Feasibility Study of LTE Middle-Mile Networks in TV White Spaces for Rural India

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Outline

Introduction

- BharatNet - $638,619$ villages via $250,000$ Village Offices (VOs)
- Point of Presence (PoP) at VOs, wireless clusters at the villages
- Middle-mile network
- Envisioned to use the underutilized TV White Spaces
- Base Station at VOs, CPEs at associated villages

Contribution

- Analyzed feasibility, estimates based upon Telecom Regulatory Authority of India targets rate of 512 kbps
- Proportional fair iterative algorithm for radio resource allocation

Two-Stage System

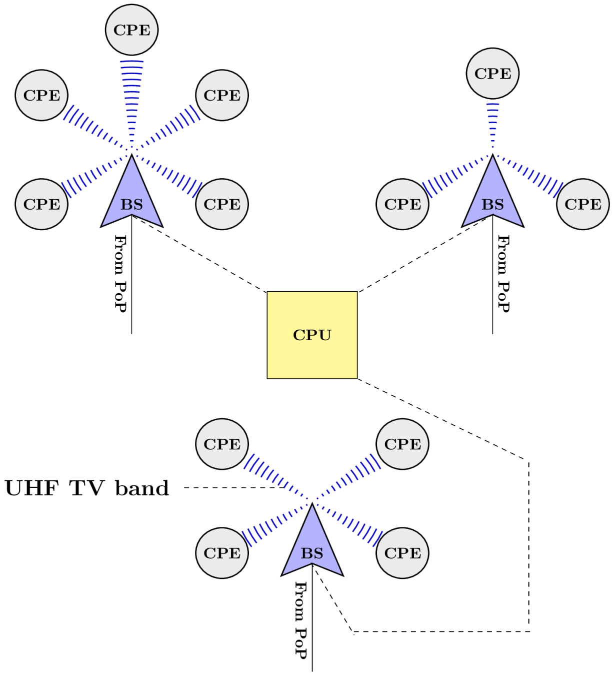

Figure: Simple overview of the two-stage system

CoR Overview

- BaseStation - omnidirectional, 3 sectoral antennas (SAs) of 120°
- Network partitioned into coordination regions (CoRs)
- Why truncated? **Negligible** interference from other tiers

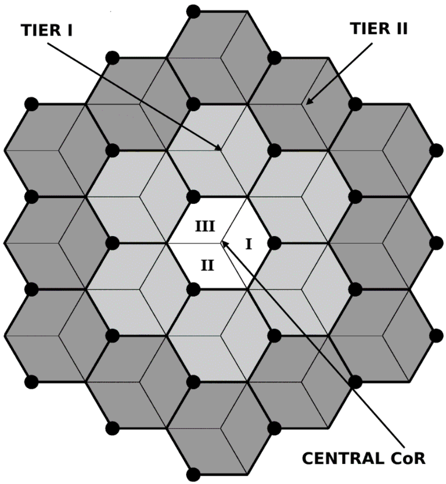

Figure: Truncated Network

Problem Formulation

- $P_b^{\max}$: Maximum transmission power of BaseStation b
- P_{bs}^k : Power of BaseStation b to a CPE in sector s on PRB k
- $r_{(m,n)}^k$: Received rate of $CPE_{(m,n)}$ on PRB k

The objective is:

$$\max \sum_{n:CPE_{(m,n)} \in \mathcal{N}_m} \sum_{k \in \mathcal{K}} r_{(m,n)}^k \; \forall\, m : CoR_m \in \mathcal{M} \tag{1}$$

$$\text{subject to: } \sum_{s \in \mathcal{S}} \sum_{k \in \mathcal{K}} P_{bs}^k \leq P_b^{\max},$$
$$P_{bs}^k \geq 0.$$

- Involves optimization over continuous and discrete variables

Interference Analysis

- No PRB is reused in a CoR $\implies$ **zero** intra-CoR interference
- **non-zero** inter-CoR interference
- Allocating PRBs:
  - **Coordinated Policy**
  - **Coordinated Policy with Bucketing**

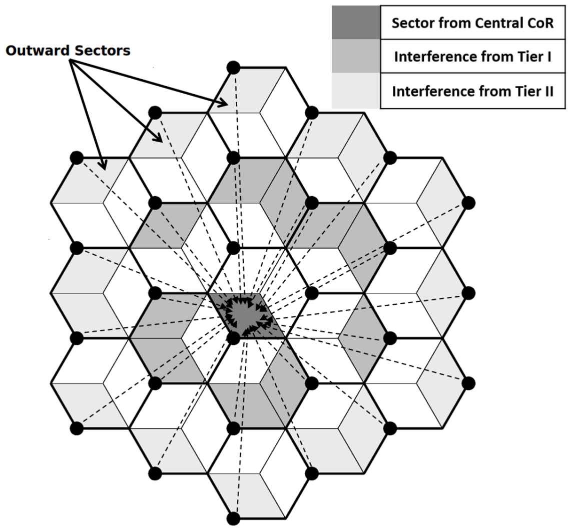

Figure: Interference Diagram for inter-CoR interference

Topology: Modelling CPE Location

The no. of CPEs in the sector belonging to each BaseStation of a CoR is randomly chosen with $q_s \in [0, 1]$ as follows:

$$\text{no. of CPEs in each sector} = \begin{cases} 2, & \text{w.p. } q_s \\ 1, & \text{w.p. } (1 - q_s) \end{cases}$$

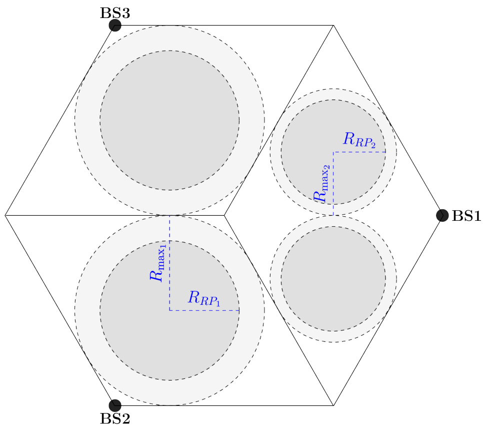

Figure: $R_{RP_1} = \gamma_1.R_{max_1}$, $R_{RP_2} = \gamma_2.R_{max_2}$, where $\gamma_1, \gamma_2 \in [0, 1)$

Using a standard Suboptimal Proportional Fair Allocation algorithm (SPFA), distribute the PRBs among the CPEs in each CoR

Results

Multiple topologies with varying values of q_s and R_{RP} whose results are:

1. Average received rate of the central CoR has little variance
2. CoR have similar data rates, irrespective of no. of CPEs and location.

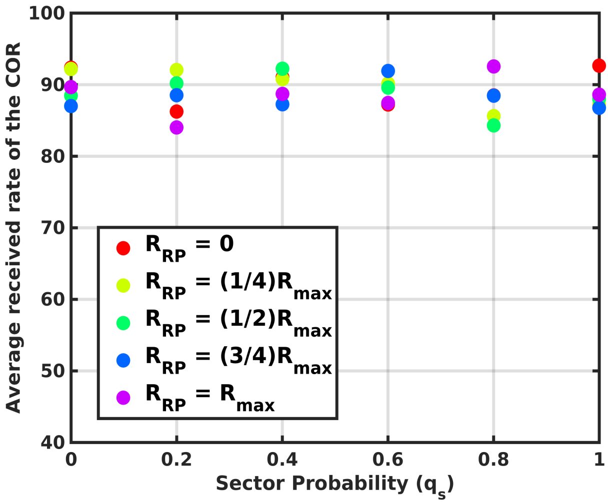

Figure: Received rate of the central CoR averaged over 10 network initializations

SPFA doesn't always allocate the PRBs fairly among all CPEs in a CoR

SPFA With Reservation (SPFAR)

- $\overline{r}_{(m,n)}$: Latest avg. rate of the $CPE_{(m,n)}$; $\mathbf{r}_m = \{\overline{r}_{(m,n)} | CPE_{(m,n)} \in \mathcal{N}_m\}$

Equations:

1. $\overline{r}_m = \dfrac{\mathbf{r}_m \cdot \mathbf{I}}{|\mathcal{N}_m|}$, $\chi_m : \{n \in \mathcal{N}_m | \overline{r}_{(m,n)} \leq \overline{r}_m \}$
2. For $CPE_{(m,n)} \in \chi_m$, difference between $\overline{r}_{(m,n)}$ and $\overline{r}_m$ is quantified as

$$K_{(m,n)} = \Gamma . \frac{\left(\overline{r}_m - \overline{r}_{(m,n)}\right)}{\overline{r}_m^{PRB}} \text{number of PRBs,} \tag{2}$$

where, $K_{(m,n)}$ is rounded off to nearest integer, Γ is a tuning parameter and

$$\overline{r}_m^{PRB} = \frac{\sum\limits_{n:CPE_{(m,n)} \in \mathcal{N}_m} \overline{r}_{(m,n)}}{K}.$$

- Select CPE with worst $\overline{r}_{(m,n)}$ and assign it best $K_{(m,n)}$ PRBs and remove them from set of PRBs that are to be assigned and so on
- Use SPFA to assign rest of PRBs
- SPFA till t_f iterations; based on average received rate over t_f iterations, SPFAR is employed in from iteration $(t_f + 1)$ to $(t_f + t_0)$

Tradeoff

Algorithm	**Γ**	**Fairness**	**CoR rate (Mbps)**
SPFA	–	0.9689	89.73
SPFAR	1	0.9828	87.31
SPFAR	2	0.9862	86.26
SPFAR	3	0.9876	85.86
SPFAR	4	0.9905	85.41

Table: For a varying Γ, the tradeoff between Fairness among the CPEs vs. their total Throughput in the central CoR

- The reservation of PRBs improves fairness while introducing sub-optimality, thereby decreasing the total average rate of a CoR

Transmission Tx Power vs. Cell Radius R_{cell}

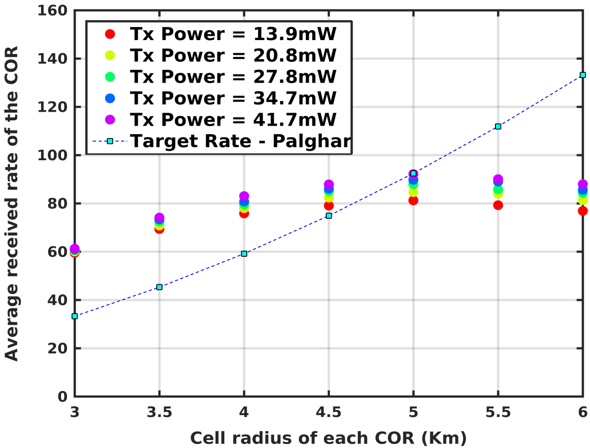

Figure: Received rate of the central CoR averaged over 10 network initializations

- Distance between the neighboring BSs decreases, the interference between them becomes more prominent
- After 5 km, path loss becomes more predominant decreasing the average rate
- Increasing the Tx power has little improvement in the total average rate due to higher inter-cell interference

Meeting the Demands

- Palghar has a density of 285 people per sq. km
- Contention ratio is $1:50$ as prescribed by TRAI
- For a cell radius of CoR below 5 km, the target rate of 1 Mbps per user is achievable

Varying Demands Based on Topology

- If rates demanded CPEs $\mathcal{N}_m$ in CoR_m are in the ratio $\lambda_{(m,1)} : \lambda_{(m,2)} : \cdots : \lambda_{(m,|\mathcal{N}_m|)}$, then

Results:

1. Average fairness among the CPEs with the new rate requirements is over 0.99 with an average standard deviation in CoR rate of just 3 Mbps
2. Average CoR rate achieved using the proposed RRA is independent of the rates demanded by its CPEs

Future Work

- Adaptive power control can be utilized for optimality
- Framework has to be established for efficient RRA and interaction among operators in case of changes in demand and entry of a new operator
- For the coexistence among multiple operators in middle-mile network, a regulatory approach needs to be developed

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Thank you

Path Loss

- Hata Model appropriate for 470 – 590 MHz band

SINR of each individual PRB on a LOS link is then calculated using

$$SINR = PTx + GTx - PL - Noise \tag{3}$$

Spectral efficiency (SE) evaluated using

$$SE = \log_{10}(1 + SINR) \tag{4}$$

Using LTE CQI table, rate (R) in that PRB of the LOS link in a SubFrame of duration $T_{SF} = 1$ms is obtained as follows:

$$R = \phi.(RE).(bpS).(CR).(\alpha)/T_{SF} \tag{5}$$

Suboptimal Proportional Fair Allocation (SPFA)

Algorithm 1 SPFA

Initialize: $\mathcal{N}_m^* = \mathcal{N}_m$
for each iteration t **do**
  for each $CoR_m \in \mathcal{M}$ **do**
    for each PRB $k \in \mathcal{K}$ **do**
      if $CoR_m \in$ Tier II **then**
        update N_m^* based on the bounds imposed by the Coordinated Policy with Bucketing
      end if
      for each $CPE_{(m,n)} \in \mathcal{N}_m$ **do**
        Compute $r^k_{(m,n)}(t)$
        Compute $SC^k_{(m,n)}(t) = \dfrac{r^k_{(m,n)}(t)}{\overline{r}^k_{(m,n)}(t-1)}$
      end for
      Assign PRB k to $CPE_{(m,n^*)} =_{\mathcal{N}_m^*} SC^k_{(m,n)}(t)$
      $\overline{r}^k_{(m,n^*)}(t) \leftarrow (1 - \frac{1}{T_c})\overline{r}^k_{(m,n^*)}(t-1) + \frac{1}{T_c} r^k_{(m,n^*)}(t)$
    end for
  end for
end for

SPFA With Reservation (SPFAR)-II

- $\mathcal{K}_1$: set of PRBs which are going to be allocated using Algorithm 2; $|\mathcal{K}_1| = \sum_{n\in\mathcal{N}_m} K_{(m,n)}$ PRBs; selected uniformly at random
- Rest are assigned to $\mathcal{K}_2$
- Allocate the PRBs in $\mathcal{K}_2$ among all CPEs $|\mathcal{N}_m|$ of the CoR_m using SPFA

Algorithm 2 Reserved PRB Allocation

for each $CoR_m \in \mathcal{M}$ **do**
  while $|\chi_m| \neq 0 \wedge |\mathcal{K}_1| \neq 0$ **do**
    Choose $CPE_{(m,n)} \in \chi_m$ such that
$$\overline{r}_{(m,n)} \leq \overline{r}_{(m,n')}, \forall CPE_{m,n'} \in \chi_m$$
    Allocate the set of PRBs $\mathcal{K}_3 \subset \mathcal{K}_1$ to $CPE_{(m,n)}$ as
$$\mathcal{K}_3 = \Big\{ y \in \mathcal{K}_1 | r^y_{(m,n)} \geq r^k_{(m,n)}, \forall k \in \mathcal{K}_1 - \mathcal{K}_3 \wedge |\mathcal{K}_3| = K_{(m,n)} \Big\}$$
    $\chi_m \leftarrow \chi_m - \{CPE_{(m,n)}\}$
    $\mathcal{K}_1 \leftarrow \mathcal{K}_1 - \mathcal{K}_3$
  end while
end for