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

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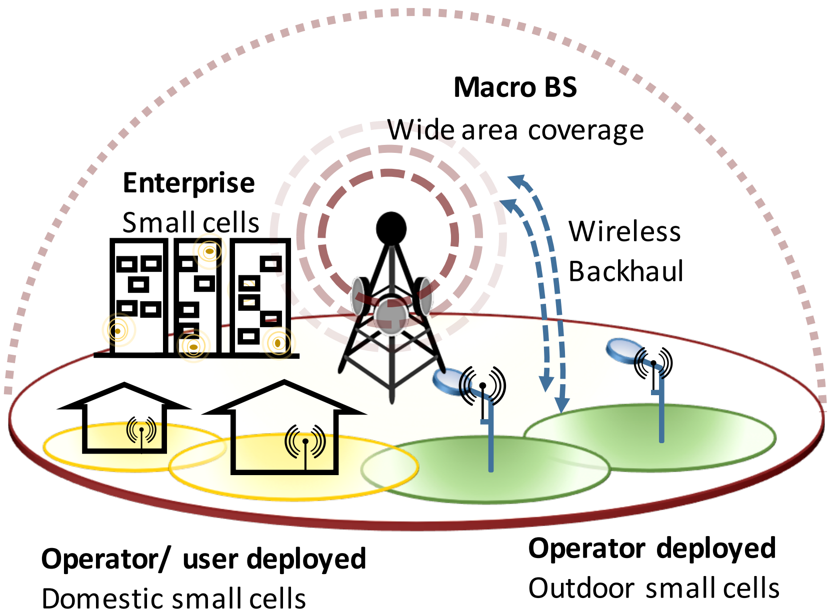
In This Talk..

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.
  - **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

Small Cell Wireless Backhaul Solutions

So far:

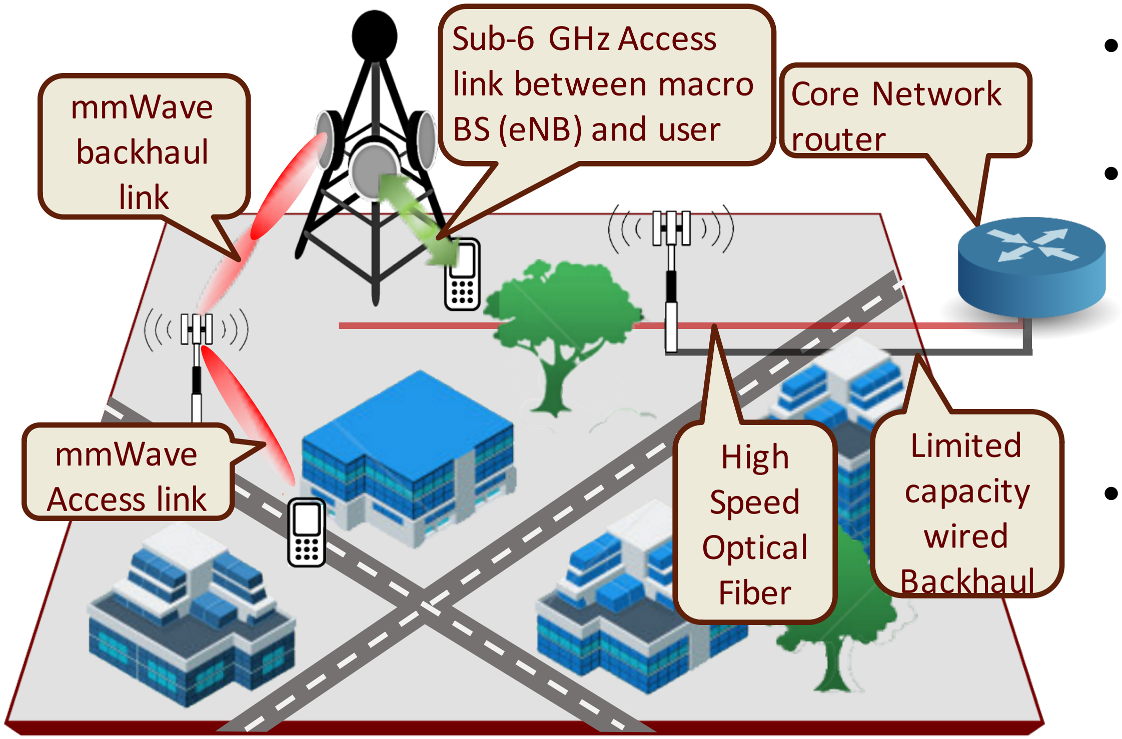
- PtP links use licensed microwave or un-licensed frequencies.
- PmP and mesh wireless systems typically operate in the **un-licensed** 2.4GHz, 5.3GHz, 5.4GHz, and 5.8GHz bands.
- Some PmP wireless systems can operate in licensed UHF/VHF, 900MHz, 3.65GHz (WiMax), and 4.9GHz (public safety) frequency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

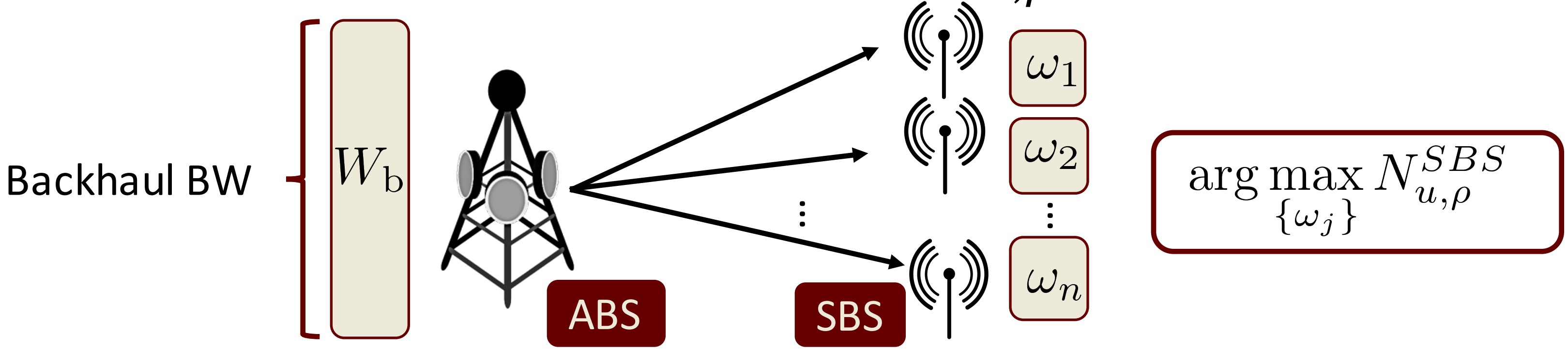


- Currently being considered by 3GPP[2].
- Self-backhaul will become a driving technology owing to more ubiquitous deployment of small cells, e.g. in vehicles, trains, lamp-posts etc.
- Major operators have evinced interest, e.g. project *Airgig* by AT&T.

Question: Resource Allocation Fundamentals

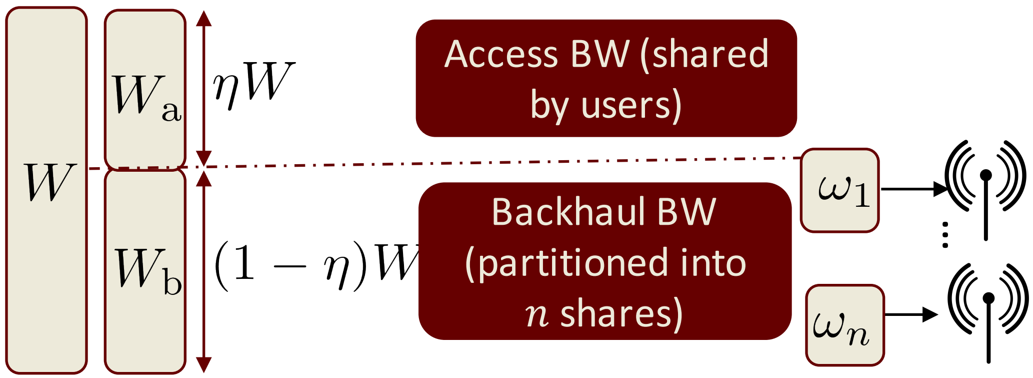
How to efficiently partition backhaul resources among different SBSs?

- 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 $\{\omega_1, \omega_2, \ldots, \omega_n\}$ 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: $\boxed{\arg\max_{\{\eta,\omega_1,\ldots,\omega_n\}} N_{\mathrm{u},\rho}}$

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

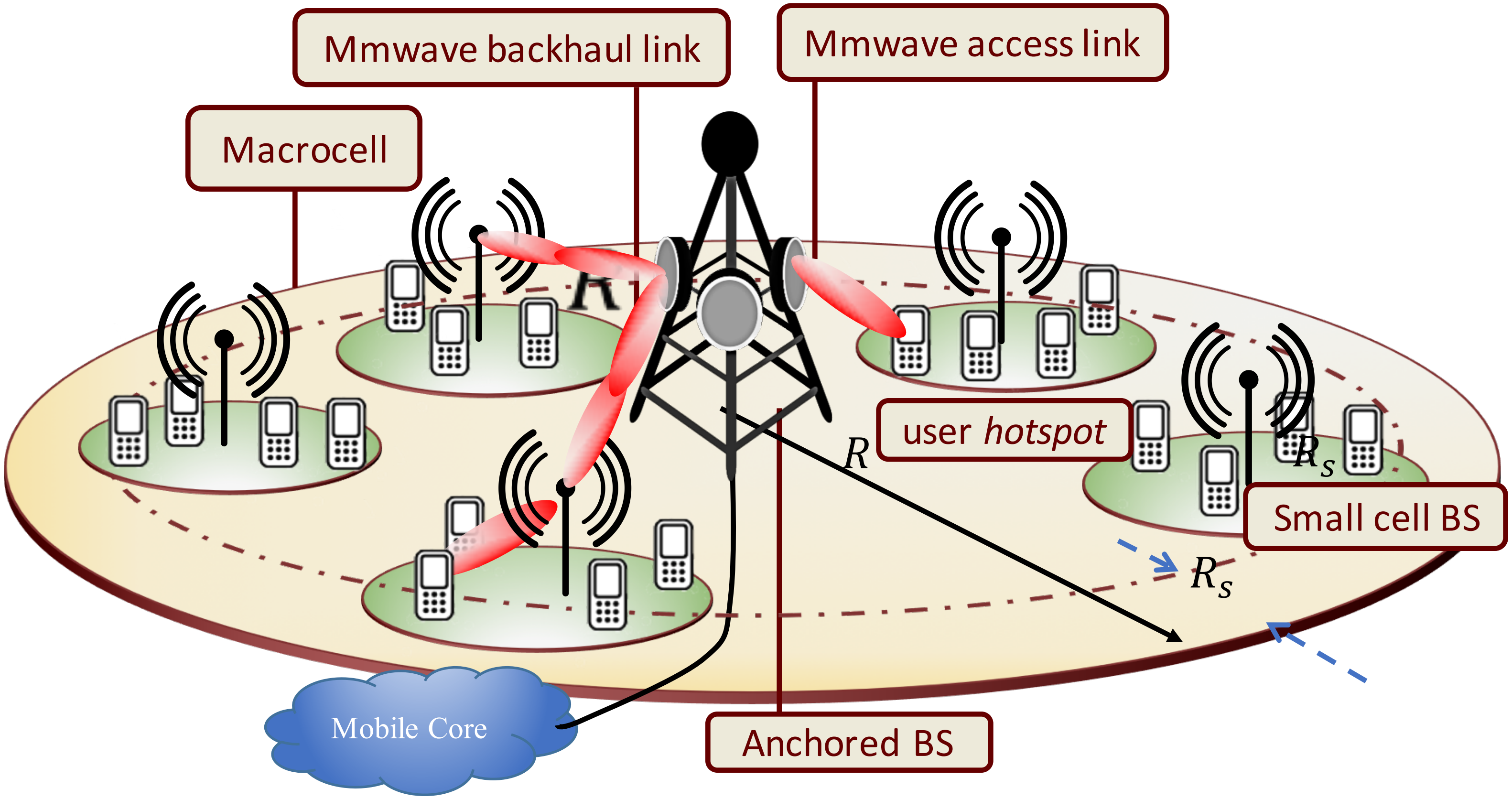
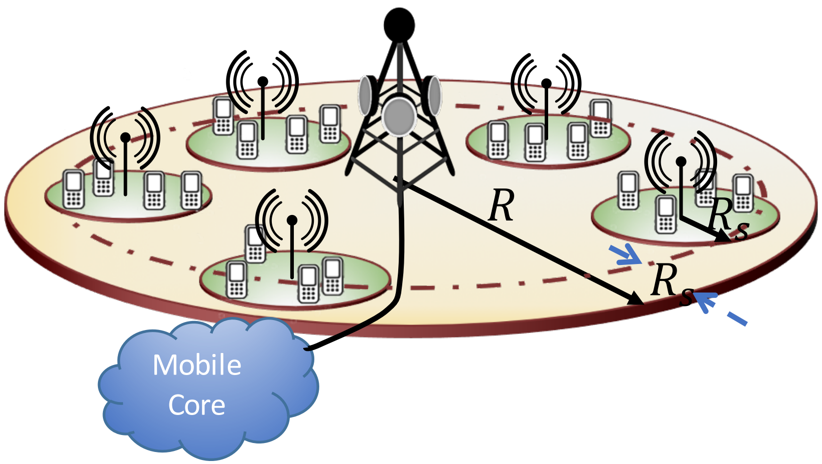


Illustration of proposed system model

Proposed System Model

User and BS locations

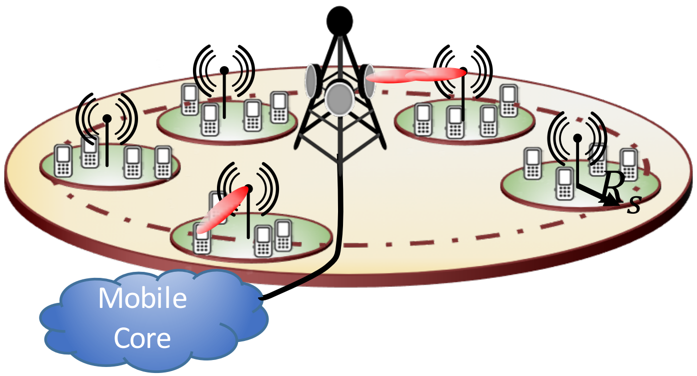


- A circular macro cell of radius R.
- The macro BS or the anchored BS is located at the center of the macro cell.
- n user hotspots (circles of radius R_s) located uniformly at random across the macro cell at locations $\{\boldsymbol{x}_1, \boldsymbol{x}_2, \dots, \boldsymbol{x}_n\}$.
- Each hotspot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

- n user hotspots (circles of radius R_s) located uniformly at random across the macro cell at locations $\{\boldsymbol{x}_1, \boldsymbol{x}_2, \dots, \boldsymbol{x}_n\}$.
- $\bar{m}$ users located uniformly at random in user hotspot.

Proposed System Model

- **Propagation assumptions**

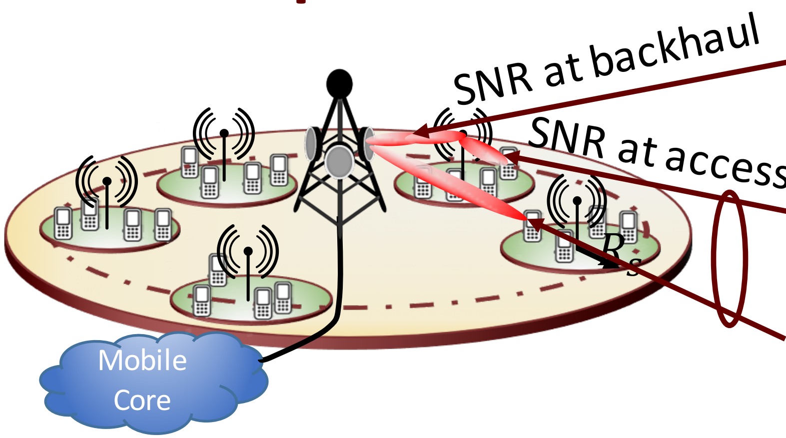


- All transmissions are in mmWave spectrum.
- BS at $\boldsymbol{y}$ transmits at a constant power spectral density $\frac{P}{W}$ over a system BW W ($P = P_m$ and P_s are the transmission powers of ABS and SBS.
- We assume noise-limited system, where N_0 is the noise PSD.
- SNR received for a link of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

- **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:

$$\mathcal{E} = 1 \text{ and } \mathtt{SNR}_{\rm b}(\mathbf{x}) > \theta_1, \mathtt{SNR}_{\rm a}^{\rm SBS}(\mathbf{u}) > \theta_2, \text{ or,}$$

SBS Coverage

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

Macro Coverage

$\{\theta_1, \theta_2, \theta_3\} \coloneqq$ 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:

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

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

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

$$\boxed{\mathbb{P}(\mathcal{E}=1|\mathbf{x})} = \mathbb{E}[\mathbf{1}(P_{\rm m}\|\mathbf{x}+\mathbf{u}\|^{-\alpha} < P_{\rm s}\|\mathbf{u}\|^{-\alpha})|\mathbf{x}]$$

$$= \mathbb{P}(P_{\rm m}(x^2+u^2+2xu\cos\xi)^{-\alpha/2} < P_{\rm s}u^{-\alpha}|x)$$

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

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

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

Coverage Probability

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

- 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.

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

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

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

- 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.

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

- 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 [4].

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:

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

Here, $v_{\rm m} = (n-1)\bar{m}\mathbb{E}[\mathcal{A}_{\rm m}(X)], v_{\rm s} = (n-1)\bar{m}\mathbb{E}[\mathcal{A}_{\rm s}(X)]$, and

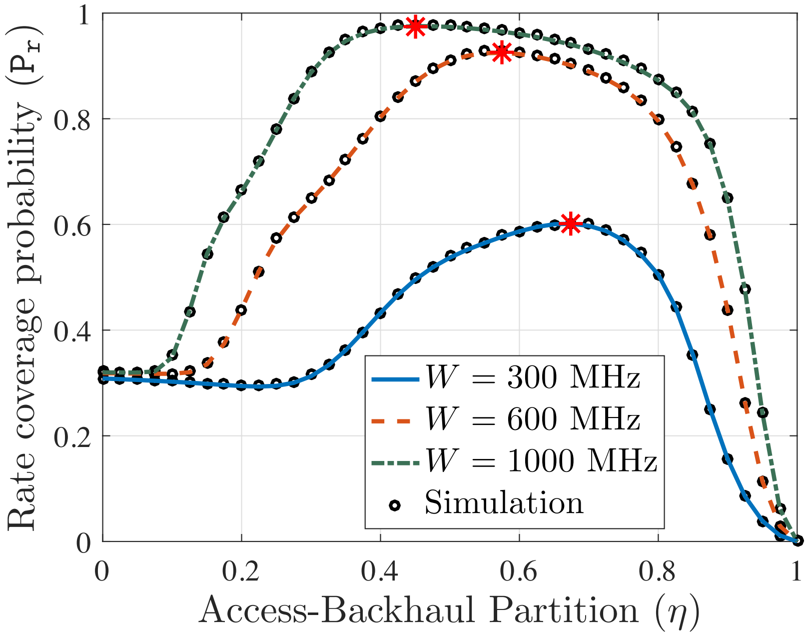
$$\sigma_{\rm m}^2 = (n-1)[\bar{m}\mathbb{E}[A_{\rm m}(X)A_{\rm s}(X)] + \bar{m}^2 \mathrm{Var}[\mathcal{A}_{\rm m}(X)]] = \sigma_{\rm s}^2$$

- 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.

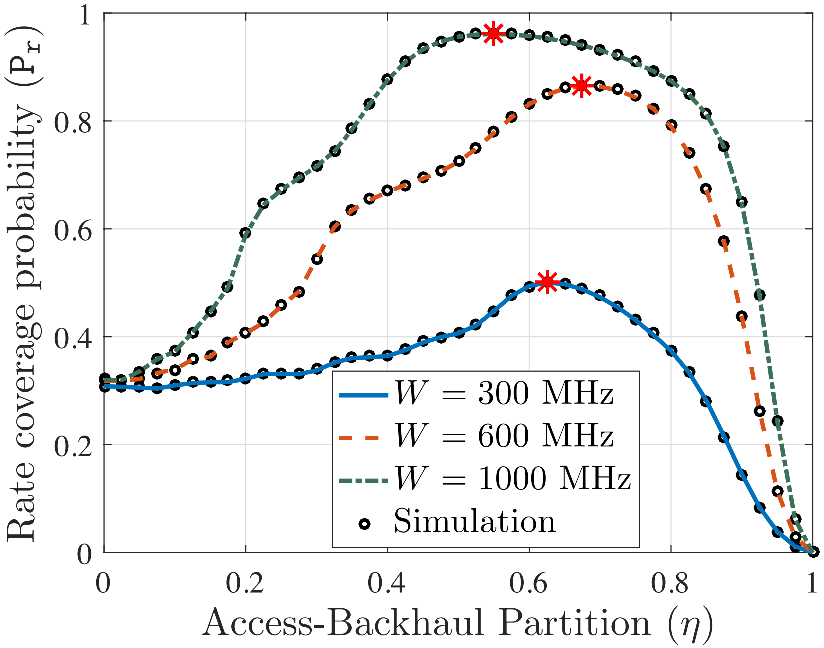
$$N_{\rm o}^{\rm ABS} = \sum_{i=1}^{n-1} N_{\mathbf{x}_i}^{\rm ABS} \qquad N_{\rm o}^{\rm SBS} = \sum_{i=1}^{n-1} N_{\mathbf{x}_i}^{\rm SBS}$$

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

Trend in Rate Coverage



Load-based partition

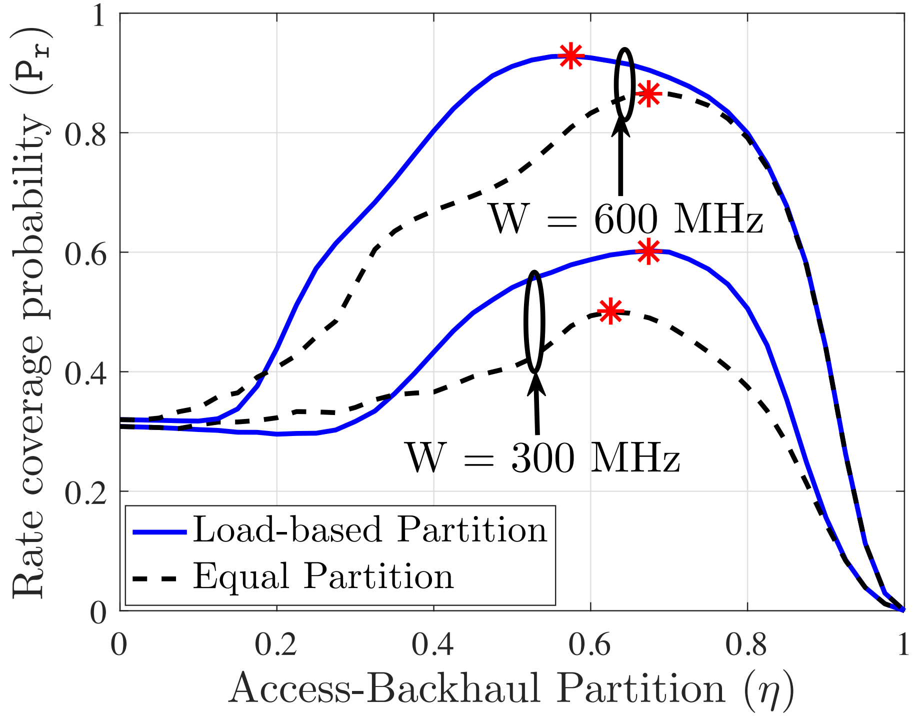


Equal partition

- 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 $n = 10$.

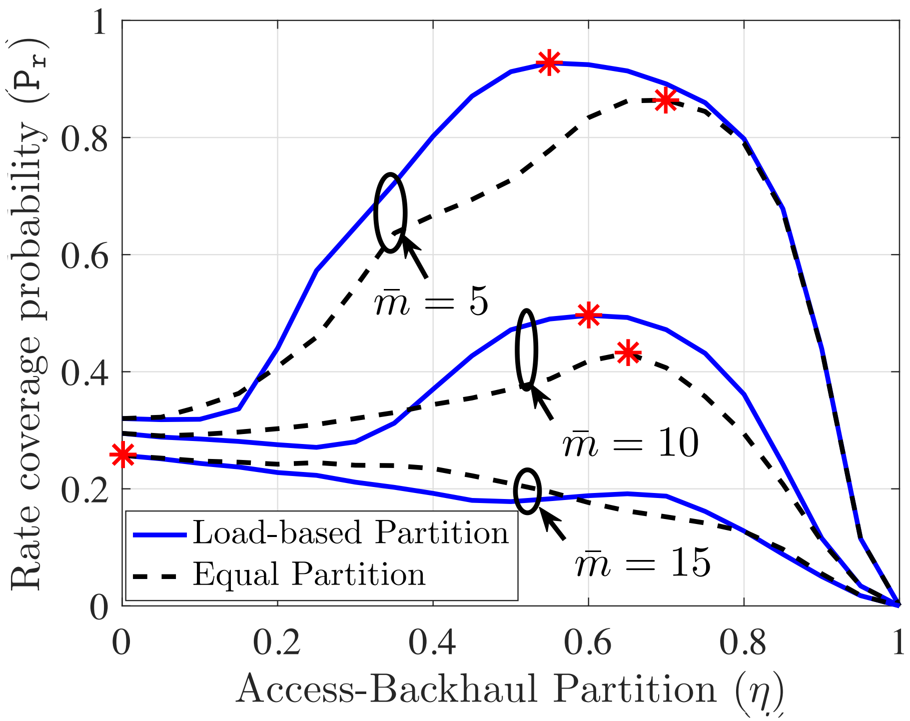
For all numerical results, $\rho = 50$ Mbps, n=10. In these figures, $\bar{m} = 5$.

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.

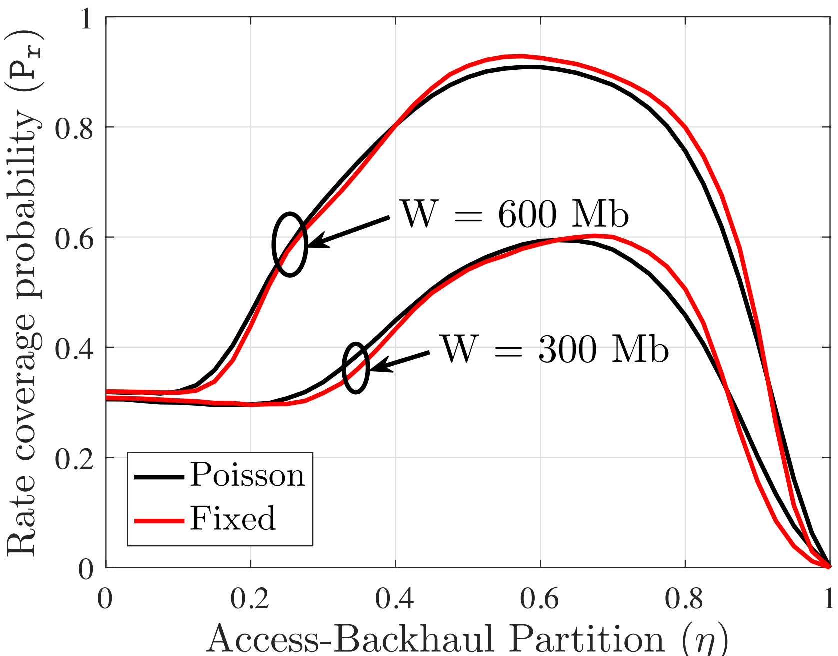
How much load can IAB support?



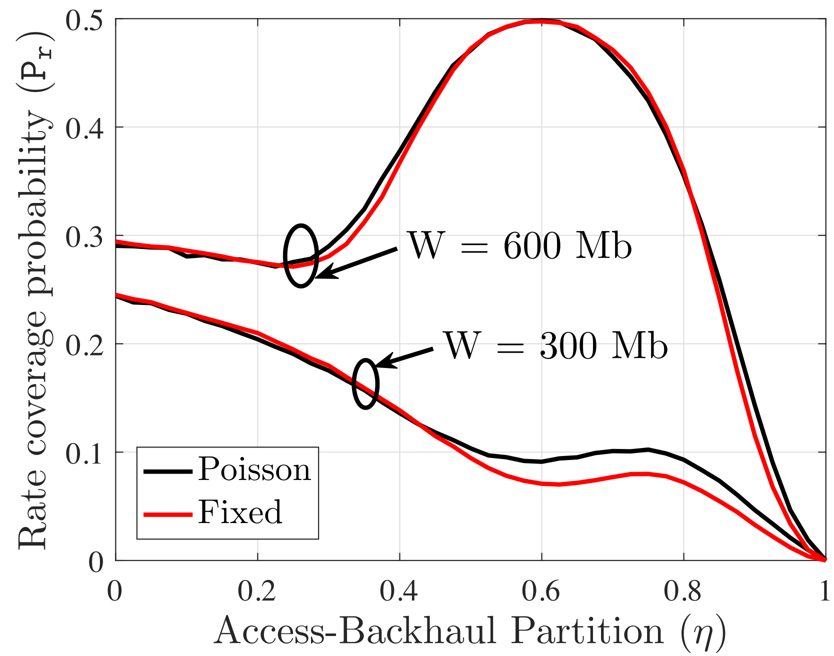
- In this plot, BW is fixed, but number of users per hotspot is varied.
- For $\bar{m} = 15$, we see that the optimal partition has moved to $\eta = 0$, which means all BW should be assigned to the access links. This is equivalent to a single tier macro-only network.

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.

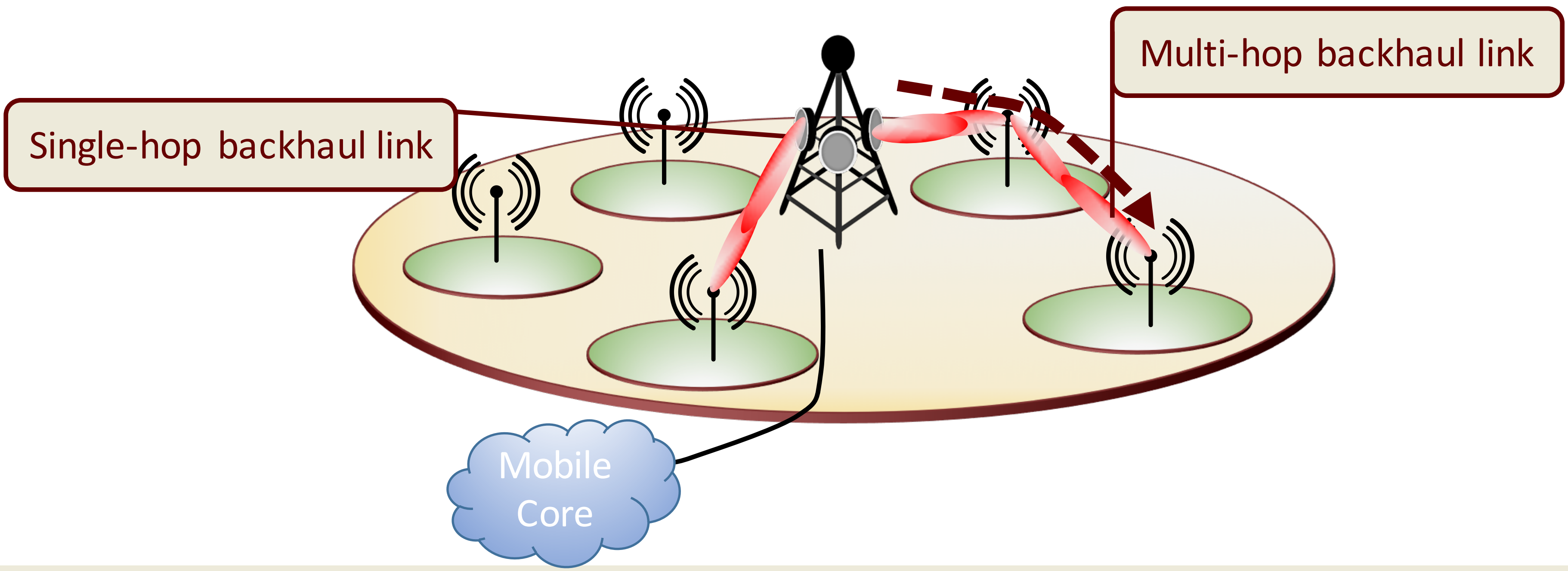
Thank you.

Questions ?

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?*