Power Delay Profile in Coordinated Distributed Networks: User-Centric v/s Disjoint Clustering

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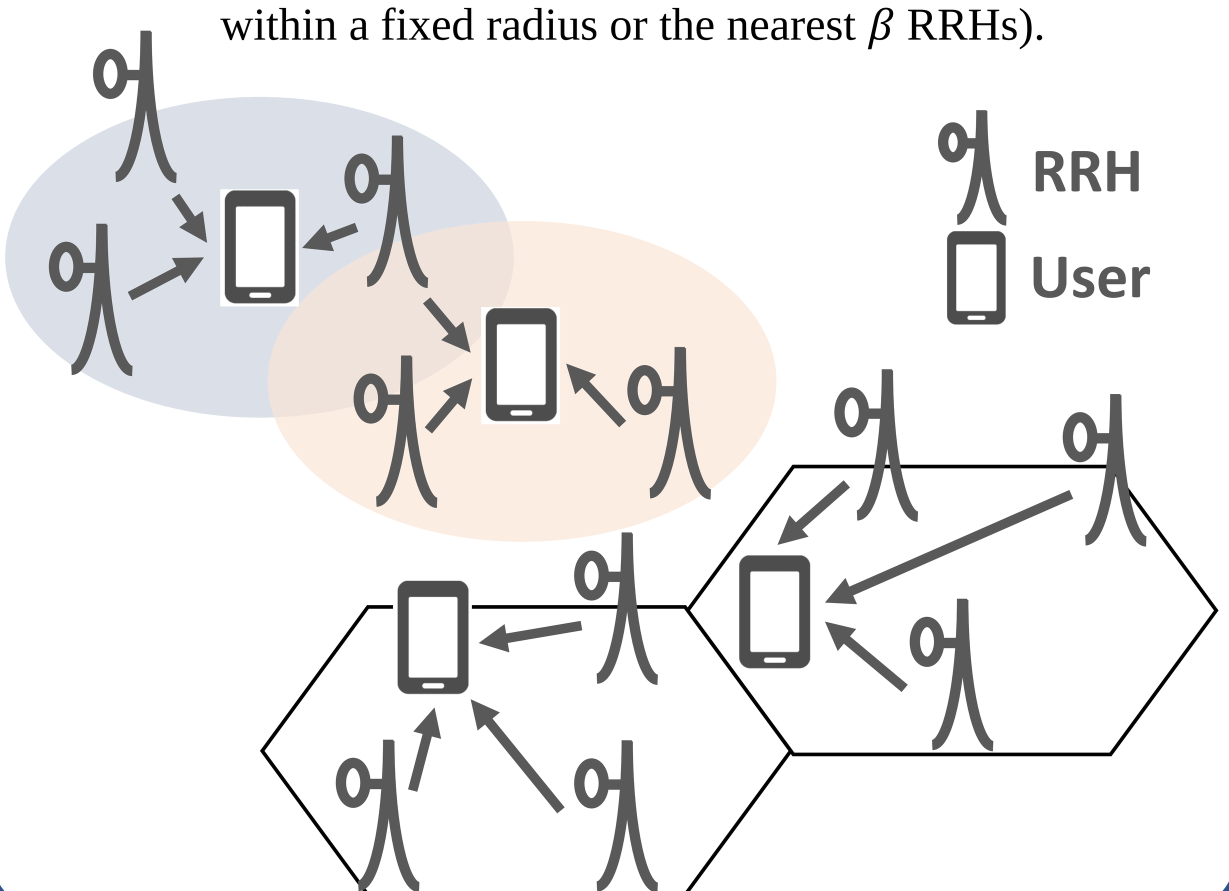
1. Introduction

- Coordinated distributed wireless networks use cooperative techniques at geographically distributed Remote Radio Heads (RRHs) to jointly serve users.
- Why many transmitters should serve users?
  - ❑ Stronger received useful signal
  - ❑ Macro-diversity
  - ❑ Interference management
- Each user is served by a cluster of RRHs, which is a **subset** of all RRHs in the network.
- We consider two popular forms of clustering:
  - ❑ **Disjoint clustering (cell-centric):**
    - Distributed network preserves the cellular concept.
    - Network service area partitioned into fixed disjoint regions.
    - Users within each region are jointly served by all the RRHs in their region.
  - ❑ **Cell-free clustering (User-centric):**
    - Each user is served by its closest RRHs (either all within a fixed radius or the nearest β RRHs).



2. Motivation

- Power Delay Profile (PDP) describes the power and signal delay spread (SDS), and it is an important factors in the design of wireless networks, e.g., in choosing the length of a cyclic prefix.
- While distributed networks are receiving increasing attention, the impact of cooperation on the PDP has not been addressed.

3. Signal Delay Spread (SDS)

- Signal delay spread is the difference between the arrival time of the signal's earliest and latest multipath component.
- For a single transmission, the delay spread is given by σ_{rms} [1].
- However, the RRHs geographical distribution causes an additional delay spread.

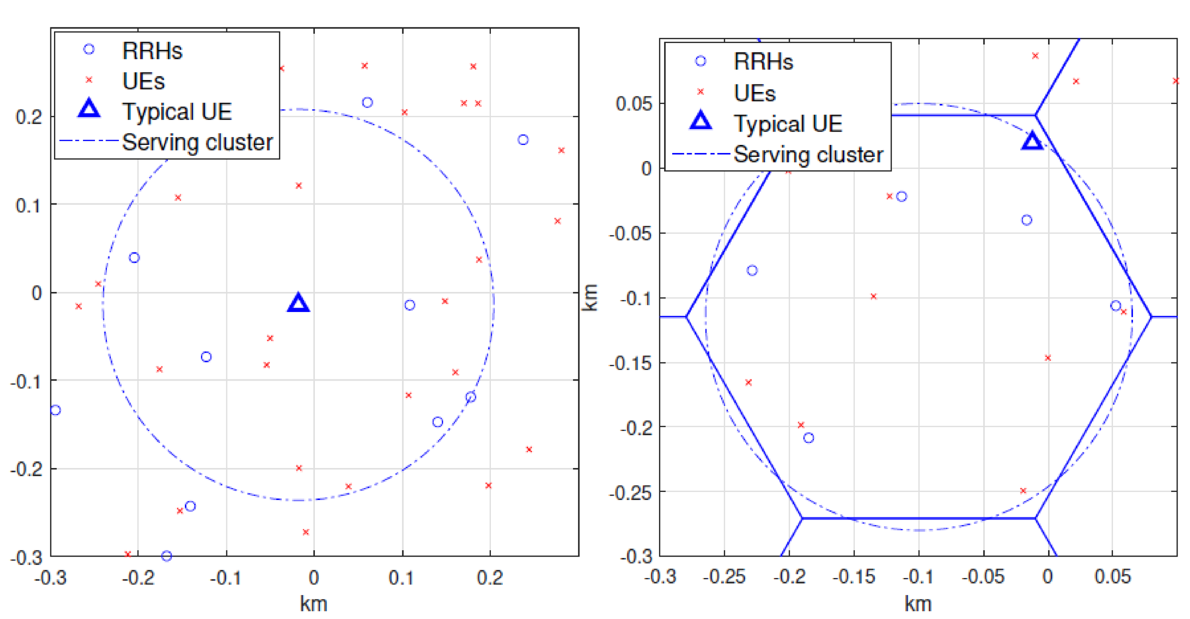
[1] A. Goldsmith. *Wireless communications*. Cambridge uni. press, 2005.

4. Major Contributions

- We analyze the PDP for both user-centric and disjoint clustering.
- We derive the PDP and analyze the additional channel delay spread due to the geographic distribution of the RRHs.
- This is the first work that analyzes the signal PDP in coordinated distributed networks.

5. System Model

- Consider a network of distributed RRHs, each equipped with a single antenna, and implementing a CoMP scheme to serve the users.
- We model the locations of the RRHs as a 2D homogeneous Poisson Point Process (PPP) Φ_b with density λ_b.
- We assume a continuum of multipath delays from each RRH (use COST207 channel delay model).
- For any user k in the network, we define a cluster of serving RRHs $\mathcal{C}_k$, comprising $\beta > 0$ RRHs.
- For user-centric clustering, we have two choices:
  - ❑ Serving cluster comprises the nearest β RRHs to each user.
  - ❑ Serving cluster is set by a cooperation radius → random number of serving RRHs (on average β).



(a) User-centric clustering. (b) Disjoint clustering.

Fig. 1: Network plot for a user served by $\beta = 5$ RRHs.

6. SDS: Disjoint Clustering

- We approximate the cell area as a circle with radius ω; hence the average number of RRHs per cell of area $\mathcal{B}$ is:

$$\beta = \mathbb{E}[\Phi_b(\mathcal{B})] = \int_0^{2\pi}\int_0^{\omega} \lambda_b r \,\mathrm{d}r\,\mathrm{d}\theta = \pi\lambda_b\omega^2$$

- Biggest possible distance between the nearest serving RRH and the furthest serving RRH to the user is 2ω.
- The maximum delay spread for disjoint clustering:

$$\sigma_{D_\beta} = \begin{cases} \sigma_{\text{rms}}, & \text{if } \beta = 1 \\ \dfrac{2\sqrt{\frac{\beta}{\pi\lambda_b}}}{c} + \sigma_{\text{rms}} & \text{if } \beta \neq 1, \end{cases}$$

7. SDS: User-centric Clustering

- For a fixed cluster radius of β the additional delay is ω/c.
- For cluster composed of the nearest β RRHs, we take a probabilistic measure of induced additional delay spread.
- Our definition of delay spread is from the distances between the points r^ℓ and r^u where

$$\nu = \int_{r^\ell}^{\infty} f_{R_1}(r_1)\,\mathrm{d}r_1 = \int_0^{r^u} f_{R_\beta}(r_\beta)\,\mathrm{d}r_\beta$$

  where $f_{(R_i)}(r_i)$ is the Probability Density Function (PDF) of the distance to the i^{th} RRH, and ν sets a statistical bound (at ν=1, we have $r^\ell = 0$, $r^u = \infty$).
- With some manipulations:

$$r^\ell = \sqrt{\frac{-\ln(v)}{\pi\lambda_b}}$$

$$\sigma_{1,\beta} = \begin{cases} \sigma_{\text{rms}} & \text{if } \beta = 1 \\ \frac{r^u - r^\ell}{c} + \sigma_{\text{rms}} & \text{if } \beta \neq 1 \end{cases} \qquad r^u = \sqrt{\frac{\Gamma^{-1}(\beta, (1-\nu)\Gamma(\beta))}{\pi\lambda_b}}$$

8. Power Delay Profile

- Using the COST207 non-hilly urban profile, i.e., the normalized PDP of single Tx is $e^{(-t/\tau_0)}$, with $\tau_0 = 1\ \mu$s, and the properties of the PPP we can derive the average PDP in disjoint clustering as:

$$\mathrm{PDP}_{\mathcal{D}_\beta}(t) = \mathbb{E}_{\phi_b}\left[\sum_{r\in\phi_b\cap \mathrm{b}(y,\omega)} p\left(\frac{r}{d_0}\right)^{-\alpha} e^{-(t-\frac{r}{c})/\tau_0}\mathrm{u}\left(t-\frac{r}{c}\right)\right]$$
$$= 2pd_0{}^{\alpha}\lambda_b e^{-t/\tau_0}\int_{d_0+\mathcal{D}_m}^{l_1} \cos^{-1}\left(\frac{r^2}{2r\omega}\right) r^{-\alpha+1} e^{\frac{r}{c}/\tau_0}\,\mathrm{d}r \quad (9)$$

- Where $l_1 = \min(\max(d_0 + \mathfrak{D}_m, ct/\omega_0), 2\omega)$
- User-centric clustering:
  - ❑ For fixed cluster radius of β RRHs:

$$\mathrm{PDP}^{(1)}_{1,\beta}(t) = 2\pi p d_0{}^{\alpha}\lambda_b e^{-t/\tau_0}\int_{d_0+\mathcal{D}_m}^{l_2} r^{-\alpha+1} e^{\frac{r}{c}/\tau_0}\,\mathrm{d}r$$

  Where $l_2 = \min(\max(d_0 + \mathfrak{D}_m, ct/\omega_0), \omega)$
  - ❑ For cluster composed of the nearest β RRHs:

$$\mathrm{PDP}^{(2)}_{1,\beta}(t) = pd_0{}^{\alpha}\sum_{i=1}^{\beta}\frac{2(\pi\lambda_b)^i}{\Gamma(i)} e^{-t/\tau_0}\int_{d_0+\mathcal{D}_m}^{\max(d_0+\mathcal{D}_m, ct\tau_0)} r_i{}^{-\alpha-1+2i} e^{\frac{\tau_0}{c}r_i - \pi\lambda_b r_i^2}\,\mathrm{d}r_i$$

9. Some Results

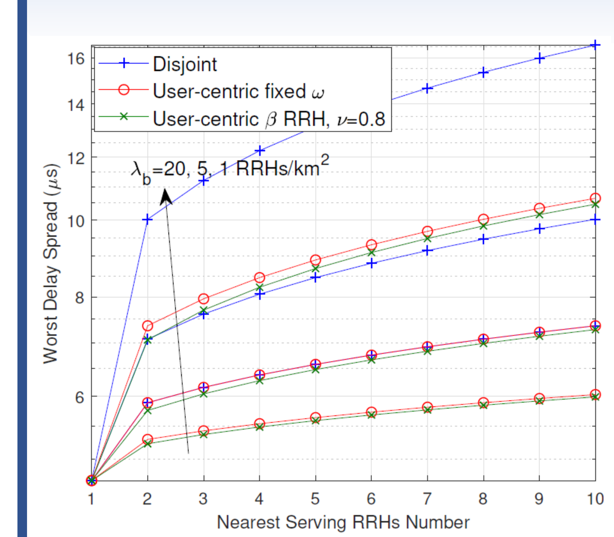


Fig. 3: Worst signal delay spread.

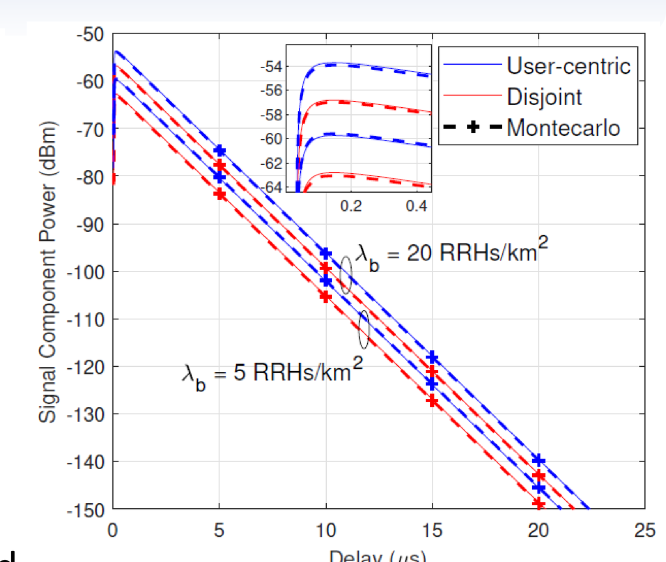


Fig. 4: User-centric vs Disjoint PDP ($\mathfrak{D}_m = 0.01$ km, $\beta = 5$)

10. Conclusions

- User-centric scheme provides an advantage over Disjoint-clustering in terms of a lower signal delay spread.
- Cluster size should be chosen carefully to ensure that the signal delay spread does not become a bottleneck.
- This analysis is key to ensuring a chosen Cyclic Prefix (CP) is adequate and to design the subcarrier spacing.