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

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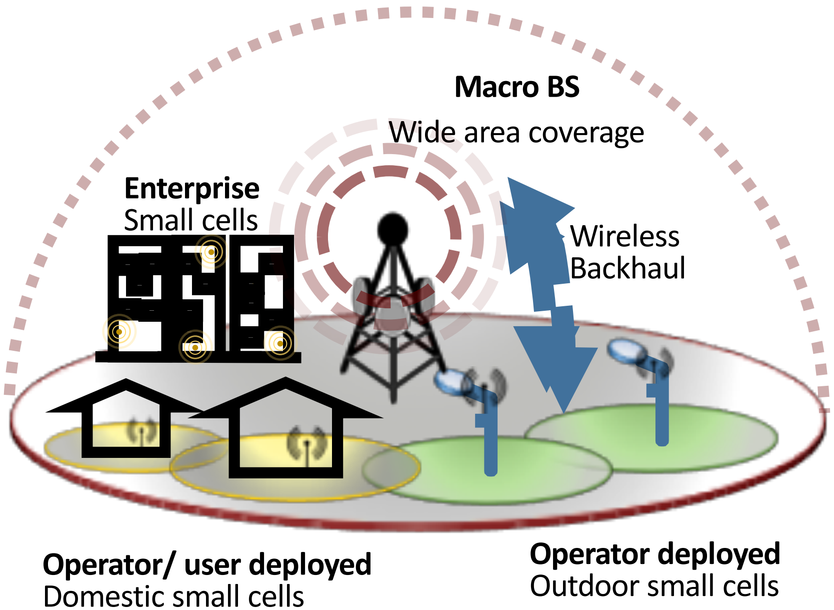
Backhaul: Why are not HetNets yet a reality?

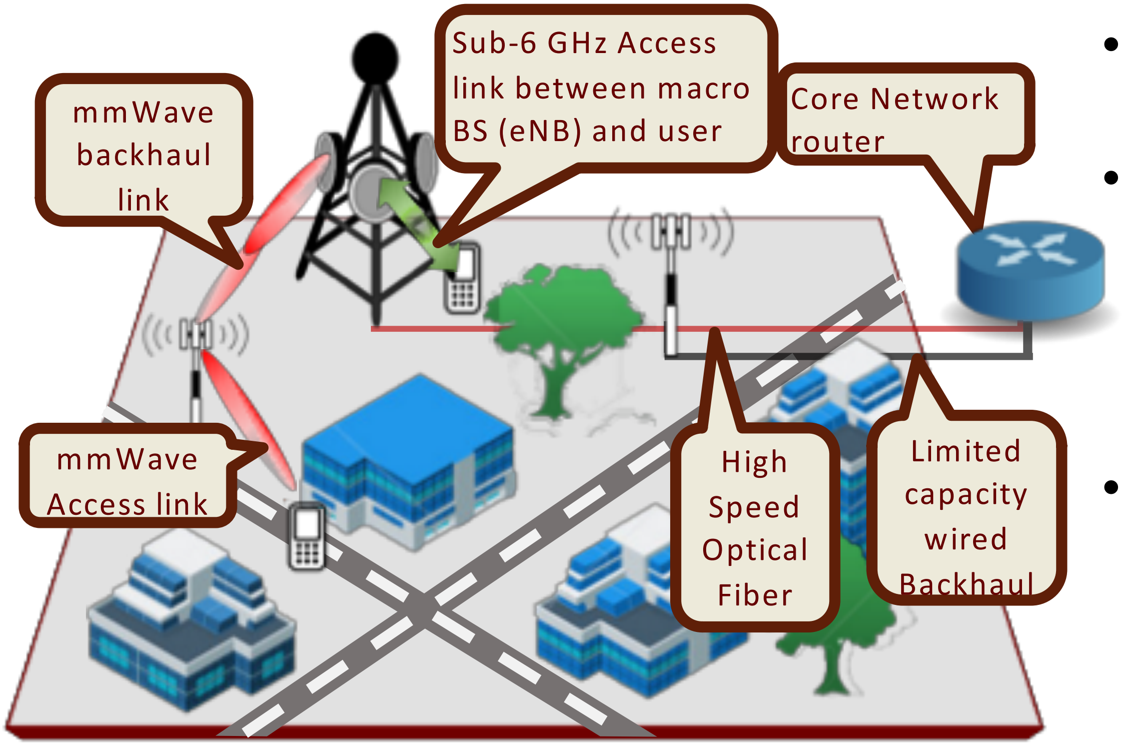


- **Vision of HetNet**: Ubiquitous small cell deployment to patch coverage holes and provide additional capacity.
- The capacity bottleneck has shifted from air-interface to the backhaul.
  - **Fiber backhaul:** costly, cannot be deployed everywhere.
  - **PtP[1] Mircowave:** limited connectivity, not suitable for bursty small cell traffic
  - **PmP[1] Mircowave:** limited data-rate

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

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** [1-4].

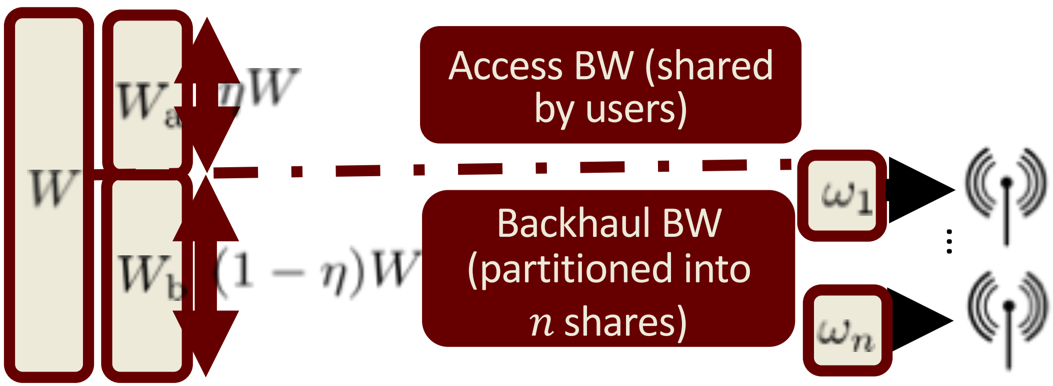


- Currently being considered by 3GPP[2].
- Self-backhaul will become a driving technology owing to more ubiquitous deployment of small cells, e.g. in vehicles, trains, lamp-posts etc.
- Major operators have evinced interest, e.g. project *Airgig* by AT&T.

Question: Resource Allocation Fundamentals

How to 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 is the total system bandwidth (BW), it is split into $W_{\mathrm{a}} = \eta W$ and $W_{\mathrm{b}} = (1-\eta)W$ for access and backhaul links.
- Further W_{b} is split into n parts $\{\omega_1, \omega_2, \ldots, \omega_n\}$ such that $\sum_i \omega_i = W_b$.
- We study the impact of bandwidth partitions on system performance.



So far on the analysis of IAB

- In [5], authors proposed a Poisson point process (PPP)-based cellular network where a fraction (κ) of BSs are ABS and the rest are backhauled wirelessly.
- **Limitation:**
  - This model is far away from the spatial setup of BSs and users considered in 3GPP simulations.
  - Not suitable to study the resource allocation problem discussed in the previous slide.
- **Our Contribution:**
  - A single macrocell model with *3GPP-like* user hotspots offering a better understanding of cell load.

[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.

Proposed System Model

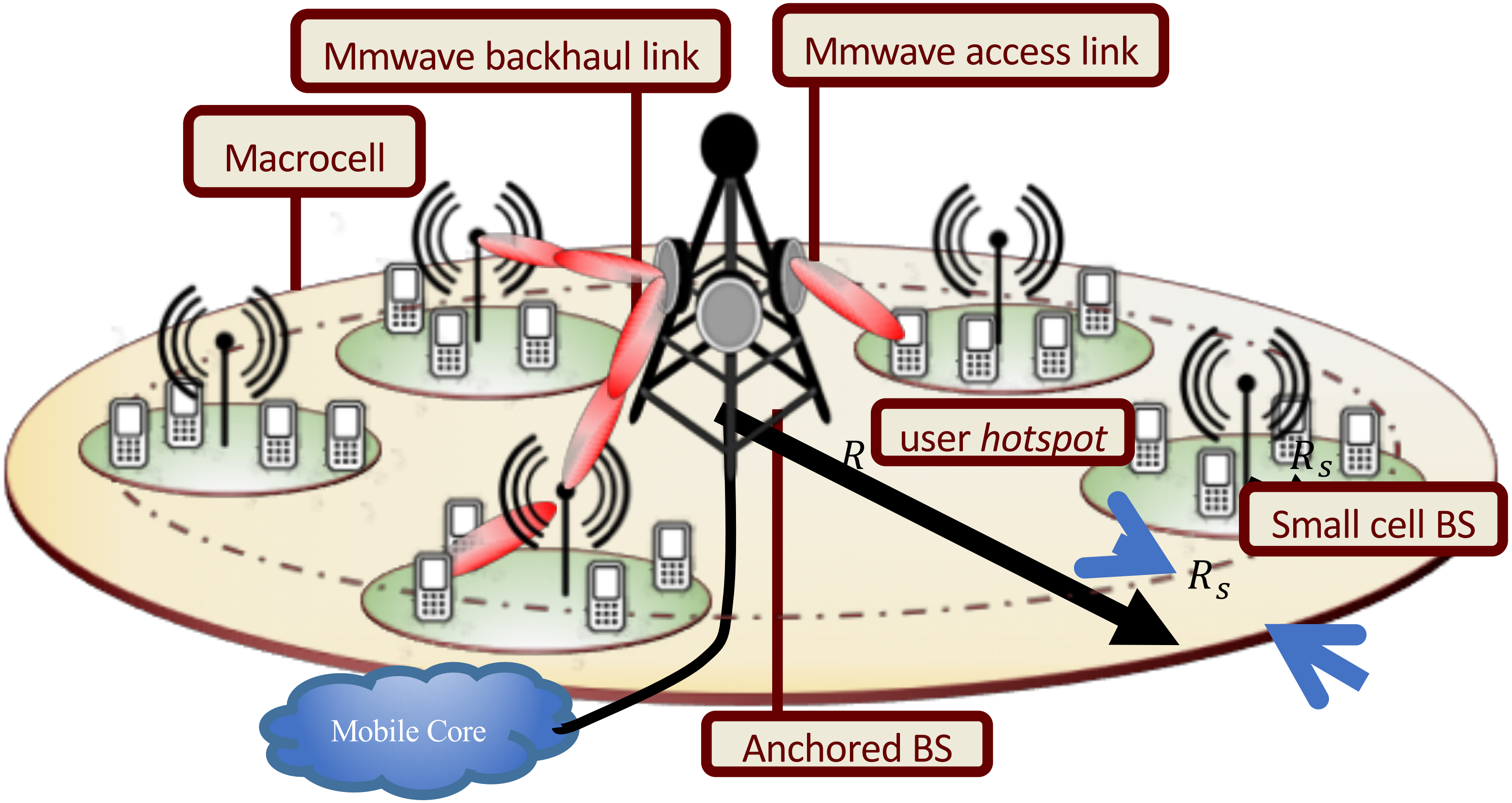
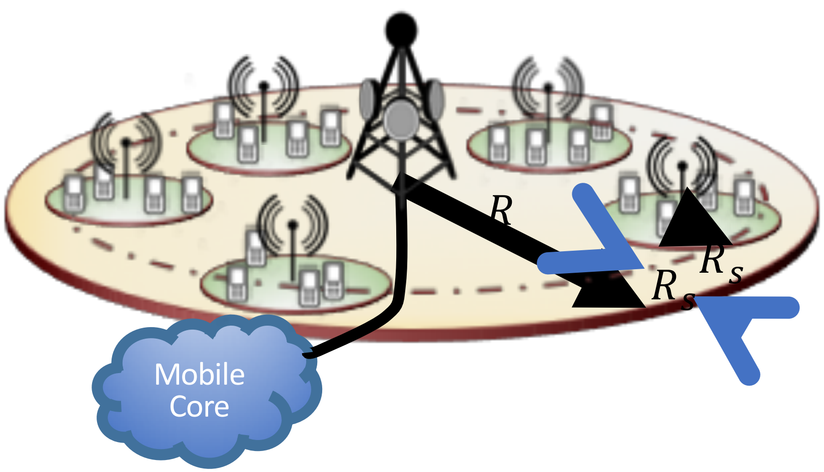


Illustration of proposed system model

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 $\{\boldsymbol{x}_1, \boldsymbol{x}_2, \ldots, \boldsymbol{x}_n\}$.
- Each hotspot has a SBS at center.
- m users located uniformly at random in user hotspot.

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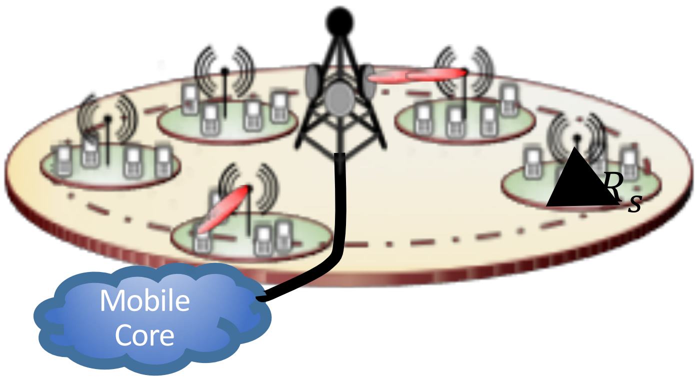
Proposed System Model

⁕ Propagation assumptions



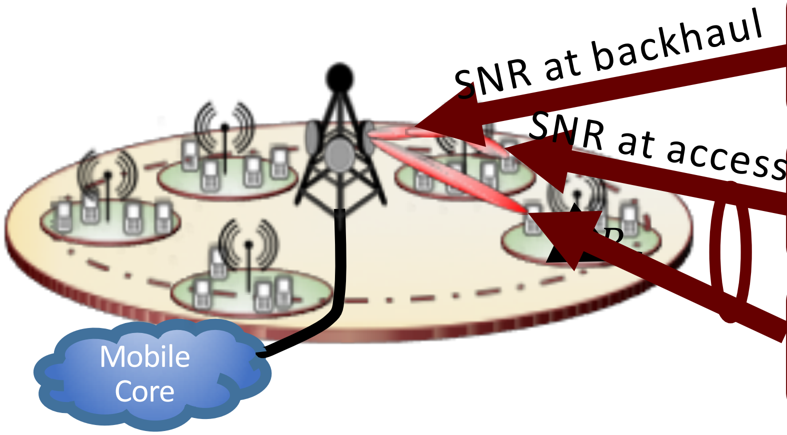
- All transmissions are in mmWave spectrum.
- BS at $\boldsymbol{y}$ transmits at a constant power spectral density $\frac{P}{W}$ over a system BW W ($P = P_m$ and P_s are the transmission powers of ABS and SBS.
- We assume noise-limited system, where N_0 is the noise PSD.
- SNR received for a link of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

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

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 **E** is defined as:

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

SBS Association

Macro Association

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

- **Coverage**

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

$$\mathcal{E} = 1 \text{ and } \mathrm{SNR_b}(\mathbf{x}) > \theta_1, \mathrm{SNR_a^{SBS}}(\mathbf{u}) > \theta_2, \text{ or,}$$

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

SBS Coverage

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 $\boldsymbol{x} = \boldsymbol{x}_i$ ($i = 1$, 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 ($W_\mathrm{a} = (1-\eta)W$)

Each BS is 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 ($W_\mathrm{b} = \eta W$)

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

Equal Partition

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

Load-based Partition

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

$\mathrm{N}_{\mathbf{x}}^{\mathrm{SBS}} :=$ Load on SBS at $\mathbf{x}$.

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.

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:

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

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

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

$$\begin{aligned}\boxed{\mathbb{P}(\mathcal{E}=1|\mathbf{x})} &= \mathbb{E}[\mathbf{1}(P_{\mathrm{m}}\|\mathbf{x}+\mathbf{u}\|^{-\alpha} < P_{\mathrm{s}}\|\mathbf{u}\|^{-\alpha})|\mathbf{x}] \\ &= \mathbb{P}(P_{\mathrm{m}}(x^2+u^2+2xu\cos\xi)^{-\alpha/2} < P_{\mathrm{s}}u^{-\alpha}|x) \\ &= \mathbb{P}(u^2(1-k_p^2) - 2x\cos\xi k_p^2 u - k_p^2x^2 < 0|x) \\ &= \mathbb{P}\left(u \in (0, \frac{xk_p\sqrt{(1-k_p^2\sin^2\xi)}+k_p\cos\xi}{1-k_p^2}), \xi \in (0, 2\pi] \middle| x\right)\end{aligned}$$

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

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

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

Coverage Probability

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

- 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.

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)

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

$$= \mathbb{P}\left(\mathtt{SNR}_{\mathrm{a}}^{\mathrm{ABS}}(\mathbf{x}+\mathbf{u}) > 2^{\frac{\rho(N_{\mathbf{x}}^{\mathrm{ABS}}+N_{\mathrm{o}}^{\mathrm{ABS}})}{W_{\mathrm{a}}}} - 1\right) = \mathrm{P_{cm}}\left(2^{\frac{\rho(N_{\mathbf{x}}^{\mathrm{ABS}}+N_{\mathrm{o}}^{\mathrm{ABS}})}{W_{\mathrm{a}}}} - 1\right).$$

$N_{\mathbf{x}}^{\mathrm{ABS}}$:= 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.

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

- 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 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 $N_{\mathbf{x}}^{\mathrm{ABS}}$,$N_{\mathbf{o}}^{\mathrm{ABS}}$, $N_{\mathbf{x}}^{\mathrm{SBS}}$, and $N_{\mathbf{o}}^{\mathrm{SBS}}$.

This cell load characterization is completely different than the well-known approaches for PPP-based networks [5].

Load Distribution

Lemma 2.

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

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

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

Load Distribution

Lemma 3.

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

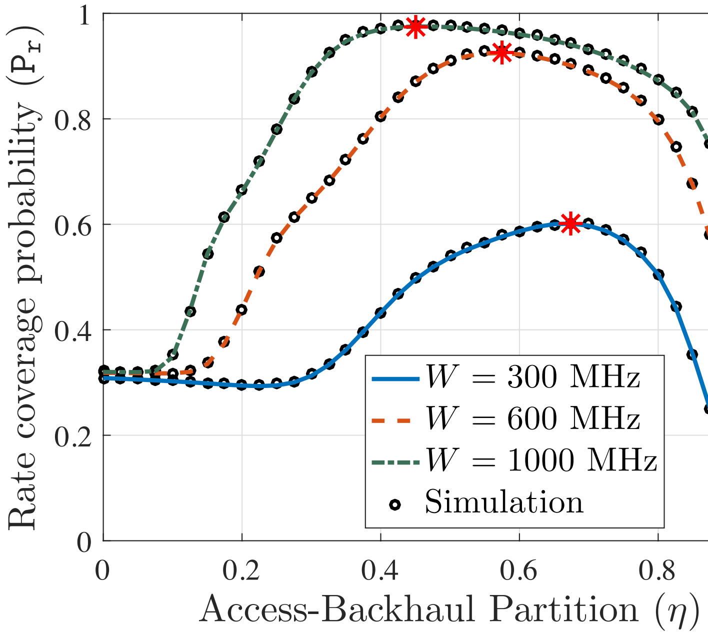
$$\sigma_{\mathrm{m}}^2 = (n-1)[\bar{m}\mathbb{E}[A_{\mathrm{m}}(X)A_{\mathrm{s}}(X)] + \bar{m}^2\mathrm{Var}[\mathcal{A}_{\mathrm{m}}(X)]] = \sigma_{\mathrm{s}}^2$$

- 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.

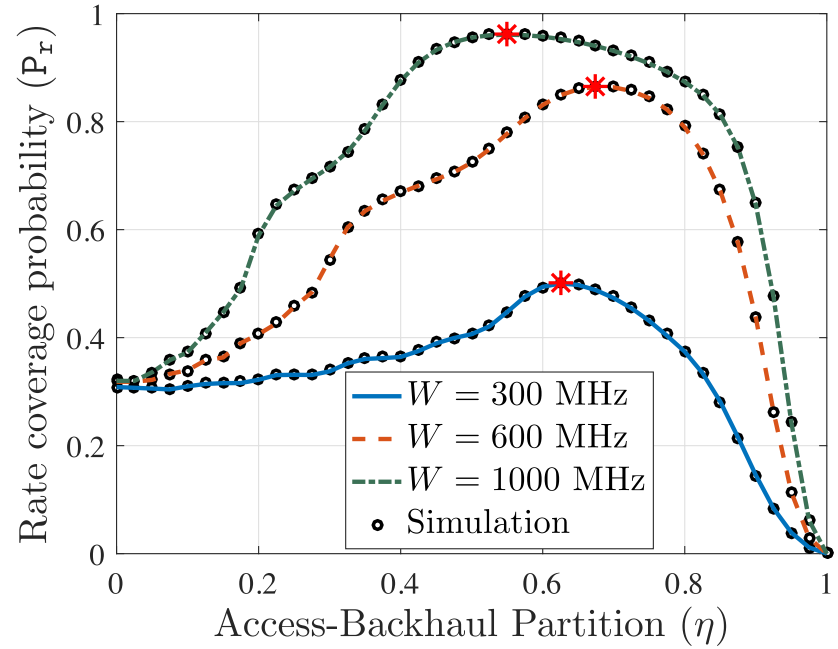
$$N_{\mathrm{o}}^{\mathrm{ABS}} = \sum_{i=1}^{n-1} N_{\mathbf{x}_i}^{\mathrm{ABS}} \qquad N_{\mathrm{o}}^{\mathrm{SBS}} = \sum_{i=1}^{n-1} N_{\mathbf{x}_i}^{\mathrm{SBS}}$$

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

Trend in Rate Coverage



Load-based partition

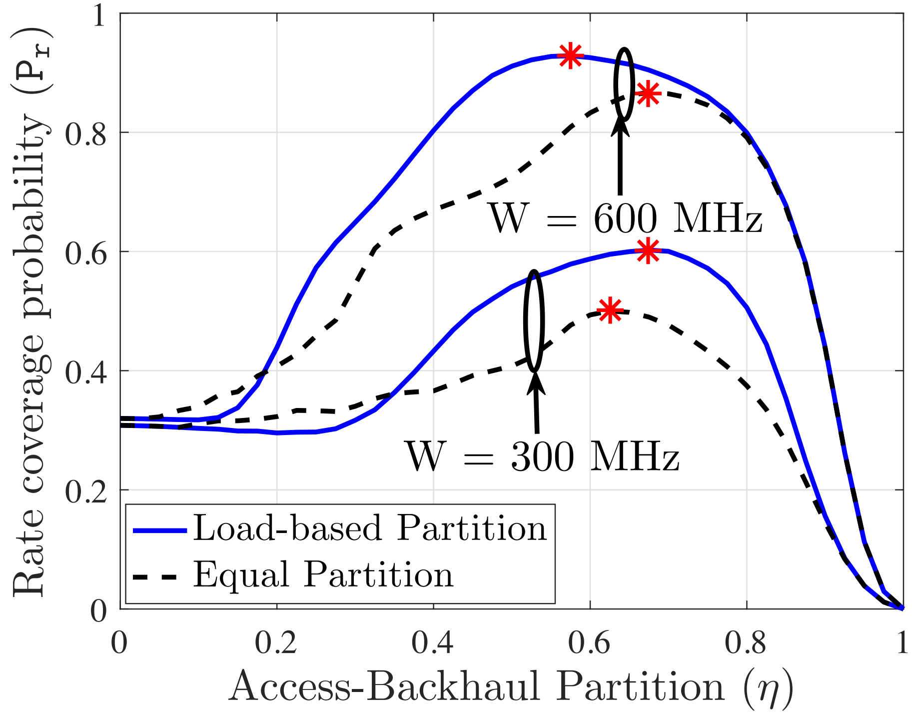


Equal partition

- 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 $n = 10$.

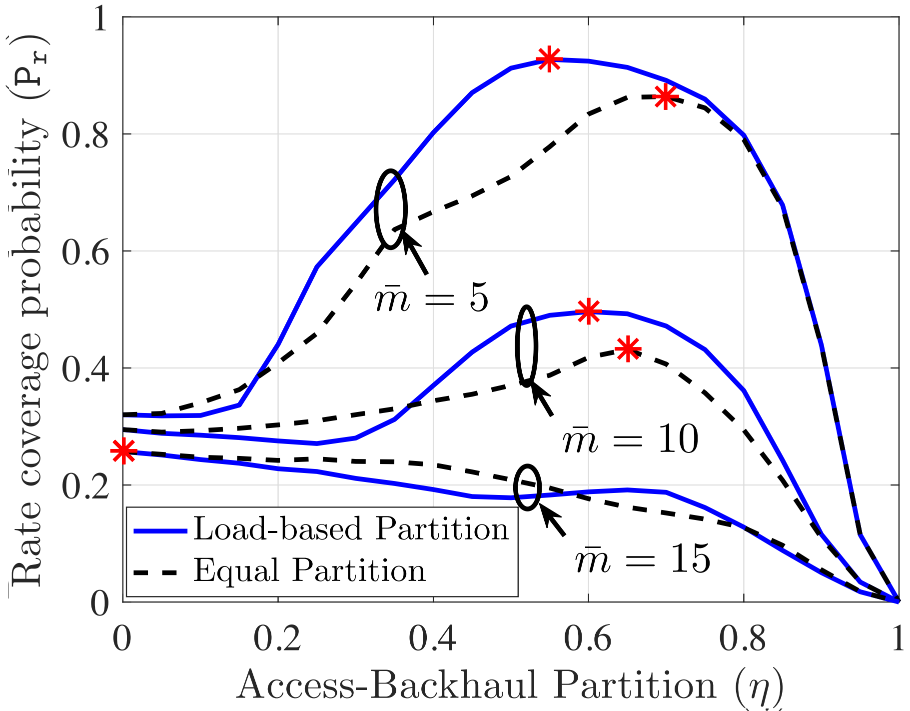
For all numerical results, $\rho = 50$ Mbps, n=10. In these figures, $m = 5$.

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 $m = 15$, 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.

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 total network load.

References

The results of this talk are the outcome of:

[1] C. Saha, M. Afshang, and H. S. Dhillon, "Integrated mmwave access and backhaul in 5G: Bandwidth partitioning and downlink analysis," to be presented in IEEE Intl. Conf. on Commun. (ICC), May, 2018.

[2] C. Saha, M. Afshang, and H. S. Dhillon, "Bandwidth Partitioning and Downlink Analysis in mmWave Integrated Access and Backhaul for 5G," submitted to IEEE Trans. Wireless Commun., available online: https://arxiv.org/pdf/1802.08776

3GPP's technical report on IAB

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

[4] 3GPP RP-170831: "New SID Proposal: Study on Integrated Access and Backhaul for NR", Source: AT&T, Qualcomm, Samsung.

Relevant prior arts: stochastic geometry

[5] 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.

[6] 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.

Thank you.

Questions ?

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.

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.