Low-Density Lattice Coded Relaying with Joint Iterative Decoding

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- Low density lattice codes (LDLCs) were introduced in [Sommer et al., 08], where it was shown that LDLCs can perform close to AWGN capacity with low decoding complexity.
- Lattice codes also naturally support higher-order modulation as well as signal shaping.

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- Recently, lattice codes have been considered for use in networks with relays:
- **Classical relay channel:** [Ferdinand *et al.* '14]
- **Two-way relay channel (TWRC):** [Baik *et al.* '08], [Wilson *et al.* '10], [Song *et al.* '13]
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- Can we do this with low-complexity joint iterative decoding at the destination?

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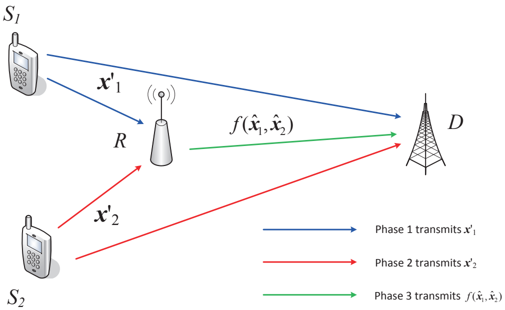
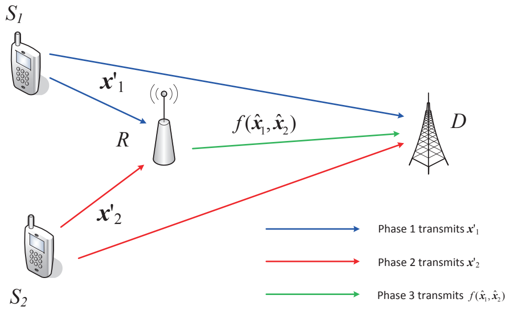
- Present two relaying methods, one having lower decoding complexity and one having a greater power efficiency.
- Propose an efficient joint iterative channel-network decoding algorithm.
- Present a soft symbol relaying technique to mitigate decoding error propagation from the relay.

Three-Phase Transmission Model



- Consider a Multiple Access Relay Channel (MARC) where Users (Sources) S_1 and S_2 each have their own information packets to transmit to the same destination via a shared relay.
- The relay node decodes and forwards a combination message to the destination.
- Three transmission phases (half duplex relay).

Three-Phase Transmission Model



- Messages: Integer (L-ary PAM) information vectors: each source S_i wishes to transmit $\mathbf{b}_i \in \{0, 1, 2, \ldots, L-1\}^n$

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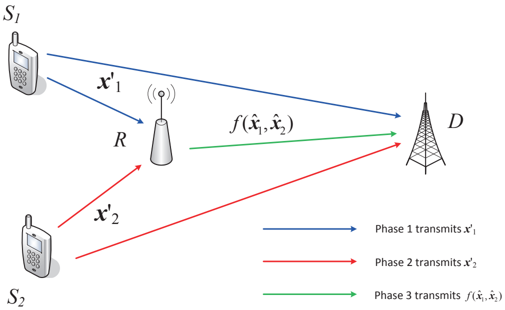

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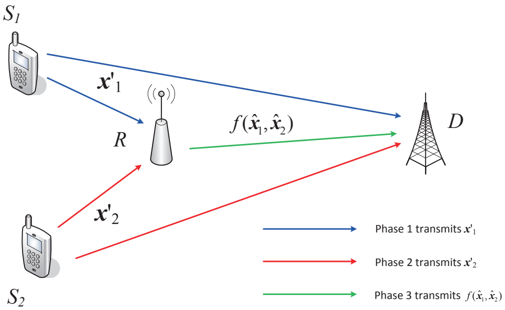

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- Encoding with hypercube shaping: Map each integer information vector $\mathbf{b}_i$ to another integer vector $\mathbf{b}'_i = \mathbf{b}_i - L\mathbf{a}$, where $\mathbf{a} \in \mathbb{Z}^n$

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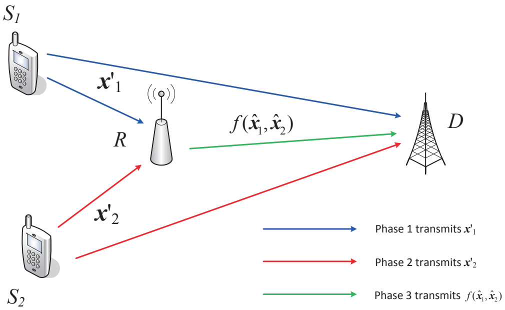

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- Form LDLC codeword $\mathbf{x}'_i = \mathbf{G}\mathbf{b}'_i$, which lies in Λ; use the lower-triangular *parity-check matrix* to encode via $\mathbf{b}'_i = \mathbf{H}\mathbf{x}'_i$

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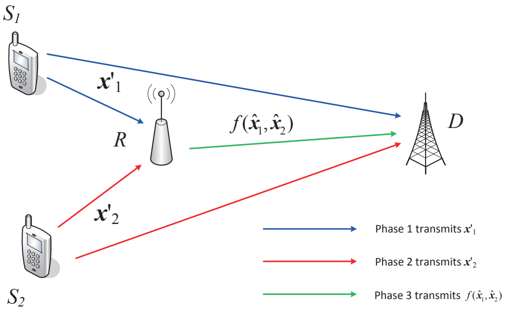

First two phases ($i = 1, 2$):

$$\mathbf{y}_i^R = \sqrt{P_i}\alpha_i^R \mathbf{x}'_i + \mathbf{n}_i^R \ ,$$

$$\mathbf{y}_i^D = \sqrt{P_i}\alpha_i^D \mathbf{x}'_i + \mathbf{n}_i^D \ ,$$

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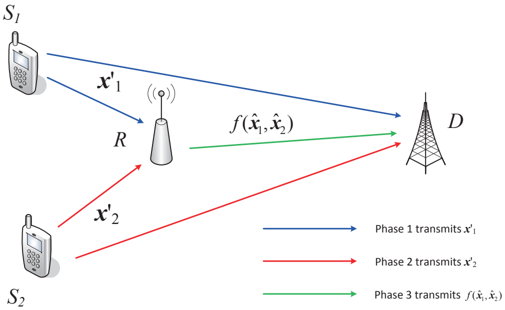

Decoding at relay:

$$\hat{\mathbf{x}}_i = \mathrm{LDLCdecoder}\left(\frac{\mathbf{y}_i^R}{\alpha_i^R \sqrt{P_i}}\right), \quad i = 1, 2$$

- Superposition LDLC (S-LDLC): In this method, the relay simply adds the lattice codewords to form

$$\mathbf{x}_3' = \hat{\mathbf{x}}_1 + \hat{\mathbf{x}}_2$$

which is equivalent to addition of the underlying information vectors, since

$$\mathbf{x}_3' = \hat{\mathbf{x}}_1 + \hat{\mathbf{x}}_2 = \mathbf{G} \cdot (\hat{\mathbf{b}}_1 + \hat{\mathbf{b}}_2)$$

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- Modulo-Addition LDLC (MA-LDLC): In this method, in order to improve the power efficiency of the relay, the LDLC codeword is generated via

$$\mathbf{x}_3' = \mathbf{G} \cdot \mathbf{b}_3'$$

where

$$\mathbf{b}_3' = \hat{\mathbf{b}}_1 + \hat{\mathbf{b}}_2 - L\mathbf{a}$$

and hypercube shaping is used to choose the integer vector $\mathbf{a}$.

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MA-LDLC provides better power efficiency, but requires more complex decoding at the destination.

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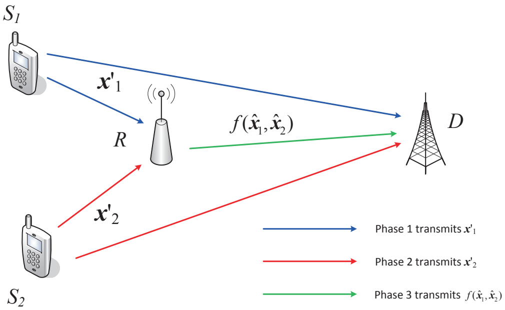

The lattice point $\mathbf{x}'_3$, which can be considered as a network coded component, will be transmitted from the relay to the destination, i.e.,

$$\mathbf{y}_3^D = \sqrt{P_3}\alpha_3^D \mathbf{x}'_3 + \mathbf{n}_3^D$$

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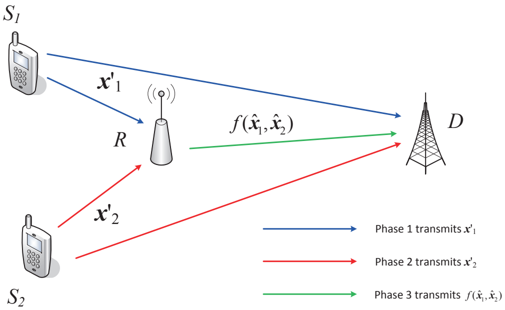

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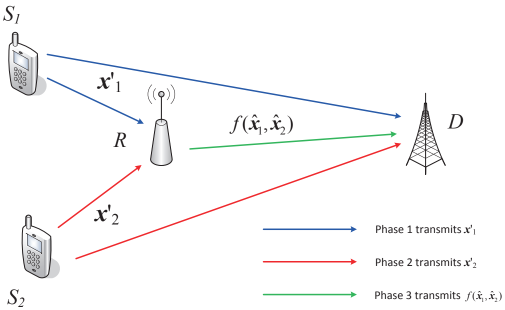
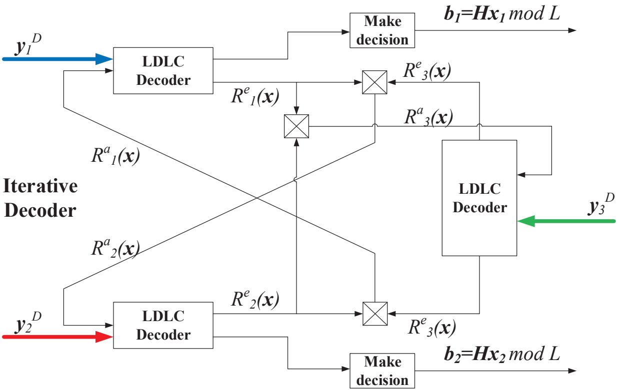
Finally, the destination uses the signals $\mathbf{y}_1^D$, $\mathbf{y}_2^D$ and $\mathbf{y}_3^D$ to jointly decode $\mathbf{b}_1$ and $\mathbf{b}_2$.

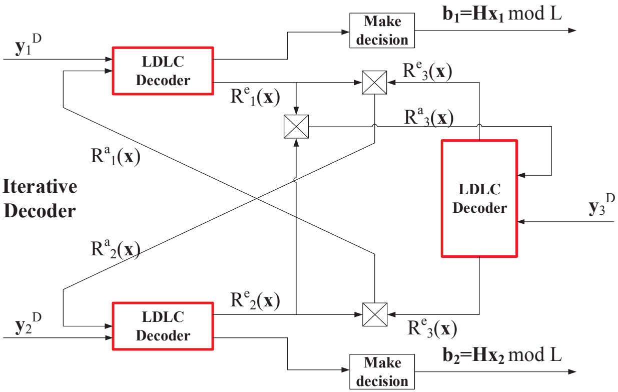
Three-Phase Transmission Model



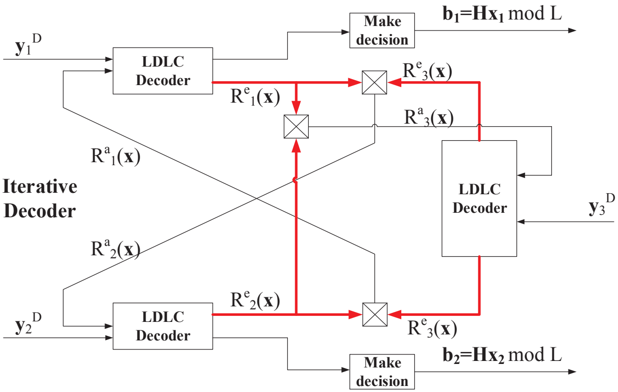
- Key problem: how to efficiently recover the information symbols at the destination based on the signals received.
- Therefore, we next focus on the joint iterative decoding structure.



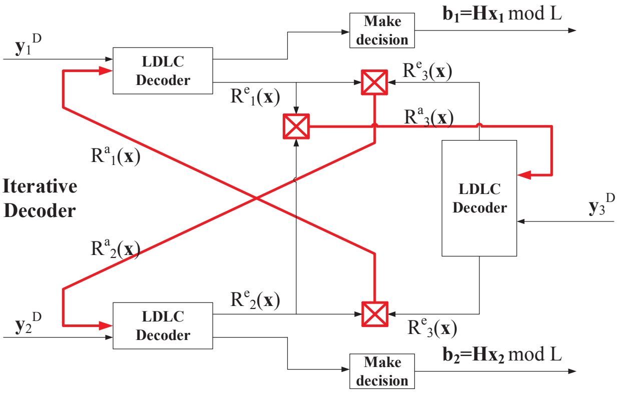
- At destination, the LDLC decoders receive three packets from three independent channels.



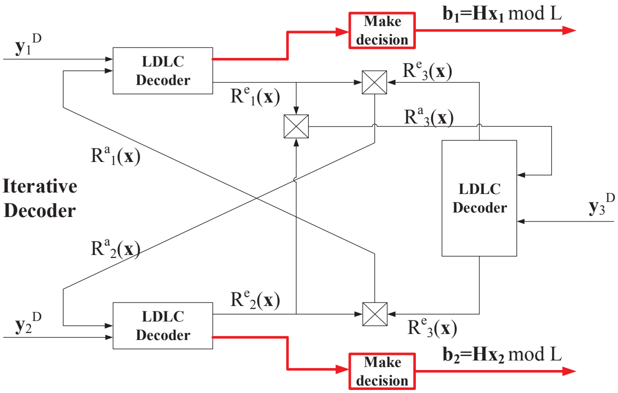
- **Inner iterations**: Each LDLC decoder performs M inner iterations.



- **Outer iteration**: After every M inner iterations of LDLC decoding, the network coding nodes implement one outer iteration to exchange extrinsic information between the LDLC decoders.

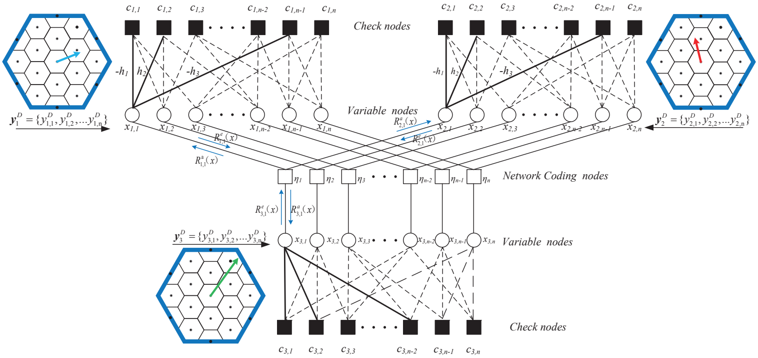


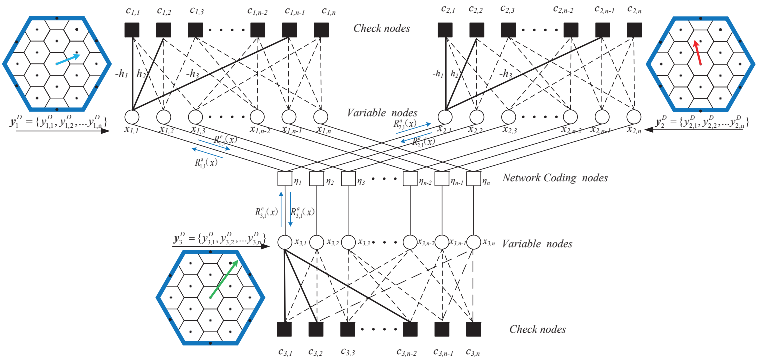
- **Outer iteration**: The extrinsic information $R^a(\mathbf{x})$ will be considered as *a priori* information for each decoder in the next iteration.



- **Final decision**: After several inner and outer iterations, the final variable node messages are calculated to make decisions for information symbol vector $\mathbf{b}_i$.

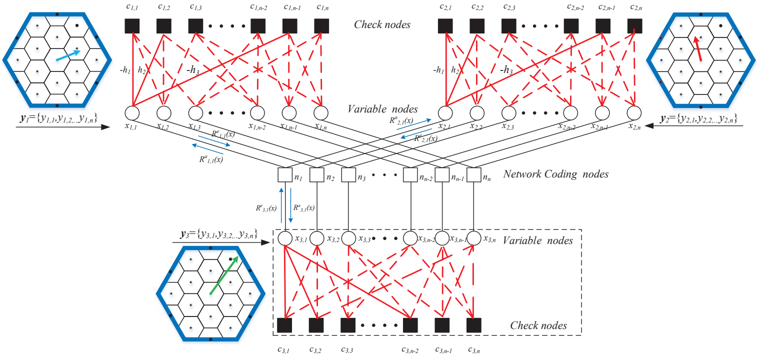
Factor graph





- **Decoder i:** Initially each variable node $x_{i,k}$ sends the message

$$f_{i,k,j}(x) = \frac{1}{\sqrt{\pi N_0}} e^{-\frac{\left(y_{i,k}^D - \sqrt{P_i}\alpha_i^D x\right)^2}{N_0}}$$ to each neighboring check node $c_{i,j}$



- **Inner iterations**: each LDLC decoder performs M inner iterations.
  1. Check-to-variable messages
  2. Variable-to-check messages

Check node message at decoder i: each check node $c_{i,j}$ sends a PDF function $Q_{i,j,k}(x)$ to each of its neighboring variable nodes $x_{i,k}$.

a. Convolution step: All messages, except $f_{i,k,j}(x)$, are convolved (after expansion of each $f_{i,l,j}(x)$ by the factor $h_{j,l}$):

$$\widetilde{p}_{i,j,k}(x) = \bigotimes_{\substack{l \in \mathcal{A}_j \\ l \neq k}} f_{i,l,j}\left(\frac{x}{h_{j,l}}\right)$$

where the set $\mathcal{A}_j$ denotes the set of indices l for which $h_{j,l} \neq 0$.

b. Stretching step:

$$p_{i,j,k}(x) = \widetilde{p}_{i,j,k}(-h_{j,k}x)$$

c. Periodic extension step: extend with period $1/|h_{j,k}|$

$$Q_{i,j,k}(x) = \sum_{a \in \mathbb{Z}} p_{i,j,k}\left(x - \frac{a}{h_{j,k}}\right)$$

Variable node message at decoder *i*: each variable node $x_{i,k}$ sends a message $f_{i,k,j}(x)$ to each of its neighboring check nodes $c_{i,j}$.

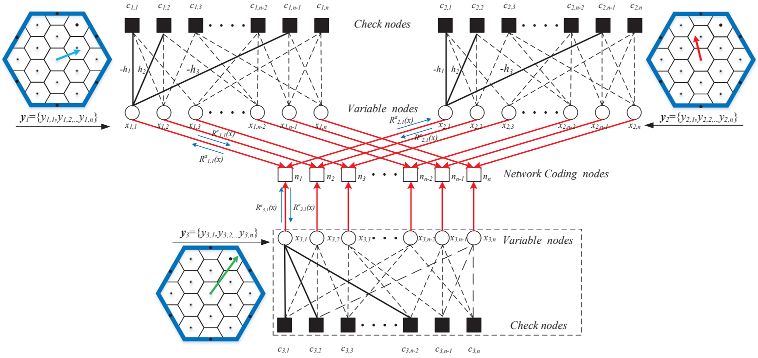
a. Variable node update rule:

$$\widetilde{f}_{i,k,j}(x) = e^{-\frac{(y^D_{i,k} - \sqrt{P_i}\alpha^D_i x)^2}{N_0}} R^a_{i,k}(x) \prod_{\substack{l \in \mathcal{B}_k \\ l \neq j}} Q_{i,l,k}(x)$$

where the set $\mathcal{B}_k$ denotes the set of indices l for which $h_{l,k} \neq 0$.

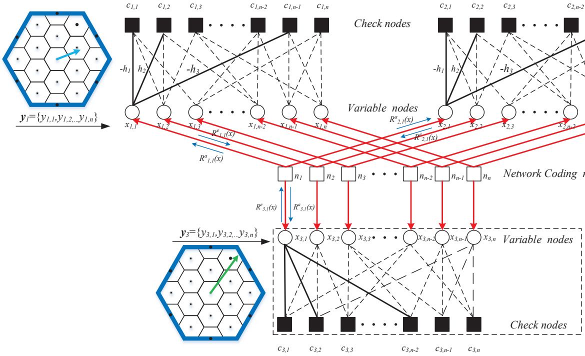
b. Normalization step:

$$f_{i,k,j}(x) = \frac{\widetilde{f}_{i,k,j}(x)}{\int_{-\infty}^{\infty} \widetilde{f}_{i,k,j}(x)dx}$$



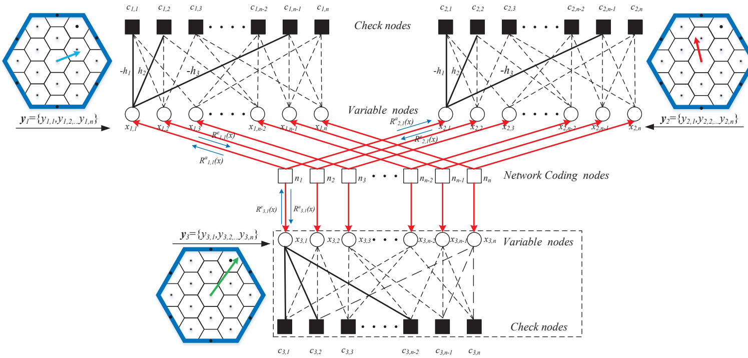
- **Outer iteration**: After M inner iterations, each variable node $x_{i,k}$ will send the extrinsic message $R^e_{i,k}(x)$ to the corresponding network coding node n_k :

$$R^e_{i,k}(x) = e^{-\frac{(y^D_{i,k} - \sqrt{P_i}\alpha^D_i x)^2}{N_0}} \prod_{l \in \mathcal{B}_k} Q_{i,l,k}(x)$$



S-LDLC:

$$\begin{array}{l} R^e_{1,k}(x') \searrow \\ \qquad\qquad \overset{\text{convolution}}{\bigotimes} \rightarrow R^a_{3,k}(x') \\ R^e_{2,k}(x') \nearrow \end{array}$$



MA-LDLC:

$$R^e_{1,k}(x') \xrightarrow{\mathbf{H}} R^e_{1,k}(b') \searrow$$

$$\overset{\text{convolution}}{\bigotimes} \xrightarrow{\text{extension}} R^a_{3,k}(b') \rightarrow R^a_{3,k}(x')$$

$$R^e_{2,k}(x') \xrightarrow{\mathbf{H}} R^e_{2,k}(b') \nearrow$$

Details: MA-LDLC

1. According to the relationship between $\mathbf{b}'_i = \mathbf{H}\mathbf{x}'_i$, we can calculate the corresponding extrinsic PDFs of $\mathbf{b}'_i$ by convolution:

$$R^e_{i,l}(b') = \bigotimes_{r \in \mathcal{A}_l} R^e_{i,r}\left(\frac{x'}{h_{l,r}}\right) .$$

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2. According to the modulo addition relationship, for each l we can write $b'_{1,l} + b'_{2,l} - b'_{3,l} = a_l L, a_l \in \mathbb{Z}$. We first calculate the PDF message for the sum of $b'_{1,l}$ and $b'_{2,l}$ using convolution:

$$r^a_{3,l}(b') = R^e_{1,l}(b') \otimes R^e_{2,l}(b')$$

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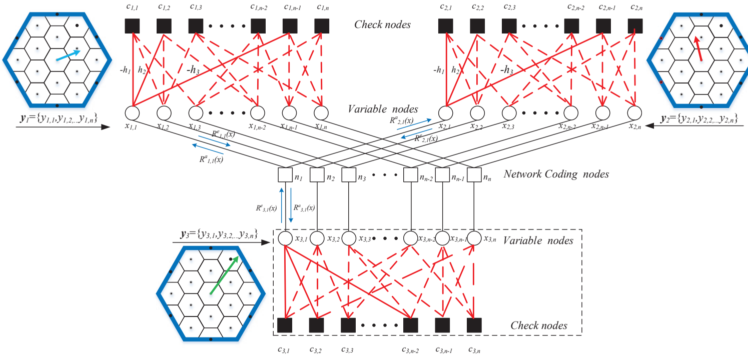
3. Then, we periodically extend the appropriate PDFs $r^a_{3,l}(b')$ via

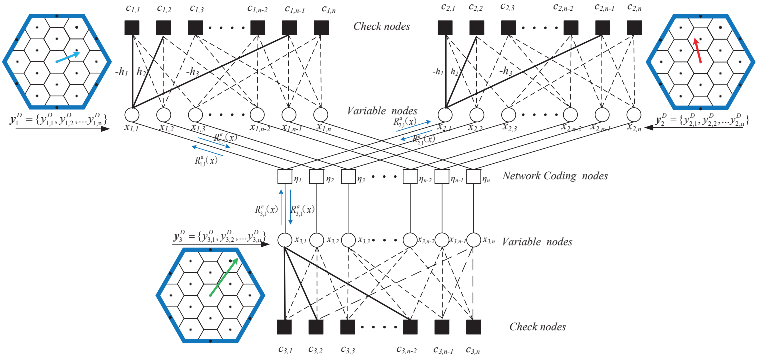
$$R^a_{3,l}(b') = \sum_{a \in \mathbb{Z}} r^a_{3,l}(b' - aL)$$

and combine to calculate the *a-priori* information for the LDLC codeword element $x'_{3,k}$ (using $\mathbf{x}'_3 = \mathbf{G}\mathbf{b}'_3$):

$$R^a_{3,k}(x') = \bigotimes_{l \in \mathcal{C}_k} R^a_{3,l}\left(\frac{b'}{g_{k,l}}\right)$$

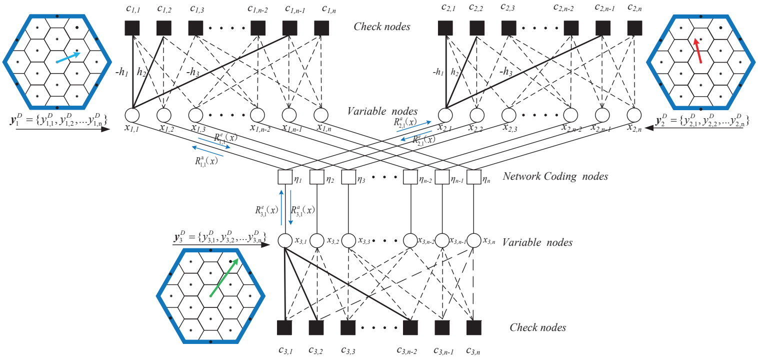


- The resulting messages $R^a_{i,k}(x)$ are generated from the network coding nodes.
- Each LDLC decoder will repeat the inner and outer iterations until the maximum outer iteration number N is achieved or until all message variances lie below a preset threshold value ξ.



- **Final decision:** after a maximum of MN LDLC iterations, the final variable node PDF is calculated via

$$\widetilde{f}_{i,k,j} = e^{-\frac{(y_{i,k}^D/(\alpha_i^D\sqrt{P_i})-x)^2}{2\sigma^2}} R_{i,k}^a(x) \prod_{l\in\mathcal{B}_k} Q_{i,l,k}(x) \, .$$



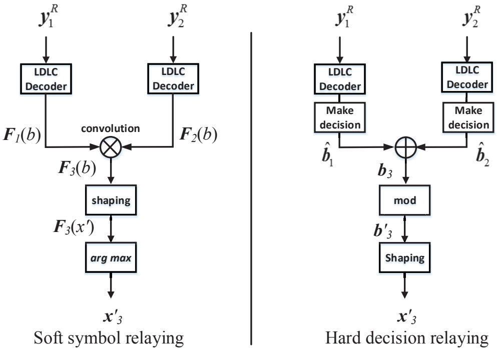
The integer vector $\mathbf{b}_i$ is then estimated as

$$\hat{\mathbf{x}}_{i,k} = \arg\max \widetilde{f}_{i,k,j}(x), \quad i = 1, 2$$

and

$$\hat{\mathbf{b}}_i = \lfloor \mathbf{H}\hat{\mathbf{x}}_i \rceil \mod L, \quad i = 1, 2$$

Soft Symbol Relaying



- Hard decision relaying can cause error propagation to the destination under poor SR-link SNR conditions (in case of incorrect decoding at the relay).
- Soft symbol relaying chooses as symbol estimate that real vector $\mathbf{x'}_3$ which maximizes the multidimensional PDF $F_3(\mathbf{x'})$.

Complexity of Joint Decoding

- Gaussian mixture model (GMM) usually used for representing PDFs (messages)
- Complexity dominated by Gaussian mixture reduction algorithm; using GMM with T Gaussians, complexity of GMR is proportional to T^4 [Kurkoski Dauwels '08]
- Let E_h = number of edges in the LDLC Tanner graph; N_d = number of outer iterations
- Check node operations: Complexity is approximately proportional to $MN_dE_hT^4$
- Variable node operations: Complexity is approximately proportional to $MN_d(E_h + n)T^4$
- Network coding nodes: Complexity is approximately proportional to $N_d(2E_h + n)T^4$
- Therefore, total complexity is proportional to $N_d[(2M + 2)E_h + (M + 1)n]T^4$.
- We use the single-Gaussian approximation method ($T = 1$, [Kurkoski *et al.* '09]) for large block size LDLCs ($n = 1000$).

Simulation scenario

We compare S-LDLC and MA-LDLC with three competing schemes in a quasi-static Rayleigh fading environment

- Non-cooperative LDLC
- Network coded 4-PAM cooperation without channel coding (NC)
- Network-Turbo-coded 4-PAM cooperation (NTC) – similar to [Hausl. et al., 06], but with 4-PAM modulation.

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We set the link SNRs as follows:

- $\gamma_{S_1 D} = \gamma_{S_2 D} = \gamma_{SD}$
- $\gamma_{S_1 R} = \gamma_{S_2 R} = \gamma_{SR}$
- $\gamma_{SR} = \gamma_{RD} = \gamma_{SD} + 6$ dB; we vary the SD link SNR.

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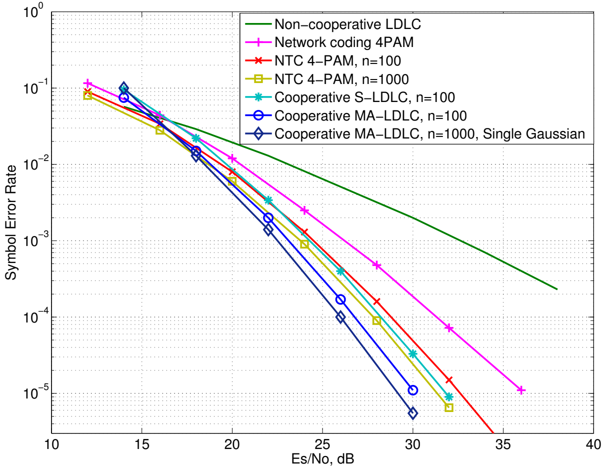
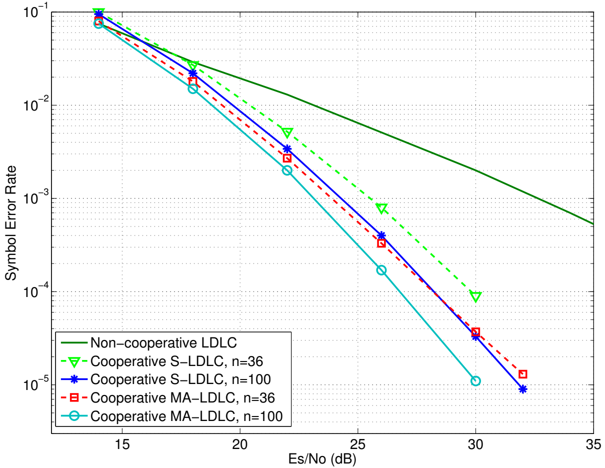
All compared schemes were normalized to have the same overall transmitted power and code rate (4/3 bits/symbol).



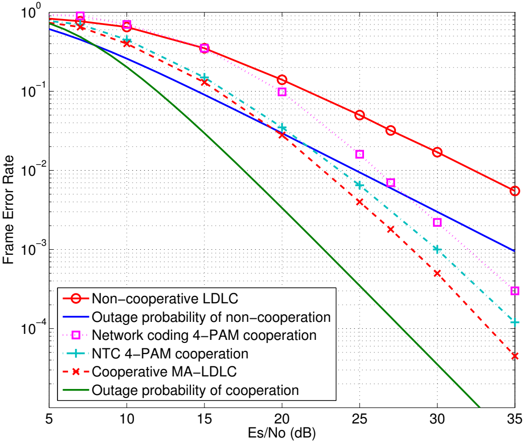
- MA-LDLC scheme outperforms all other cooperative schemes
- At SER of 10^{-5}, gain is 6.2dB over NC 4-PAM, and 2.5dB over NTC 4-PAM.

Performance variation with block length



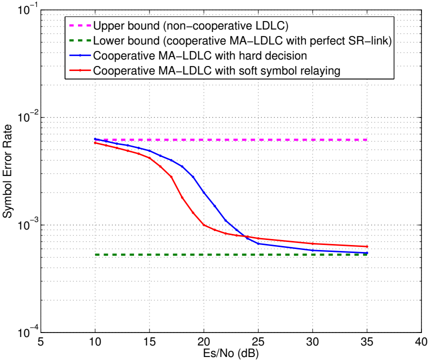
- For fixed block length, MA-LDLC outperforms S-LDLC.

Outage Probability and FER



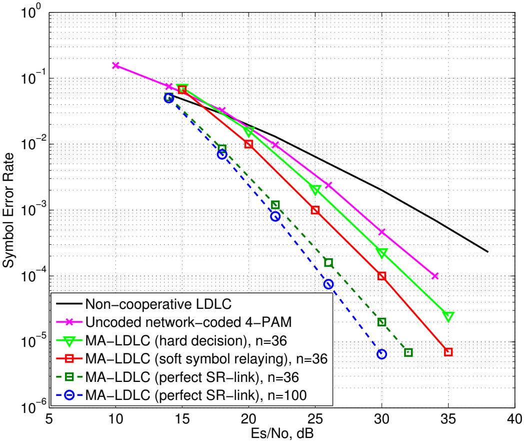
- At an FER of 10^{-4}, MA-LDLC outperforms NC 4-PAM by about 4dB, and NTC 4-PAM by about 2dB.

Soft symbol relaying



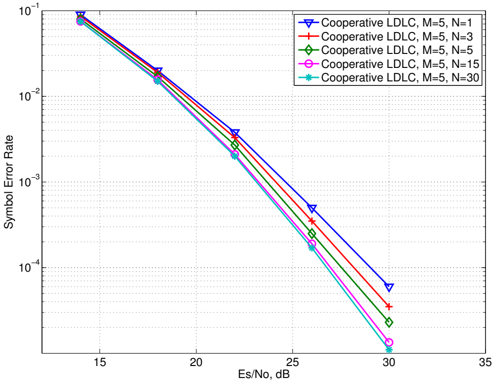
- We fix $\gamma_{SD} = \gamma_{RD} - 3$ dB $= 25$ dB and vary γ_{SR}.
- Soft symbol relaying outperforms hard decision relaying when γ_{SR} is worse than γ_{SD} (the maximum gain is 2.5dB at an SER of 10^{-3}).
- As γ_{SR} increases, hard decision relaying outperforms soft symbol relaying due to the forwarding of the correct LDLC codeword almost every time by the relay.

Soft symbol relaying



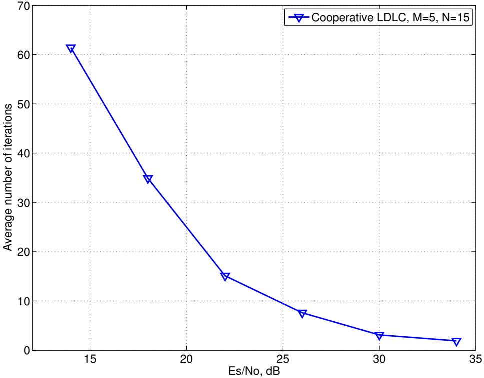
- Here $\gamma_{SD} = \gamma_{SR} + 5dB = \gamma_{RD} - 3dB$, and we vary γ_{SD}.

Choosing the inner and outer iteration numbers



- Inner iteration number M is chosen as 5 to balance the convergence rate and decoding complexity.
- It can be seen that there is marginal benefit for increasing outer iterations N beyond 15.

Investigation of the average required number of iterations



- Plot shown for $n = 1000$, single-Gaussian approximation decoding.
- Average required number of iterations per LDLC decoder decreases quickly with increasing SNR.

Summary

- We have proposed a new scheme for coded cooperation, based on joint network coding and low-density lattice coding
- Outlined two approaches for relay processing: S-LDLC and MA-LDLC
  - S-LDLC has low decoding complexity due to the simple superposition of codewords;
  - MA-LDLC has better performance (shaping gain) due to the usage of modulo-addition which can improve the power efficiency of the relay.
- Designed an efficient joint iterative decoding structure at the destination node.
- Proposed a soft symbol relaying method to mitigate the error propagation.
- The proposed scheme provides 2.5dB SER gain over network-turbo-coded 4-PAM and may be easily extended to the case of multiple sources.

Thank You