An Iterative Noncoherent Relay Receiver for the Two-way Relay Channel

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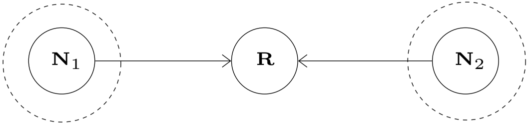
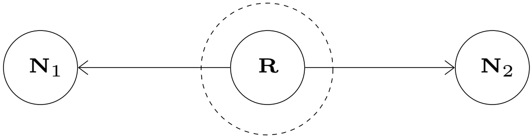
Outline

Physical-Layer Network Coding

- *Two-way relay channel (TWRC)*
  - Two *source* nodes exchange information through a *relay* node.
- *Physical-layer network coding (PLNC)*
  - Sources *deliberately* interfere by transmitting simultaneously to relay.

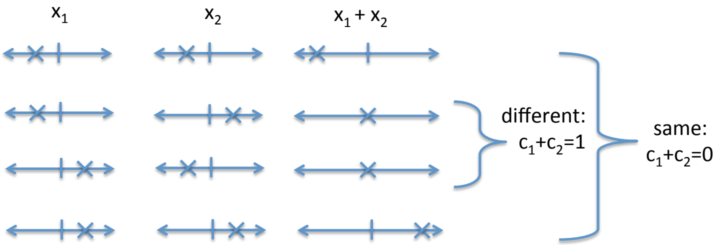


  - Relay broadcasts network-coded information to sources.



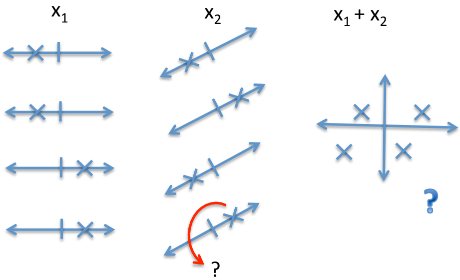
  - Each source subtracts its own information to reveal the information of the other source.

Coherent PLNC with BPSK



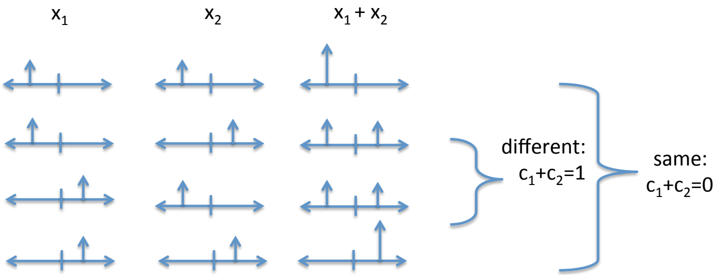
- With BPSK and equal-energy coherent channels, only three possible signals can be received.
- A regenerative relay receiver (decode-and-forward) needs to just determine if the same or different signals were transmitted.
- The relay forwards either a 0 or 1, depending on whether it thinks the same or different signals were received.

Noncoherent PLNC with BPSK



- In a noncoherent channel, the phases of each source-relay link are unknown and generally different.
- The two signals are recieved with an unknown phase offset.
- Creates a distorted constellation.
- Impossible to create decision regions if full receive CSI not available.
- Deviates from the spirit of PLNC.

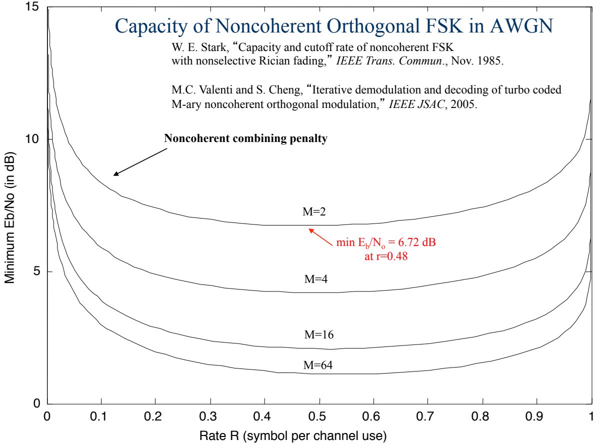
Noncoherent PLNC with FSK



- FSK more amenable to noncoherent communications.
- Receiver senses energy at the two possible tones to determine if the same or different signals were transmitted.
- Noncoherent PLNC with *binary* FSK has been published†.

† [2] M. C. Valenti, D. Torrieri, and T. Ferrett, "Noncoherent physical-layer network coding with FSK modulation: Relay receiver design issues," *IEEE Trans. Commun.*, vol. 59, Sept. 2011.

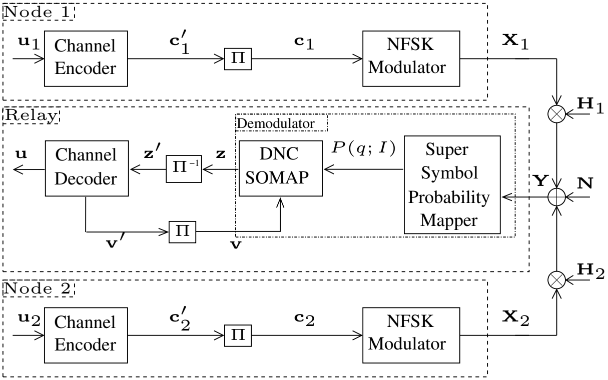
Nonbinary FSK



- It is well known that the energy-efficiency of coded noncoherent FSK improves with increasing M (number of frequency tones).
- Can FSK-based noncoherent PLNC also benefit from increasing M?

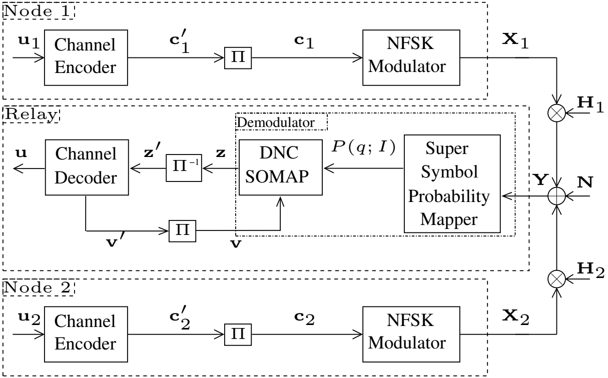
Source Transmission

- Each source generates a binary information sequence.
- Turbo code applied to sequence producing a channel codeword.
- Codeword interleaved and mapped to M-FSK symbols.



Channel Model

- Channel gains are i.i.d., zero-mean, complex Gaussian.
- Relay receives noisy sum of signals from sources.
- Symbols and frames assumed to be perfectly synchronized.



Relay Receiver: Goals

- The relay receiver detects the network-coded combination of bits

$$\mathbf{u} = \mathbf{u}_1 \oplus \mathbf{u}_2$$

- The relay demodulator forms soft bit metrics (LLRs) on

$$\mathbf{c} = \mathbf{c}_1 \oplus \mathbf{c}_2$$

where $\mathbf{c}$ is a codeword from the codebook generating $\mathbf{c}_1$ and $\mathbf{c}_2$, and

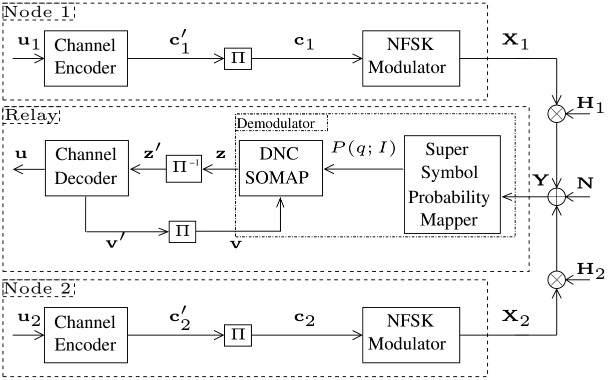
$$\mathbf{c} = f(\mathbf{u}_1 \oplus \mathbf{u}_2)$$
$$\mathbf{c} = f(\mathbf{u}_1) \oplus f(\mathbf{u}_2)$$

and $f(\cdot)$ is the linear channel encoding function,

- The soft bit metrics on $\mathbf{c}$ are passed to the decoder which refines the metrics and feeds them back to the demodulator (BICM-ID processing).

Receiver Diagram

- Goal of relay receiver is to detect network-coded combination of source bits $\mathbf{u} = \mathbf{u}_1 \oplus \mathbf{u}_2$.
- Partial CSI (amplitudes known) and no CSI considered



Super-Symbol Mapping

- The demodulator first computes the probability of all possible combinations of received symbol for each channel observation
- This probability is denoted as $P(q; I)$, where the *super-symbol* q is defined as

$$q = (q_1, q_2) \quad q_1, q_2 \in \mathcal{D} \quad q \in \mathcal{D} \times \mathcal{D}$$

  where:
  - q_1 and q_2 represent symbols transmitted by the two sources.
  - $\mathcal{D}$ is the set of all possible symbols available at sources.
- The cardinality of $\mathcal{D} \times \mathcal{D}$ is M^2, thus the receiver computes M^2 probabilities.

DNC Soft Mapper

- The DNC soft mapper (DNC-SOMAP) computes the LLR of the network coded bits mapped to each received super symbol.

$$z_k = \log \frac{\displaystyle\sum_{q:c_k=1} p(\mathbf{y}|q) \prod_{\substack{j=0 \\ j\neq k}}^{\mu-1} e^{c_j v_j}}{\displaystyle\sum_{q:c_k=0} p(\mathbf{y}|q) \prod_{\substack{j=0 \\ j\neq k}}^{\mu-1} e^{c_j v_j}}$$

where

- z_k - LLR of k-th network-coded bit for the received super symbol.
- $c_{\{k,j\}}$ - $\{k, j\}$-th network-coded bit mapped to super symbol q.
- $\mathbf{y}$ - channel observation for the received super symbol.
- $\mu = \log_2(M)$.
- v_j - j-th extrinsic LLR fed back from decoder.

Super Symbol Probability Model

- The model for $p(\mathbf{y}|q)$ depends on the available CSI
- When the fading amplitudes are known at the relay,
  - Case 1: sources transmit different symbols

$$p(\mathbf{y}|q) = \exp\left\{-\frac{\alpha_1^2+\alpha_2^2}{N_0}\right\} I_0\left(\frac{2|y_{q_1}|\alpha_1}{N_0}\right) I_0\left(\frac{2|y_{q_2}|\alpha_2}{N_0}\right)$$

    where $|y_{q_1}|$ and $|y_{q_2}|$ are the channel observations for the FSK dimensions associated to symbols q_1 and q_2
  - Case 2: sources transmit same symbols

$$p(\mathbf{y}|q) = \exp\left\{-\frac{\alpha^2}{N_0}\right\} I_0\left(\frac{2|y_{q_1}|\alpha}{N_0}\right)$$

    where $\alpha = |\mathbf{h}_1 + \mathbf{h}_2|$ and is approximated as $\alpha = \sqrt{\alpha_1^2+\alpha_2^2}$ [1]

[1] A discussion of this approximation is found in
M. C. Valenti, D. Torrieri, and T. Ferrett, Noncoherent physical-layer network coding with FSK modulation: Relay receiver design issues, IEEE Trans. Commun., vol. 59, Sept. 2011.

Super Symbol Probability Model

- When the fading amplitudes are not known at the relay,
  - Sources transmit different symbols

$$p(\mathbf{y}|q) = \left[\left(\frac{1}{\mathcal{E}_1\mathcal{E}_2}\right)\left(\frac{1}{\mathcal{E}_1} + \frac{1}{N_o}\right)\left(\frac{1}{\mathcal{E}_2} + \frac{1}{N_0}\right)\right]^{-1} \times \exp\left\{\frac{|y_{q_1}|^2\mathcal{E}_1}{N_0(N_0+\mathcal{E}_1)} + \frac{|y_{q_2}|^2\mathcal{E}_2}{N_0(N_0+\mathcal{E}_2)}\right\}$$

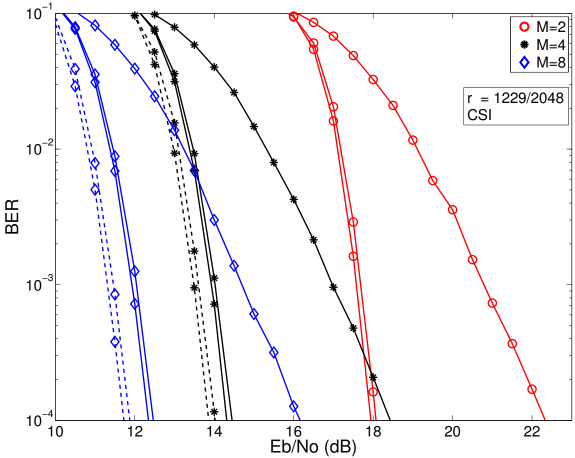
  - Sources transmit same symbols

$$p(\mathbf{y}|q) = \left(\frac{1}{\mathcal{E}_1+\mathcal{E}_2}\right)\left(\frac{1}{\mathcal{E}_1+\mathcal{E}_2} + \frac{1}{N_0}\right)^{-1} \times \exp\left\{\frac{|y_{q_1}|^2(\mathcal{E}_1+\mathcal{E}_2)}{N_0^2 + N_0(\mathcal{E}_1+\mathcal{E}_2)}\right\}$$

Metrics and Parameters

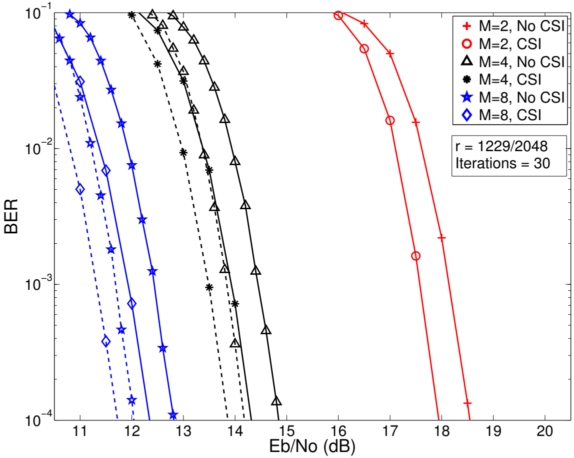
- This section presents simulated error-rate and capacity performance for the relay receiver
- Error-rate performance is simulated as a function of
  - FSK modulation order $\{2, 4, 8\}$
  - Channel state information $\{\text{Partial, None}\}$
  - Decoding iterations $\{1, 2, 4, 30\}$
  - Decoder feedback $\{\text{BICM, BICM-ID}\}$
- The channel code is a UMTS Turbo code with rate $R = 0.6$
- There is a 1:1 ratio of inner decoder to outer BICM-ID iterations
- The sources transmit with equal energy
- Channel capacity is simulated as a function of channel state information and modulation order

Error Rate vs Modulation order and Decoding Iterations



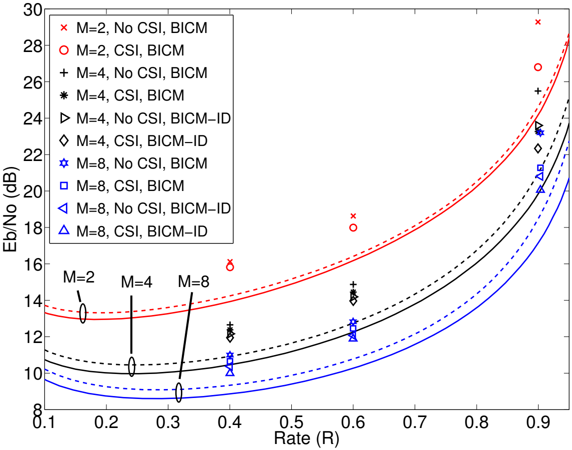
- Partial CSI for all cases
- Solid lines - BICM, dashed lines - BICM-ID
- For each modulation order, right-to-left, iterations are 1, 10, 30

Error Rate vs Modulation Order and CSI



- Solid lines - BICM, dashed lines - BICM-ID
- Number of iterations is 30 for all cases

Binary Information Rate



- Solid lines - CSI, Dashed lines - no CSI
- Symbols denote E_b/N_0 required to reach error rate 10^{-4}
- All receivers perform 30 decoding iterations

- This works presents a relay receiver capable of performing physical-layer network coding in the two-way relay channel using
  - noncoherent FSK modulation
  - iterative soft-decision channel decoding
  - CSI for computation of bit metrics
- Simulation results using the UMTS Turbo code, 4, and 8-ary modulation, and different levels of channel state information show error rate improvements between 0.4-0.9 dB over non-BICM-ID systems.
- Approximately 4 dB gain when going from $M = 2$ to $M = 4$.
- Approximately 2.5 dB gain when going from $M = 4$ to $M = 8$.

Thank you.