Capacity Evaluation of DF Protocols for OFDMA Infrastructure Relay Links

Taneli Riihonen*, Risto Wichman, and Stefan Werner
Helsinki University of Technology, Finland

* This work was partially funded by The Finnish Foundation for Economic and Technology Sciences — KAUTE

IEEE GLOBECOM, Honolulu, Hawaii
December 02, 2009

HELSINKI UNIVERSITY OF TECHNOLOGY
SMARAD Centre of Excellence

Outline

HELSINKI UNIVERSITY OF TECHNOLOGY
SMARAD Centre of Excellence

Introduction

- High data rates require dense network infrastructure while cell sites contribute substantially to the system cost
  - Two-hop communication via a relay node
- IEEE 802.16j and 3GPP LTE-Advanced air interface spec. processes
  - Which functionalities and protocols should be included?
  - Should relays operate at the physical, link, or network layer?
- Usually increased complexity and cost gives better performance
  - But severe impact on adaptive modulation and coding, scheduling, packet segmentation, signaling, handovers, etc.
  - It would be beneficial to resort to as few changes as possible in the system specification
- Our contribution: evaluating the performance of various relay functionalities under a unified analytical framework

HELSINKI UNIVERSITY OF TECHNOLOGY
SMARAD Centre of Excellence

OFDMA relay link

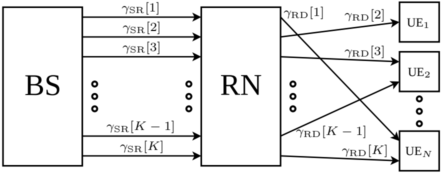


Fig. 1. Two-hop OFDMA relay link. The γ variables denote the subcarrier signal-to-noise ratios.

- BS–RN hop: subcarrier SNRs $\gamma_{\mathrm{SR}}[k] = \bar{\gamma}_{\mathrm{SR}}[k]$, $\bar{\gamma}_{\mathrm{SR}} = \frac{1}{K}\sum_{k=1}^{K}\bar{\gamma}_{\mathrm{SR}}[k]$
  - Static frequency-selective channel, because BS and RN are stationary
- RN–UEs hop: subcarrier SNRs $\gamma_{\mathrm{RD}}[l]$, $f_{\gamma_{\mathrm{RD}}[l]}(x) = (1/\bar{\gamma}_{\mathrm{RD}})e^{-x/\bar{\gamma}_{\mathrm{RD}}}$
  - Mobile users (round robin scheduling) without line-of-sight
- Time sharing factor τ for the half-duplex time slots

Relay functionalities and protocols

- Decode-and-forward (DF) vs. amplify-and-forward (AF)[1]
  - Simplest analog physical-layer repeaters omitted here
- Subcarrier pairing vs. information redistribution (only with DF)
  - Fixed vs. optimized pairing
  - Or decoding and restructuring data frames at the relay
- Buffering to overcome deep temporal channel fades
  - Possible only with DF
- Optimization of time sharing between BS–RN and RN–UE hops
  - Possible only with DF
- Different combinations of the above are of particular interest

[1] AF results available in [8] Riihonen *et al.* WSA 2008

Fixed pairing without buffering

- BS–RN subcarriers are pairwise-connected with RN–UE subcarriers
  - Fixed or random mapping $l = v[k]$
  - Relay decodes, stores and forwards without buffering
- The average capacity becomes

$$\begin{aligned}\bar{\mathcal{C}} &= \frac{1}{K}\sum_{k=1}^{K}\mathcal{E}\left\{\min\left\{\bar{\mathcal{C}}_{\mathrm{SR}}[k],\mathcal{C}_{\mathrm{RD}}[k]\right\}\right\} \\ &= \frac{1}{K}\sum_{k=1}^{K}\int_0^\infty \min\left\{\tau\log_2(1+\bar{\gamma}_{\mathrm{SR}}[k]),(1-\tau)\log_2(1+s)\right\} f_{\gamma_{\mathrm{RD}}[k]}(s)ds \\ &= \frac{1}{K}\sum_{k=1}^{K}\frac{(1-\tau)e^{\frac{1}{\bar{\gamma}_{\mathrm{RD}}}}}{\log_e(2)}\left[E_1\left(\frac{1}{\bar{\gamma}_{\mathrm{RD}}}\right)-E_1\left(\frac{(1+\bar{\gamma}_{\mathrm{SR}}[k])^{\frac{\tau}{1-\tau}}}{\bar{\gamma}_{\mathrm{RD}}}\right)\right]\end{aligned}$$

- Time sharing factor τ can be arbitrary

Optimized pairing without buffering

- BS–RN subcarriers are pairwise-connected with RN–UE subcarriers
  - Optimal pairing $l = v^*[k]$ based on ordered SNRs
  - Relay decodes, stores and forwards without buffering
- From order statistics

$$f_{\gamma_{\mathrm{RD}}[v^*[k]]}(x) = k\binom{K}{k}\sum_{l=k}^{K}\frac{(-1)^{l-k}}{\bar{\gamma}_{\mathrm{RD}}}\binom{K-k}{K-l}e^{-\frac{x}{\bar{\gamma}_{\mathrm{RD}}}l}$$

- The average capacity becomes

$$\bar{C} = \frac{1}{K}\sum_{k=1}^{K}\sum_{l=k}^{K}(-1)^{l-k}\frac{k}{l}\binom{K}{k}\binom{K-k}{K-l}\frac{(1-\tau)e^{\frac{l}{\bar{\gamma}_{\mathrm{RD}}}}}{\log_e(2)} \times\left[E_1\left(\frac{l}{\bar{\gamma}_{\mathrm{RD}}}\right)-E_1\left(\frac{(1+\bar{\gamma}_{\mathrm{SR}}[k])^{\frac{\tau}{1-\tau}}}{\bar{\gamma}_{\mathrm{RD}}/l}\right)\right]$$

- Time sharing factor τ can be arbitrary

Pairwise subcarriers with buffering

- BS–RN subcarriers are pairwise-connected with RN–UE subcarriers
  - Decode, store and forward
  - Infinite buffer for each subcarrier pair
- The average capacity becomes

$$\bar{\mathcal{C}} = \frac{1}{K}\sum_{k=1}^{K}\min\left\{\bar{\mathcal{C}}_{\mathrm{SR}}[k], \bar{\mathcal{C}}_{\mathrm{RD}}[k]\right\}$$

where

$$\begin{aligned}\bar{\mathcal{C}}_{\mathrm{RD}}[k] &= \int_0^\infty (1-\tau)\log_2(1+s) f_{\gamma_{\mathrm{RD}}[k]}(s)ds \\ &= \frac{(1-\tau)e^{\frac{1}{\bar{\gamma}_{\mathrm{RD}}}} E_1\left(\frac{1}{\bar{\gamma}_{\mathrm{RD}}}\right)}{\log_e(2)}\end{aligned}$$

- Time sharing factor τ can be arbitrary

Information redistribution without buffering

- Relay extracts all information from the decoded BS–RN subcarriers and then redistributes to the RN–UE subcarriers
- Average capacity is determined by the per-hop mean capacities of all subcarriers

$$\bar{\mathcal{C}} = \mathcal{E}\left\{\min\left\{\mathcal{C}_{\mathrm{SR}}, \mathcal{C}_{\mathrm{RD}}\right\}\right\}$$

  - BS–RN subcarriers

$$\mathcal{C}_{\mathrm{SR}} = \bar{\mathcal{C}}_{\mathrm{SR}} = \frac{1}{K}\sum_{k=1}^{K}\mathcal{C}_{\mathrm{SR}}[k] = \frac{1}{K}\sum_{k=1}^{K}\bar{\mathcal{C}}_{\mathrm{SR}}[k]$$

  - RN–UE subcarriers

$$\mathcal{C}_{\mathrm{RD}} = \frac{1}{K}\sum_{k=1}^{K}\mathcal{C}_{\mathrm{RD}}[k], \;\; \bar{\mathcal{C}}_{\mathrm{RD}} = \mathcal{E}\left\{\mathcal{C}_{\mathrm{RD}}\right\} = \frac{1}{K}\sum_{k=1}^{K}\bar{\mathcal{C}}_{\mathrm{RD}}[k] = \bar{\mathcal{C}}_{\mathrm{RD}}[k]$$

    - Approximation using the central limit theorem
- Time sharing factor τ can be arbitrary

Information redistribution with buffering

- Relay extracts all information from the decoded BS–RN subcarriers and then redistributes to the RN–UE subcarriers
  - Buffering compensates for the fading on the RN–UE hop
  - Complete restructuring of data frames over both time and frequency
- Average capacity becomes simply

$$\bar{\mathcal{C}} = \min\left\{\bar{\mathcal{C}}_{\mathrm{SR}}, \bar{\mathcal{C}}_{\mathrm{RD}}\right\}$$

- Time sharing factor τ can still be arbitrary

Optimization of time allocation

- All of the derived capacity expressions depend on the time shares τ and $1-\tau$ of the respective BS–RN and RN–UE hops
- Optimization problem can be expressed as

$$\tau^* = \arg\max_{\tau} \bar{\mathcal{C}} \text{ subject to } 0 \leq \tau \leq 1$$

  - We resort to numerical optimization
- Analytical closed-form expression only for information redistribution with buffering

$$\tau^* = \frac{e^{\frac{1}{\bar{\gamma}_{\mathrm{RD}}}} E_1\left(\frac{1}{\bar{\gamma}_{\mathrm{RD}}}\right)}{\frac{1}{K}\sum_{k=1}^{K}\log_e(1+\bar{\gamma}_{\mathrm{SR}}[k]) + e^{\frac{1}{\bar{\gamma}_{\mathrm{RD}}}} E_1\left(\frac{1}{\bar{\gamma}_{\mathrm{RD}}}\right)}$$

Example setup

- For the BS–RN channel we adopt the B5f non-line-of-sight (NLOS) rooftop-to-below rooftop channel model from the WINNER project:

TABLE I
POWER-DELAY PROFILE FOR THE BS–RN LINK

B5f-NLOS rooftop-to-below rooftop					
Delay [ns]	0	10	20	50	90
Power [dB]	-0.1	-5.3	-11.5	-8.9	0.0
Delay [ns]	95	100	180	205	260
Power [dB]	-5.2	-12.7	-3.5	-6.3	-4.6

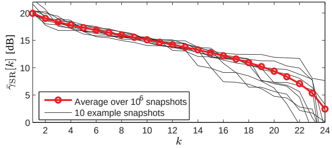
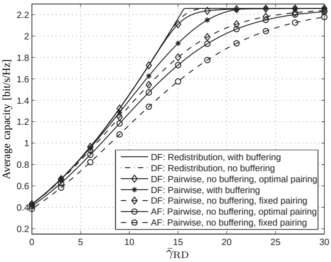


Fig. 2. The sorted BS–RN subcarrier SNRs from WINNER B5f-NLOS rooftop-to-below rooftop channel model when $K = 24$ and $\bar{\gamma}_{SR} = 15$dB. The average channel is used in numerical performance evaluation.

- Implementation with subcarrier chunks, i.e., resource blocks (RBs)
  - 3GPP Release 7 baseline proposal: 375kHz RBs (25 consecutive subcarriers for 6 or 7 consecutive OFDM symbols), system bandwidth 10MHz, 600 occupied subcarriers
  - Thus, $K = 24$

HELSINKI UNIVERSITY OF TECHNOLOGY
SMARAD Centre of Excellence

Comparison with equal time sharing



(a) With equal time sharing ($\tau = \frac{1}{2}$)

Fig. 4. The average end-to-end capacities of the proposed protocols in terms of the average second hop SNR when $\bar{\gamma}_{\mathrm{SR}} = 15$dB.

- Complex functionalities improve capacity but differences are small
  - DF protocol with optimized subcarrier pairing seems to offer a good trade-off between complexity and capacity
  - Benefit of buffering is comparatively small
  - AF protocols are simple but have lowest capacity

Optimization of time sharing

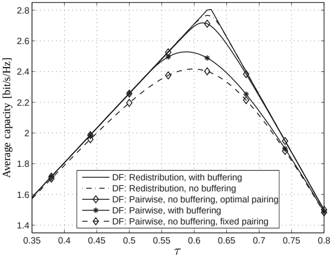
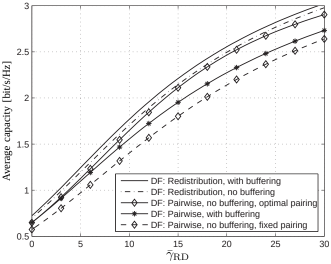


Fig. 3. Optimization of time sharing when $\bar{\gamma}_{\mathrm{SR}} = 15\mathrm{dB}$ and $\bar{\gamma}_{\mathrm{RD}} = 25\mathrm{dB}$.

- The optimal value of τ is quite the same for all considered protocols
- 50%/50% time sharing is reasonably good

Comparison with optimized time sharing



(b) With optimized time sharing ($\tau = \tau^*$)

Fig. 4. The average end-to-end capacities of the proposed protocols in terms of the average second hop SNR when $\bar{\gamma}_{SR} = 15$dB.

- Optimal time sharing is beneficial when the hops are unbalanced
  - In general, the weakest hop limits the performance

Conclusion

- Analysis of the performance of OFDMA decode-and-forward relays
  - New closed-form expressions for average end-to-end capacities
- Various relaying protocols were proposed
  - Different sets of functionalities implemented in the relay
  - A common framework to allow comparison
- Useful information for specifying new systems
  - Evaluation and comparison of the performance gains due to the functionalities that can be employed only at the expense of increased complexity and cost of the network architecture
- Power allocation not considered — a future research topic (?)

Thank you!

- Questions?
- Discussion?