Opportunistic Relay Selection for Cooperative Networks with Buffers

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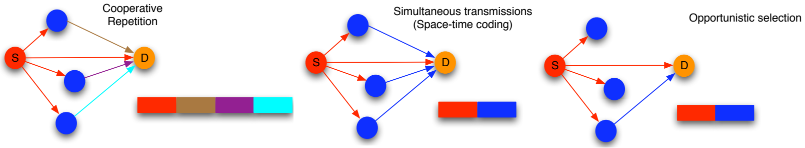
Outline

1. Background-Introduction
2. max-link relay selection
3. Numerical results
4. Conclusion and future work

Opportunistic relay selection

It has been considered in Half-duplex relay systems as an attractive relaying solution.

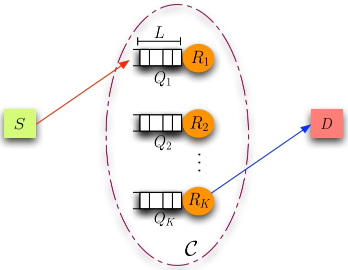


- High performance.
- Efficient use of system resources (e.g. power, bandwidth).
- Hardware simplicity (e.g., distributed implementations).

- A selected relay node receives and retransmits the source data in orthogonal channels.
- Conventional approaches do not consider any storage ability at the relay nodes.

Relay selection and storage ability at the relay nodes

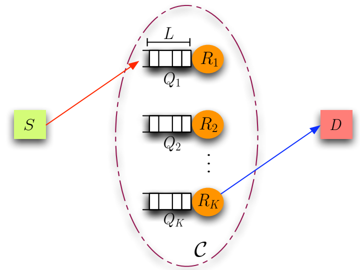
- Conventional relay selection schemes incorporate **only** the instantaneous strength of the wireless links.
- We introduce a storage ability (buffers) at the relay nodes, which allows a more flexible use of the wireless links.



A simple system model

- A clustered i.i.d. relay confuguration with K DF relays.
- A data buffer Q_k of finite size L for each relay.
- ACK/NACK mechanism and centralized decision.
- $\Psi(Q_k)$ gives the number of packets stored in Q_k.

Previous studies



1. Conventional $\max - \min$ relay selection [Bletsas et. al., 2006]
   - Strongest end-to-end path ($R^* = \arg\max_{R_k \in \mathcal{C}} \min\left\{\left|h_{S,R_k}\right|^2, \left|h_{R_k,D}\right|^2\right\}$).
   - Diversity gain $d = K$.
2. $\max - \max$ relay selection [Ikhlef et. al., 2011]
   - It selects the relay with the best source-relay link for reception and the relay with the best relay-destination link for transmission.
   - Diversity gain $d = K$; It provides only a coding gain.
   - Limitation: The schedule for the source and relay transmission is fixed a priori.

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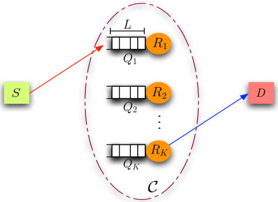
The proposed relay selection scheme



3. Proposed max-link relay selection
   - We allow each slot to be allocated dynamically to the source or a relay transmission.
   - It compares the quality of the available links and adjusts the relay selection decision and the time slot allocation to the strongest link.

$$R^* = \arg \max_{R_k \in \mathcal{C}} \left\{ \bigcup_{R_k \in \mathcal{C}: \Psi(Q_k) \neq L} \left\{ |h_{S,R_k}|^2 \right\} \bigcup_{R_k \in \mathcal{C}: \Psi(Q_k) \neq 0} \left\{ |h_{R_k,D}|^2 \right\} \right\}.$$

- A relay with an empty queue can only receive data (It offers one link on the relay slection process).
- A relay with a full queue can only transmit data (It offers one link on the relay slection process).

Markov Model

For the max-link relay selection policy the outage probability is defined as the probability that the selected link is in outage, i.e.,

$$P_{\text{out}} \triangleq \begin{cases} \mathbb{P}\left(\frac{1}{2}\log_2(1+P|h_{S,R^*}|^2) < r_0\right) \\ \quad \text{for relay reception;} \\ \mathbb{P}\left(\frac{1}{2}\log_2(1+P|h_{R^*,D}|^2) < r_0\right) \\ \quad \text{for relay transmission.} \end{cases}$$

- We investigate a theoretical framework for the computation of the outage probability (and diversity order).
- We model the evolution of the relay buffers as a state Markov chain (MC).
- A state of the MC represents the number of elements at each buffer and thus $s_l \triangleq \left(\Psi(Q_1)\Psi(Q_2)\ldots\Psi(Q_K)\right)$ denotes the l-th state of the MC with $l \in \mathbb{N}_+$, $1 \le l \le (L+1)^K$.
- Theoretical computation of the state transition matrix $\boldsymbol{A}$ and steady state distribution $\boldsymbol{\pi}$.

Construction of the state transition matrix of the MC (1)

Let $\mathbf{A}$ denote the $(L+1)^K \times (L+1)^K$ state transition matrix of the MC, in which the entry $\mathbf{A}_{i,j} = \mathbb{P}\left(s_j \to s_i\right) = \mathbb{P}\left(X_{t+1} = s_i | X_t = s_j\right)$ is the transition probability to move from state s_i at time t to state s_j at time $(t+1)$

For the s_l state of the buffers, the total number of the available links that participate in the max-link selection process is equal to:

$$D_l = \sum_{i=1}^{K} \Phi\left(Q_i\right).$$

where

$$\Phi\left(Q_i\right) = \begin{cases} 2 & \text{if } 0 < \Psi(Q_i) < L; \\ 1 & \text{elsewhere.} \end{cases}$$

Construction of the state transition matrix of the MC (2)

For each time slot, the buffer status can be modified as follows:

(a) The number of elements of one relay buffer can be decreased by one, if a relay node is selected for transmission and the transmission is successful.

(b) The number of elements of one buffer can be increased by one, if the source node is selected for transmission and the transmission is successful.

(c) The buffer status remains unchanged in case of outage.

The set U_l contains all the buffer states that are connected to the state s_l based on the previous connectivity rule:

$$U_l = \left\{ \bigcup_{1 \leq i \leq (L+1)^K} s_i : \mathbf{s}_i - \mathbf{s}_l \in \mathcal{Q} \right\}.$$

Construction of the state transition matrix of the MC (3)

The probability to select a specific link is equal to $1/D_l$ and thus the probability that the selected link is not in outage (probability to leave from the state s_l):

$$p_{D_l} \triangleq \frac{1}{D_l}\left[1-\left(1-\exp\left(-\frac{2^{2r_0}-1}{P}\right)\right)^{D_l}\right].$$

On the other hand the probability to have an outage event and therefore no change in the buffer status is equal to

$$\overline{p}_{D_l} \triangleq 1-\sum_{i=1}^{D_l} p_{D_l} = \left(1-\exp\left(-\frac{2^{2r_0}-1}{P}\right)\right)^{D_l}.$$

By using the previous notation, the entries of the state transition matrix are given as

$$\mathbf{A}_{i,j} = \begin{cases} \overline{p}_{D_j} & \text{if } s_i \notin U_j \\ p_{D_j} & \text{if } s_i \in U_j \\ 0 & \text{elsewhere} \end{cases}, \quad \text{for} \quad i,j \in \{1,\ldots,(L+1)^K\}$$

Outage Probability

Lemma

The stationary distribution of the column stochastic matrix $\mathbf{A}$ of the MC that models the buffer states is given by

$$\boldsymbol{\pi} = (\mathbf{A} - \mathbf{I} + \mathbf{B})^{-1}\boldsymbol{b}.$$

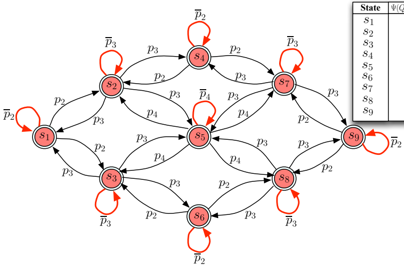
where $\boldsymbol{\pi}$ is the stationary distribution, $\boldsymbol{b} = (1\ 1\ \ldots\ 1)^T$ and $\mathbf{B}_{i,j} = 1,\ \forall i,j$.

By using the steady state of the MC and the fact that an outage event occurs when there is no change in the buffer status, the outage probability of the system can be expressed as

$$P_{\rm out} = \sum_{i=1}^{(L+1)^K} \boldsymbol{\pi}_i \overline{p}_{D_i} = \text{diag}(\mathbf{A})\boldsymbol{\pi}.$$

Illustrative Examples

- MC for a case with $K = 2$ relays and $L = 2$.



State	$\Psi(Q_1)\Psi(Q_2)$
s_1	00
s_2	01
s_3	10
s_4	02
s_5	11
s_6	20
s_7	12
s_8	21
s_9	22

$$\mathbf{A} = \begin{pmatrix} \overline{p}_2 & p_3 & p_3 & 0 & 0 & 0 & 0 & 0 & 0 \\ p_2 & \overline{p}_3 & 0 & p_2 & p_4 & 0 & 0 & 0 & 0 \\ p_2 & 0 & \overline{p}_3 & 0 & p_4 & p_2 & 0 & 0 & 0 \\ 0 & p_3 & 0 & \overline{p}_2 & 0 & 0 & p_3 & 0 & 0 \\ 0 & p_3 & p_3 & 0 & \overline{p}_4 & 0 & p_3 & p_3 & 0 \\ 0 & 0 & p_3 & 0 & 0 & \overline{p}_2 & 0 & p_3 & 0 \\ 0 & 0 & 0 & p_2 & p_4 & 0 & \overline{p}_3 & 0 & p_2 \\ 0 & 0 & 0 & 0 & p_4 & p_2 & 0 & \overline{p}_3 & p_2 \\ 0 & 0 & 0 & 0 & 0 & 0 & p_3 & p_3 & \overline{p}_2 \end{pmatrix}$$

- For the extreme case with infinite buffer sizes $L \rightarrow \infty$, the outage probability is simplified to:
  (Diversity gain $2K$)

$$P_{\text{out}}^{\infty} = \lim_{L\rightarrow\infty} \left[\underbrace{\left(\frac{L-1}{L+1}\right)^K}_{\rightarrow 1} \overline{p}_{2K} + \sum_{i=1}^{K} \underbrace{\frac{2^i \binom{K}{i} (L-1)^{K-i}}{(L+1)^K}}_{\rightarrow 0} \overline{p}_{2K-i} \right] = \overline{p}_{2K}.$$

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Simulation results (1)

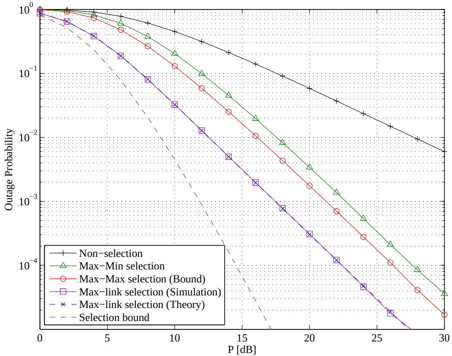

Figure: $K = 2$ relays, $L = 2$ and $r_0 = 1$ BPCU.

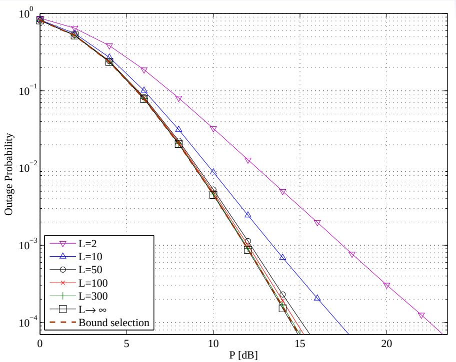

Figure: *max*-link relay selection with $K = 2$ relays, $L = 2, 10, 50, 100, 300, \infty$ and $r_0 = 1$ BPCU.

- Coding gain for small L.
- Diversity gain $K \leq d \leq 2K$, Diversity gain $2K$ for large L ($L \rightarrow \infty$).

Simulation results (2)

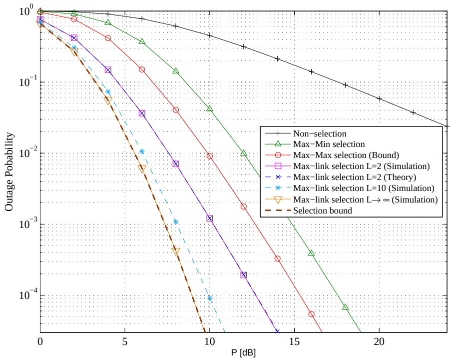

Figure: $K = 4$ relays, $L = 2, 10, \infty$ and $r_0 = 1$ BPCU.

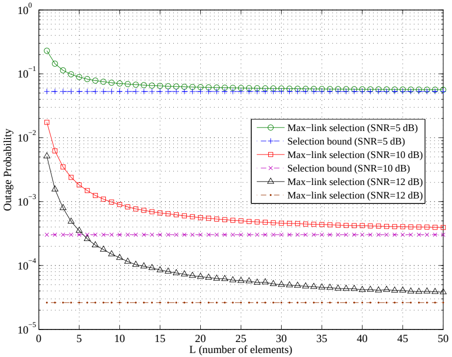

Figure: $K = 3$ relays, $P = 5, 10, 12$ dB (SNR) and $r_0 = 1$ BPCU.

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Conclusion and future work

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- Conventional schemes do not take into account the storage ability at the relay nodes or assume a predefined schedule (Diversity K).
- Investigation of a max-link relay selection scheme that selects the best available link.
- Theoretical analysis of the outage probability; $K \leq d \leq 2K$ (the proposed scheme achieves a diversity $2K$ for large buffer sizes).
- The proposed scheme does not take into account delay constraints (we focus on the diversity aspect).

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- Extension to more practical/general configurations (asymmetric topologies).
- Extension of the analysis for systems with Delay constraints.

Thank you!