Buffer-aided Successive Opportunistic Relaying with Inter-Relay Interference Cancellation

Nikolaos Nomikos†, Themistoklis Charalambous*, Ioannis Krikidis§, Dimitrios N. Skoutas†, Demosthenis Vouyioukas† and Mikael Johansson*

†Department of Information and Communication System Engineering, University of the Aegean
*Department of Automatic Control, Royal Institute of Technology (KTH)
§Department of Electrical and Computer Engineering, University of Cyprus
Outline of the presentation

- Cooperative relaying
- System model
- min-power relay selection policy
  - Power levels of relay pairs
  - Description of the algorithm
  - Model and outage probability analysis
- Numerical results
  - Outage probability
  - Average throughout
  - Average delay
- Conclusions and future directions
Cooperative relaying

- **Cooperative relaying** increases *diversity gain* - offers alternative and independent transmission paths [Laneman et al., 2004]

- **Opportunistic relay selection** improves usage of network resources - selects one best relay among multiple [Bletsas et al., 2006]

- **Buffers in relays** increases *degrees of freedom* in the network - improves diversity since relays have packets in buffers to be scheduled [Krikidis et al., 2012]

- **Successive relaying** allows *simultaneous transmission* by the source and a relay node - full duplex operation with Inter-Relay Interference (IRI) [Ding et al., 2012]


System Model (1)

- Cooperative network consisting of a source $S$, a destination $D$ and a cluster $C$ with $K$ Decode-and-Forward (DF) relays
- Fading (stationary, frequency non-selective Rayleigh block fading) and Additive White Gaussian Noise (AWGN)
- Half-duplex buffer-aided relays - either transmit or receive packets
- Inter-relay interference (IRI) between the relays in a relay pair ($R_r, R_t$)
- Global CSI available
**System Model (2)**

- Due to battery limitations, each transmitting node $i$ (source and relays) has a maximum power $P^{\text{max}}_i$

- Power constraint - a critical design parameter in relay networks

- A packet is successfully transmitted from $R_t$ to $D$ if $\text{SNR}$ is greater than or equal to the capture ratio $\gamma_0$, i.e.,
  \[
  \frac{g_{R_t} P_{R_t} D}{n_D} \geq \gamma_0
  \]

- A packet is successfully transmitted from source $S$ to the receiving relay $R_r$, if $\text{SINR}$ at the receiving relay is greater than or equal to $\gamma_0$, i.e.,
  \[
  \frac{g_{SR_r} P_S}{g_{R_t R_r} P_{R_t} \mathbb{I}(R_t R_r) + n_{R_r}} \geq \gamma_0
  \]

  where $\mathbb{I}(R_t R_r)$ is an indicating factor

  \[
  \mathbb{I}(R_t R_r) = \begin{cases} 
  0, & \text{if } \frac{g_{R_t R_r} P_{R_t}}{g_{SR_r} P_S + n_{R_r}} \geq \gamma_0, \\
  1, & \text{otherwise.}
  \end{cases}
  \]
Water levels of relay pairs

**Proposition 1**

Let $P_{S}^{\text{max}} = \infty$ and $P_{Rt}^{\text{max}} = \infty$. For each pair of relays $R_r$ and $R_t$, there exist $P_S$ and $P_{Rt}$ such that $I(R_t R_r) = 0$, $\text{SNR}_{Rt D} \geq \gamma_0$ and $\text{SINR}_{SR_r} \geq \gamma_0$. The minimum power levels $P_S^*$ and $P_{Rt}^*$ are achieved when $\text{SNR}_{Rt D} = \text{SINR}_{SR_r} = \gamma_0$, and are given by

$$P_S^* = \frac{\gamma_0 n_{R_r}}{g_{SR_r}},$$  \hspace{1cm} (1a)

$$P_{Rt}^* = \max \left\{ \frac{\gamma_0 n_D}{g_{Rt D}}, \frac{n_{R_r} \gamma_0 (\gamma_0 + 1)}{g_{Rt R_r}} \right\}. \hspace{1cm} (1b)$$

**Proposition 2**

When interference cancellation is infeasible, the minimum power levels $P_S^\dagger$ and $P_{Rt}^\dagger$ are achieved when $\text{SNR}_{Rt D} = \text{SINR}_{SR_r} = \gamma_0$, and are given by

$$P_S^\dagger = \gamma_0 \left( \frac{g_{Rt R_r} \gamma_0 n_D}{g_{SR_r} g_{Rt D}} + \frac{n_{R_r}}{g_{SR_r}} \right),$$  \hspace{1cm} (2a)

$$P_{Rt}^\dagger = \frac{\gamma_0 n_D}{g_{Rt D}}. \hspace{1cm} (2b)$$
**min-power relay selection policy**

- Due to the concurrent transmissions, relay selection does not depend solely on the quality of the SR and RD links

- IRI is the defining factor in this relay selection policy

- Desirable to have simultaneous SR and RD transmissions (successive) - increased throughput.

- Successive transmission can occur *with* or *without* IC.

- If no successive transmission is possible, min-power uses a single link relay scheme, i.e., there is only one link activation.

- **Feasibility check:** IC can take place if and only if

  \[
  P_{R_t}^{\text{max}} \geq \max \left\{ \frac{\gamma_0 n_D}{g_{R_t} D}, \frac{n_{R_r} \gamma_0 (\gamma_0 + 1)}{g_{R_t} R_r} \right\}
  \]

  This is a corollary from Proposition 1.
**min-power relay selection policy**

- If IC is *feasible* (through the *feasibility check*), then
  - if IC did not take place, powers ($P^\dagger_S, P^\dagger_{R_t}$) are given as in Proposition 2
  - if IC took place, powers ($P^*_S, P^*_R$) are given as in Proposition 2
  - minimum energy expenditure
    \[
    \min \left\{ P^*_S + P^*_R, P^\dagger_S + P^\dagger_{R_t} \right\}
    \]

- If IC is *not feasible*, then
  - check whether $P^\dagger_{R_t} \leq P^\text{max}_{R_t}$ and $P^\dagger_S \leq P^\text{max}_S$

- Compare the minimum energy expenditure for all *possible relay pairs* ($R_r, R_t$)
  - choose the minimum among them

- **Note:** if there exist no relay pairs, a single link is selected based on *max-link*
  
  [Krikidis et al., 2012]

---

Model and outage probability analysis (I)

Finite buffers:

- relays that have full buffers cannot compete in the selection of the best relay
- relays with empty buffers are not able to transmit and as a result they are excluded from the best transmitting relay selection
- when no successive transmission through two selected relays our system reduces to the max-link relay selection scheme

- The outage probability behavior of min-power follows the same theoretical framework as max-link
- Markov Chain (MC), denoted as $A$, $A \in \mathbb{R}^{(L+1)^K \times (L+1)^K}$
- $A_{i,j} = P(s_i \rightarrow s_j) = P(X_{t+1} = s_j | X_t = s_i)$
- We have additional ways of transmission through successive relaying
- Easily shown that the state transition matrix $A$ of the MC is SIA
- The MC has a stationary distribution, denoted as $\pi$. 

Model and outage probability analysis (II)

Illustrative example:

- 9 possible states for 2 buffer-aided relays of buffer size equal to 2

\[
A = \begin{pmatrix}
\bar{p}_1 & p_{12} & p_{13} & 0 & 0 & 0 & 0 & 0 & 0 \\
p_{21} & \bar{p}_2 & p_{23} & p_{24} & p_{25} & 0 & 0 & 0 & 0 \\
p_{31} & p_{32} & \bar{p}_3 & 0 & p_{35} & p_{36} & 0 & 0 & 0 \\
0 & p_{42} & 0 & \bar{p}_4 & p_{45} & 0 & p_{47} & 0 & 0 \\
0 & p_{52} & p_{53} & p_{54} & \bar{p}_5 & p_{56} & p_{57} & p_{58} & 0 \\
0 & 0 & p_{63} & 0 & p_{65} & \bar{p}_6 & 0 & p_{66} & 0 \\
0 & 0 & 0 & p_{74} & p_{75} & 0 & \bar{p}_7 & p_{78} & p_{79} \\
0 & 0 & 0 & 0 & p_{85} & p_{86} & p_{87} & \bar{p}_8 & p_{89} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & p_{97} & p_{98} & \bar{p}_9
\end{pmatrix}
\]

- \(A\) captures in its diagonal the probabilities of no change in buffer states
- With the steady state probabilities, we compute the outage probability of the system:

\[
P_{\text{out}} = \sum_{i=1}^{(L+1)^K} \pi_i \bar{p}_D_i = \text{diag}(A)\pi
\]
Numerical results

- Comparisons with *successive* and *non-successive* relay selection schemes

- The *successive* category includes:
  - the SFD-MMRS of [Ikhlef et al., 2012] - upper bound to our work due to the absence of both IRI and constraints due to full or empty buffers
  - the SOR of [Nomikos et al., 2012/1] - capacity maximization without power adaptation, buffer-aided relays or opportunistic relaying
  - the BA-SOR of [Nomikos et al., 2012/2] - capacity maximization without power adaptation or opportunistic relaying (but with buffer-aided relays)

- The *non-successive* category includes:
  - the HRS of [Ikhlef et al., 2012]
  - the max-link of [Krikidis et al., 2012]

- The capacity threshold is \( r_0 = 1 \text{bps/Hz} \)

- The results are obtained in terms of:
  - outage probability
  - average end-to-end capacity
  - average delay
Numerical results > Outage probability (1)

- each scheme employs K=2 relays with buffer size L=2
- SOR has the worst performance
  - it lacks buffers
  - selection coupled to the previous transmission phase
- BA-SOR better - due to buffering
- max-max improvement over BRS due to buffering
- Better results for max-link due to the flexible link selection

- min-power reduces to max-link when successive transmissions fail
- Similar results between these two schemes; min-power exhibits a 0.5dB gain for high SNR.
- Theoretical curve of the outage probability matches the simulation results validating the analysis
Numerical results > Outage probability (2)

- As $K$ and $L$ increase, the curves become steeper, indicating the increase in diversity as *more links are available for selection.*
Numerical results > **Average throughput (1)**

- Compared policies are divided in two groups
- The **1st group** consists of the half-duplex schemes, namely BRS, max-max and max-link
- They achieve a maximum average throughput of 0.5\(bps/Hz\) (half the constant rate)
- **max-link** outperforms BRS and max-max

**2nd group**: we have SOR, BA-SOR, selection bound and min-power

- **min-power** achieves the best performance reaching 1\(bps/Hz\) for high SNR
- SOR does not reach the upper bound even for high SNR as IRI and the lack of buffering cause many outages
• When $K$ and $L$ increases, min-power approaches the selection bound
• When the SNR is low, interference cancellation does not take place often and the proposed scheme chooses half-duplex transmissions instead of successive ones.
Numerical results > Average delay

- The half-duplex schemes experience increased delay
- Due to successive transmissions packets tend to stay less in the buffers

Average delay converges to 1 due to successive transmission - a relay receives a packet while the other relay forwards the packet received in preceding slot.

Average delay converges to 3 - a packet in the other relay is transmitted before the packet is forwarded to the destination, in order to have diversity gain.
Conclusions and Future Directions

Conclusions

• Opportunistic relaying protocol min-power - minimizes the total energy expenditure per time slot using:
  - an IRI cancellation scheme
  - buffer-aided relays
  - power adaptation

• Thus, the detrimental effect of IRI is mitigated.

• Performance of the proposed relay-pair selection scheme in terms of outage probability and average throughput

• Comparisons with other state-of-the-art relay selection schemes

Future directions

• Approach not feasible when the channels change fast - consider the case for which the channels change fast and only statistical channel information is available.
Thank you!

Questions?