Fairness-aware Joint Routing and Scheduling in OFDMA-based Cellular Fixed-Relay Networks

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Outline

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- The BS Algorithm for Joint Routing and Fair Scheduling
  - Mathematical Formulation of the Resource Allocation at the BS
  - The Low-complexity Iterative Algorithm
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- Conclusion
Background

- Orthogonal frequency division multiple access (OFDMA) and relaying are the envisioned technologies for the future broadband wireless communication networks (as in LTE-A, IEEE 802.16j and 802.16m).

- Aggressive channel reuse is required.

- Efficient radio resource management (RRM) is crucial to exploit the opportunities offered by such networks.

- Interference associated with aggressive channel reuse schemes could put cell edge users at a disadvantaged situation.

- The conventional (opportunistic) scheduler will rarely serve users in such a bad channel condition; it defeats ubiquitous coverage and exposes the importance of fair algorithms.

- Relays introduce more opportunities as well as new challenges such as routing.
Background: Shortcomings in existing works

- Single-cell or single-relay scenarios are often considered to enable analysis
- Fairness is often not incorporated
- Resource partitioning is often considered to reduce inter-cell interference and the size of the optimization problem → suboptimal and requires planning
- Decoupled routing and scheduling for simplicity → suboptimal
- Full-queues assumption → traffic diversity is not exploited
- Load balancing (even distribution of subchannels among nodes) is either ignored or performed as a refinement process which affects the optimality of the allocation
- Over-simplified channel models
- Usually difficult to accommodate different service classes
System Model

- OFDMA-based cellular network in TDD mode
- Downlink scenario
- $K$ users, $M$ fixed digital relay stations (RSs) per cell
- OFDM subchannel is the basic allocation unit, $N$ subchannels

- Any user terminal (UT) in a cell can be connected to any combination of nodes (generic ‘open’ routing)
  - Not restricted to a particular geographical deployment of relay stations
- In any cell, the serving BS and each of the $M$ RSs have $K$ user buffers

- Relays can receive and transmit different data concurrently on different orthogonal subchannels (quasi-full-duplex)
- User terminals can receive from multiple nodes (BS or RSs) simultaneously on different subchannels
System Model

- Fixed power allocation for BSs and RSs per subchannel
- Adaptive modulation is assumed (CR-QAM) so that on each subchannel the achievable Tx. rate is a function of the received SINR at destination node (user or relay) and the target BER as in [X.Qiu 1999]

\[ R_{\text{org}, \text{dest}, n} = W \log_2 \left( 1 + \frac{-1.5}{\ln(5P_e)} \text{SINR}_{\text{dest}, n} \right) \]

- CSI is available at transmitter
Mathematical Formulation of the RRA at the BS

- Sum-demand (Sum-utility) maximization formulation
- The demand metric employed is proportional to the queue length at the source node and the achievable rate on its link to destination

- [Viswanathan 05]
  - A centralized joint scheduling and routing algorithm
  - Single-carrier CDMA relay network
  - Not applicable to multi-carrier networks

We propose a novel formulation and a novel low complexity cell-level centralized algorithm for downlink OFDMA-based multi-cell fixed relay networks that
- Maximizes total cell throughput
- Achieves a high degree of fairness
- Has a learning routing (relay-selection) strategy
- Substantially improves cell-edge performance
- Enables intra-cell load balancing
Mathematical Formulation of the RRA at the BS

- Definition of the demand metric of $RS_m$ on subchannel $n$
  
  $$D_{n,m \rightarrow UT_k} = R_{m,k,n} Q^m_k$$
  
  $$D_{n,m} = \max_k \{ R_{m,k,n} Q^m_k \}$$

- Definition of the demand metric of the BS on subchannel $n$
  
  $$D_{n,BS \rightarrow RS_m} = R_{0,m,n} \max_k \{ (Q^0_k - Q^m_k)^+ \}$$
  
  $$D_{n,0} = \max_j \{ D_{n,BS \rightarrow j} \} \quad j \in \mathcal{K} \cup \mathcal{M}$$

The demand metric on BS-RS links incorporates the queues at the BS and those at the RS.

Objective: Maximize the total cell throughput while maintaining fairness among users.
BILP Mathematical Formulation

\[
\max_{\rho, \gamma} \left\{ \sum_{n=1}^{N} \sum_{m=1}^{M} \sum_{k=1}^{K} \rho_{m,k,n} R_{m,k,n} Q_k^m \right\},
\]

\[
+ \sum_{n=1}^{N} \sum_{m=1}^{M} \gamma_{0,m,n} R_{0,m,n} \max_k \{ (Q_k^0 - Q_k^m)^+ \},
\]

s.t.

\[
\rho_{m,k,n} \in \{0, 1\} \quad \forall m,k,n, \quad \gamma_{0,m,n} \in \{0, 1\} \quad \forall m,n,
\]

\[
\sum_{m=1}^{M} \sum_{k=1}^{K} \rho_{m,k,n} + \sum_{m=1}^{M} \gamma_{0,m,n} \leq 1 \quad \forall n,
\]

\[
\sum_{n=1}^{N} \sum_{k=1}^{K} \rho_{0,k,n} + \sum_{n=1}^{N} \sum_{m=1}^{M} \gamma_{0,m,n} \geq \mu,
\]

\[
\sum_{n=1}^{N} \sum_{k=1}^{K} \rho_{m,k,n} \geq \lceil N/(M+1) \rceil \quad \forall m \neq 0,
\]

\[
T \sum_{n=1}^{N} \left( \rho_{0,k,n} R_{0,k,n} + \sum_{m=1}^{M} \gamma_{0,m,n} R_{0,m,n} \kappa_k^m \right) \leq Q_k^0 \quad \forall k,
\]

\[
T \sum_{n=1}^{N} \rho_{m,k,n} R_{m,k,n} \leq Q_k^m \quad \forall m,k, \quad m \neq 0,
\]

where \( \kappa_k^m = \begin{cases} 
1, & k = \arg \max_{j} \{ Q_j^0 - Q_j^m \}^+ \\
0, & \text{otherwise}.
\end{cases} \)
The Low-complexity Iterative Algorithm

1) For each unassigned subchannel, calculate the demand metric for each RS and the BS as defined earlier

2) The algorithm solves a one-to-one optimization problem by applying the Hungarian Algorithm to the N-chunks by (M+1)-Tx nodes Demand matrix $[D_{n,m}]$

3) The algorithm virtually updates the affected user queues accordingly (entries shown in red)

4) Eliminate assigned subchannels

5) Repeat steps 1) to 4) until all the packets in user buffers are scheduled or the chunks are exhausted. The number of iteration is $\left\lceil \frac{N}{M+1} \right\rceil$
Pseudo-code for the Iterative Algorithm

Initialization: $\mathcal{U} = \mathcal{N}$
while $|\mathcal{U}| \neq 0$ and $\sum Q^m \neq 0$
    for each $n \in \mathcal{U}$
        for $m = 1$ to $M$
            $D_{n,m} = \max_k \{ R_{m,k,n} Q^m_k \}$
            $\kappa_{n,m} = \text{arg max}_k \{ R_{m,k,n} Q^m_k \}$
        end for
        $D_{n,0\rightarrow m} = R_{0,m,n} \max_k \{ (Q^0_k - Q^m_k)^+ \}$
        $\kappa_{n,0} = \text{arg max}_k \{ Q^0_k - Q^m_k \}$
    end for
    $D_{n,0\rightarrow k} = R_{0,k,n} Q^0_k$
    $D_{n,0} = \max_j \{ D_{n,0\rightarrow j} \}, \quad j \in \mathcal{K} \cup \mathcal{M}$
    $\kappa_{n,0} = \text{arg max}_j \{ D_{n,0\rightarrow j} \}$
end for

$\% D = [D_{n,m}]$ is the demand matrix.
$(\hat{n}, \hat{m}) \leftarrow \text{Hungarian}(D)$ $\%$ Vectors of indices
$\mathcal{U} = \mathcal{U} - \{ \hat{n}, \hat{m} \}, N_{\text{assigned}} = |\hat{n}| = |\hat{m}|$
$\% N_{\text{assigned}} \leq \min\{ M + 1, |\mathcal{U}| \}$

for $i = 1$ to $N_{\text{assigned}}$
    $\hat{n} = \hat{n}(i), \hat{m} = \hat{m}(i), \hat{r} = \kappa_{\hat{n},\hat{m}}$
    if $\hat{r} \in \mathcal{M}$ then
        $k = \kappa_{\hat{r},\hat{m}}$
        $Q^0_k = (Q^0_k - [R_{0,k,\hat{n}} T]^+)$
    else
        $Q^0_{\hat{r}} = (Q^0_{\hat{r}} - [R_{\hat{n},k,\hat{m}} T]^+)$
    end if
end for
end while
The brute-force solution of the optimal BILP is NP-hard $O((K(M+1))^N)$.

The complexity estimate for the proposed iterative algorithm is polynomial in time.

Unlike the majority of formulations, the computational complexity decreases as the number of nodes increases, for moderate number of UTs.
## Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS-BS distance</td>
<td>1 Km</td>
</tr>
<tr>
<td>RS distance from BS</td>
<td>0.65 x cell radius</td>
</tr>
<tr>
<td>User min. close-in distance to BS</td>
<td>35 m</td>
</tr>
<tr>
<td>BS Tx. antenna gain</td>
<td>15 dB</td>
</tr>
<tr>
<td>RS Tx. antenna gain</td>
<td>10 dB</td>
</tr>
<tr>
<td>RS Rx. antenna $\theta_{3\text{dB}}$</td>
<td>20 deg</td>
</tr>
<tr>
<td>UT Rx. antenna gain</td>
<td>0 dB</td>
</tr>
<tr>
<td>Shadowing st. dev. on user and interference links</td>
<td>8.9 dB</td>
</tr>
<tr>
<td>Shadowing st. dev. on BS-RS links</td>
<td>4 dB</td>
</tr>
<tr>
<td>Rician K-factor for BS-RS links</td>
<td>10 dB</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>2.5 GHz</td>
</tr>
<tr>
<td>User mobility</td>
<td>20 Km/hr (0-90)</td>
</tr>
<tr>
<td>BS-RS links max. Doppler spread</td>
<td>4 Hz</td>
</tr>
<tr>
<td>Power delay profile taps LOS (WINNER C2)</td>
<td>8 taps</td>
</tr>
<tr>
<td>Power delay profile taps NLOS (WiMax Forum)</td>
<td>6 taps</td>
</tr>
</tbody>
</table>
Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel sampling time = TDD frame length</td>
<td>2 msec</td>
</tr>
<tr>
<td>Downlink : Uplink ratio</td>
<td>2:1</td>
</tr>
<tr>
<td>DL Tx. time in OFDM data symbols</td>
<td>11 symbols</td>
</tr>
<tr>
<td>OFDM subcarrier bandwidth</td>
<td>10.9375 KHz</td>
</tr>
<tr>
<td>OFDM symbol duration</td>
<td>102.86 usec</td>
</tr>
<tr>
<td>Subchannel width</td>
<td>18 subcarriers</td>
</tr>
<tr>
<td>Total bandwidth</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Number of subchannels</td>
<td>102</td>
</tr>
<tr>
<td>CR-QAM target BER</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Noise power density at Rx. nodes</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>BS total Tx. power</td>
<td>46 dBm</td>
</tr>
<tr>
<td>RS total Tx. power</td>
<td>37 dBm</td>
</tr>
</tbody>
</table>
Simulation Results: User throughput

Time-average user throughput in Mbps vs. user distance with 15 UTs/cell

- Scatter Algo. 6 RSs
- Algorithm 6 RSs
- Algorithm (no RSs)
- Scatter Max-SINR (no RSs)
- Max-SINR (no RSs)

Relay Location
Simulation Results: User throughput with 15 UTs/cell
Simulation Results: CDF of time-average user throughput in Mbps with 25 UTs/cell
Simulation Results: Average total cell throughput

Average total cell throughput at 632 packets/sec average arrival rate

- Algorithm 6 relays
- Algorithm 3 relays
- Algorithm (no relays)
- Max-SINR (no Relays)
Simulation Results: Open routing vs. constrained routing (a proof of concept)
Simulation Results: Open routing vs. constrained routing (lower tail)
Simulation Results: User fairness

CDF of the IEEE 802.16m fairness index with 20 UTs/cell

\[ F_i(t) = \frac{r_i(t)}{\frac{1}{K} \sum_{j=1}^{K} r_j(t)} \]
Simulation Results: User fairness

CDF of instantaneous Jain's fairness index with 15 UTs/cell, Window=1 frame

\[ x(t) = \frac{\left( \sum_{i=1}^{K} r_i(t) \right)^2}{K \sum_{i=1}^{K} r_i^2(t)} \]
Simulation Results: User fairness

CDF of long-term Jain's fairness index, Window =20 frames with 30 UTs/cell

\[ x(t) = \left( \frac{\sum_{i=1}^{K} r_i(t)}{K \sum_{i=1}^{K} r_i^2(t)} \right)^2 \]
Simulation Results: Load balancing

Load Balancing Normalized Histogram
N=100 Subchannels, M=4 Relays

Number of subchannels assigned to the node
Conclusion

- A novel fairness-aware joint routing and scheduling algorithm is proposed for OFDMA-based cellular relay networks.

- The algorithm ensures short- as well as long-term fairness among users, including cell-edge users.

- The fairness is achieved with minimal impact on the overall network throughput.

- The algorithm exploits the opportunities in OFDM sub-carriers, channel dynamism, and queue and traffic diversities.

- Simulation results prove the learning ability and the efficiency of the routing strategy which dynamically converges to better routes, even under the challenging uniform relay deployment examined.

- The inherent load-balancing feature works independently from the traffic load at adjacent BSs and results as well in spatial spreading of the co-channel interference across the network.