Energy Efficient Multi-Hop Wireless Backhaul in Heterogeneous Cellular Networks

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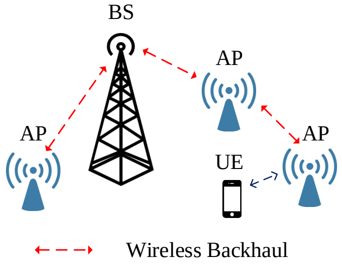
Introduction

To satisfy the ever-increasing demand on ubiquitous access to the Internet, one trend in cellular network design is the deployment of small low power base stations, which transforms the traditional macrocell-based cellular network into a heterogeneous one.

The densification of small cells necessitates the densification of backhaul connections to the core network. However, it may not be cost-effective, or even possible, to provide each small base station with a wired backhaul.

One possible solution is wireless backhaul, where small base stations backhaul their data through the wireless links to their neighbors, which have wired connections to the core network.

System Description



We analyze the performance of multi-hop backhaul in a cellular network. We use access point (AP) to refer to a small base station with only wireless backhaul and base station (BS) to refer to one equipped with dedicated wired backhaul.

Considering the spatial randomness in the distribution of nodes in heterogeneous cellular networks, we use stochastic geometry to model the network.

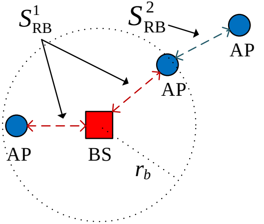
We model the BSs as a homogeneous Poisson Point Process (PPP) Φ_{BS} of intensity λ_{BS}, and the APs as another independent homogeneous PPP Φ_{AP} of intensity λ_{AP}.

System Description

The MAC protocol works in a virtual circuit fashion: once a multi-hop route is established, a virtual link would be reserved at each hop dedicated to the route. A n hop backhaul would occupy n resource blocks (time slots/frequency bands).

To improve the spectral efficiency, part of the resource blocks can be reused within a cell. We use $S^1_{\mathrm{RB},i}$ to denote the set of RBs that are used only once within the cell of $\boldsymbol{X}_{\mathrm{BS},i}$ and $S^2_{\mathrm{RB},i}$ to denote the set of RBs that can be reused.

We propose that the virtual links within a distance of r_b from the BS would be assigned with the RBs in $S^1_{\mathrm{RB},i}$ while the virtual links out of that region would use RBs in $S^2_{\mathrm{RB},i}$.



System Description

We aim to calculate and optimize the mean of the spectral efficiency of a generic cell $\boldsymbol{X}_{\mathrm{BS},0}$

$$\eta = \frac{1}{B} \sum_{\boldsymbol{X}_{\mathrm{AP},j} \in \Phi_{\mathrm{AP}}^{\boldsymbol{X}_{\mathrm{BS},0}}} \mathrm{T}_{\mathrm{b}}(\boldsymbol{X}_{\mathrm{AP},j}). \tag{1}$$

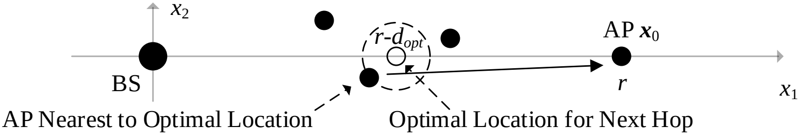
where B is the total bandwidth of spectrum, $\Phi_{\mathrm{AP}}^{\boldsymbol{X}_{\mathrm{BS},0}}$ denotes the set of APs associated with BS $\boldsymbol{X}_{\mathrm{BS},0}$ and $\mathrm{T}_{\mathrm{b}}(\boldsymbol{X}_{\mathrm{AP},j})$ denotes the throughput of the backhaul to AP $\boldsymbol{X}_{\mathrm{AP},j}$.

Two challenges in the analysis of a multi-hop cellular network:

- The routing protocol. – Determines the bandwidth per link
- The interference modeling. – Determines the SINR

Routing Protocol

- Each AP backhauls to its nearest BS.
- Suppose an AP located at $(r, 0)$ and its nearest BS located at $(0, 0)$, it selects its next hop nearest to $(r - d_{opt}, 0)$, where d_{opt} is a predetermined parameter that can be optimized.
- Approximation: For λ_{AP} sufficiently large, the deviation of each hop from its optimal location is bounded by τ, where $e^{-\lambda_{\mathrm{AP}} \cdot \pi \tau^2} \approx 0$.
- Given the AP $\boldsymbol{X}_{\mathrm{AP},j}$ located at a distance of r from its nearest BS $\boldsymbol{X}_{\mathrm{BS},i}$, the hop number on the backhaul of $\boldsymbol{X}_{\mathrm{AP},j}$ is upper bounded by $N_{j,i} \leq 1 + \frac{r}{d_{opt} - \tau}$



Routing Protocol

$$\mathbb{E}\{|S_{\mathrm{RB},i}^{1}|\} = \mathbb{E}\left\{ \sum_{\boldsymbol{x}_{\mathrm{AP},j} \in \Phi_{\mathrm{AP}}} \mathbb{1}(\boldsymbol{X}_{\mathrm{AP},j} \in \Phi_{\mathrm{AP}}^{\boldsymbol{x}_{\mathrm{BS},i}}) \cdot N_{j,i}^{1} \right\}$$

$$\leq \quad \frac{\lambda_{\mathrm{AP}}}{\lambda_{\mathrm{BS}} \cdot FP_{\min}} [d_{opt} \cdot (e^{-\pi \lambda_{\mathrm{BS}} d_{opt}^{2}} - e^{-\pi \lambda_{\mathrm{BS}} r_{b}^{2}}) + \frac{\mathrm{erfc}(\sqrt{\lambda_{\mathrm{BS}} \pi} \cdot d_{opt}) - \mathrm{erfc}(\sqrt{\lambda_{\mathrm{BS}} \pi} \cdot r_{b})}{2\sqrt{\lambda_{\mathrm{BS}}}}] + \frac{\lambda_{\mathrm{AP}}}{\lambda_{\mathrm{BS}}}$$

$$\mathbb{E}\{|S_{\mathrm{RB},i}^{2}|\} = \mathbb{E}\left\{ \sum_{\boldsymbol{x}_{\mathrm{AP},j} \in \Phi_{\mathrm{AP}}} \mathbb{1}(\boldsymbol{X}_{\mathrm{AP},j} \in \Phi_{\mathrm{AP}}^{\boldsymbol{x}_{\mathrm{BS},i}}) \cdot N_{j,i}^{2} \right\}$$

$$\leq \quad \frac{\lambda_{\mathrm{AP}}}{\lambda_{\mathrm{BS}} \cdot FP_{\min} \cdot \mu} [d_{opt} \cdot e^{-\pi \lambda_{\mathrm{BS}} r_{b}^{2}} + \frac{1}{2\sqrt{\lambda_{\mathrm{BS}}}} \cdot \mathrm{erfc}(\sqrt{\lambda_{\mathrm{BS}} \pi} \cdot r_{b})]$$

The bandwidth per resource block is $B/(\mathbb{E}\{|S_{\mathrm{RB},i}^{1}|\} + \mathbb{E}\{|S_{\mathrm{RB},i}^{2}|\})$

Interference Modeling: Intra-Cell Interference

Since APs closer to the BS are likely to generate more interference due to a heavier load of relaying, the distribution of interferers is not homogeneous.

Approximations:

- The distribution of $\Phi_{\mathrm{AP}}^{\boldsymbol{X}_{\mathrm{BS},i}}$ is approximated as an independent thinning of Φ_{AP} with retention function $p(\rho) = e^{-\pi\lambda_{\mathrm{BS}}\rho^2}$.
- For any given RB in $S_{\mathrm{RB},i}^2$ and any AP $\boldsymbol{X}_{\mathrm{AP},j} \in \Phi_{\mathrm{AP}}^{\boldsymbol{X}_{\mathrm{BS},i}}$ at a distance ρ from $\boldsymbol{X}_{\mathrm{BS},0}$, the probability that the RB will be allocated to the backhaul of $\boldsymbol{X}_{\mathrm{AP},j}$ is $\overline{N_{j,i}^2}(\rho)/\overline{|S_{\mathrm{RB}}^2|}$.
- Given RB 1 allocated to the backhaul of $\boldsymbol{X}_{\mathrm{AP},j}$, the hop on the backhaul of $\boldsymbol{X}_{\mathrm{AP},j}$ transmitting over RB 1 is uniformly distributed over $(r_b - d_{opt}, |\boldsymbol{X}_{\mathrm{AP},j}|)$.

Interference Modeling: Intra-Cell Interference

Based on the displacement theorem, for a given resource block, the interferers can still be modeled as a PPP, with intensity function

$$\lambda(\rho) = \begin{cases} 0, & \rho \leq r_b - d_{opt}, \\ \frac{\lambda_{\mathrm{AP}} \cdot e^{-\pi \cdot \lambda_{\mathrm{BS}} \cdot r_b^2}}{|\overline{S_{\mathrm{RB}}^2}| \cdot FP_{\min} \cdot \lambda_{\mathrm{BS}} \cdot 2\pi \cdot \rho}, & r_b - d_{opt} < \rho \leq r_b, \\ \frac{\lambda_{\mathrm{AP}} \cdot e^{-\pi \cdot \lambda_{\mathrm{BS}} \cdot \rho^2}}{|\overline{S_{\mathrm{RB}}^2}| \cdot FP_{\min} \cdot \lambda_{\mathrm{BS}} \cdot 2\pi \cdot \rho}, & r_b < \rho. \end{cases}$$

Interference Modeling: Inter-Cell Interference

We assume that the allocation of resource blocks to S_{RB}^1 and S_{RB}^2 are independent across different cells. Note that an arbitrary resource block would be reused

$$\overline{\mu} = \frac{|S_{\mathrm{RB}}^1| + \mu \cdot |S_{\mathrm{RB}}^2|}{|S_{\mathrm{RB}}^1| + |S_{\mathrm{RB}}^2|} \tag{2}$$

times per cell on average, where μ is the resource reuse factor, the average times that a resource block in S_{RB}^2 would be reused.

Approximation: The distribution of out-of-cell interferers is approximated as a homogeneous PPP with intensity $\overline{\mu} \cdot \lambda_{\mathrm{BS}}$ over $\mathbb{R}^2$.

Numerical Results

Parameters:

- BS & AP intensities: $\lambda_{\mathrm{BS}} = 10^{-6}\ /\mathrm{m}^2$, $\lambda_{\mathrm{AP}} = 1 \times 10^{-2}\ /\mathrm{m}^2$.
- Path-loss exponent: $\beta = 4$.
- SINR threshold: $\theta_{\mathrm{SINR}} = 10$ dB.
- Power spectrum density of noise: $N_0 = -165$ dBm/Hz.
- Bandwidth: $B = 10$ MHz.

To make the comparison fair, the transmit power is normalized by the average resource reuse factor, $P_T/\overline{\mu}$, to ensure equal power consumption for different μ.

Numerical Results

Table: The optimal d_{opt} and r_b for different P_T/B_{RB} and μ

P_T/B_{RB}	-40 dBm/Hz			-30 dBm/Hz		
μ (m)	1	7	13	1	7	13
d_{opt} (m)	71.28	39.14	30.53	115.47	55.79	39.03
r_b (m)	-	39.14	30.53	-	55.79	39.03

- The optimal d_{opt} decreases as transmit power increases.
- The optimal d_{opt} decreases as the resource reuse factor , μ, increases.
- For $\mu \neq 1$, the optimal r_b always equals d_{opt}, indicating that it is not efficient to sacrifice the bandwidth for exchange of a lower intra cell interference.

Numerical Results

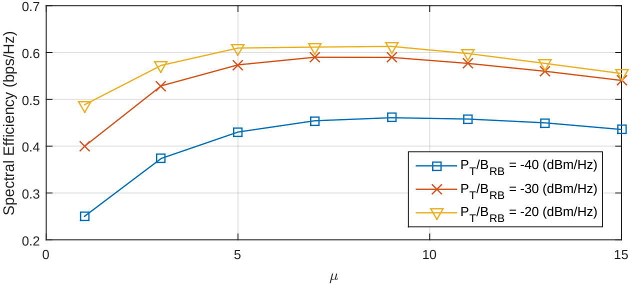
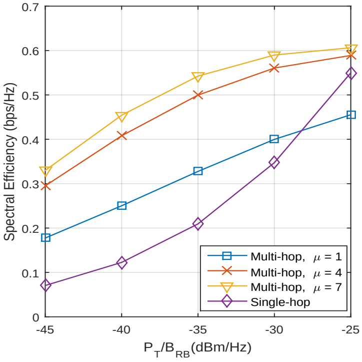
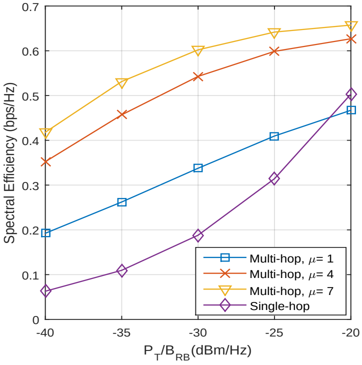


Figure: Spectral efficiency for different μ and P_T/B_{RB}

Resource reuse can significantly improve the spectral efficiency, but spectral efficiency is not monotonically increasing with respect to μ.

Numerical Results





When the transmit power is low or the BSs are sparse, the proposed scheme obtains a much higher spectral efficiency than the single-hop wireless backhaul.

Thanks!