Performance Evaluation of Relay Deployment Strategies in Multi-Cell Single Frequency Networks

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Renaud-Alexandre Pitaval\textsuperscript{1,2}, Taneli Riihonen\textsuperscript{2}, Risto Wichman\textsuperscript{2}, and Steven Blostein\textsuperscript{1}

\textsuperscript{1}Department of Electrical and Computer Engineering
Queen’s University, Canada

\textsuperscript{2}Department of Signal Processing and Acoustics
Aalto University School of Science and Technology, Finland
Contents of the Presentation

**Goal:** to investigate the impact of fixed relay station deployment in a single frequency network (SFN) using orthogonal frequency-division multiplexing (OFDM)

**Agenda:**
- Context
- System model, OFDM, performance measures
- SFN with relays:
  - Performance with full-duplex (FD) mode
  - Impact of the relay gains
  - Performance with half-duplex (HD) mode
  - HD versus FD
  - Impact of relay topology
  - Performance at the SFN area borders
- Conclusions
Context

• Single frequency network, e.g., MBMS or DVB-T/H
  – Large time dispersion phenomenon

• OFDM
  – Robustness against ISI/ICI

• Deployment of fixed relay stations
  – Increases received signal power
  – But further increases the overall time dispersion in the network

• Relaying methods
  – AF, fixed gain / variable gain
  – Full duplex / Half duplex
OFDM

- OFDM block \(i\) for \(-\nu \leq m \leq N-1\)
  \[ s_i[m] = \frac{1}{\sqrt{N}} \sum_{l=0}^{N-1} x_{i,l}e^{j2\pi lm/N} \]

- Demodulation via DFT at the receiver

- For block ‘0’ at the \(n\)th subcarrier
  \[ y[n] = x_{0,n}H_{n,n,0} + \sum_{l=0}^{N-1} x_{0,l}H_{l,n,0} + \sum_{i=-\infty}^{+\infty} \sum_{l=0}^{N-1} x_{i,l}H_{l,n,i} + \bar{n}[n] \]

\( ICI \) and \( ISI \)
OFDM: a performance measure

- “Average SINR”: the ratio of average useful power to average interference plus noise power

\[
\Gamma = \frac{\mathcal{E}[S(n)]}{\mathcal{E}[I(n)] + N_0/\sigma_x^2}
\]

- For time-flat multipath channel: \( h(\tau) = \sum_i h_i \delta(\tau - \tau_i) \)
  \( E_i = \mathcal{E}[|h_i|^2] \)

- Average SINR (Steendam and Moeneclaey)

\[
\Gamma = \frac{P_S}{P_I + N_0/\sigma_x^2}
\]

\[
\begin{align*}
P_S &= \mathcal{E}[S[n]] = \sum_i c[i]^2 E_i \\
P_I &= \mathcal{E}[I[n]] = \sum_i (1 - c[i]^2) E_i.
\end{align*}
\]

- Can be used to approximate the ergodic capacity: \( C \approx N \log(1 + \Gamma) \)
# Simulator description

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network</td>
<td>5 tiers tri-sector cell</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Center frequency</td>
<td>2 GHz</td>
</tr>
<tr>
<td>No. of subcarriers</td>
<td>1024</td>
</tr>
<tr>
<td>No. of occupied subcarriers</td>
<td>601</td>
</tr>
<tr>
<td>Cell synchronization</td>
<td>20μs</td>
</tr>
<tr>
<td>CP</td>
<td>16.67μs</td>
</tr>
<tr>
<td>Relay processing delay</td>
<td>0.5μs</td>
</tr>
<tr>
<td>ISI and ICI modeling</td>
<td>According to [15]</td>
</tr>
<tr>
<td>Beam Tx power</td>
<td>40 Watts / 46 dBm</td>
</tr>
<tr>
<td>Relay Tx power</td>
<td>5 Watts / 37 dBm</td>
</tr>
<tr>
<td>Antenna gain BS</td>
<td>14 dBi</td>
</tr>
<tr>
<td>Antenna gain RS</td>
<td>12 dBi (in total for Rx and Tx)</td>
</tr>
<tr>
<td>Antenna pattern BS</td>
<td>3 sectors</td>
</tr>
<tr>
<td></td>
<td>$A(\theta) = \min \left[ 12 \left( \frac{\theta}{\theta_{3dB}} \right)^2, A_m \right]$, $\theta_{3dB} = 70^\circ$, $A_m = 20dB$</td>
</tr>
<tr>
<td>Antenna pattern RS</td>
<td>omnidirectional</td>
</tr>
<tr>
<td>Noise figure</td>
<td>9 dB</td>
</tr>
<tr>
<td>Thermal noise</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>Pathloss BS-MS link and RS-MS link (NLOS, SCM macro)</td>
<td>$PL(dB) = (44.9 - 6.55 \log_{10} h_{bs}) \log_{10}(d[km]) + (35.46 - 1.1h_{ms}) \log_{10}(f_c[MHz]) + 13.82 \log_{10}(h_{bs}) + 0.7h_{ms} + 48.5$</td>
</tr>
<tr>
<td>Pathloss BS-RS link (LOS,IEEE 802.16 type C)</td>
<td>$PL(dB) = -35.4 + 26 \log_{10}(d[m]) + 20 \log_{10}(f_c[MHz])$</td>
</tr>
<tr>
<td>Heights $h_{bs}, h_{rs}, h_{ms}$</td>
<td>32, 12, 1.5 meters</td>
</tr>
<tr>
<td>Shadowing standard deviation</td>
<td>8 dB for BS-MS and RS-MS link</td>
</tr>
<tr>
<td></td>
<td>4 dB for BS-RS link</td>
</tr>
<tr>
<td>Channel model</td>
<td>BS-MS and RN-MS link</td>
</tr>
<tr>
<td></td>
<td>6 taps TU channel model</td>
</tr>
<tr>
<td></td>
<td>flat Rayleigh channel</td>
</tr>
</tbody>
</table>
Amplify and forward relay channel

- Relay gain
  - Fixed gain
  - Variable gain

- Full-duplex (FD) or half-duplex (HD) transmission mode

\[ \beta^{FG} = \sqrt{\frac{\sigma_{rn}^2}{\sigma_{bs}^2 E_{SR} + N_0}} \]

\[ \beta^{VG} = \sqrt{\frac{\sigma_{rn}^2}{\sigma_{bs}^2 | h_{SR} |^2 + N_0}} \]
Performance with full-duplex mode

- Received signal:  
  \[ r_{FD}[k] = h_{eq} * s[k] + n_{eq}[k] \]
  where 
  \[ h_{eq} = h_{SD} + h_{SRD} \]
  \[ n_{eq} = \beta h_{RD} * n_1 + n_2 \]

- Average SINR

\[ \Gamma_{FD} = \frac{P_{SFD}}{P_{LFD} + P_{NFD}/\sigma_x^2} \]

\[ P_{SFD} = \sum_i c[i]^2 E_i^{eq} \]

\[ P_{LFD} = \sum_i (1 - c[i]^2) E_i^{eq} \]

\[ P_{NFD} = (\mathcal{E} [\beta^2] E_{RD} + 1) N_0 \]

- depends on the channel distribution with variable gain

with

\[ E_i^{eq} = E_i^{sd} + \mathcal{E} \left[ |\beta h_{SR}|^2 \right] E_i^{rd} \]
Performance with full-duplex mode

• Fixed gain

\[ \mathcal{E} [ | \beta_{FG} h_{SR} |^2 ] = \frac{\sigma_{rn}^2 E_{SR}}{\sigma_{bs}^2 E_{SR} + N_0} \]

\[ \mathcal{E} [ | \beta_{FG} |^2 ] = \frac{\sigma_{rn}^2}{\sigma_{bs}^2 E_{SR} + N_0} \]

• Variable gain with Nakagami fading

\[ \mathcal{E} [ | \beta_{VG} h_{SR} |^2 ] = \frac{\sigma_{rn}^2 m}{\sigma_{bs}^2} e^{\frac{mN_0}{E_{SR}\sigma_{bs}^2}} \mathbb{E}_{m+1} \left( \frac{mN_0}{E_{SR}\sigma_{bs}^2} \right) \]

\[ \mathcal{E} [ | \beta_{VG} |^2 ] = \frac{\sigma_{rn}^2 m}{E_{SR}\sigma_{bs}^2} e^{\frac{mN_0}{E_{SR}\sigma_{bs}^2}} \mathbb{E}_m \left( \frac{mN_0}{E_{SR}\sigma_{bs}^2} \right) \]
Impact of the relay gains

- For a Rayleigh channel \((m=1)\), since \(\frac{1}{x+1} < e^x E_1(x)\) and the average transmit power is constant, we have

  Noise amplification
  \[ E\{(|\beta^{FG}|^2) < E\{(|\beta^{VG}|^2) \] 

  Signal and interference amplification
  \[ E\{(|\beta^{VG}h_{SR}|^2) < E\{(|\beta^{FG}h_{SR}|^2) \] 

- Simulations indicate similar performance
Performance with half-duplex mode

- Two diversity branches:

\[
y_{SD}[n] = x_{0,n} \mathcal{H}_{n,n,0}^{sd} + \sum_{l=0}^{N-1} x_{0,l} \mathcal{H}_{l,n,0}^{sd} + \sum_{i=-\infty}^{+\infty} \sum_{l=0}^{N-1} x_{i,l} \mathcal{H}_{l,n,i}^{sd} + \tilde{n}_{SD}[n]
\]

\[
y_{SRD}[n] = x_{0,n} \mathcal{H}_{n,n,0}^{sr} + \sum_{l=0}^{N-1} x_{0,l} \mathcal{H}_{l,n,0}^{sr} + \sum_{i=-\infty}^{+\infty} \sum_{l=0}^{N-1} x_{i,l} \mathcal{H}_{l,n,i}^{sr} + \tilde{n}_{SRD}[n]
\]

- Selection combining
  - Select the signal with the best instantaneous SINR
  - Lower bound on the average SINR

\[
\Gamma_{HD-SC} \geq \max(\Gamma_{SD}, \Gamma_{SRD})
\]
Performance with half-duplex mode

• Equal gain combining:
  The receiver sums up the two signals after co-phasing

\[ y_{HD-EGC}[n] = e^{-j\theta_{sd}}y_{SD}[n] + e^{-j\theta_{sr}}y_{SRD}[n] \]

  - Average SINR

\[ \Gamma_{HD-EGC} = \frac{P_{SHD-EGC}}{P_{IHDF-EGC} + P_{NHDF-EGC}/\sigma_x^2} \]

with

\[ P_{SHD-EGC} = \sum_i c[i]^2 E_i^{eq} + 2E[|h_{n,n,0}|]E[|h_{n,n,0}|] \]

\[ P_{IHDF-EGC} = \sum_i (1 - c[i]^2)E_i^{eq} \]

\[ P_{NHDF-EGC} = (E[|\beta|^2]E_{RD} + 2)N_0. \]

Useful power with fixed gain

\[ P_{SHDF-ECC} = \sum_i c[i]^2 E_i^{eq} + 2\left(\frac{\pi}{4}\right)^{3/2}\sqrt{\sum_i c[i]^2 E_i^{sd}}\sqrt{\sum_i c[i]^2 E_i^{sr}} \]
HD versus FD

• To overcome FD, HD should improve the SINR sufficiently to compensate for the loss of 1/2 in the transmission rate:

\[ C_{FD} \approx \log_2(1 + \Gamma_{FD}), \quad C_{HD} \approx \frac{1}{2} \log_2(1 + \Gamma_{HD}) \]

• High SINR

\[ C_{FD} \approx \log_2(\Gamma_{FD}) \approx \frac{\ln 10}{10 \ln 2} \Gamma_{FD}[\text{dB}] \]
\[ C_{HD} \approx \frac{1}{2} \log_2(\Gamma_{HD}) \approx \frac{1}{2} \frac{\ln 10}{10 \ln 2} \Gamma_{HD}[\text{dB}] \]

The same performance if:

\[ \Gamma_{HD}[\text{dB}] = 2\Gamma_{FD}[\text{dB}] \]

• Low SINR

\[ C_{FD} \approx \log_2(1 + \Gamma_{FD}) \approx \frac{1}{\ln 2} \Gamma_{FD} \]
\[ C_{HD} \approx \frac{1}{2} \log_2(1 + \Gamma_{HD}) \approx \frac{1}{2} \frac{1}{\ln 2} \Gamma_{HD} \]

The same performance if:

\[ \Gamma_{HD}[\text{dB}] = \Gamma_{FD}[\text{dB}] + 3\text{dB} \]
HD versus FD

• In our scenario FD outperforms HD
Impact of relay topology

(c) 6 relays per cell

(d) 6 relays per cell

(e) 8 relays per cell

(f) 9 relays per cell

(g) 12 relays per cell

(h) 15 relays per cell

Fix Gain – FD –ISD, 2km

- No Relay
- Scenario (a) – 3 RNs per cell
- Scenario (b) – 3 RNs per cell
- Scenario (c) – 6 RNs per cell
- Scenario (d) – 6 RNs per cell
- Scenario (e) – 8 RNs per cell
- Scenario (f) – 9 RNs per cell
- Scenario (g) – 12 RNs per cell
- Scenario (h) – 15 RNs per cell

CDF vs. SINR[dB]
Impact of relay topology
Performance at the SFN area borders

- Higher performance improvement at the edge of the network than at its center
Conclusions

• Evaluation of some classical relaying methods in a broadcast network using OFDM

• Variable and fixed gain give similar performance

• FD better than HD (but loop interference should be fully cancelled)

• Regular SINR increase with the number of relays in the central cell

• A roughly equidistant relay repartitions give better performance

• Relay deployment increases particularly the performance at the border of two SFNs