

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

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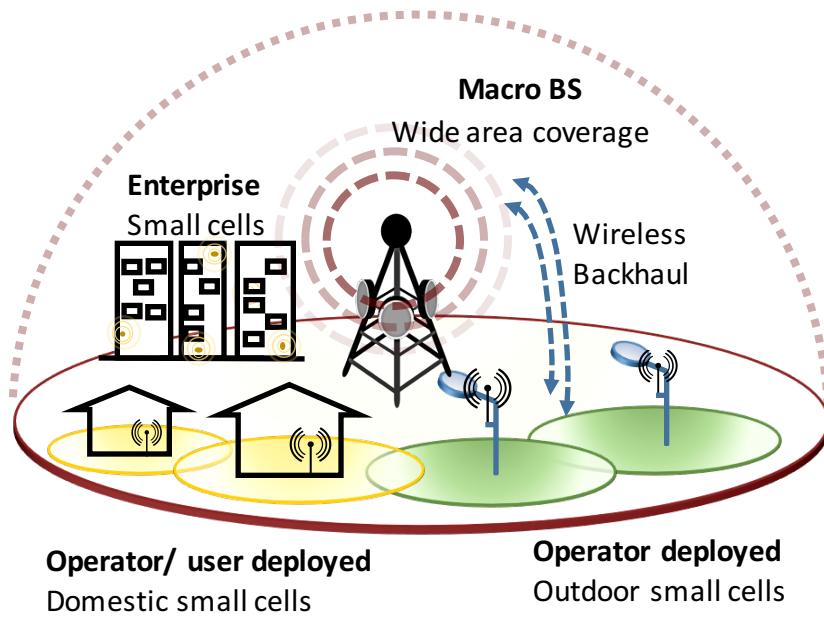
Joint work with Mehrnaz Afshang and Harpreet S. Dhillon

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In This Talk..

1. **mmWave Integrated access-and-backhaul (IAB):**
 - * While IAB is currently tested by 3GPP, we will discuss three relevant research Questions related to IAB.
2. **New Analytical framework for IAB:**
 - * We demonstrate our new analytical framework of mmWave IAB and discuss some key design insights.

Backhaul: Why are not HetNets yet a reality?



- **Vision of HetNet:** Ubiquitous small cell deployment to patch coverage holes and provide additional capacity.
- The capacity bottleneck has shifted from air-interface to the backhaul.
 - **Fiber backhaul:** costly, cannot be deployed everywhere.
 - **PtP¹ Mircowave:** limited connectivity, not suitable for bursty small cell traffic
 - **PmP¹ Mircowave:** limited data-rate

¹PtP: Point-to-point, PmP: Point to multipoint

Small Cell Wireless Backhaul Solutions

So far:

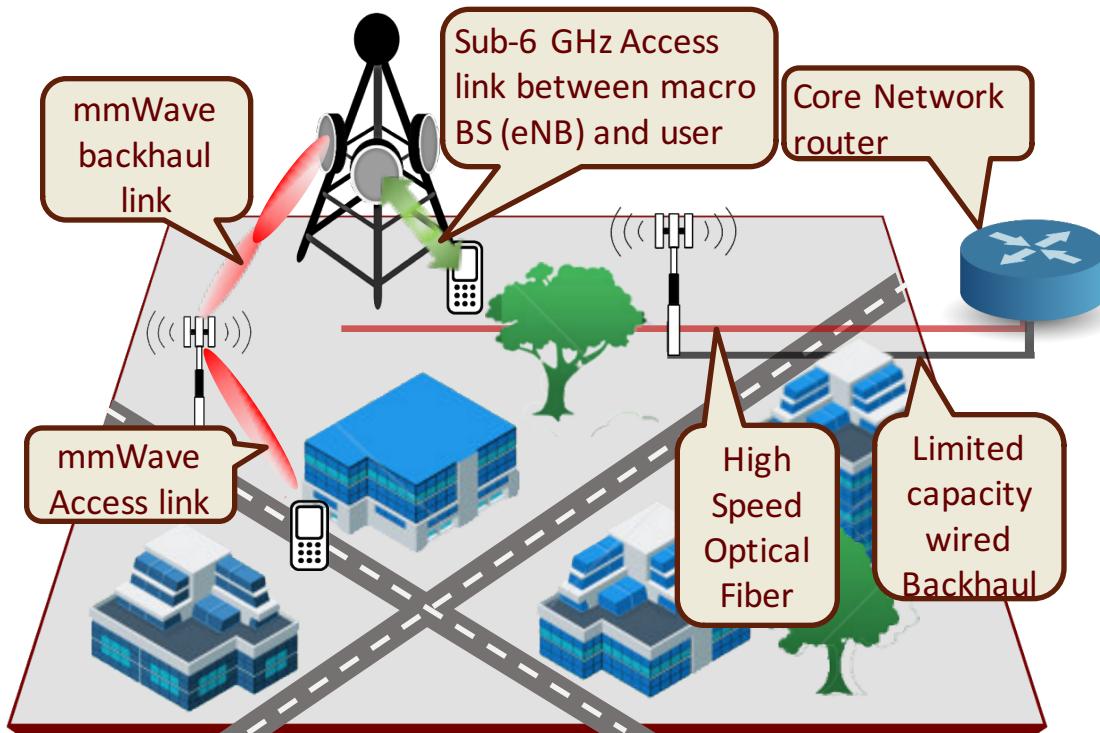
- PtP links use licensed microwave or un-licensed frequencies.
- PmP and mesh wireless systems typically operate in the **un-licensed** 2.4GHz, 5.3GHz, 5.4GHz, and 5.8GHz bands.
- Some PmP wireless systems can operate in licensed UHF/VHF, 900MHz, 3.65GHz (WiMax), and 4.9GHz (public safety) frequency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

Backhaul Solutions in 5G: Self-backhaul

- 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].

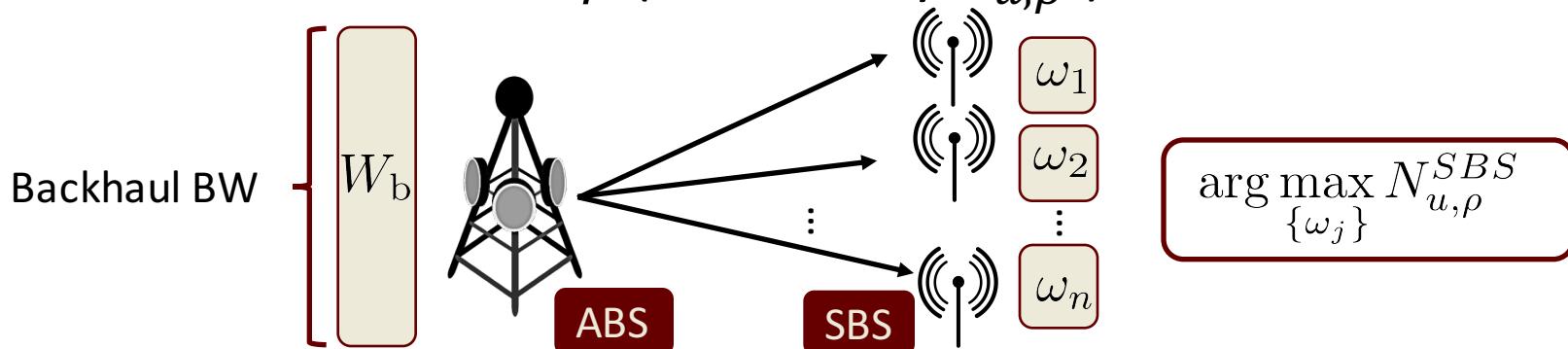


- Currently being considered by 3GPP².
- Self-backhaul will become a driving technology owing to more ubiquitous deployment of small cells, e.g. in vehicles, trains, lamp-posts etc.
- Major operators have evinced interest, e.g. project Airgig by AT&T.

Question: Resource Allocation Fundamentals

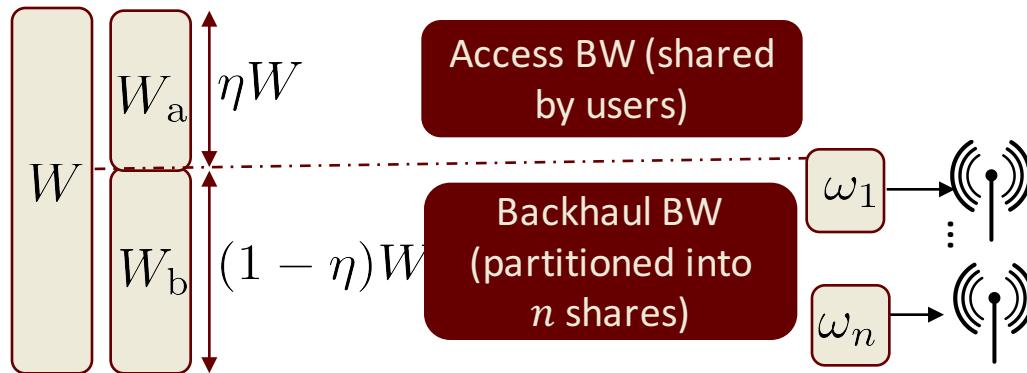
How to efficiently partition backhaul resources among different SBSs?

- 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 $N_{u,\rho}^{SBS}$)?



Question: Resource Allocation Fundamentals

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:

$$\arg \max_{\{\eta, \omega_1, \dots, \omega_n\}} N_{u,\rho}$$

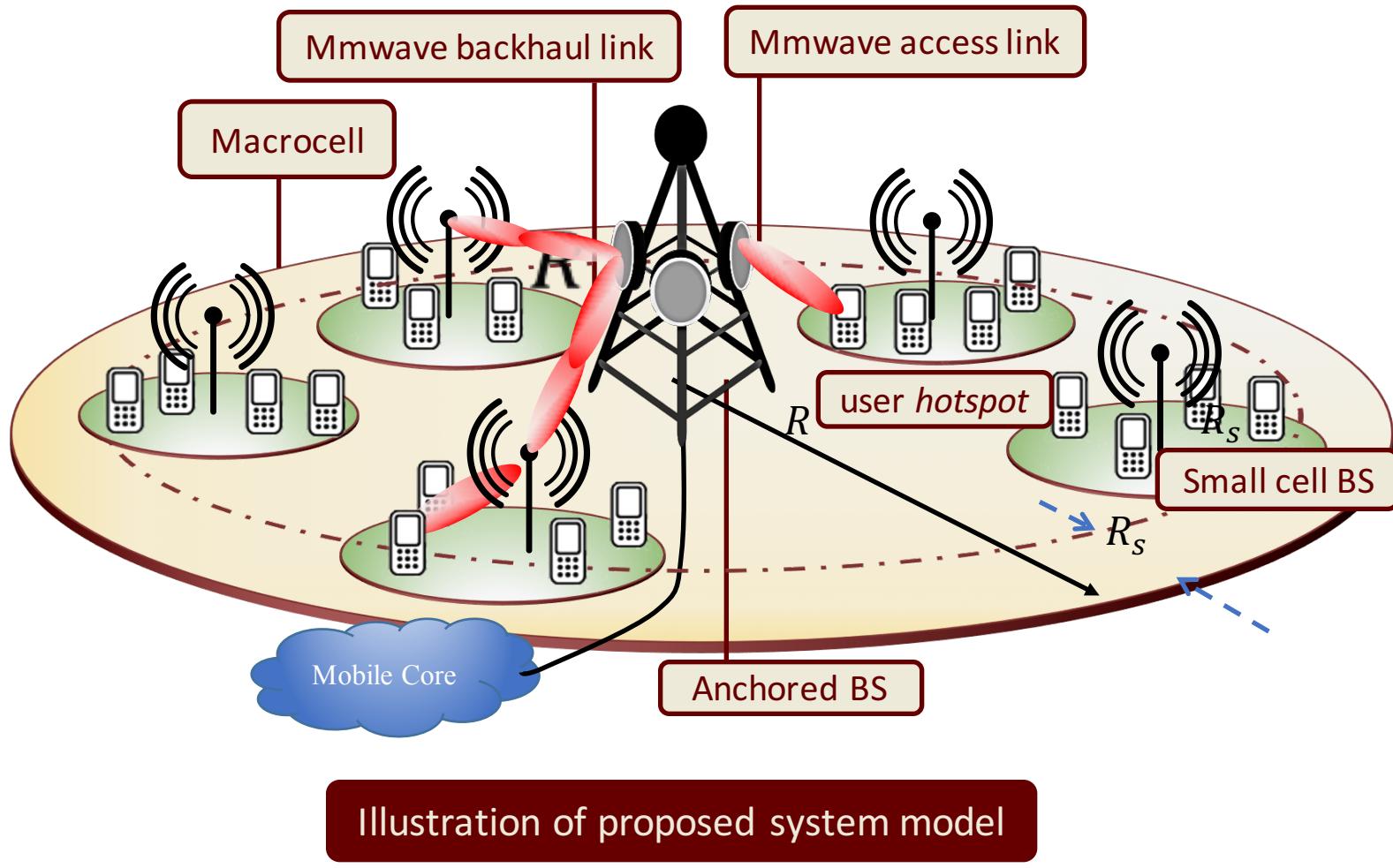
So Far in IAB

- * 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.

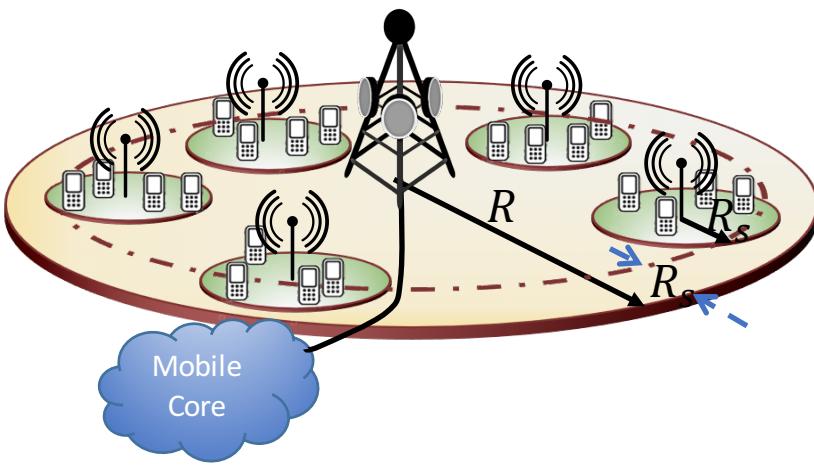
New Analytical framework for IAB

Proposed System Model



Proposed System Model

* User and BS locations

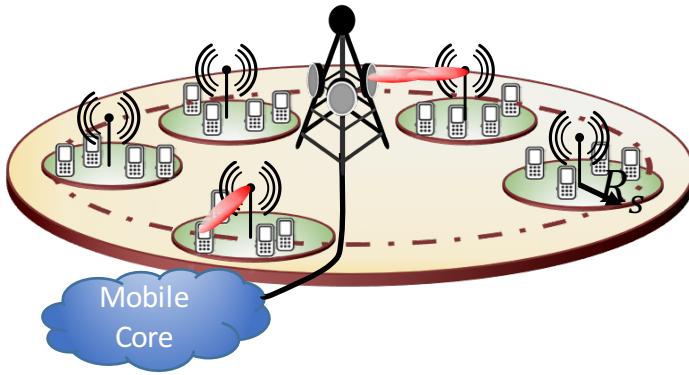


- * A circular macro cell of radius R .
- * The macro BS or the anchored BS is located at the center of the macro cell.
- * n user hotspots (circles of radius R_s) located uniformly at random across the macro cell at locations $\{x_1, x_2, \dots, x_n\}$.
- * Each hotspot has a SBS at center.
- * \bar{m} users located uniformly at random in user hotspot.

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Proposed System Model

* Propagation assumptions



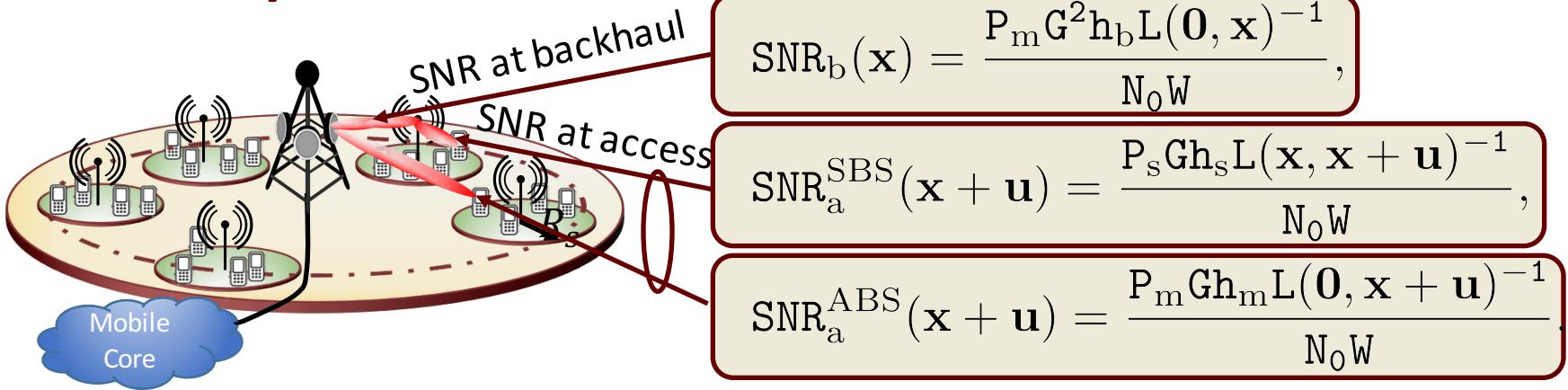
- * All transmissions are in mmWave spectrum.
- * BS at y transmits at a constant power spectral density $\frac{P}{W}$ over a system BW W ($P = P_m$ and P_s are the transmission powers of ABS and SBS).
- * We assume noise-limited system, where N_0 is the noise PSD.
- * SNR received for a link of BW \tilde{W} is proportional to $\frac{\frac{P}{W}\tilde{W}}{N_0\tilde{W}} = \frac{P}{N_0W}$.

* 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.

User Association and Coverage

* SNR Expressions



where $h_b, h_s, h_m \stackrel{i.i.d.}{\sim} \text{Gamma}(m, m^{-1})$.

* 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

* User Association

The association event for the typical user \mathbf{E} is defined as:

$$\mathcal{E} = \begin{cases} 1 & \text{if } P_s \|\mathbf{u}\|^{-\alpha} > P_m \|\mathbf{x} + \mathbf{u}\|^{-\alpha}, \\ 0, & \text{otherwise.} \end{cases}$$

SBS Association

Macro Association

α = Path-loss exponent for sub-6 GHz broadcast signal.

* Coverage

The typical user at $\mathbf{x} + \mathbf{u}$ is *under coverage* in the *downlink* if either of the following two events occurs:

$$\mathcal{E} = 1 \text{ and } \text{SNR}_b(\mathbf{x}) > \theta_1, \text{SNR}_a^{\text{SBS}}(\mathbf{u}) > \theta_2, \text{ or,}$$

SBS Coverage

$$\mathcal{E} = 0 \text{ and } \text{SNR}_a^{\text{ABS}}(\mathbf{x} + \mathbf{u}) > \theta_3.$$

Macro Coverage

$\{\theta_1, \theta_2, \theta_3\}$:= Coverage thresholds for successful demodulation and decoding.

- **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 $\mathbf{x} = \mathbf{x}_i$ ($i = 1$, without loss of generality) and $\mathbf{x} + \mathbf{u}$) and later decondition w.r.t. \mathbf{u} and \mathbf{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.

$$\eta \in [0,1] := \text{access-backhaul split.}$$

Access BW ($W_a = (1 - \eta)W$)

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 ($W_b = \eta W$)

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

Equal Partition

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

Load-based Partition

$$W_s(x) = \frac{N_x^{\text{SBS}}}{N_x^{\text{SBS}} + \sum_{i=1}^{n-1} N_{x_i}^{\text{SBS}}} W_b$$

N_x^{SBS} := Load on SBS at x .

Downlink data-rate and Rate-coverage

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

Rate on backhaul link

$$\mathcal{R}_b^{\text{ABS}} = W_s(\mathbf{x}) \log_2(1 + \text{SNR}_b(\mathbf{x}))$$

Rate on access link

$$\mathcal{R}_a^{\text{SBS}} = \min \left(\frac{W_a}{N_x^{\text{SBS}}} \log_2(1 + \text{SNR}_a^{\text{SBS}}(\mathbf{u})), \right.$$

From SBS to user

$$\left. \frac{W_s(\mathbf{x})}{N_x^{\text{SBS}}} \log_2(1 + \text{SNR}_b(\mathbf{x})) \right)$$

From ABS to user

$$\mathcal{R}_a^{\text{ABS}} = \frac{W_a}{N_x^{\text{ABS}} + \sum_{i=1}^{n-1} N_{\mathbf{x}_i}^{\text{ABS}}} \log_2(1 + \text{SNR}_a^{\text{ABS}}(\mathbf{x} + \mathbf{u}))$$

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

$$\mathbb{P}(\tilde{W} \log_2(1 + \text{SNR}) > \rho)$$

$\rho :=$ Rate threshold or target data-rate

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

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

Association Probability: First step to Coverage

Lemma 1.

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

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

Here, $k_p = \left(\frac{P_s}{P_m} \right)^{1/\alpha}$.

Proof Sketch: Conditioned on the location of the hotspot center at \mathbf{x} ,

$$\mathbb{P}(\mathcal{E} = 1 | \mathbf{x}) = \mathbb{E}[\mathbf{1}(P_m \|\mathbf{x} + \mathbf{u}\|^{-\alpha} < P_s \|\mathbf{u}\|^{-\alpha}) | \mathbf{x}]$$

The probability of the ‘association’ event conditioned on \mathbf{x}

$$= \mathbb{P}(P_m(x^2 + u^2 + 2xu \cos \xi)^{-\alpha/2} < P_s u^{-\alpha}) | \mathbf{x}$$

Due to symmetry, conditioning on location \mathbf{x} boils down to conditioning on distance, $\|\mathbf{x}\| = x$.

$$= \mathbb{P}(u^2(1 - k_p^2) - 2x \cos \xi k_p^2 u - k_p^2 x^2 < 0 | x)$$

$$= \mathbb{P}\left(u \in \left(0, \frac{xk_p \sqrt{(1 - k_p^2 \sin^2 \xi) + k_p \cos \xi}}{1 - k_p^2}\right), \xi \in (0, 2\pi] | x\right)$$

Here, $\xi = \arg(\mathbf{u} - \mathbf{x})$ is uniformly distributed in $(0, 2\pi]$.

Coverage Probability

$$P_c = \int_0^{R-R_s} \left(P_{cs}(\theta_1, \theta_2|x) + P_{cm}(\theta_3|x) \right) f_X(x) dx,$$

Deconditioned over x : distance of hotspot center from ABS

- 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.

$$\begin{aligned}
 P_{cs}(\theta_1, \theta_2|x) &= \mathbb{P}(\text{SNR}_a^{\text{SBS}}(u) > \theta_2, \text{SNR}_b(x) > \theta_1, \mathcal{E} = 1|x) \\
 &= \mathbb{P}(\text{SNR}_a^{\text{SBS}}(u) > \theta_2, \mathcal{E} = 1|x) \mathbb{P}(\text{SNR}_b(x) > \theta_1|x) = \left[\sum_{\text{link}=\{\text{LOS}, \text{NLOS}\}} \mathbb{P}(\text{SNR}_a^{\text{SBS}}(u) > \theta_2, \mathcal{E} = 1|\text{link}, x) p(\text{link}) \right] \\
 &\times \left[\sum_{\text{link}=\{\text{LOS}, \text{NLOS}\}} \mathbb{P}(\text{SNR}_b(x) > \theta_1|x, \text{link}) p(\text{link}) \right]
 \end{aligned}$$

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

$$P_r = P_{rs} + P_{rm}$$

SBS rate Coverage MBS rate Coverage

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

$$\begin{aligned} P_{rm} &= \mathbb{P}(R_a^{\text{ABS}} > \rho) = \mathbb{P}\left[\text{SNR}\left(\frac{W_a}{N_x^{\text{ABS}} + N_o^{\text{ABS}}} \log_2(1 + \text{SNR}_a^{\text{ABS}}(\mathbf{x} + \mathbf{u}))\right) > \rho\right] \\ &= \mathbb{P}\left(\text{SNR}_a^{\text{ABS}}(\mathbf{x} + \mathbf{u}) > 2^{\frac{\rho(N_x^{\text{ABS}} + N_o^{\text{ABS}})}{W_a}} - 1\right) = P_{cm}\left(2^{\frac{\rho(N_x^{\text{ABS}} + N_o^{\text{ABS}})}{W_a}} - 1\right). \end{aligned}$$

N_x^{ABS} := Macro load from user hotspot N_o^{ABS} := Macro load from other hotspots

We don't yet know, what are the distributions of N_x^{ABS} and N_o^{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.

$$P_{rs} = \mathbb{P}\left(\frac{W_b}{N_x^{SBS} + N_o^{SBS}} \log_2(1 + \text{SNR}_b^{\text{SBS}}(\mathbf{x})) > \rho\right) \mathbb{P}\left(\frac{W_a}{N_x^{SBS}} \log_2(1 + \text{SNR}_a(\mathbf{u})) > \rho\right)$$

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

N_x^{SBS} := SBS load at the user hotspot

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

We have developed a completely 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 $N_x^{\text{ABS}}, N_o^{\text{ABS}}, N_x^{\text{SBS}}$, and N_o^{SBS} .

This cell load characterization is completely different than the well-known approaches for PPP-based networks [4].

Load Distribution

Lemma 2.

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

$$\mathbb{P}(N_{\mathbf{x}}^{\text{ABS}} = k | \mathbf{x}) = \binom{\bar{m} - 1}{k - 1} \mathcal{A}_m(x)^{k-1} \mathcal{A}_s(x)^{\bar{m}-k},$$

$$\mathbb{P}(N_{\mathbf{x}}^{\text{SBS}} = k | \mathbf{x}) = \binom{\bar{m} - 1}{k - 1} \mathcal{A}_s(x)^{n-1} \mathcal{A}_m(x)^{\bar{m}-k}.$$

Load Distribution

Lemma 3.

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

$$N_o^{\text{ABS}} \sim \mathcal{N}(\nu_m, \sigma_m^2), \text{ for large } n,$$

$$N_o^{\text{SBS}} \sim \mathcal{N}(\nu_s, \sigma_s^2), \text{ for large } n.$$

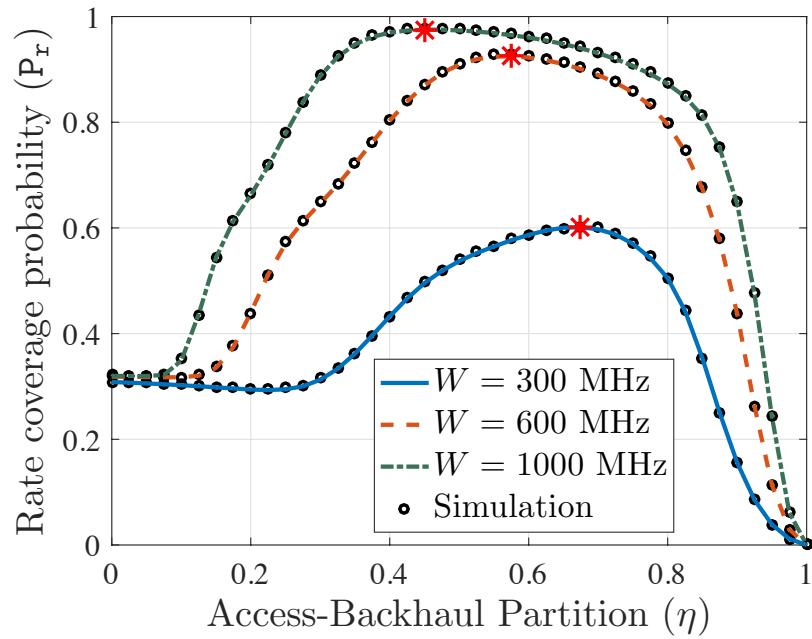
Here, $\nu_m = (n - 1)\bar{m}\mathbb{E}[\mathcal{A}_m(X)]$, $\nu_s = (n - 1)\bar{m}\mathbb{E}[\mathcal{A}_s(X)]$, and
 $\sigma_m^2 = (n - 1)[\bar{m}\mathbb{E}[A_m(X)A_s(X)] + \bar{m}^2\text{Var}[\mathcal{A}_m(X)]] = \sigma_s^2$

- 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.

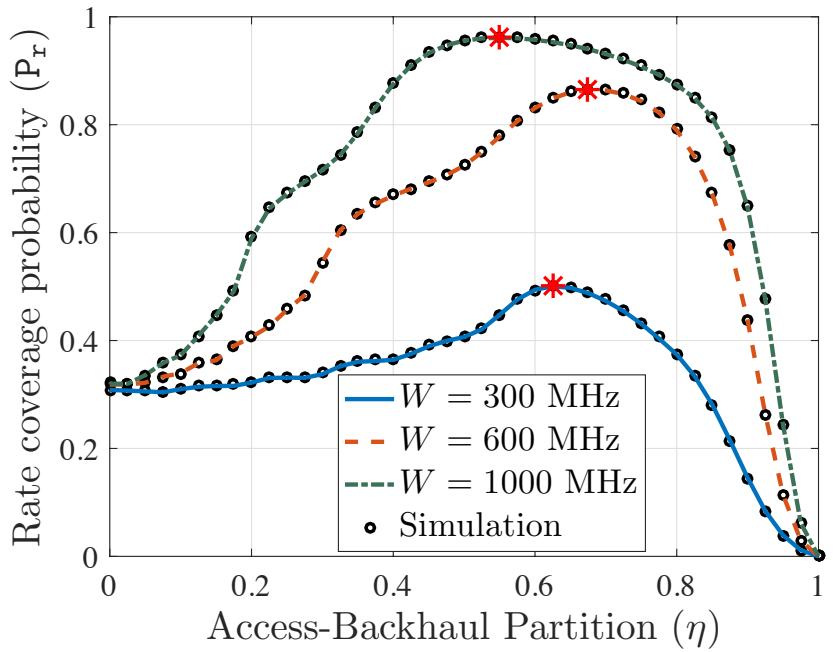
$$N_o^{\text{ABS}} = \sum_{i=1}^{n-1} N_{\mathbf{x}_i}^{\text{ABS}} \quad N_o^{\text{SBS}} = \sum_{i=1}^{n-1} N_{\mathbf{x}_i}^{\text{SBS}}$$

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

Trend in Rate Coverage



Load-based partition

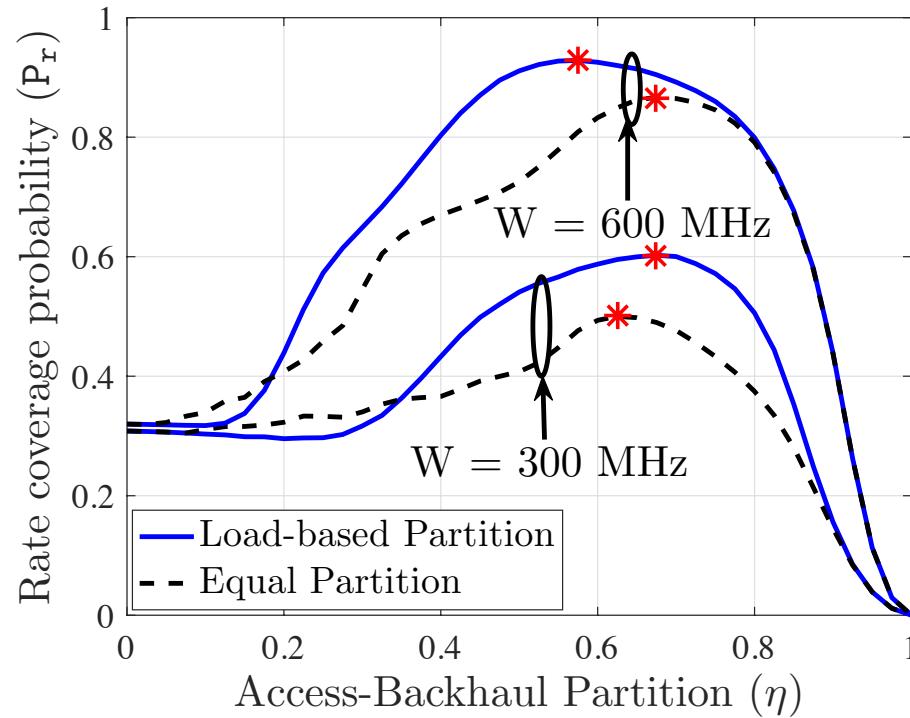


Equal partition

- 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 $n = 10$.

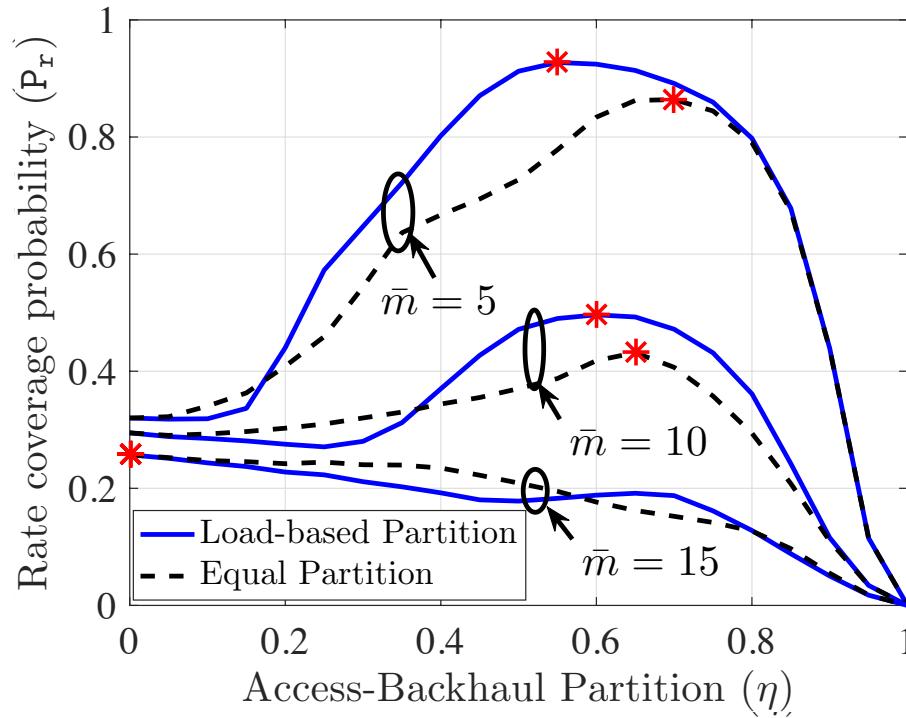
For all numerical results, $\rho = 50$ Mbps, $n=10$. In these figures, $\bar{m} = 5$.

Which policy is better?



- Load-based backhaul BW partition gives higher optimal rate coverage than equal partition.
- Remember that, equal partition always has less signaling overhead. So there exists a complexity performance trade-off for designing IAB networks.
- The performance gain becomes less prominent if system BW is increased.

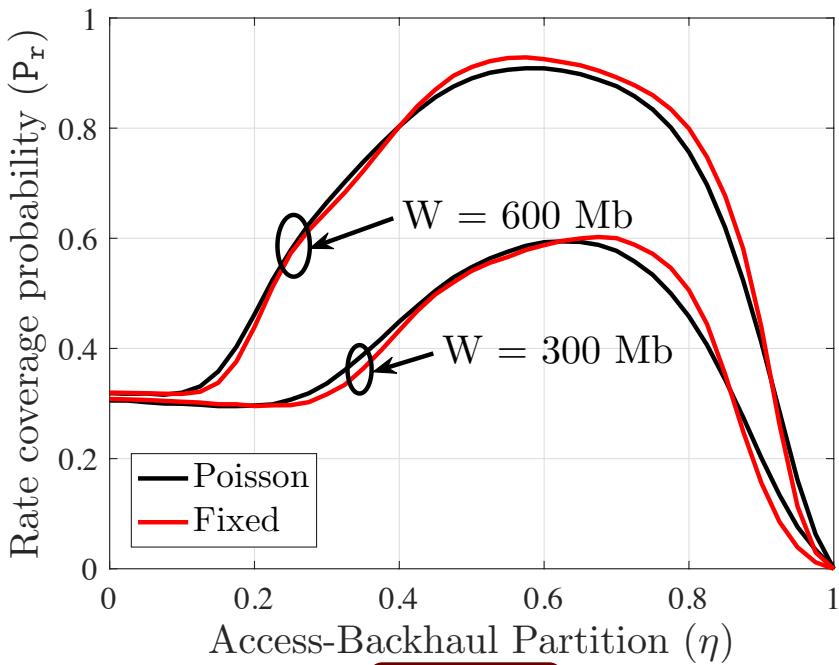
How much load can IAB support?



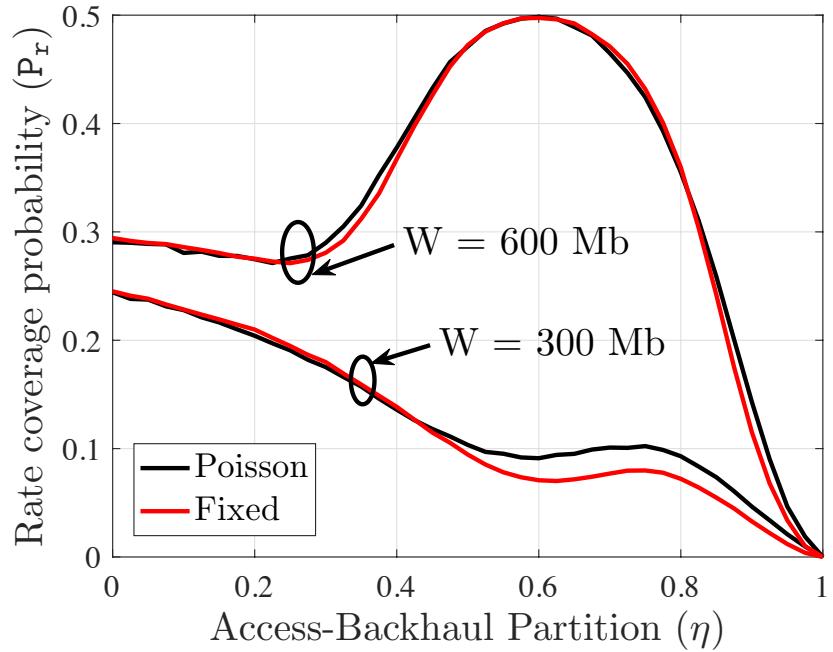
- In this plot, BW is fixed, but number of users per hotspot is varied.
- For $\bar{m} = 15$, we see that the optimal partition has moved to $\eta = 0$, which means all BW should be assigned to the access links. This is equivalent to a single tier macro-only network.

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

Is fixed number of users per hotspot a good assumption?



$$\bar{m} = 5$$



$$\bar{m} = 10$$

- We compare our results of fixed number of users (\bar{m}) per hotspot with the case where number of users per hotspot is i.i.d. Poisson(\bar{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.
- We found that 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

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 arts: 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 ?