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

WCNC 2010, Sydney, Australia

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Contents of the Presentation

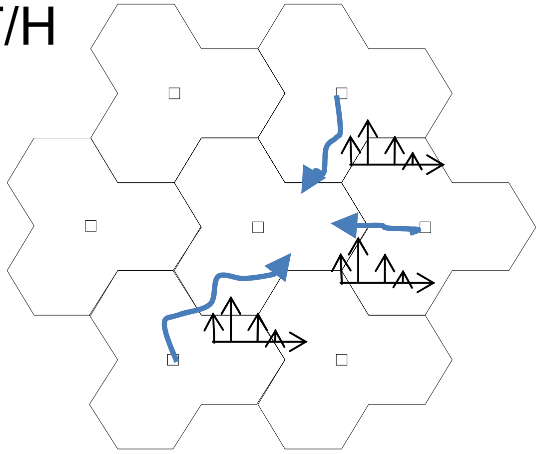
Goal: to investigate the impact of fixed relay station deployment in a single frequency network (SFN) using orthogonal frequency-division multiplexing (OFDM)

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

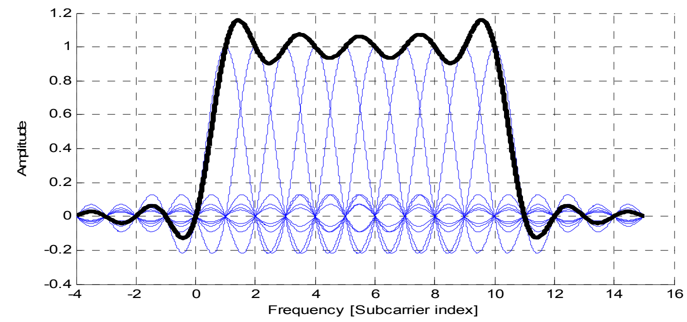


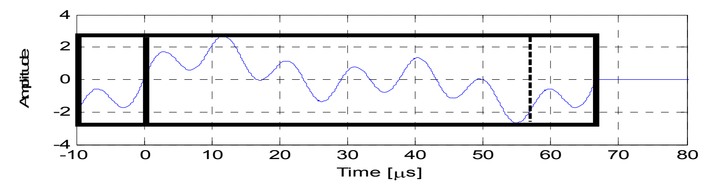
- OFDM
  - Robustness against ISI/ICI

- 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

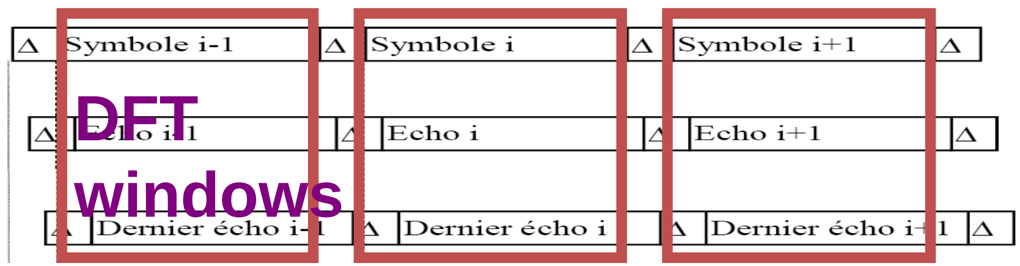




- OFDM block #*i* for $-\nu \leq m \leq N-1$

$$s_i[m] = \frac{1}{\sqrt{N}} \sum_{l=0}^{N-1} x_{i,l} e^{j2\pi \frac{lm}{N}}$$

- Demodulation via DFT at the receiver



- For block '0' at the *n*th subcarrier

$$y[n] = x_{0,n}\mathcal{H}_{n,n,0} + \underbrace{\sum_{\substack{l=0\\l\neq n}}^{N-1} x_{0,l}\mathcal{H}_{l,n,0}}_{ICI} + \underbrace{\sum_{\substack{i=-\infty\\i\neq 0}}^{+\infty} \sum_{l=0}^{N-1} x_{i,l}\mathcal{H}_{l,n,i}}_{ISI} + \tilde{n}[n]$$

OFDM: a performance measure

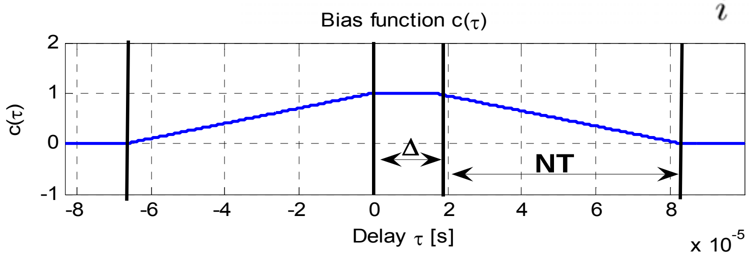
- "Average SINR": the ratio of average useful power to average interference plus noise power

Independent of the subcarrier index if all the subcarriers are modulated

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

- For time-flat multipath channel: $h(\tau) = \sum_i h_i \delta(\tau - \tau_i) \quad E_i = \mathcal{E}\left[|h_i|^2\right]$
- Average SINR (Steendam and Moeneclaey)

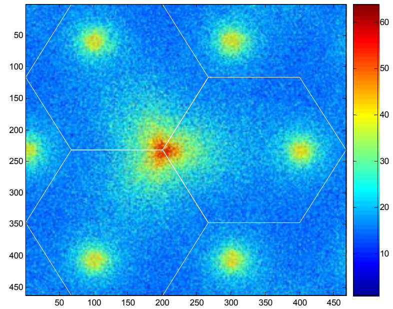
$$\Gamma = \frac{P_{\mathcal{S}}}{P_{\mathcal{I}} + N_0/\sigma_x^2} \quad \left\{ \begin{aligned} P_{\mathcal{S}} &= \mathcal{E}\left[\mathcal{S}[n]\right] = \sum_i c[i]^2 E_i \\ P_{\mathcal{I}} &= \mathcal{E}\left[\mathcal{I}[n]\right] = \sum_i (1 - c[i]^2) E_i . \end{aligned} \right.$$

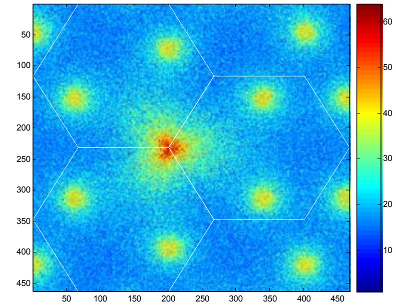


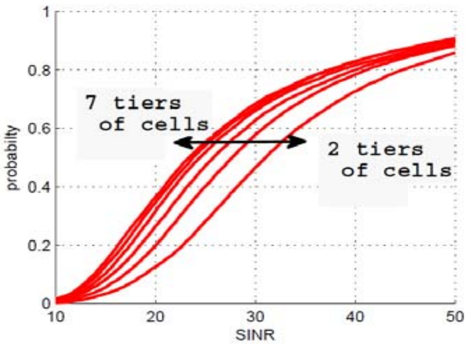
- Can be used to approximate the ergodic capacity: $\mathcal{C} \lessapprox N \log(1 + \Gamma)$

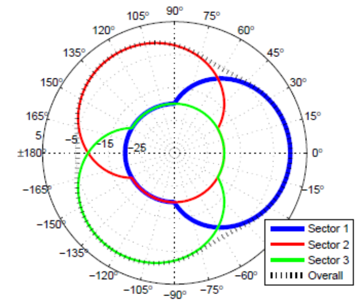
Simulator description

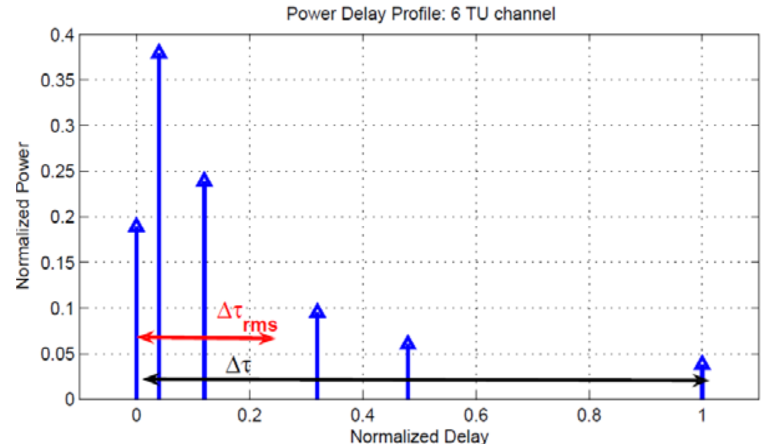
Parameter	Assumption
Network	5 tiers tri-sector cell
Bandwidth	10 MHz
Center frequency	2 GHz
No. of subcarriers	1024
No. of occupied subcarriers	601
Cell synchronization	$20\mu s$
CP	$16.67\mu s$
Relay processing delay	$0.5\mu s$
ISI and ICI modeling	According to [15]
Beam Tx power Relay Tx power	40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



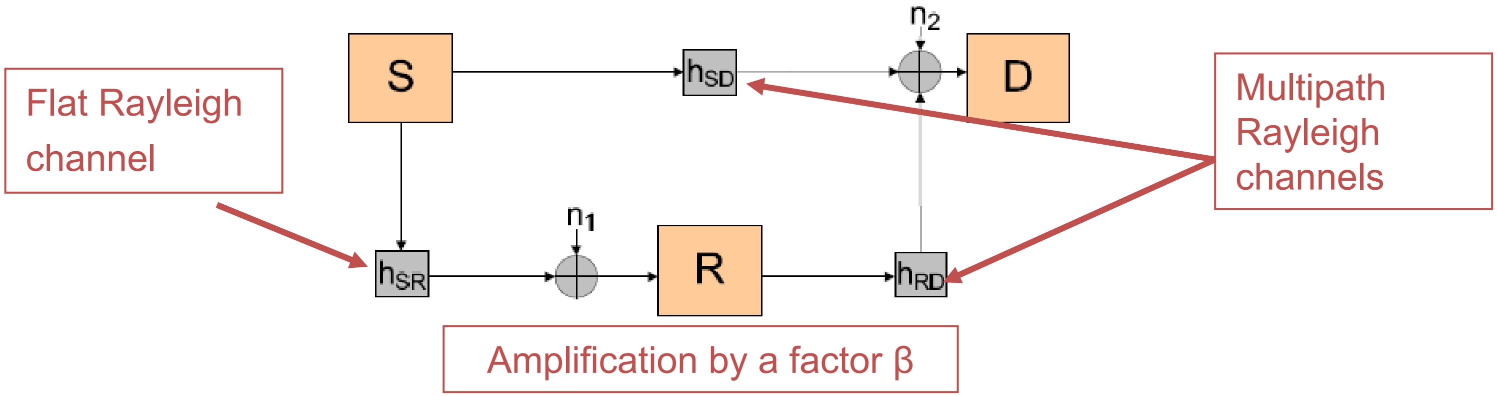








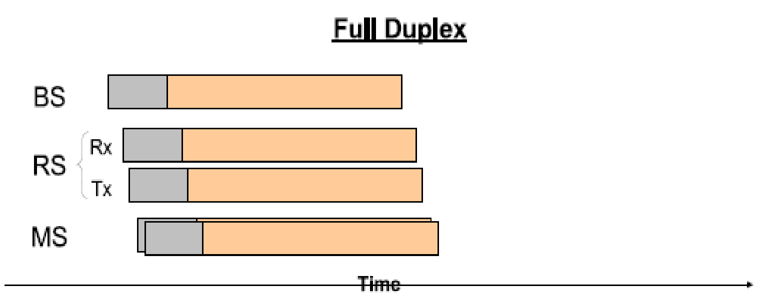
Amplify and forward relay channel

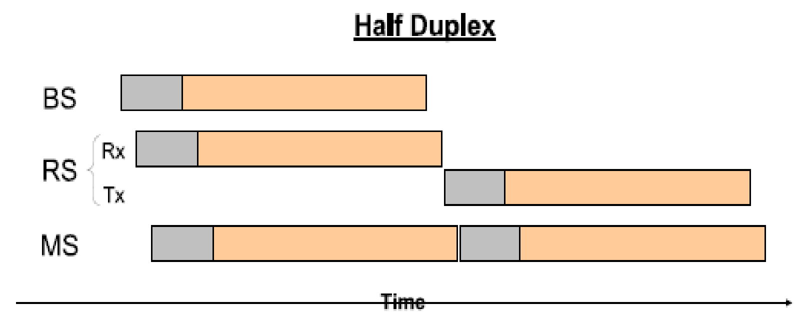


- Relay gain
  - Fixed gain
  - Variable gain

$$\beta^{FG} = \sqrt{\frac{\sigma_{rn}^2}{\sigma_{bs}^2 E_{SR} + N_0}} \qquad \beta^{VG} = \sqrt{\frac{\sigma_{rn}^2}{\sigma_{bs}^2 \mid h_{SR} \mid^2 + N_0}}$$

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





Performance with full-duplex mode

- Received signal: $$r_{FD}[k] = h_{eq} * s[k] + n_{eq}[k]$$

  where $$h_{eq} = h_{SD} + h_{SRD} \qquad n_{eq} = \beta h_{RD} * n_1 + n_2$$

- Average SINR

$$\Gamma_{FD} = \frac{P_{\mathcal{S}_{FD}}}{P_{\mathcal{I}_{FD}} + P_{\mathcal{N}_{FD}}/\sigma_x^2} \qquad \begin{cases} P_{\mathcal{S}_{FD}} = \sum_i c[i]^2 E_i^{eq} \\ P_{\mathcal{I}_{FD}} = \sum_i (1 - c[i]^2) E_i^{eq} \\ P_{\mathcal{N}_{FD}} = \left(\mathcal{E}\left[|\beta|^2\right] E_{RD} + 1\right) N_0 \end{cases}$$

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

$$\mathcal{E}\left[\mid \beta^{FG} h_{SR} \mid^2\right] = \frac{\sigma_{rn}^2 E_{SR}}{\sigma_{bs}^2 E_{SR} + N_0} \qquad \mathcal{E}\left[\mid \beta^{FG} \mid^2\right] = \frac{\sigma_{rn}^2}{\sigma_{bs}^2 E_{SR} + N_0}$$

- Variable gain with Nakagami fading

$$\mathcal{E}\left[\mid \beta^{VG} h_{SR} \mid^2\right] = \frac{\sigma_{rn}^2 m}{\sigma_{bs}^2} \, e^{\frac{mN_0}{E_{SR}\sigma_{bs}^2}} \, \mathrm{E}_{m+1}\left(\frac{m\,N_0}{E_{SR}\sigma_{bs}^2}\right)$$

$$\mathcal{E}\left[\mid \beta^{VG} \mid^2\right] = \frac{\sigma_{rn}^2 m}{E_{SR}\sigma_{bs}^2} \, e^{\frac{mN_0}{E_{SR}\sigma_{bs}^2}} \, \mathrm{E}_{m}\left(\frac{m\,N_0}{E_{SR}\sigma_{bs}^2}\right)$$

Impact of the relay gains

- For a Rayleigh channel (m=1), since $\frac{1}{x+1} < e^{x}\,\mathrm{E}_1(x)$ and the average transmit power is constant, we have

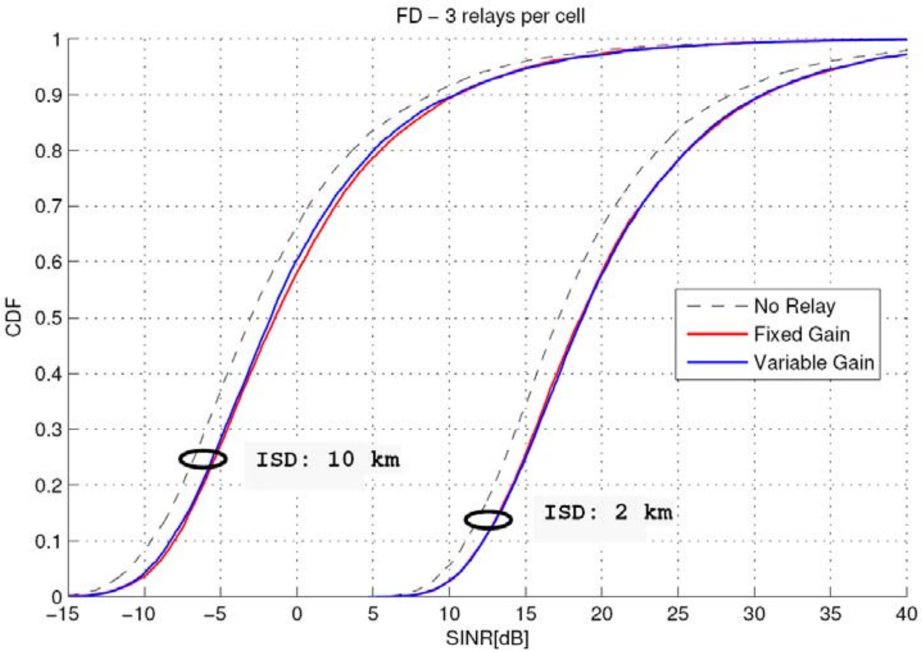
Noise amplification

$$\mathcal{E}\{|\beta^{FG}|^2\} < \mathcal{E}\{|\beta^{VG}|^2\}$$

Signal and interference amplification

$$\mathcal{E}\{|\beta^{VG}h_{SR}|^2\} < \mathcal{E}\{|\beta^{FG}h_{SR}|^2\}$$

- Simulations indicate similar performance



Performance with half-duplex mode

- Two diversity branches:

$$
\begin{aligned}
y_{SD}[n] &= x_{0,n}\mathcal{H}^{sd}_{n,n,0} + \sum_{\substack{l=0\\l\neq n}}^{N-1} x_{0,l}\mathcal{H}^{sd}_{l,n,0} + \sum_{\substack{i=-\infty\\i\neq 0}}^{+\infty}\sum_{l=0}^{N-1} x_{i,l}\mathcal{H}^{sd}_{l,n,i} + \tilde{n}_{SD}[n] \\
y_{SRD}[n] &= x_{0,n}\mathcal{H}^{srd}_{n,n,0} + \sum_{\substack{l=0\\l\neq n}}^{N-1} x_{0,l}\mathcal{H}^{srd}_{l,n,0} + \sum_{\substack{i=-\infty\\i\neq 0}}^{+\infty}\sum_{l=0}^{N-1} x_{i,l}\mathcal{H}^{srd}_{l,n,i} + \tilde{n}_{SRD}[n]
\end{aligned}
$$

- 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

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

– Average SINR

$$\Gamma_{HD-EGC} = \frac{P_{\mathcal{S}_{HD-EGC}}}{P_{\mathcal{I}_{HD-EGC}} + P_{\mathcal{N}_{HD-EGC}}/\sigma_x^2}$$

with

$$\begin{aligned} P_{\mathcal{S}_{HD-EGC}} &= \sum_i c[i]^2 E_i^{eq} + 2\mathcal{E}\left[|\mathcal{H}_{n,n,0}^{sd}|\right]\mathcal{E}\left[|\mathcal{H}_{n,n,0}^{srd}|\right] \\ P_{\mathcal{I}_{HD-EGC}} &= \sum_i (1 - c[i]^2) E_i^{eq} \\ P_{\mathcal{N}_{HD-EGC}} &= \left(\mathcal{E}\left[|\beta|^2\right] E_{RD} + 2\right) N_0. \end{aligned}$$

Differences to FD

Useful power with fixed gain

$$P_{\mathcal{S}_{HD-EGC}} = \sum_i c[i]^2 E_i^{eq} + 2\left(\frac{\pi}{4}\right)^{3/2} \sqrt{\sum_i c[i]^2 E_i^{sd}} \sqrt{\sum_i c[i]^2 E_i^{srd}}$$

HD versus FD

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

$$\mathcal{C}_{FD} \lessapprox \log_2(1+\Gamma_{FD}), \quad \mathcal{C}_{HD} \lessapprox \frac{1}{2}\log_2(1+\Gamma_{HD})$$

- High SINR

$$\left.\begin{aligned} \mathcal{C}_{FD} &\lessapprox \log_2(\Gamma_{FD}) \approx \frac{\ln 10}{10\ln 2}\Gamma_{FD}[\text{dB}] \\ \mathcal{C}_{HD} &\lessapprox \frac{1}{2}\log_2(\Gamma_{HD}) \approx \frac{1}{2}\frac{\ln 10}{10\ln 2}\Gamma_{HD}[\text{dB}] \end{aligned}\right\}$$

The same performance if:

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

- Low SINR

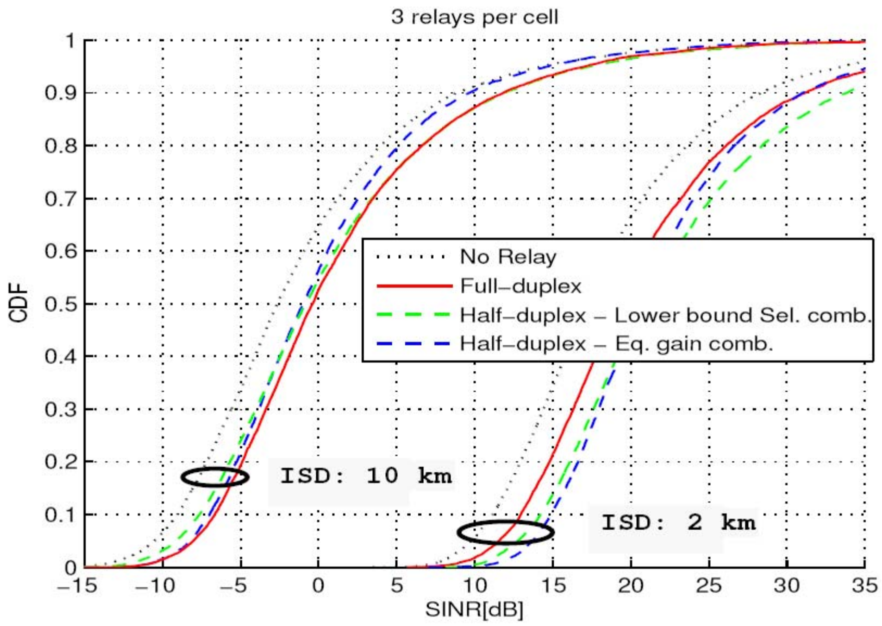
$$\left.\begin{aligned} \mathcal{C}_{FD} &\lessapprox \log_2(1+\Gamma_{FD}) \approx \frac{1}{\ln 2}\Gamma_{FD} \\ \mathcal{C}_{HD} &\lessapprox \frac{1}{2}\log_2(1+\Gamma_{HD}) \approx \frac{1}{2}\frac{1}{\ln 2}\Gamma_{HD} \end{aligned}\right\}$$

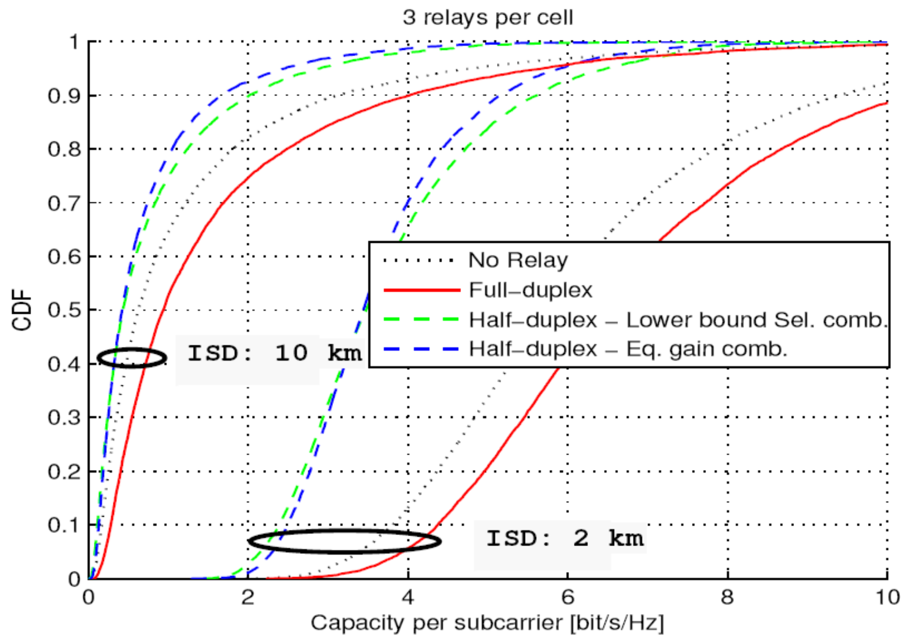
The same performance if:

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

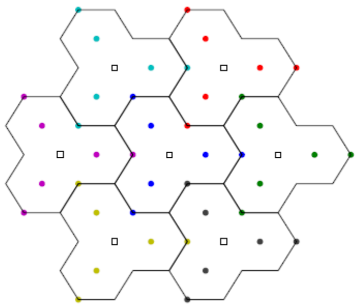
HD versus FD

- In our scenario FD outperforms HD

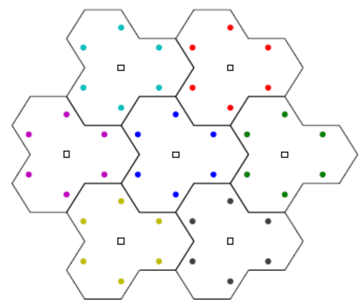




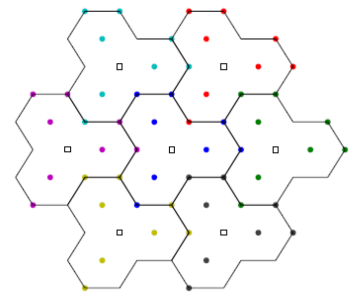
Impact of relay topology



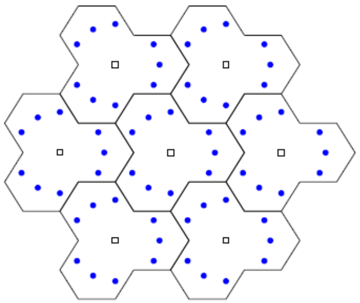
(c) 6 relays per cell



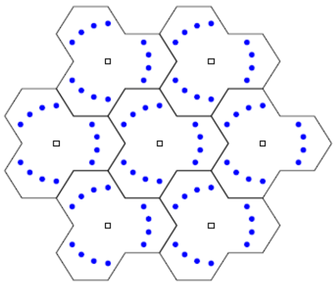
(d) 6 relays per cell



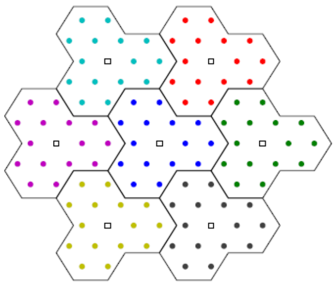
(e) 8 relays per cell



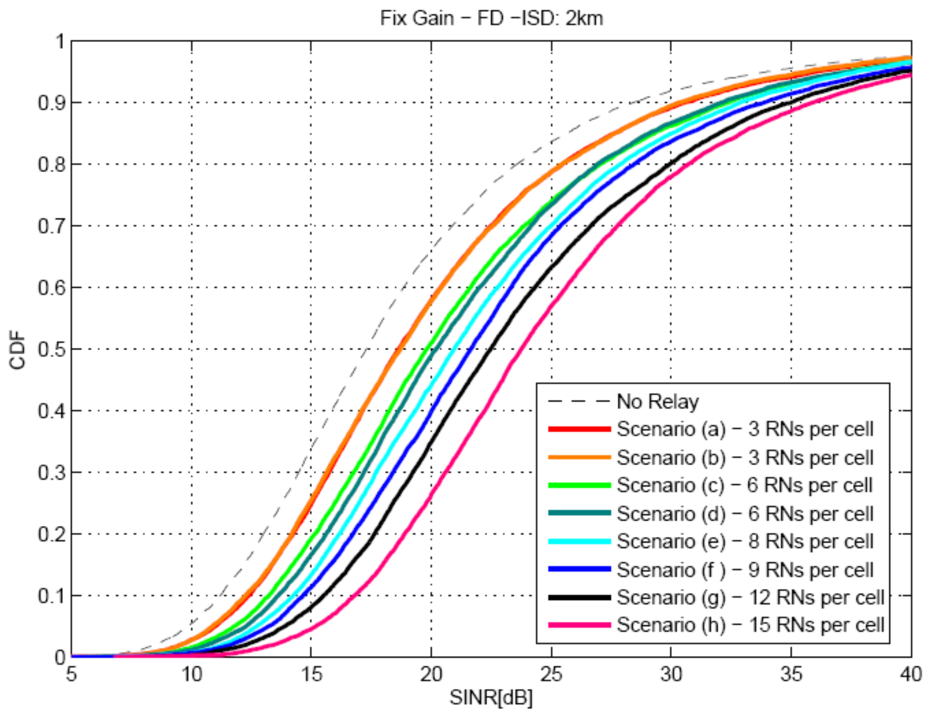
(f) 9 relays per cell



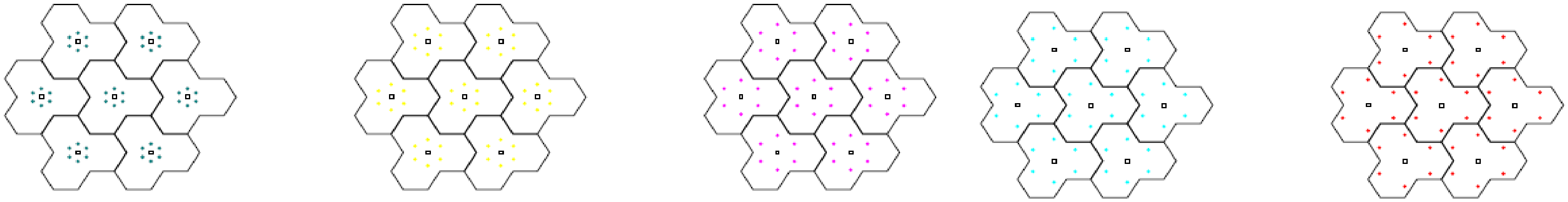
(g) 12 relays per cell

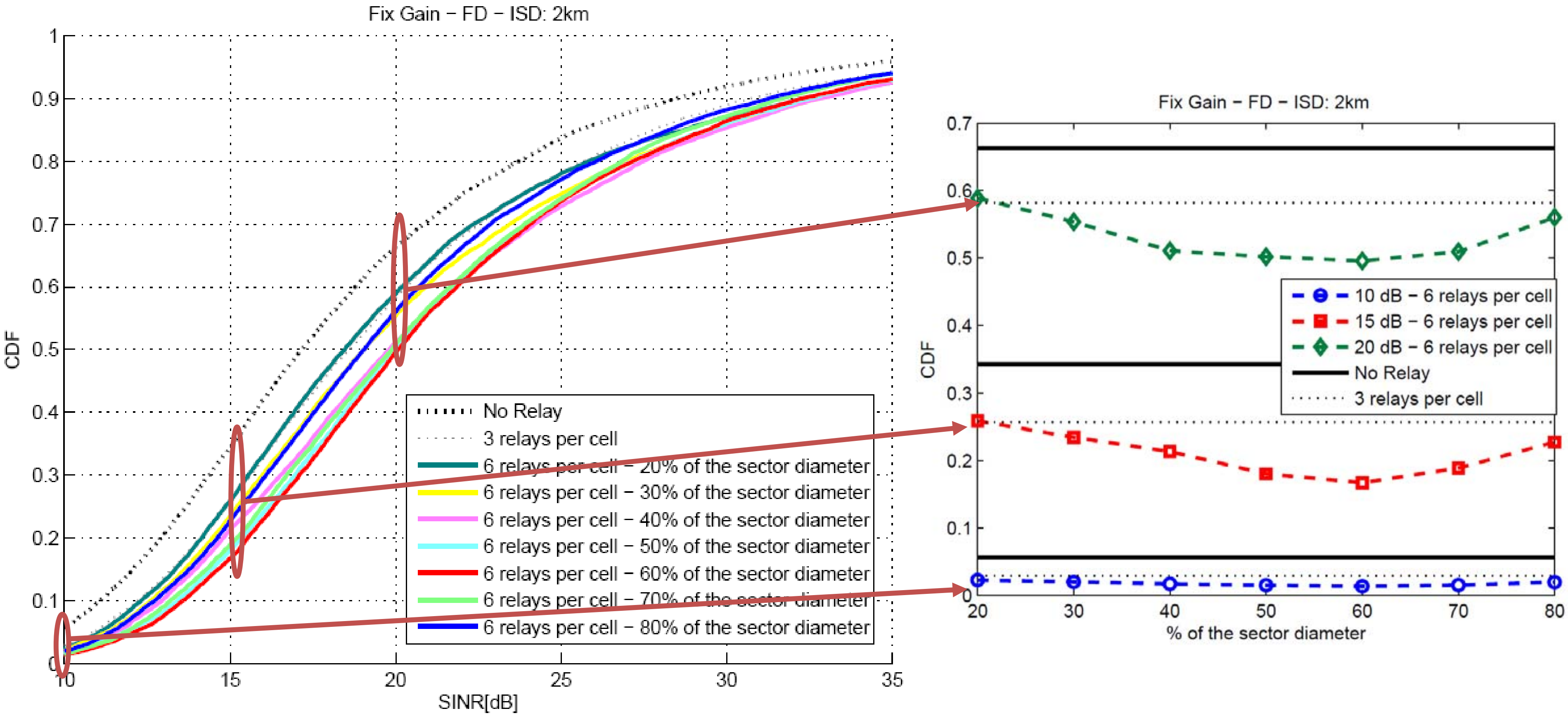


(h) 15 relays per cell



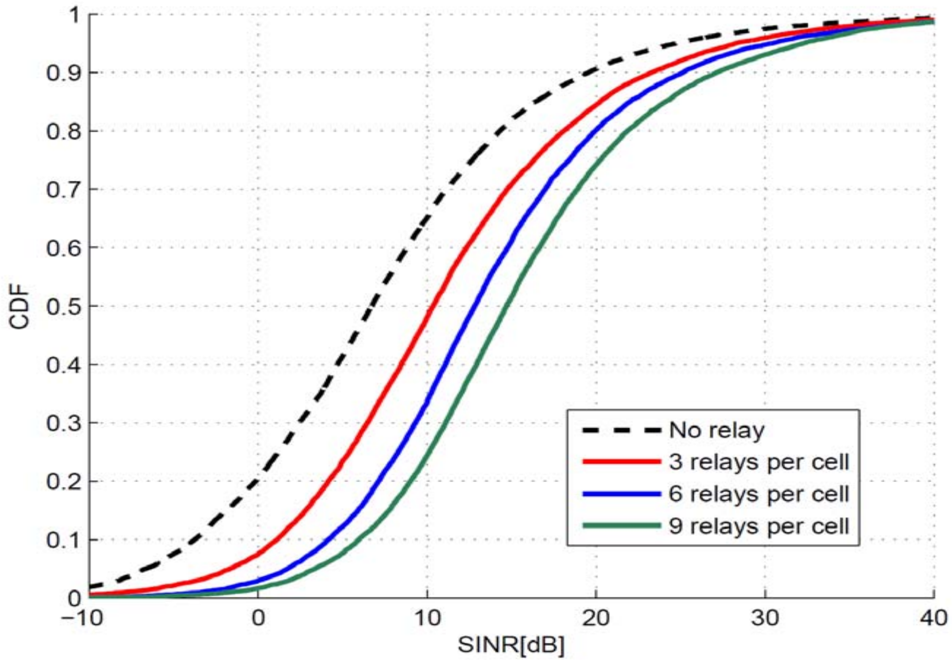
Impact of relay topology





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