Cooperative networks: From half-duplex to full-duplex relaying

Ioannis Krikidis

Dept. Electrical and Computer Engineering
University of Cyprus
E-mail: krikidis@ucy.ac.cy

Department of Electrical and Electronic Engineering,
Niigata University

July 2013
Outline

1. Context of cooperation
2. Combating the half-duplex constraint
   - Buffer-aided relay selection
   - Two-way relay channel
   - Cognitive cooperation
   - Full-duplex relaying
3. Applications
4. Conclusion and future work
Napoleonic semaphore

- The earliest technical invention to use the “relaying concept”.

- Chapper, 1792
Napoleonic semaphore

- The earliest technical invention to use the “relaying concept”.

- Chapper, 1792
- Source/Channel Coding
- Multihop transmission
- Mesh Networks
**Relay Channel**

- **Relay channel**: A combination of a Broadcast and Multi-access channel (basic information theoretic network structure).
- Encoder broadcast?
- Relay processing (relaying strategy, duplex-mode)?
- Multi-access decoding?
Relay processing - strategy

- Capacity unknown in general.
- Cover & El Gamal’79 derived the cut-set capacity upper bound, and two relay strategies:

**Amplify-and-Forward (AF):** Amplification of an analogue version of the received signal.

**Decode-and-Forward (DF):** Decoding of the received signal at the relay.
Relay process - duplex mode

Half-duplex relaying:

- TX/RX in orthogonal channels.
- Spectral efficiency loss.
- How to combat this spectral efficiency loss?
Half-duplex relaying:

**Channel II**
(time-slot II, frequency II)

- TX/RX in orthogonal channels.
- **Spectral efficiency loss.**
- How to combat this spectral efficiency loss?
Relay process - duplex mode

1. **Half-duplex relaying:**

   **Channel II**
   (time-slot II, frequency II)

   - TX/RX in orthogonal channels.
   - Spectral efficiency loss.
   - How to combat this spectral efficiency loss?

2. **Full-duplex relaying:**

   - TX/RX in the same time-slot/frequency.
   - Loop interference from the relay output to the relay input.
   - How to combat this loop interference?
Modern Relays

a) Multihop transmission
   - combat path loss.
   - extend the coverage.
Modern Relays

a) Multihop transmission
- combat path loss.
- extend the coverage.

b) Cooperative MAC
[Sendonaris et. al., 2003; Laneman et. al., 2004]
- combat fading (diversity gain).
- increase the capacity (multiplexing gain).
Modern Relays

a) Multihop transmission
- combat path loss.
- extend the coverage.

b) Cooperative MAC
[Sendonaris et. al., 2003; Laneman et. al., 2004]
- combat fading (diversity gain).
- increase the capacity (multiplexing gain).

c) General design strategy with several applications.
- Energy efficiency (green radio communications).
- Cognitive radio applications.
- Physical (PHY) layer secrecy.
Outline

1. Context of cooperation

2. Combating the half-duplex constraint
   - Buffer-aided relay selection
   - Two-way relay channel
   - Cognitive cooperation
   - Full-duplex relaying

3. Applications

4. Conclusion and future work
On recovering the bandwidth loss

- Previous work (last 10 years) on cooperative systems assumes half-duplex relaying.
  - Implementation simplicity (one antenna).
  - No problems of loop interference (assumed to be large and unremovable).
- Main research problem: How to combat the associated bandwidth loss?
On recovering the bandwidth loss

- Previous work (last 10 years) on cooperative systems assumes half-duplex relaying.
  - Implementation simplicity (one antenna).
  - No problems of loop interference (assumed to be large and unremovable).
- Main research problem: How to combat the associated bandwidth loss?

Non-orthogonal cooperative protocols
- The source is active (sends the next codeword) during relaying.
- i.e., Dynamic Decode-and-Forward (DDF) [Azarian et al., 2005]; a codeword is divided in $M$ subcodewords/slot.
On recovering the bandwidth loss

- Previous work (last 10 years) on cooperative systems assumes **half-duplex relaying**.
  - Implementation simplicity (one antenna).
  - No problems of loop interference (assumed to be large and unremovable).
- **Main research problem**: How to combat the associated bandwidth loss?

Non-orthogonal cooperative protocols
- The source is active (sends the next codeword) during relaying.
- i.e., Dynamic Decode-and-Forward (DDF) [Azarian et al., 2005]; a codeword is divided in $M$ subcodewords/slot.
On recovering the bandwidth loss

- Previous work (last 10 years) on cooperative systems assumes **half-duplex relaying**.
  - Implementation simplicity (one antenna).
  - No problems of loop interference (assumed to be large and unremovable).
- **Main research problem:** How to combat the associated bandwidth loss?

**Non-orthogonal cooperative protocols**
- The source is active (sends the next codeword) during relaying.
- i.e., Dynamic Decode-and-Forward (DDF) [Azarian et al., 2005]; a codeword is divided in $M$ subcodewords/slot.
- i.e, Block-Fading Non-orthogonal AF (BFNAF) [[Krikidis et al., 2010]].
On recovering the bandwidth loss

- Previous work (last 10 years) on cooperative systems assumes **half-duplex relaying**.
  - Implementation simplicity (one antenna).
  - No problems of loop interference (assumed to be large and unremovable).

**Main research problem**: How to combat the associated bandwidth loss?

**Opportunistic relay selection**
- For networks with multiple relays, only the **best** relay accesses the channel.
- [Bletsas et al., 2005] \( k^* = \arg_{k \in S_{\text{relay}}} \max \min \{ \gamma_S, k, \gamma_k, D \} \)
On recovering the bandwidth loss

Previous work (last 10 years) on cooperative systems assumes half-duplex relaying.
- Implementation simplicity (one antenna).
- No problems of loop interference (assumed to be large and unremovable).

Main research problem: How to combat the associated bandwidth loss?

Opportunistic relay selection
- For networks with multiple relays, only the best relay accesses the channel.
- [Bletsas et al., 2005] \( k^* = \arg \max_{k \in S_{\text{relay}}} \min\{\gamma_S, \gamma_k, D\} \)
- Relay selection with partial channel knowledge
  [Krikidis et al., 2008] (141 citations).
On recovering the bandwidth loss

Previous work (last 10 years) on cooperative systems assumes **half-duplex relaying**.
- Implementation simplicity (one antenna).
- No problems of loop interference (assumed to be large and unremovable).

**Main research problem**:
How to combat the associated bandwidth loss?

Opportunistic relay selection
- For networks with multiple relays, only the **best** relay accesses the channel.
- [Bletsas et al., 2005] \( k^* = \arg_{k \in S_{\text{relay}}} \max \min \{ \gamma_S, k, \gamma_k, D \} \)
- Relay selection with partial channel knowledge [Krikidis et al., 2008] (141 citations).
- Relay selection for networks with interference [Krikidis et al., 2009] (111 citations).
On recovering the bandwidth loss- \textit{max-link} relay selection scheme

- Conventional relay selection schemes incorporate \textbf{only} the instantaneous strength of the wireless links.
- It introduces a storage ability (buffers) at the relay nodes, which allows a more flexible use of the wireless links.

\begin{itemize}
  \item A clustered i.i.d. relay configuration with \( K \) DF relays.
  \item A data buffer \( Q_k \) of finite size \( L \) for each relay.
  \item ACK/NACK mechanism and centralized decision.
  \item \( \Psi(Q_k) \) gives the number of packets stored in \( Q_k \).
\end{itemize}
On recovering the bandwidth loss- \textit{max}-link relay selection scheme

Conventional max -- min relay selection [Bletsas et. al., 2006]

- Strongest end-to-end path ($R^* = \arg \max_{R_k \in C} \min \{ |h_{S,R_k}|^2, |h_{R_k,D}|^2 \}$).
- $d = K$. 

Cooperative networks: From half-duplex to full-duplex relaying
On recovering the bandwidth loss-\textit{max-link} relay selection scheme

Conventional \textit{max} -- \textit{min} relay selection [Bletsas et. al., 2006]

- Strongest end-to-end path \((R^* = \arg \max_{R_k \in C} \min \{|h_{S,R_k}|^2, |h_{R_k,D}|^2\})\).
- \(d = K\).

\textbf{max} -- \textit{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.
- It provides only a coding gain, \(d = K\).
- The schedule for the source and relay transmission is fixed a priori.
On recovering the bandwidth loss- *max*-link relay selection scheme

- **Conventional max — min relay selection** [Bletsas et. al., 2006]
  - Strongest end-to-end path ($R^* = \arg \max_{R_k \in C} \min \{ |h_{S,R_k}|^2, |h_{R_k,D}|^2 \}$).
  - $d = K$.

- **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.
  - It provides only a coding gain, $d = K$.
  - The schedule for the source and relay transmission is fixed a priori.

- **Proposed max-link relay selection**
  - We allow each slot to be allocated dynamically to the source or a relay transmission.
On recovering the bandwidth loss- \textit{max}-link relay selection scheme

- We investigated 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 $s_i \triangleq (\Psi(Q_1)\Psi(Q_2)\ldots\Psi(Q_K))$ denotes the $l$-th state of the MC with $l \in \mathbb{N}_+, 1 \leq l \leq (L+1)^K$.
- Theoretical computation of the state transition matrix $A$ and steady state distribution $\pi$.
On recovering the bandwidth loss- \textit{max}-link relay selection scheme

- $P_{\text{out}} = (A)\pi$.
- Coding gain for small buffer sizes.
- A diversity gain equals to $2K$ for $L \to \infty$.

On recovering the bandwidth loss

- **Superposition modulation/coding** [Larsson et. al., 2005, Xia et. al., 2007]
  - It allows a node to be simultaneously source and relay.

- Achievable rate for different relaying protocols and optimal power split [Krikidis et al., 2009]
On recovering the bandwidth loss

Superposition modulation/coding [Larsson et. al., 2005, Xia et. al., 2007]
- It allows a node to be simultaneously source and relay.

- Achievable rate for different relaying protocols and optimal power split [Krikidis et al., 2009]

Successive relaying
- Overlap of several relaying transmissions in order to mimic an ideal full-duplex operation.
On recovering the bandwidth loss

Superposition modulation/coding [Larsson et. al., 2005, Xia et. al., 2007]
- It allows a node to be simultaneously source and relay.
- Achievable rate for different relaying protocols and optimal power split [Krikidis et al., 2009]

Successive relaying
- Overlap of several relaying transmissions in order to mimic an ideal full-duplex operation.

Dirty-paper coding
- Relaying transmission is considered as an “interference” known at the transmitter.
On recovering the bandwidth loss - TWRC

Two-way relay channel (TWRC)

- Basic *information theoretic* structure.
- Two sources wish to exchange information via a *shared half-duplex relay*.
- Several protocols have been investigated for the TWRC (relaying scheme, #-phases).
On recovering the bandwidth loss-TWRC

Two-way relay channel (TWRC)

- Basic *information theoretic* structure.
- Two sources wish to exchange information via a *shared half-duplex relay*.
- Several protocols have been investigated for the TWRC (relaying scheme, #-phases).

**Phase 1**

4-phase TWRC $\Rightarrow$ 4 channel uses for 2 messages.

Cooperative networks: From half-duplex to full-duplex relaying
On recovering the bandwidth loss-TWRC

Two-way relay channel (TWRC)

- Basic *information theoretic* structure.
- Two sources wish to exchange information via a **shared half-duplex relay**.
- Several protocols have been investigated for the TWRC (relaying scheme, #-phases).

- 4-phase TWRC ⇒ 4 channel uses for 2 messages.
On recovering the bandwidth loss-TWRC

Two-way relay channel (TWRC)

- Basic *information theoretic* structure.
- Two sources wish to exchange information via a *shared half-duplex relay*.
- Several protocols have been investigated for the TWRC (relaying scheme, \#-phases).

4-phase TWRC \(\Rightarrow\) 4 channel uses for 2 messages.
On recovering the bandwidth loss-TWRC

Two-way relay channel (TWRC)

- Basic *information theoretic* structure.
- Two sources wish to exchange information via a **shared half-duplex relay**.
- Several protocols have been investigated for the TWRC (relaying scheme, #-phases).

4-phase TWRC ⇒ 4 channel uses for 2 messages.
On recovering the bandwidth loss-TWRC

Two-way relay channel (TWRC)

- Basic information theoretic structure.
- Two sources wish to exchange information via a shared half-duplex relay.
- Several protocols have been investigated for the TWRC (relaying scheme, \#-phases).

- 4-phase TWRC $\Rightarrow$ 4 channel uses for 2 messages.
- 3-phase TWRC $\Rightarrow$ 3 channel uses for 2 messages.
On recovering the bandwidth loss-TWRC

Two-way relay channel (TWRC)

- Basic *information theoretic* structure.
- Two sources wish to exchange information via a *shared half-duplex relay*.
- Several protocols have been investigated for the TWRC (relaying scheme, #-phases).

4-phase TWRC $\Rightarrow$ 4 channel uses for 2 messages.

3-phase TWRC $\Rightarrow$ 3 channel uses for 2 messages.
On recovering the bandwidth loss-TWRC

Two-way relay channel (TWRC)

- Basic information theoretic structure.
- Two sources wish to exchange information via a shared half-duplex relay.
- Several protocols have been investigated for the TWRC (relaying scheme, \#-phases).

- 4-phase TWRC ⇒ 4 channel uses for 2 messages.
- 3-phase TWRC ⇒ 3 channel uses for 2 messages.
On recovering the bandwidth loss-TWRC

Two-way relay channel (TWRC)

- Basic information theoretic structure.
- Two sources wish to exchange information via a shared half-duplex relay.
- Several protocols have been investigated for the TWRC (relaying scheme, #-phases).

4-phase TWRC $\Rightarrow$ 4 channel uses for 2 messages.

3-phase TWRC $\Rightarrow$ 3 channel uses for 2 messages.

2-phase TWRC $\Rightarrow$ 2 channel uses for 2 messages.
On recovering the bandwidth loss-TWRC

Two-way relay channel (TWRC)

- Basic *information theoretic* structure.
- Two sources wish to exchange information via a *shared half-duplex relay*.
- Several protocols have been investigated for the TWRC (relaying scheme, #-phases).

- 4-phase TWRC ⇒ 4 channel uses for 2 messages.
- 3-phase TWRC ⇒ 3 channel uses for 2 messages.
- 2-phase TWRC ⇒ 2 channel uses for 2 messages.

- The 2-phase protocol uses more efficiently the available channel resources.
- 1st phase: Multiple-access channel (MAC), 2nd phase: Broadcast channel (BC). ⇒ Multiple-access broadcast (MABC) protocol.
On recovering the bandwidth loss-TWRC

- MABC from information theoretic standpoint S. J. Kim et al., 2009.

- High computation ability at the sources or the relays (high complexity).
  - Coding/Decoding operation (DF).
  - Substraction of self-interference components (AF).
  - Channel knowledge required (channel estimation).

- **Uncoded MABC** is suitable for systems with critical energy and latency constraints T. Cui et al., 2009.
  - Channel estimation (coherent detection).

- Uncoded MABC without channel estimation (non-coherent) is suitable for systems with very critical energy and latency constraints.
  - Advanced modulation schemes (i.e., differential modulation).
  - ML demodulation, Bayesian detection regions.
  - still a high Complexity!
On recovering the bandwidth loss - TWRC

**Uncoded low-cost MABC**

- No-channel estimation (non-coherent detection).
- Simple modulation/demodulation.
- Networks with very critical energy/latency constraints (i.e., sensor networks for monitoring).

![Diagram](image)

The sources exchange 1-bit information (binary signalling).
- i.i.d. channels (symmetric topology).

How we design $w_A, w_B, W$ as well as the demodulation process at the relay/sources?

$$r[m] = w_A[m]h_{A,R}[m] + w_B[m]h_{B,R}[m] + n[m], \quad \text{(MAC)} \quad (1)$$

$$r_i[m] = W[m]h_{i,R}[m] + n'[m], \quad \text{(BC)} \quad (2)$$
On recovering the bandwidth loss-TWRC

- The sources use Binary pulse-position modulation (PPM) in order to transmit their 1-bit information.
- PPM is an orthogonal signaling and represents a special type of coding between symbols.
  - The position of the pulse is varied in accordance with the information message for a period of the time.

By using matrix representation:

\[
\mathbf{x}_0 \triangleq \begin{bmatrix} x^{(0)}_0 \\ x^{(1)}_0 \end{bmatrix} = \begin{bmatrix} \sqrt{\alpha} \\ 0 \end{bmatrix}, \quad \mathbf{x}_1 \triangleq \begin{bmatrix} x^{(0)}_1 \\ x^{(1)}_1 \end{bmatrix} = \begin{bmatrix} 0 \\ \sqrt{\alpha} \end{bmatrix}
\]  (3)
Relay decision based on the energy of the received signal during the first half and the second half of a time period.

A single threshold-based energy detection where the relay node compares the received energy with a single threshold and decides about the transmitted codewords.

- Simple demodulation at the relay $\Rightarrow$ Low complexity.

$$
\mathbf{r}[m] = \begin{bmatrix} r^{(0)}[m] \\ r^{(1)}[m] \end{bmatrix} = \mathbf{x}_A[m]h_{RA}[m] + \mathbf{x}_B[m]h_{RB}[m] + \mathbf{n}.
$$

(4)
On recovering the bandwidth loss-TWRC

- (decision region $R_1$) If $|r^{(0)}[m]|^2 \geq T$ and $|r^{(1)}[m]|^2 < T$, the transmitted codewords are $(x_0, x_0)$.
- (decision region $R_2$) If $|r^{(0)}[m]|^2 < T$ and $|r^{(1)}[m]|^2 \geq T$, the transmitted codewords are $(x_1, x_1)$.
- (decision region $R_3$) If $|r^{(0)}[m]|^2 \geq T$ and $|r^{(1)}[m]|^2 \geq T$, the transmitted codewords are $(x_0, x_1)$.
- (decision region $R_4$) If $|r^{(0)}[m]|^2 < T$ and $|r^{(1)}[m]|^2 < T$, no decision (the detector fails to detect/estimate the transmitted codewords).

The relay node simply detects the transmitted codewords and not their exact mapping to the sources (e.g. $(x_0, x_1) \equiv (x_1, x_0)$).
On recovering the bandwidth loss-TWRC

- If the codewords $x_0$ and $x_1$ are the mapping of the information symbols $+1$ and $-1$, respectively, the proposed codeword generation process corresponds to a simple multiplication of the detected information symbols.

Modulation at the relay (rule):

- The relay node generates a codeword $X = x_0$, if the detected codewords during the MAC phase are $(x_0, x_0)$ or $(x_1, x_1)$.
- The relay node generates a codeword $X = x_1$, if the detected codewords during the MAC phase are $(x_0, x_1)$. 

\[
\begin{align*}
+1 \times +1 &= -1 \times -1 = +1 \\
+1 \times -1 &= -1 \times +1 = -1 \\
\end{align*}
\]
On recovering the bandwidth loss-TWRC

Each destination employs a simple comparison in order to detect the transmitted symbol.

It multiplies the detected symbol with its own information in order to detect the symbol transmitted by the other source.

\[ r_i[m] = \begin{bmatrix} r_i^{(0)}[m] \\ r_i^{(1)}[m] \end{bmatrix} = X[m]h_{R,i}[m] + n'[m] \]  

- (decision region \( R'_1 \)) if \( |r_i^{(0)}|^2 \geq |r_i^{(1)}|^2 \) the transmitted codeword is \( \hat{X}_i = x_0 \).
- (decision region \( R'_2 \)) if \( |r_i^{(0)}|^2 < |r_i^{(1)}|^2 \) the transmitted codeword is \( \hat{X}_i = x_1 \).
On recovering the bandwidth loss-TWRC

Each destination employs a simple comparison in order to detect the transmitted symbol.

It multiplies the detected symbol with its own information in order to detect the symbol transmitted by the other source.

\[
\begin{bmatrix}
    r_i^{(0)}[m] \\
    r_i^{(1)}[m]
\end{bmatrix} = \begin{bmatrix}
    r_i[m] \cdot h_{R,i}[m] + n'[m]
\end{bmatrix}
\]

- \(x_0\), if \(\hat{X}_i = x_0\) and \(x_i = x_0\).
- \(x_0\), if \(\hat{X}_i = x_1\) and \(x_i = x_1\).
- \(x_1\), if \(\hat{X}_i = x_1\) and \(x_i = x_0\).
- \(x_1\), if \(\hat{X}_i = x_0\) and \(x_i = x_1\).
Optimization of the MAC phase → Optimization of the end-to-end performance.

A wrong detection is dominated by the following two events:

1. The relay node generates the codeword $X = x_0$ for the BC phase when the transmitted couple of codewords was $(x_0, x_0)$ or $(x_1, x_1)$; this means that the relay detects a codeword mixture as $(x_0, x_1)$.

2. The relay node generates the codeword $X = x_1$ for the BC phase when the transmitted couple of codewords was $(x_0, x_1)$ (or $(x_1, x_0)$); this means that the relay detects a codeword mixture $(x_0, x_0)$ or $(x_1, x_1)$. 
On recovering the bandwidth loss—TWRC

\[ T^* = \arg \min_T \left\{ P_e(T) \right\} \]

(\text{where } P_e(T) \propto \mathbb{P} \left[ |r^{(i)}[m]|^2 \geq T \bigg| x_A^{(i)} = x_B^{(i)} = 0 \right] + \mathbb{P} \left[ |r^{(i)}[m]|^2 < T \bigg| x_A^{(i)} = \sqrt{\alpha}, x_B^{(i)} = 0 \right] )

= \arg \min_T \left\{ \mathbb{P} \left[ |r^{(i)}[m]|^2 \geq T \bigg| x_A^{(i)} = x_B^{(i)} = 0 \right] + \mathbb{P} \left[ |r^{(i)}[m]|^2 < T \bigg| x_A^{(i)} = \sqrt{\alpha}, x_B^{(i)} = 0 \right] \right\}

= \arg \min_T \left\{ \mathbb{P} \left[ |n^{(i)}|^2 \geq T \right] + \mathbb{P} \left[ \alpha |h_{RA}|^2 + |n^{(i)}|^2 < T \right] \right\}

= \begin{cases} \frac{\ln \lambda}{\lambda - 1} & \text{If } \lambda \neq 1 \\ 1 & \text{If } \lambda = 1 \end{cases}

(6)

where \( \lambda \triangleq 1/\alpha \). The optimal threshold depends on the average SNR!
The MAC decision threshold significantly impacts on the achieved system performance as it defines the codeword transmitted during the BC phase.

The optimal decision threshold $T^*$ outperforms all the suboptimal $T$ values and ensures a diversity gain equal to 1 at high SNRs.
On recovering the bandwidth loss-TWRC

- The optimal decision threshold ($T^*$) depends on the average SNR and requires an efficient estimation of the average channel statistics.
- $\hat{\alpha} \triangleq \alpha + \epsilon \cdot \alpha$ (overestimation, linear scale), where $\hat{\alpha}$ denotes the estimated average SNR and the parameter $0 \leq \epsilon \leq 1$ represents the percentage error.

- The proposed scheme is not very sensitive to SNR estimation errors and it results in further reductions of implementation complexity, as a strict long-term SNR estimation process is not required.
- A constant threshold ($T \approx 7$) achieves a performance close to the optimal one for the SNR interval considered $\Rightarrow$ Low complexity!
On recovering the bandwidth loss- Cognitive cooperation

- Previous techniques combat the half-duplex limitation from a Physical (PHY) layer (information theoretic) standpoint.
- Higher layers and **bursty nature** of data transmission are not considered.

**Cognitive Cooperation** [Sadek et al., 2007]
- Cross-layer view of cooperation (PHY+NET layers).
- It takes into account (and exploits) the **bursty nature** of data transmission.
- **Key idea:** According to the principles of *Cognitive Radio (CR)*, the relay senses the radio and relays data only when the source is inactive.

Cooperation without extra bandwidth resources.

Existing work incorporates a simple PHY layer.

**More advanced PHY layer schemes?**

Cognitive DDF and superposition [Krikidis et al, 2011].
On recovering the bandwidth loss- Cognitive cooperation

Background on CR:

- Cognitive Radio (CR) senses the radio for transmission opportunities (spectrum holes).
On recovering the bandwidth loss - Cognitive cooperation

Background on CR:

- Cognitive Radio (CR) senses the radio for transmission opportunities (spectrum holes).

Cooperative networks: From half-duplex to full-duplex relaying
On recovering the bandwidth loss- Cognitive cooperation

Cognitive DDF with superposition:

- 2 primary sources $A, B$, 1 relay $S$ with cognition and 1 primary destination $D$ (MARC topology).
- TDMA ($\omega_i$ denote the probability that the $i$-th source is allocated the whole time slot with $0 \leq \omega_i \leq 1$ and $\omega_A + \omega_B = 1$).
- DDF protocol with $M$ subcodewords.
- Bursty traffic ($\lambda_A, \lambda_B$, queues of infinity capacity).
- $R_i$ bits/packet, ACK/NACK mechanism.
- Rayleigh fading, success probability $f_{i,j}(R) \triangleq \mathbb{P}\{\log(1 + P_0|h_{i,j}|^2) > R\}$.

1. a dynamic cooperation when the source is active based on the DDF protocol.
2. a cognitive cooperation when the source is idle.
On recovering the bandwidth loss - Cognitive cooperation

A packet is removed from the $i$ primary queue, when:
- the slot is dedicated to the $i$ source.
- the packet is correctly decoded at the destination or the relay (ACK/NACK); the relay assists the source transmission according to DDF.

By using Loynes’ theorem, the stability region of the user queues, denoted by $L_{C-DDF}^{1}(\omega_A, \omega_B)$, is characterized by:

$$\lambda_i < \mu_i^{(max)} = \omega_i \left[ f_{i,S,D}(R_i) + [1 - f_{i,S,D}(R_i)]f_{i,S}(R_i) \right], \quad i \in \{A, B\}. \quad (7)$$
On recovering the bandwidth loss- Cognitive cooperation

A packet is removed from the $i$ primary queue, when:
- the slot is dedicated to the $i$ source.
- the packet is correctly decoded at the destination or the relay (ACK/NACK); the relay assists the source transmission according to DDF.

By using Loynes’ theorem, the stability region of the user queues, denoted by $L_{C-DDF}^{1}(\omega_A, \omega_B)$, is characterized by:

$$\lambda_i < \mu_i^{(max)} = \omega_i \left[ f_{i,S,D}(R_i) + \left[ 1 - f_{i,S,D}(R_i) \right] f_i,S(R_i) \right], \quad i \in \{A, B\}. \quad (7)$$
On recovering the bandwidth loss- Cognitive cooperation

A packet is removed from the $i$ primary queue, when:
- the slot is dedicated to the $i$ source.
- the packet is correctly decoded at the destination or the relay (ACK/NACK); the relay assists the source transmission according to DDF.

By using Loynes’ theorem, the stability region of the user queues, denoted by $L_{C-DDF}^1(\omega_A, \omega_B)$, is characterized by:

$$\lambda_i < \mu_i^{(\text{max})} = \omega_i \left[ f_i,S,D(R_i) + [1 - f_i,S,D(R_i)] f_i,S(R_i) \right], \ i \in \{A, B\}. \quad (7)$$
On recovering the bandwidth loss- Cognitive cooperation

The relay is **cognitive** and assists the source transmission, when the corresponding source is inactive (silent).

Stability at the relaying queue requires:

\[
\lambda_{Ri} = \omega_i \mathbb{P}\{Q_i \neq 0\} v_{i,S}(R_i) = \omega_i \frac{\lambda_i}{\mu_i^{(\text{max})}} v_{i,S}(R_i) \tag{8}
\]

\[
\mu_{Ri}^{(\text{max})} = \omega_i \mathbb{P}\{Q_i = 0\} f_{S,D}(R_i) = \omega_i \left[1 - \frac{\lambda_i}{\mu_i^{(\text{max})}}\right] f_{S,D}(R_i). \tag{9}
\]

and thus \(L_{C-\text{DDF}^2}(\omega_A, \omega_B)\), is characterized by

\[
\frac{\lambda_i [v_{i,S}(R_i) + f_{S,D}(R_i)]}{f_{i,S,D}(R_i) + v_{i,S}(R_i)} < \omega_i f_{S,D}(R_i), \quad i \in \{A, B\}. \tag{10}
\]
On recovering the bandwidth loss - Cognitive cooperation

- The system is stable if and only if both the users’ queues and the relay’s queues are stable.
- For every \((\omega_A, \omega_B)\), the resulting stability region for the C-DDF protocol is given by the intersection of \(L_{CC1}(\omega_A, \omega_B)\) and \(L_{CC2}(\omega_A, \omega_B)\), which is easily shown to be equal to \(L_{CC2}(\omega_A, \omega_B)\).
- The entire stability region of the conventional CC protocol is given by the union over all \((\omega_A, \omega_B)\) such that \(\omega_A + \omega_B \leq 1\).

\[
L_{C-DDF} = \left\{ (\lambda_A, \lambda_B) : \frac{\lambda_A [v_{A,S}(R_A) + f_{S,D}(R_A)]}{f_{S,D}(R_A) [f_{A,S,D}(R_A) + v_{A,S}(R_A)]} + \frac{\lambda_B [v_{B,S}(R_B) + f_{S,D}(R_B)]}{f_{S,D}(R_B) [f_{B,S,D}(R_B) + v_{B,S}(R_B)]} < 1 \right\} \quad (11)
\]
On recovering the bandwidth loss- Cognitive cooperation

In order to **boost** further cognitive cooperation, we investigate/integrate a *superposition relaying*.

$$Q_B = 0$$

- **superposition with 1-bit feedback** (e.g., 1 when $S \rightarrow D$ can support the rate $R_A + R_B$ otherwise 0)
- **superposition without feedback**.

a) If $Q_{RA} \neq 0, Q_{RB} \neq 0$, the relay serves both relaying queues, one packet from $Q_{RA}$, and one packet from $Q_{RB}$.

b) If $Q_{RA} \neq 0, Q_{RB} = 0$, the relay serves a packet from the relaying queue $Q_{RA}$.

c) If $Q_{RA} = 0, Q_{RB} \neq 0$, the relay serves a packet from the relaying queue $Q_{RB}$.
On recovering the bandwidth loss- Cognitive cooperation

We consider two parallel dominant systems as follows:

- In the dominant system $\mathcal{M}^1$, the relaying queue $Q_{RA}$ will contribute a dummy packet if it is empty, while $Q_{RB}$ acts the same as in the original system.
- In the dominant system $\mathcal{M}^2$, the relaying queue $Q_{RB}$ will contribute a dummy packet if it is empty, while $Q_{RA}$ acts the same as in the original system.

The stability region of the investigated scheme without feedback is $L_{\mathcal{M}^1} \cup L_{\mathcal{M}^2}$.
On recovering the bandwidth loss- Cognitive cooperation

We consider two parallel dominant systems as follows:

- $\mathcal{M}^1$: the relaying queue $Q_{RA}$ will contribute a dummy packet if it is empty, while $Q_{RB}$ acts the same as in the original system.
- $\mathcal{M}^2$: the relaying queue $Q_{RB}$ will contribute a dummy packet if it is empty, while $Q_{RA}$ acts the same as in the original system.

The stability region of the investigated scheme without feedback is $L_{\mathcal{M}^1} \cup L_{\mathcal{M}^2}$.

Stochastic dominance

The above stability conditions are **sufficient** and **necessary** conditions for the stability of the original system.

- The data queues of the dominant system are always larger in size that those of the original system (inner bound $\rightarrow$ sufficient).
- The dominant system becomes similar to the original system at the bounds (indistinguishability $\rightarrow$ necessary)
On recovering the bandwidth loss- Cognitive cooperation

- \( R_A = R_B = 2 \text{ bits per channel use (BPCU)} \).
- \( \rho_{A,D} = \rho_{B,D} = 5 \text{ dB}, \rho_{A,S} = \rho_{B,S} = 12 \text{ dB}, \rho_{S,D} = 30 \text{ dB} \).
- \( M = 3 \)
On recovering the bandwidth loss—Cognitive cooperation

- \( R_A = R_B = 2 \) bits per channel use (BPCU).
- \( \rho_{A,D} = \rho_{B,D} = 5 \) dB, \( \rho_{A,S} = \rho_{B,S} = 12 \) dB, \( \rho_{S,D} = 30 \) dB.
- \( M = 3, \lambda_A = \lambda_B \).

Maximum stable throughput (MST) for the above symmetric configuration:
On recovering the bandwidth loss- Cognitive cooperation

- $R_A = R_B = 2$ bits per channel use (BPCU).
- $\rho_{A,D} = \rho_{B,D} = 4$ dB, $\rho_{A,S} = \rho_{B,S} = 10$ dB, $\rho_{S,D} = 20$ dB.
- $M = 3$
- The cognitive node is able to correctly detect the transmission of the $i$-th primary user if the instantaneous capacity of the link source-relay is larger than a threshold that is equal to $R_i/Q$, where $Q$ is a constant with $Q > 1$.

Impact of sensing error on the stability region:

![Graphs showing the impact of sensing error on stability region for different $Q$ values.](image-url)
On recovering the bandwidth loss- Cognitive cooperation

- $R_A = R_B = 2$ bits per channel use (BPCU).
- $\rho_{A,D} = \rho_{B,D} = 5 \text{ dB}$, $\rho_{A,S} = \rho_{B,S} = 12 \text{ dB}$, $\rho_{S,D} = 15 \text{ dB}$.
- $M = 3$

Impact of feedback on the stability region:

Cooperative networks: From half-duplex to full-duplex relaying
Extension of this work

- This work is based on a TDMA scheduling.
  - Simplifies the analysis.
  - Decouples the interaction between the queues at the sources.
- Extension to conventional Multiple-access channel (MAC) in [Krikidis et al., 2010].
On recovering the bandwidth loss-FD

Full-duplex relaying

- One channel use for the end-to-end transmission.
- Loop interference due to signal leakage between the relay output and input.

Recent advances in antenna technology and signal processing make it feasible.

- Physical distance (isolation) of the transmitted/received antenna front ends.
- Directional antennas.
- Time-domain interference cancellation (analog/digital).
- MIMO precoding schemes (zero-forcing).

Even if a LIC scheme is applied, practical FD implementation suffer from a residual interference (due to practical non-idealities).
On recovering the bandwidth loss-FD

- FD suffers from error floor when loop interference scales with SNR.
- Relay selection can be a useful direction (?)
On recovering the bandwidth loss-FD

- Investigation and theoretical evaluation of several relay selection schemes.
- All the FD-based schemes suffer from error floor (zero-diversity).
- An hybrid scheme ensures diversity.
  - Dynamic switching between HD and FD transmission.

\[
k = \arg \max_i \max \left\{ C_{R_i}^{(HD)}, C_{R_i}^{(FD)} \right\}
\]
\[
= \arg \max_i \max \left\{ \sqrt{1 + \frac{\gamma_{S,R_i} \gamma_{R_i,D}}{\gamma_{S,R_i} + \gamma_{R_i,D} + 1}}, 1 + \gamma_i \right\}
\]
On recovering the bandwidth loss-FD

Figure: $N = 4$ relays, $R_0 = 2$ BPCU, $\sigma_{SR}^2 = \sigma_{RD}^2 = 1$ and $\sigma_{RR}^2 = 0.08$.

Figure: $N = 3$ relays, $R_0 = 2$ BPCU, $\sigma_{SR}^2 = \sigma_{RD}^2 = 1$ and $\sigma_{RR}^2 = 0.01$.

Outline

1. Context of cooperation

2. Combating the half-duplex constraint
   - Buffer-aided relay selection
   - Two-way relay channel
   - Cognitive cooperation
   - Full-duplex relaying

3. Applications

4. Conclusion and future work
Cooperative networks and Cognitive radio (CR)

Cooperation between primary and secondary users

More opportunities for secondary transmission

Cooperative networks: applications
Cooperative networks: applications

Cooperative networks and Cognitive radio (CR)
Cooperation between primary and secondary users
→ More opportunities for secondary transmission

Advanced schemes for cooperation between primary and (clustered) secondary users

Cooperation between primary and secondary users for a primary MAC
Cooperative networks: applications

Cooperative networks and PHY layer secrecy
A source wishes to transmit confidential messages to a destination while keeping the messages as secret as possible from a wiretapper.

Wiretapper channel/Perfect capacity
[Wyner, 1975]
The source can communicate with a perfect secrecy at a rate $R_S = [C_D - C_E]^+$.
Cooperative networks: applications

Cooperative networks and PHY layer secrecy
A source wishes to transmit confidential messages to a destination while keeping the messages as secret as possible from a wiretapper.

Wiretapper channel/Perfect capacity

[Wyner, 1975]

The source can communicate with a perfect secrecy at a rate $R_S = [C_D - C_E]^+$. - Relaying can increase the perfect capacity [Lai et. al., 2008].
Cooperative networks: applications

Cooperative networks and PHY layer secrecy

A source wishes to transmit confidential messages to a destination while keeping the messages as secret as possible from a wiretapper.

Wiretapper channel/Perfect capacity

[Wyner, 1975]

The source can communicate with a perfect secrecy at a rate $R_S = [C_D - C_E]^+$.  
- Relaying can increase the perfect capacity [Lai et. al., 2008].  
- Jamming can increase further the perfect capacity [Yener et. al., 2008]
Cooperative networks: applications

Cooperative networks and PHY layer secrecy
A source wishes to transmit confidential messages to a destination while keeping the messages as secret as possible from a wiretapper.

Wiretapper channel/Perfect capacity
[Wyner, 1975]

The source can communicate with a perfect secrecy at a rate $R_S = [C_D - C_E]^+$. 
- Relaying can increase the perfect capacity [Lai et. al., 2008].
- Jamming can increase further the perfect capacity [Yener et. al., 2008]

An interesting trade-off between relaying and jamming → An appropriate selection of the relay and jammer nodes is required.

Outline

1. Context of cooperation
2. Combating the half-duplex constraint
   - Buffer-aided relay selection
   - Two-way relay channel
   - Cognitive cooperation
   - Full-duplex relaying
3. Applications
4. Conclusion and future work
Conclusion

- Introduction to the cooperation/relaying concept
- Half-duplex relaying- 2 channels $\rightarrow$ spectral loss
  - Buffer-aided relay selection (diversity $2K$)
  - Two-way relay channel (uncoded TWRC with energy detector)
  - Cognitive cooperation (cross-layer cooperation)
  - Full-duplex relaying

- Applications $\rightarrow$ Relaying is a general design paradigm with several applications.
  - Cognitive radio
  - PHY-layer secrecy
Future research plan

Full-duplex relaying

- Investigation of new cooperative schemes that employ a Full-duplex (FD) relaying.
- MIMO relays with FD relaying (precoding strategies), scenarios with loop interference and multi-user interference (space alignment).
- Applications of FD to PHY-layer secrecy, energy efficiency, cognitive radio.
- Integration of FD technology to basic relaying architectures such as TWRC.
**Future research plan**

### Full-duplex relaying

- Investigation of new cooperative schemes that employ a Full-duplex (FD) relaying.
- MIMO relays with FD relaying (precoding strategies), scenarios with loop interference and multi-user interference (space alignment).
- Applications of FD to PHY-layer secrecy, energy efficiency, cognitive radio.
- Integration of FD technology to basic relaying architectures such as TWRC.

**Block-based precoding for single antenna FD (AF/DF) relaying → diversity:**

Cooperative networks: From half-duplex to full-duplex relaying

Thank you!