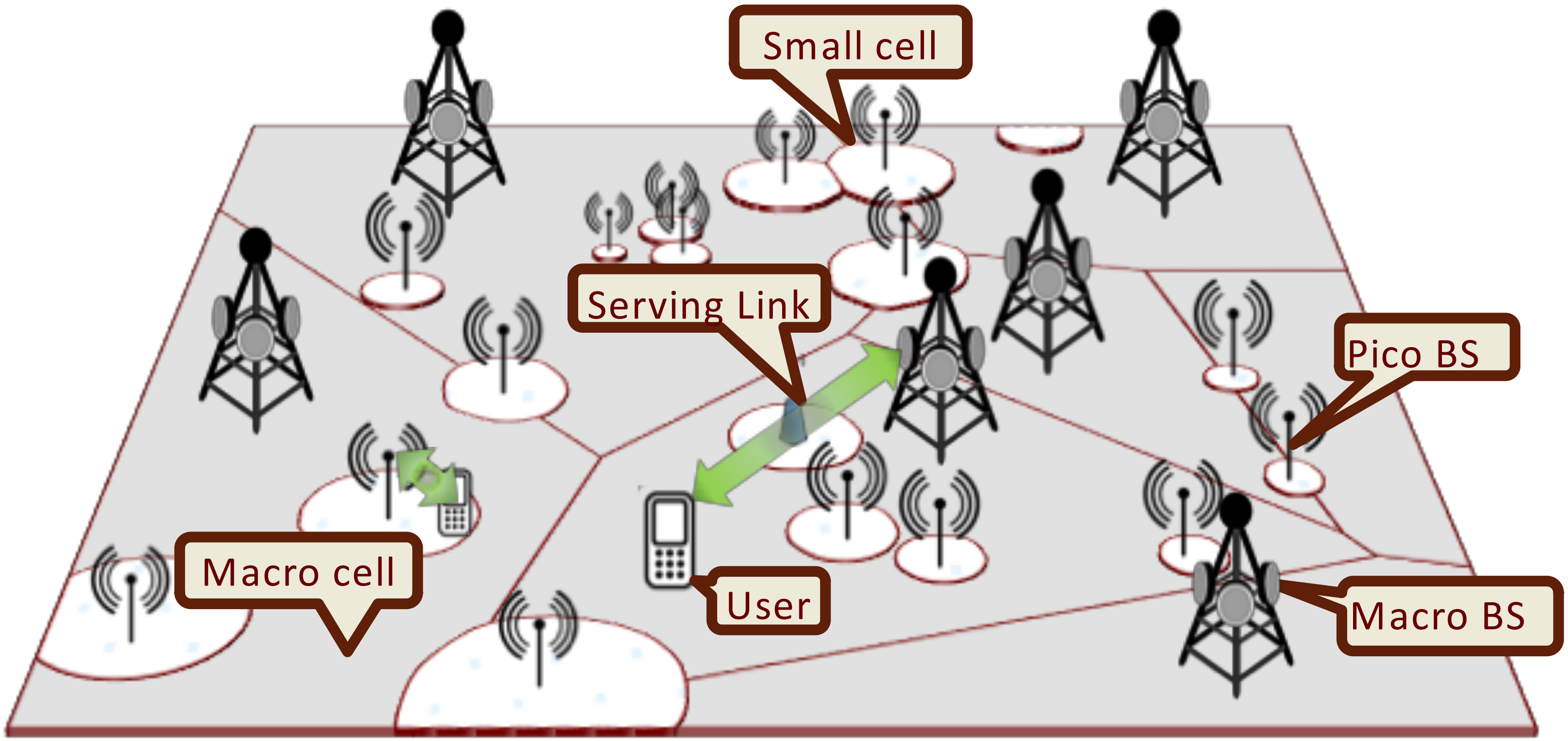
Here, $\upsilon_{\rm m} = (n-1)\bar{m}\mathbb{E}[\mathcal{A}_{\rm m}(X)], \upsilon_{\rm s} = (n-1)\bar{m}\mathbb{E}[\mathcal{A}_{\rm s}(X)]$, and
$\sigma_{\rm m}^2 = (n-1)[\bar{m}\mathbb{E}[A_{\rm m}(X)A_{\rm s}(X)] + \bar{m}^2{\rm Var}[\mathcal{A}_{\rm m}(X)]] = \sigma_{\rm s}^2$

- The exact distribution is not computationally efficient.
- These loads can be written as i.i.d. sum of (n-1) load variables related to the other hotspots.

$$N_{\rm o}^{\rm ABS} = \sum_{i=1}^{n-1} N_{\mathbf{x}_i}^{\rm ABS} \qquad N_{\rm o}^{\rm SBS} = \sum_{i=1}^{n-1} N_{\mathbf{x}_i}^{\rm SBS}$$

- We instead use central limit theorem to compute the distribution.

Heterogeneous Network (HetNet)



HetNet formed by different types of Base Stations (BSs)