Optimal Intra-cell Cooperation in the Heterogeneous Relay Networks

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OUTLINE

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Motivation and Challenges

People want to solve—

- Conflict between proliferation of wireless devices and applications and scarce network resource as well as severe environment

People prefer to—

- Exploit the cell-edge performance to improve the system throughput
- Increase the user utilization and ensuring good QoS
Heterogeneous Networks Model

- Why Introduce Heterogeneous?
  - Decrease Propagation Distance
  - Exploit network spectrum efficiency
  - Achieve Energy Efficiency

Notations:
- Base Station (BS): index $i$
- Relay Node (RN): index $j$
- User Equipment (UE): index $k$

In each cell, we have
- One macro node (BS)
- Multiple relay nodes which function as mini-BS
Cooperative Transmission

Why use Cooperative Transmission (CoTs)?

- Improve coverage of high data rate
- Increase cell-edge throughput

Three transmission types in a heterogeneous network.
1. Direct transmission: BS→UE (B_{UE})
2. Two-hop transmission: BS→RN→UE (R_{UE})
3. Cooperative transmission: BS→UE(C_{UE})←RN

RN is connected to BS with an offline-backhaul link.

Signal to Interference and Noise Ratio (SINR):

\[ SINR = \frac{P}{I + N} \]

Shannon formula

\[ R = W \log(1 + SINR) \]
Based on different transmission types, the received SINR at the $k$th UE can be expressed as

$$
SINR_{k,0,i}^b = \frac{P_b |h_{k,0,i}|^2}{\sum_{i'=1,i'\neq i}^{N_c} |h_{k,0,i'}|^2 P_b + \sum_{i'=1}^{N_c} \sum_{j'=1}^{N_r} |h_{k,j',i'}|^2 P_r + N_0},
$$

$$
SINR_{k,j,i}^r = \frac{P_r |h_{k,j,i}|^2}{\sum_{i'=1}^{N_c} |h_{k,0,i'}|^2 P_b + \sum_{i'=1}^{N_c} \sum_{j'=1}^{N_r} |h_{k,j',i'}|^2 P_r + N_0},
$$

and

$$
SINR_{k,j,i}^{r,b} = \frac{P_b |h_{k,j,i}|^2 + P_r |h_{k,j,i}|^2}{\sum_{i'=1,i'\neq i}^{N_c} |h_{k,0,i'}|^2 P_b + \sum_{i'=1}^{N_c} \sum_{j'=1}^{N_r} |h_{k,j',i'}|^2 P_r + N_0}.
$$

$SINR_{k,0,i}^b$ and $SINR_{k,j,i}^r$ are channel gains of BS-UE and RN-UE, respectively.

Use Shannon formula to get the unit achievable data rate

$$
R_Y^X = \log(1 + SINR_Y^X)
$$

$X \in \{b, r, (r, b)\}$

$Y \in \{(k, 0, i), (k, j, i)\}$
Cooperative Transmission in Heterogeneous Networks

We combine an intra-cell cooperative transmission in a relay based heterogeneous networks, which can dramatically improve the overall system performance.

Due to the disparity in transmit power and processing capabilities between the macro and micro BSs, to fully exploit the advantages of CoTs and HetNets, the following issues need to be well investigated:

1. Mobile association
2. Intra-cell interference cancellation (Cooperative transmission)
3. Radio resource allocation
Mobile Association

- **Best-power based:** UEs are associated with the BS or RN according to the received signal strength.
- **Range-expansion based:** UEs are associated with the BS or RN according to the path loss (distance).

Conventional mobile association schemes (shown above) cannot exploit the utilization of RNs (Best-power) or balance the traffic load (Range-expansion based).
We propose a bias-based range-expansion mobile association scheme to achieve a more efficient use of frequency resources and load balance.

\[ (i^*, j^*)_k = \arg \max_{i \in \{1, \ldots, N_c\}, j \in \{1, \ldots, N_r\}} \left( |h_{k,j,i}|^2 / \delta_{i,j} \right) \]

\( \delta_{i,j} \) is the bias value, \( \delta_{i,0}=1 \) and \( 1<\delta_{i,j}<(P_b/P_r) \) for \( j>0 \).
Mobile Association

- We use decision variables to indicate association status for each type of UEs.

**B_UE:**

\[ x_{k,0,i}^b = \begin{cases} 
1 & \text{if } k\text{th UE is associated with } i\text{th BS} \\
0 & \text{otherwise} 
\end{cases} \]

**R_UE:**

\[ x_{k,j,i}^r = \begin{cases} 
1 & \text{if } k\text{th UE is associated with } j\text{th RN in the } i\text{th sector} \\
0 & \text{otherwise} 
\end{cases} \]
Intra-cell Cooperative Transmission

- For the UE associated with RN, we further decide if a cooperative transmission is needed or not based on the following criterion:
  1. SINR is lower than certain threshold $\alpha$;
  2. The interference power from neighboring BS is larger than portion of the received power from UE’s serving RN, e.g., $P_I > 0.5P_{re}$, so that ensure it is interference limited.

- The association status for cooperative user (C_UUE) can be expressed as

$$x_{k,j,i}^r,b = \begin{cases} 
1 & \text{if } k\text{th UE is served with } j\text{th RN and the } i\text{th BS together} \\
0 & \text{otherwise} 
\end{cases}$$
Problem Formulation

Objective: Optimize the resource allocation for each UE to maximize the long-term system throughput as well as ensure good user experience.

The optimization problem can be formulated as

\[
[P]: \min \ - \sum_{i=1}^{N_c} \sum_{j=1}^{N_r} \sum_{k=1}^{N_u} \log(x_{k,0,i}^b n_{k,0,i}^b R_{k,0,i}^b + x_{k,j,i}^r n_{k,j,i}^r R_{k,j,i}^r + x_{k,j,i}^{r,b} n_{k,j,i}^{r,b} R_{k,j,i}^{r,b})
\]

\(n_{k,0,i}^b, n_{k,j,i}^r\) and \(n_{k,j,i}^{r,b}\) are denoted as the time averaged allocated resources for B_UE, R_UE, C_UE, respectively.
Problem Formulation

Denote the total frequency bands in BS and RN as $F$. We have the following constraints:

$$
\sum_{k=1}^{N_b} x_{k,0,i}^b n_{k,0,i}^b + \sum_{j=1}^{N_u} \sum_{k=1}^{N_u} x_{k,j,i}^{r,b} n_{k,j,i}^{r,b} \leq F
$$

for $i=1,\ldots, N_c$ \hspace{1cm} (1)

$$
\sum_{k=1}^{N_r} x_{k,j,i}^r n_{k,j,i}^r + \sum_{k=1}^{N_u} x_{k,j,i}^{r,b} n_{k,j,i}^{r,b} \leq F
$$

for $i=1,\ldots, N_c$ ; $j = 1,\ldots, N_r$ \hspace{1cm} (2)

$$
\sum_{i=1}^{N_c} x_{k,0,i}^b + \sum_{i=1}^{N_c} \sum_{j=1}^{N_r} (x_{k,j,i}^r + x_{k,j,i}^{r,b}) = 1
$$

(3)

$$
x_{k,0,i}^b, n_{k,0,i}^b, x_{k,j,i}^r, n_{k,j,i}^r, x_{k,j,i}^{r,b}, n_{k,j,i}^{r,b} \geq 0
$$

for $i = 1,\ldots, N_c$ ; $j = 1,\ldots, N_r$ ; $k = 1,\ldots, N_u$ \hspace{1cm} (4)
Problem Formulation

- **Constraint 1**: Regulate the usage of network resources at the BSs;
- **Constraint 2**: Regulate the usage of network resources at the RNs;
- **Constraint 3**: Make sure a granted UE can only be one of the three types defined before;
- **Constraint 4**: Allocated resource must be nonnegative.
Method of Lagrange Multipliers

To solve the problem, we can first fix the variables $\alpha$ and $\delta_{i,j}$. Then the preceding problem is converted to a convex optimization problem respect to $n_{k,0,i}^b, n_{k,j,i}^r$ and $n_{k,j,i}^{r,b}$.

Introduce Lagrange multipliers $\lambda_i^b, \lambda_{j,i}^r$ and $\lambda_k^m$, for $m=(b,r,(r,b))$, we can form the Lagrange function

$$L(n_{k,j,i}^m, \lambda) = - \sum_{i=1}^{N_c} \sum_{j=1}^{N_r} \sum_{k=1}^{N_a} \log(x_{k,0,i}^b n_{k,0,i}^b R_{k,0,i}^b + x_{k,j,i}^r n_{k,j,i}^r R_{k,j,i}^r + x_{k,j,i}^{r,b} n_{k,j,i}^{r,b} R_{k,j,i}^{r,b})$$

$$+ \sum_{i=1}^{N_c} \lambda_i^b \left( \sum_{k=1}^{N_a} x_{k,0,i}^b n_{k,0,i}^b + \sum_{j=1}^{N_r} \sum_{k=1}^{N_a} x_{k,j,i}^r n_{k,j,i}^r - F \right)$$

$$+ \sum_{i=1}^{N_c} \sum_{j=1}^{N_r} \lambda_{j,i}^r \left( \sum_{k=1}^{N_a} x_{k,j,i}^r n_{k,j,i}^r + \sum_{k=1}^{N_a} \sum_{1(j,i)}^{N_a} x_{k,j,i}^{r,b} n_{k,j,i}^{r,b} - F \right)$$

$$- \sum_{i=1}^{N_c} \sum_{j=1}^{N_r} \sum_{k=1}^{N_a} \left( \lambda_k^b x_{k,0,i}^b n_{k,0,i}^b + \lambda_k^r x_{k,j,i}^r n_{k,j,i}^r + \lambda_k^{r,b} x_{k,j,i}^{r,b} n_{k,j,i}^{r,b} \right).$$

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Primal-Dual Optimality

Formulate dual function and dual problem from Lagrange function. Because of **strong duality property**, we can solve our primal problem from its dual problem.

**Dual Function:**
\[ g(\lambda) = \inf_{n_{k,j,i}^m} L(n_{k,j,i}^m, \lambda) \]

\[ \lambda_i^b, \lambda_{j,i}^r, \lambda_{j,i}^m \in \lambda \text{ for } m = (b, r, (r, b)) \]

**Dual Problem:**
\[ \max g(\lambda) \]
\[ \text{s.t. } \lambda_i^b \geq 0, \lambda_{j,i}^r \geq 0, \lambda_{j,i}^m \geq 0 \]

**Primal-Dual Optimality:**
\[ f_0(n_{k,j,i}^m) = g(\lambda^*) = \inf_{n_{k,j,i}^m} L(n_{k,j,i}^m, \lambda^*) \]

**Proof of Strong duality**
1. Given \( \alpha \), the primal problem is convex, and
2. The constraints are linear functions, satisfying the Slater’s condition.
Gradient-descent search

The optimal $n_{k,j,i}^m$ can be found by setting the gradient of $L(n_{k,j,i}^m, \lambda^*)$ with respect to $n_{k,j,i}^m$ equal to zero:

$$\frac{\partial L(n_{k,j,i}^m, \lambda^*)}{\partial n_{k,j,i}^m} = 0 \text{ for } m = (b,r,(r,b))$$

$$n_{k,0,i}^b = \frac{1}{\lambda_i x_{k,0,i}^b - \lambda_k x_{k,0,i}^b}$$

$$n_{k,j,i}^r = \frac{1}{\lambda_{j,i} x_{k,j,i}^r - \lambda_k x_{k,j,i}^r}$$

$$n_{k,j,i}^{(r,b)} = \frac{1}{\lambda_i x_{k,j,i}^{r,b} + \lambda_{j,i} x_{k,j,i}^{r,b} - \lambda_k x_{k,j,i}^{r,b}}$$

Note that $n_{k,j,i}^m$ is a function of $\lambda^*$. 
**Gradient-descent search**

By taking the gradient of $g(\lambda)$ with respect to $\lambda_i^b, \lambda_{j,i}^r$ and $\lambda_k^m$, we can obtain the expressions of $\Delta \lambda_i^b, \Delta \lambda_{j,i}^r$ and $\Delta \lambda_k^m$.

We can use gradient-descent method to update Lagrange multipliers in the following manners ($\mu$ is the step size, $\varepsilon \rightarrow 0^+$):

\[
\lambda_i^b(t + 1) = \lambda_i^b(t) + \mu \Delta \lambda_i^b(t) \quad |\Delta \lambda_i^b(t)| \leq \varepsilon
\]

\[
\lambda_{j,i}^r(t + 1) = \lambda_{j,i}^r(t) + \mu \Delta \lambda_{j,i}^r(t) \quad \text{stop when} \quad |\Delta \lambda_{j,i}^r(t)| \leq \varepsilon
\]

\[
\lambda_k^m(t + 1) = \lambda_k^m(t) + \mu \Delta \lambda_k^m(t) \quad |\Delta \lambda_k^m(t)| \leq \varepsilon
\]
Two-loop optimization procedure—

**Outer-loop**
- Determine Association Status
- Initialize System Parameters
- Bias δ

**Inner-loop**
- Compute optimal \( n^* \) based on optimal \( \lambda^* \)
- Converge?
- \( \alpha(t+1)=\alpha(t)+\Delta\alpha \)
- Bias \( \alpha \)
- CoTs?
- \( P \geq 0.5P_{re} \)
- \( \text{UEs associated with BSs} \)
- \( \text{UEs associated with RNs} \)
- \( \text{BUE} \)
- \( \text{RUE} \)
- \( \text{CUE} \)
- Gradient Descent Search
- Initialize Lagrange Multipliers \( \lambda \)
- Converge?
- Yes
- No

Output
Simulation Setup

- Follow 3GPP evaluation methodology
- 19-cell 3-sector three-ring hexagonal cell structure with a cell radius at 2 km;
- BS transmit power $P_b = 46$dBm (40W), RN transmit power $P_r = 30$dBm (1W);
- In each cell, there is one BS which is equipped with three directional antennas, one antenna per sector. Four RNs are uniformly deployed in each sector;
- 200 UEs are uniformly distributed in each cell.
Intra-cell Cooperative Transmission vs. Inter-cell Cooperative Transmission

Set $\delta = 0$dB

$\delta = 0$dB, $P_b = 46$dBm, $P_r = 30$dBm
Intra-cell CoTs under different mobile association bias values

Intra-cell CoTs: $P_b = 46$dBm, $P_r = 30$dBm, $\delta = \{0\text{dB}, 2\text{dB}, 5\text{dB}\}$

Intra-cell CoTs under different $\delta = 0\text{dB}, 2\text{dB}, 5\text{dB}$
Intra-cell CoT Ts under different RN transmit powers

Intra-cell CoT Ts: $P_b = 46$dBm, $P_r = [28$dBm, $30$dBm, $32$dBm]; $\delta = 0$dB

Intra-cell CoT Ts under different RN transmit powers = 28dBm, 30dBm, 32dBm
Non-CoTs vs. Intra-cell CoTs: Empirical Cumulative Distribution for UEs’ SINR

Non-CoTs: $P_b = 46\text{dBm}$, $P_r = 30\text{dBm}$, $\delta = 0\text{ dB}$

Intra-cell CoTs: $P_b = 46\text{dBm}$, $P_r = 30\text{dBm}$, $\alpha = -9.214\text{ dB}$, $\delta = 0\text{ dB}$
Conclusion

- Optimal intra-cell cooperation transmission can dramatically improve the network performance in terms of system throughput and cell-edge users’ SINR.

- Bias-based range expansion mobile association scheme also play an important role on network performance by exploiting the RN’s network resource and balancing BS’s traffic load.
Q&A