Traffic-Aware Association in HetNet

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Problem Statement

- Conventional User Association in HetNet:
  - Max-DL-SINR association as in 2G/3G/4G networks
  - Cell Range Expansion [Sesia et al’11, Andrews et al’14]
  - Joint optimization of association and resource allocation
    - Assuming Best-Effort (BE) traffic
    - Performance metrics
      - the sum of log-rate [Fooladivanda et al’13, Ye et al’13, Deb et al’14]
      - number of admitted users [Li et al’12]
      - sum of the inverse of the per-user throughput [Chen’11]

- Our proposed association rule:
  ✓ Model the DL QoS traffic explicitly
  ✓ Optimize the network-wide packet delay performance
HetNet with QoS Traffic

Definitions:

\[ B : \text{system BW in Hz} \]
\[ P_n : \text{txmn pwr of BS-n} \]
\[ \lambda_k : \text{pkt arrival rate of MS-k} \]
\[ L_k : \text{avg pkt length in bits of MS-k} \]
\[ h_{k,n} : \text{channel btw MS-k and BS-n} \]
\[ x_{k,n} : \text{assoc indx of MS-k to BS-n} \]
\[ y_{k,n} : \text{resource alloc} \]

Assumptions:

i.i.d. exp inter-arrival times
i.i.d. exp packet lengths
BS always ON
full freq. reuse
Problem Formulation

- Avg rate of MS-k associated with BS-n occupying all resources:

\[ R_{k,n} = B \log \left( 1 + \frac{P_n|h_{k,n}|^2}{\sum_{l=1, l \neq n}^N P_l|h_{k,l}|^2 + \sigma^2} \right) \]

- Service time for the traffic towards MS-k is i.i.d. exp with mean:

\[ t_{k,n} = \frac{L_k}{y_{k,n}R_{k,n}} = \frac{1}{y_{k,n}r_{k,n}} \]

- Avg delay for a packet in the M/M/1 queue:

\[ \tau_{k,n} = \frac{1}{1/t_{k,n} - \lambda_k} = \frac{1}{y_{k,n}r_{k,n} - \lambda_k} \]
Problem Formulation

- Optimal association rule to minimize the average pkt delay across the whole network:

\[
\begin{align*}
\text{minimize} & \quad \frac{1}{\sum_{k=1}^{K} \lambda_k} \sum_{n=1}^{N} \sum_{k=1}^{K} \frac{x_{k,n} \lambda_k}{y_{k,n} r_{k,n}} \\
\text{subject to} & \quad \sum_{n=1}^{N} x_{k,n} = 1.0, \forall k = 1, \ldots, K \\
& \quad \sum_{k=1}^{K} y_{k,n} \leq 1.0, \forall n = 1, \ldots, N \\
& \quad x_{k,n} \in \{0, 1\}, \forall k = 1, \ldots, K, n = 1, \ldots, N \\
& \quad y_{k,n} > \frac{x_{k,n} \lambda_k}{r_{k,n}}, \forall k = 1, \ldots, K, n = 1, \ldots, N.
\end{align*}
\]

- A classic knapsack problem is NP-hard [Bertsekas’99]
- We try to find low-complexity approx. solutions!
Step 1: Opt Resource Alloc

Proposition 1:

At BS-n, given user association, when the following feasibility condition is met:

$$\sum_{k=1}^{K} \frac{x_{k,n} \lambda_k}{r_{k,n}} < 1.0,$$

the optimal resource allocation minimizing the average pkt delay is as follows:

$$y_{k,n} = \frac{x_{k,n} \lambda_k}{r_{k,n}} + \frac{1 - \sum_{u=1}^{K} \frac{x_{u,n} \lambda_u}{r_{u,n}}}{\sum_{u=1}^{K} \sqrt{\frac{x_{u,n} \lambda_u}{r_{u,n}}}} \sqrt{\frac{x_{k,n} \lambda_k}{r_{k,n}}}.$$
Simplified Problem

Optimal Association:

\[
\begin{align*}
\text{minimize} & \quad \sum_{k=1}^{K} \sum_{n=1}^{N} \frac{x_{k,n} \lambda_k}{r_{k,n}} \left( 1 - \sum_{u=1}^{K} \frac{x_{u,n} \lambda_u}{r_{u,n}} \right) \\
\text{subject to} & \quad \sum_{n=1}^{N} x_{k,n} = 1, \forall k = 1, \ldots, K \\
& \quad x_{k,n} \in \{0, 1\}, \forall k = 1, \ldots, K, n = 1, \ldots, N \\
& \quad \sum_{k=1}^{K} \frac{x_{k,n} \lambda_k}{r_{k,n}} < 1, \forall n = 1, \ldots, N
\end{align*}
\]

\[P2\]

\[
\begin{align*}
\text{minimize} & \quad f(\{x_{u,n}\}) = \sum_{k=1}^{K} f_k(\{x_{u,n}\}) \\
\text{subject to} & \quad \sum_{n=1}^{N} x_{k,n} = 1, \forall k = 1, \ldots, K \\
& \quad x_{k,n} \in [0, 1], \forall k = 1, \ldots, K, n = 1, \ldots, N \\
& \quad \sum_{k=1}^{K} \frac{x_{k,n} \lambda_k}{r_{k,n}} < 1, \forall n = 1, \ldots, N
\end{align*}
\]

\[P3\]
Proposition 2

For MS-k, given others’ association, the optimal association of MS-k minimizing the objective function in problem P3 is as follows:

\[ x_{k,n} = \max \left\{ 0, \frac{r_{k,n} \delta_{k,n}}{\lambda_k} + \alpha \sqrt{\frac{r_{k,n}}{\lambda_k}} \right\} \]

chosen such that \( \sum x_{k,n} = 1 \)

\[ \delta_{k,n} := 1 - \sum_{u=1, u \neq k}^{K} \frac{x_{u,n} \lambda_u}{r_{u,n}} \]

available load in BS-n for MS-k
Traffic-Aware Assoc Algorithm

1. Feasible start: (LP)

\[
\begin{align*}
    \text{minimize} & \quad s \\
    \text{subject to} & \quad \sum_{n=1}^{N} x_{k,n} = 1, \forall k \\
    & \quad x_{k,n} \in [0, 1], \forall k, n \\
    & \quad \sum_{k=1}^{K} x_{k,n} \frac{\lambda_k}{r_{k,n}} - 1 \leq s, \forall n.
\end{align*}
\]

2. Iterations:
Update the association pattern of each MS 1-by-1 with the rule in Proposition 2.

3. Finalizing:
Make the converging association pattern a practical one:

\[
x^{(f)}_{k,n} = 1 \{ x_{k,n} > x_{k,l}, \forall l \neq n \}
\]
Simulations

Max DL SINR Association

Traffic-Aware Association

Maximum DL SINR association (Red Triangle: Macro-BS; Green Circle: Pico-BS; Black Dot: MS).

Traffic-aware association (Blue links indicate the association changes w.r.t. the Max-DL-SINR rule).
Simulations

Average packet delay and load of each BS

Max-DL-SINR

TAAA
Conclusion

- In heterogeneous networks with QoS traffic:
  - Closed-form optimal resource allocation when users’ association pattern is fixed
  - Closed-form optimal association scheme for one MS when given others’ association
  - Our proposed low-complexity association algorithm: TAAA enjoys fast convergence and provides significant performance gain