Spectrum Efficient Cooperative Communications A Message Partitioning Based Approach

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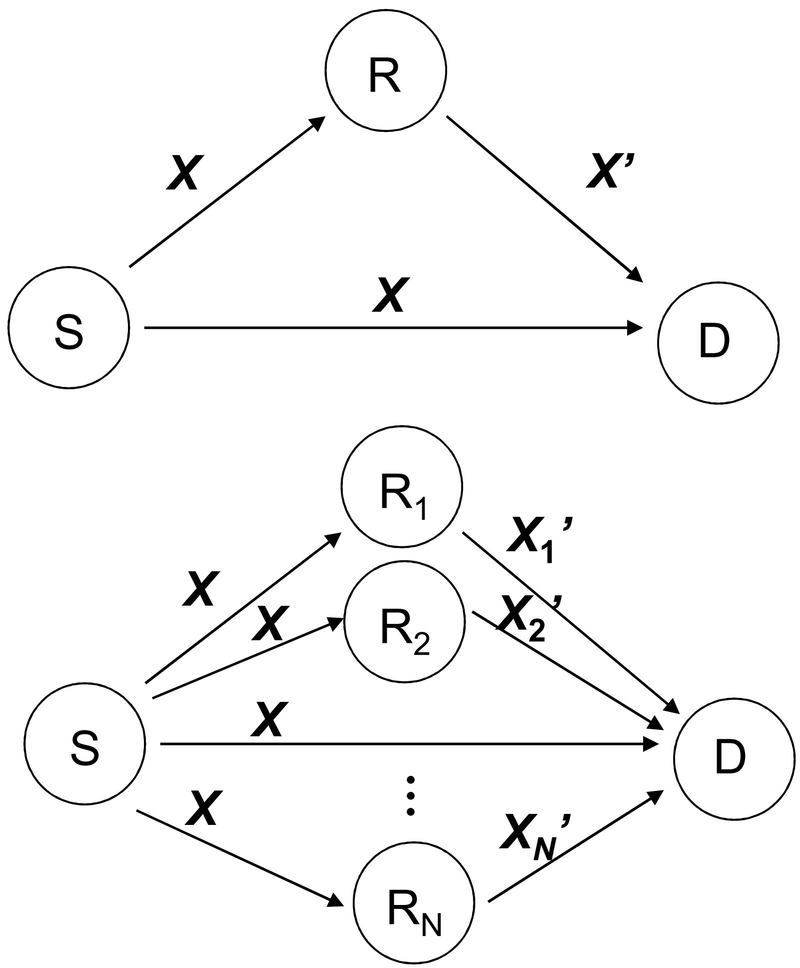
Outline

- Distributed cooperative communications
- The existing distributed cooperation approaches
- Advantage and prices
- The MPDAF scheme and its system model (physical and MAC layers)
- DMT analysis (outage probability performance validation)
- Code MPDAF systems (an example on realising the diversity gain)
- Conclusions and future work

Distributed cooperative communications



Cooperation with a single relay

$Y_D = \alpha_{SD}\, X + \alpha_{RD}\, X' + N$

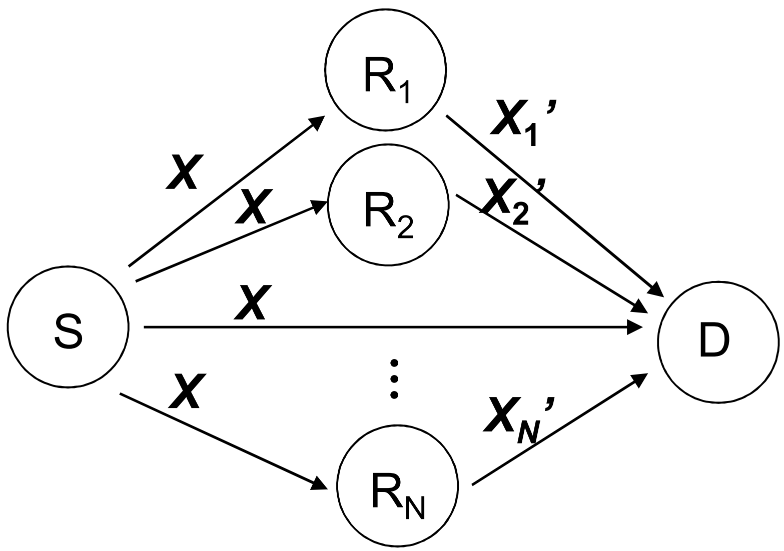
Transmission diversity has been increased

Cooperation with multiple relays

$Y_D = \alpha_{SD}\, X + \alpha_{R1D}\, X_1' + \alpha_{R2D}\, X_2' + \ldots + \alpha_{RND}\, X_N' + N$

Received symbols Y_D are more reliable!

The existing dist. coop. approaches



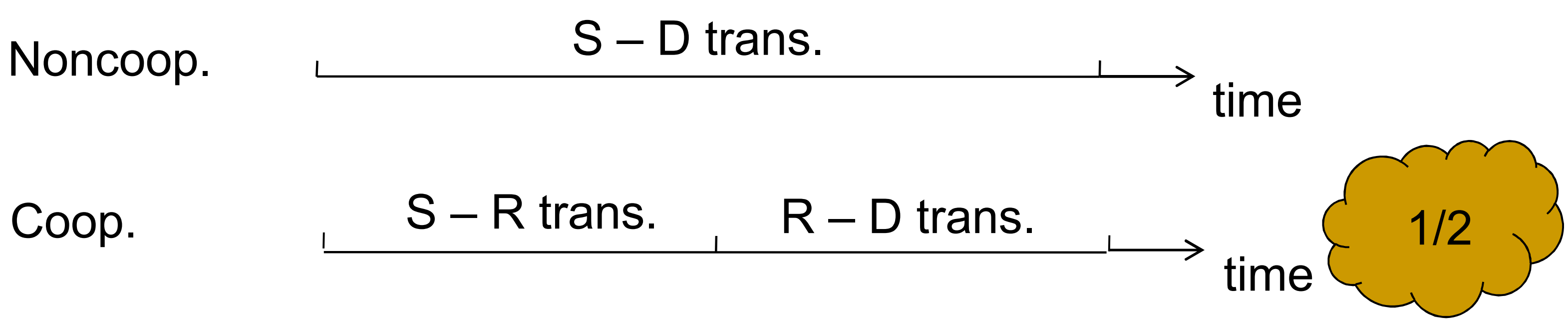
- Repetition-based dist. coop.
  - X_i' is either the amplified or re-encoded version of ***X***;
  - RDAF & RDDF
  - Relays have to take turns for signal retransmission;
- Space-time coded dist. Coop.
  - X_i' are the re-encoded version of ***X***;
  - STC;
  - Relays can simultaneously re-transmit X_i';

Advantages and prices

- Diversity gains come with prices
  - Usage of channel freedom (vs. noncoop.)
  - Efficiency of transmission (vs. noncoop.)

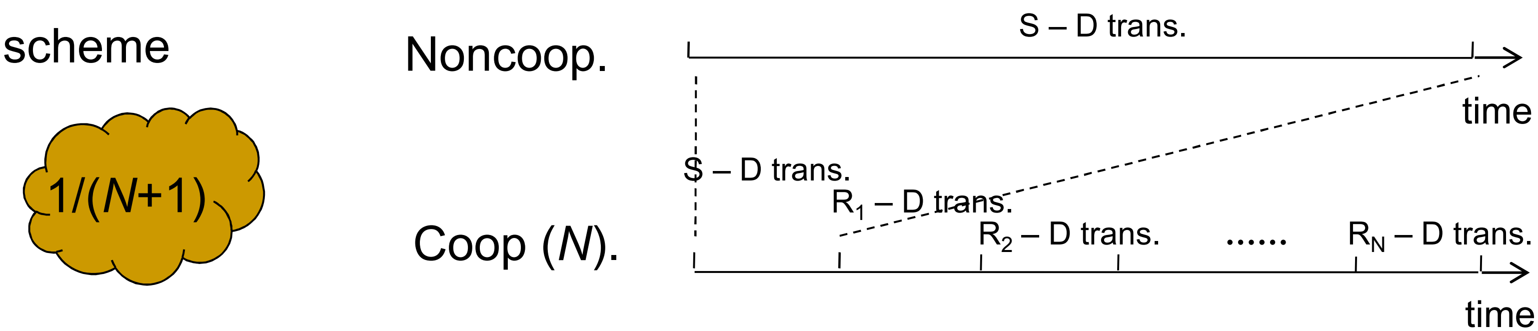
- Problem formulations
  - ***Definition I:*** *In a cooperative network, a user's transmission freedom is defined as the ratio of the broadcasting transmission employed by a user in a particular cooperative scheme to that employed in a noncooperative scheme.*

  - E.g. In a (S, R, D) three users classical network, usage of channel



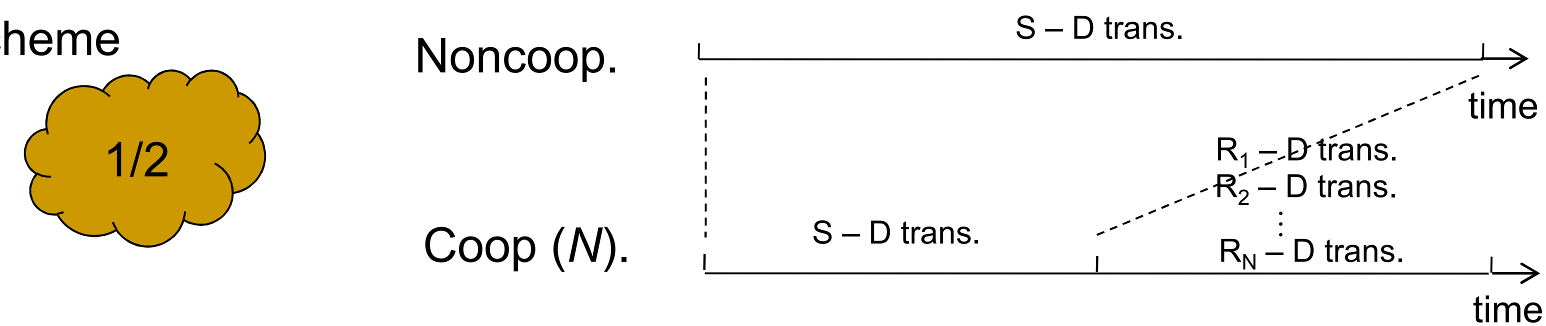
Advantages and prices

- Usage of channel freedom
- RDAF scheme



Transmission freedom is decreased by increasing *N*!

- STC scheme



Transmission freedom can be maintained at ratio ½!

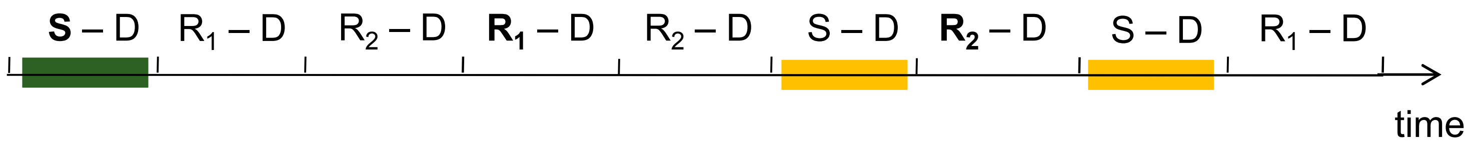
- Analytical tool: diversity-multiplexing tradeoff (DMT).

Advantages and prices

- Problem formulation
  - Efficiency of transmission

    E.g., in RDAF with users S, R_1, R_2 and D

    TDMA channel allocation



  - ***Definition II:*** *In a cooperative network, a user's spectral efficiency is defined as the number of its own information bits carried by each of its transmitted symbol, denoted by Γ bits/symbol.*

  - S_{BT} – number of symbols transmitted during the broadcasting interval

    S_{RT} – number of symbols transmitted during the relaying interval

    θ – code rate, m – order of the modulation scheme (e.g. m = 2 for QPSK, m = 4 for 16QAM)

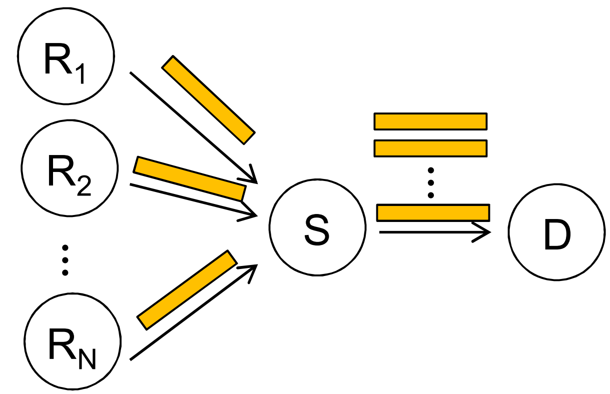
$$\Gamma = \theta \cdot m \cdot S_{BT} / (S_{BT} + S_{RT})$$

Advantages and prices

- Special cases:

  Noncoop. $S_{RT} = 0$, $\Gamma = \theta \cdot m$

  In (S, R, D) network, $S_{RT} = S_{BT}$, $\Gamma = \theta \cdot m / 2$.



- For both the RDAF/RDDF and STC schemes:

  $S_{RT} = N \cdot S_{BT}$,

  $$\Gamma = \theta \cdot m \cdot S_{BT} / (S_{BT} + S_{RT}) = \theta \cdot m \cdot S_{BT} / (S_{BT} + NS_{BT}) = \theta \cdot m / (N+1)$$

- The existing dist. coop. approaches achieve diversity gain on the expense of user spectral efficiency.

- Note, opportunistic relaying is an exemption, but requires more intelligent users coordination and system complexity.

Advantages and prices

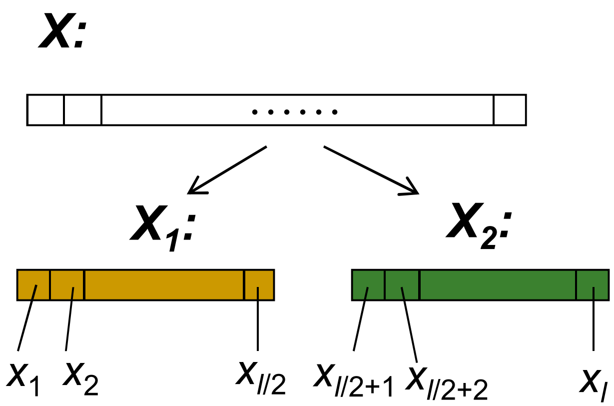
Schemes / Relays (*N*)	RDAF	STC
Transmission freedom	$1/(N+1)$	1/2
Spectral efficiency (Γ bits/symbol)	$\theta \cdot m / (N+1)$	$\theta \cdot m / (N+1)$
System complexity	Ana. manipulations, no dec. & re-enc. are required at relays	Dig. manipulations, dec. & re-enc. are required at relays

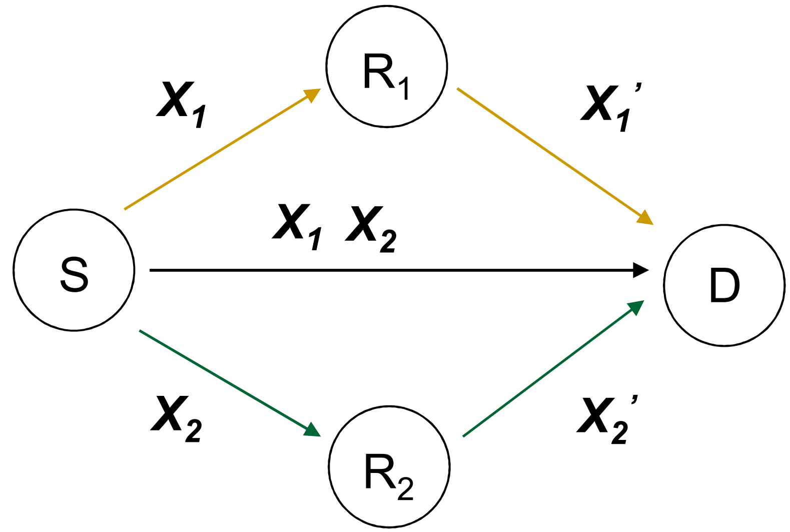
Motivation: Can we design a scheme that maintains {transmission freedom, spectral efficiency, low system complexity}?

The MPDAF scheme

Message Partitioning Based Distributed Amplify-and-Forward Cooperation

With two relays





$\boldsymbol{Y}_D = [\boldsymbol{Y}_D^{I}\ \boldsymbol{Y}_D^{II}] + \boldsymbol{N}$

$\boldsymbol{Y}_D^{I} = \alpha_{SD}\, \boldsymbol{X}_1 + \alpha_{R1D} \boldsymbol{X}_1'$

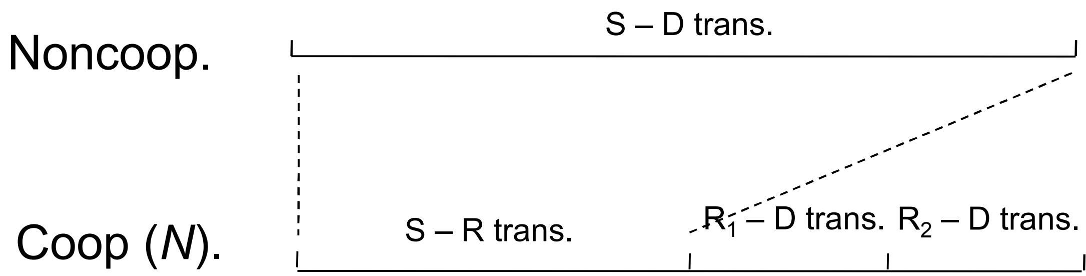
$\boldsymbol{Y}_D^{II} = \alpha_{SD}\, \boldsymbol{X}_2 + \alpha_{R2D}\, \boldsymbol{X}_2'$

Diversity order: $|\ \alpha_{SD}, \alpha_{R1D}, \alpha_{R2D}\ | = 3.$

Note that with *N* relays, the message ***X*** will be partitioned into *N* equal parts. Each relays only re-transmits *l*/*N* symbols.

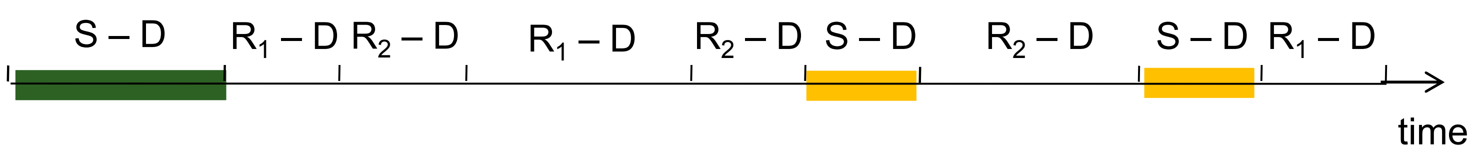
The MPDAF scheme

- Usage of transmission freedom



- Efficiency of transmission

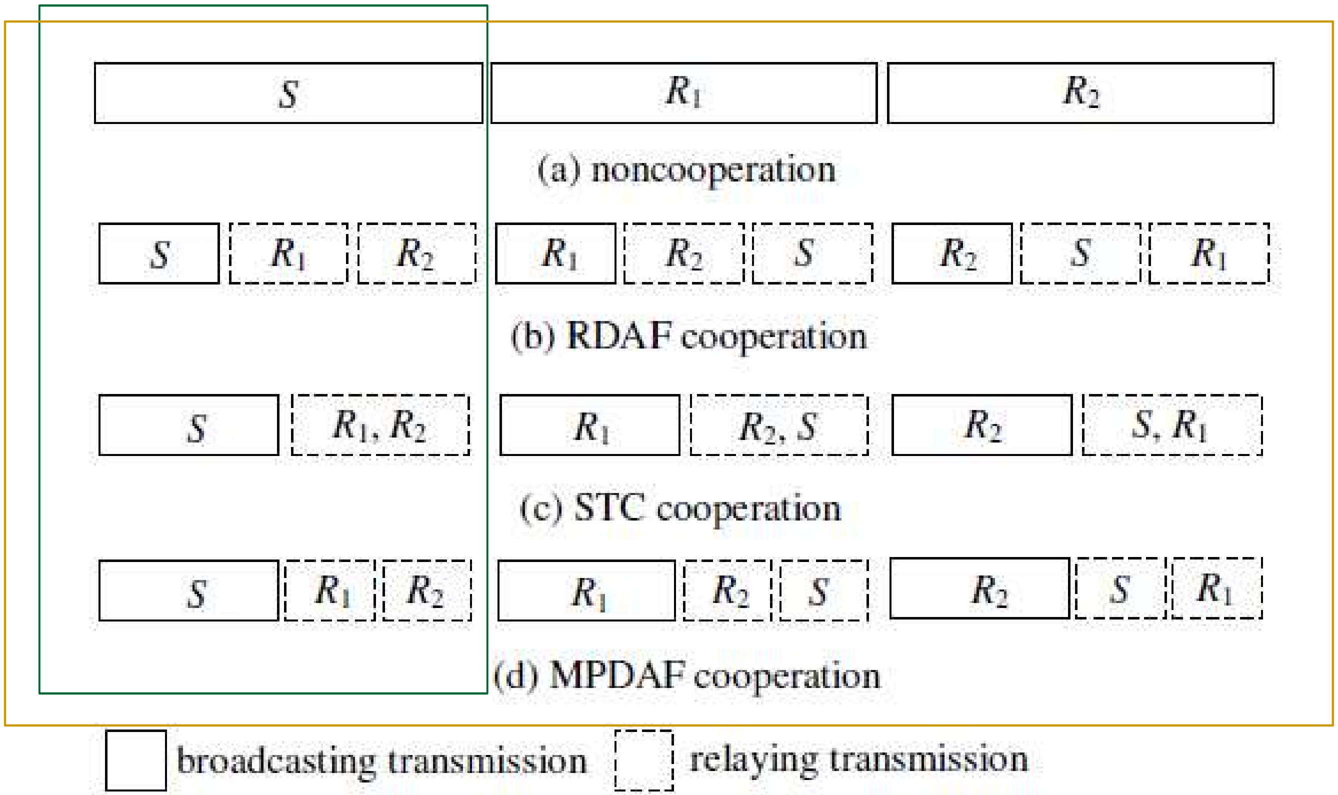
TDMA channel allocation



$S_{RT} = S_{BT} \rightarrow \Gamma = \theta \cdot m / 2$ bits/symbol!

The MPDAF scheme

A comparison on the channel usage

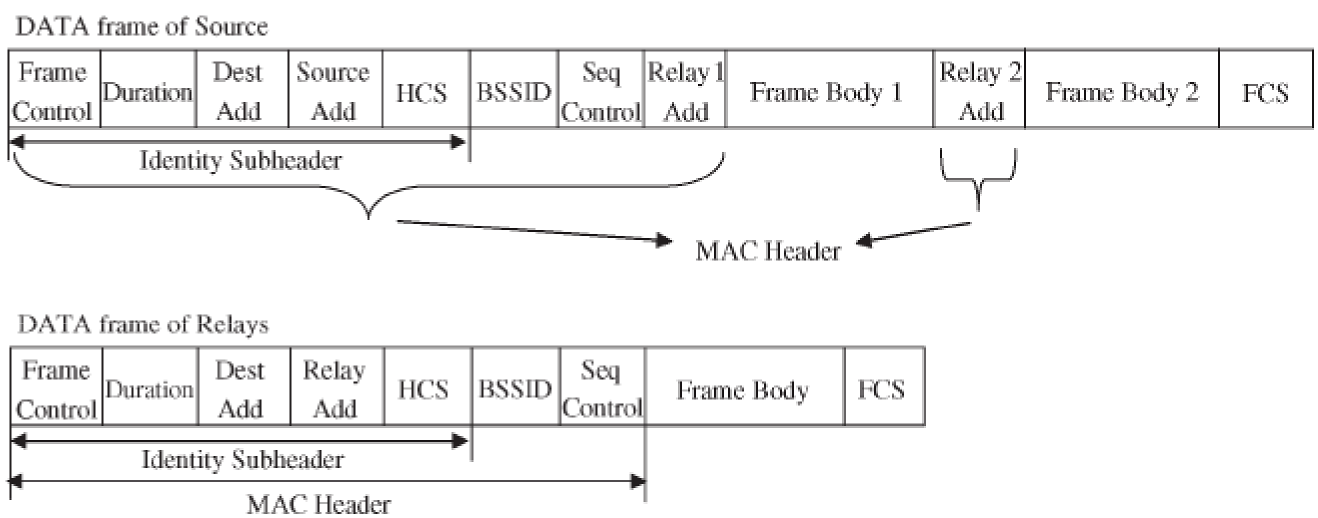


▭ (green) reflects the usage of transmission freedom

▭ (orange) reflects the efficiency of transmission

The MPDAF scheme

- The MAC layer frame format



Subframe synchronisation → Relay address is needed in the beginning of each partitioned frame body!

The MPDAF scheme

A comparison remark

Schemes / Relays (N)	RDAF	STC	MPDAF
Transmission freedom	$1/N$	1/2	1/2
Spectral efficiency (Γ bits/symbol)	$\theta \cdot m / (N+1)$	$\theta \cdot m / (N+1)$	$\theta \cdot m / 2$
System complexity	Ana. manipulations, no dec. & re-enc. are required at relays	Dig. manipulations, dec. & re-enc. are required at relays	Ana. manipulations, no dec. & re-enc. are required at relays

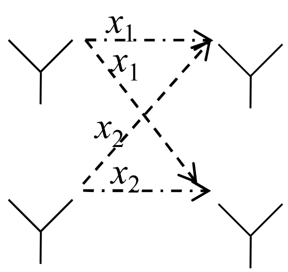
DMT Analysis

- ***Definition III:*** *Consider a coded system operating at SNR of ρ, achieving a maximum-likelihood (ML) error probability of $P_E(\rho)$ and an average transmission rate of R(ρ) bits/s/Hz. Its diversity gain (d) and multiplexing gain (r) are defined as:*

$$d = -\lim_{\rho\to\infty}\frac{\log(P_E(\rho))}{\log\rho},\ r = \lim_{\rho\to\infty}\frac{\mathrm{R}(\rho)}{\log\rho}.$$

The derived relationship between d and r is known as the diversity-multiplexing tradeoff (*DMT*), denoted by *d*(*r*).

- A concept inspired by the MIMO phenomenon



• Diversity is increased – diversity gain;
• Transmission rate is also increased as different symbols can be transmitted simultaneously through parallel spatial paths – multiplexing gain;

DMT Analysis

- For a MIMO system with m tx. antennas and n rx. antennas:
  $d = mn$;
  $r = \min\{m, n\}$;

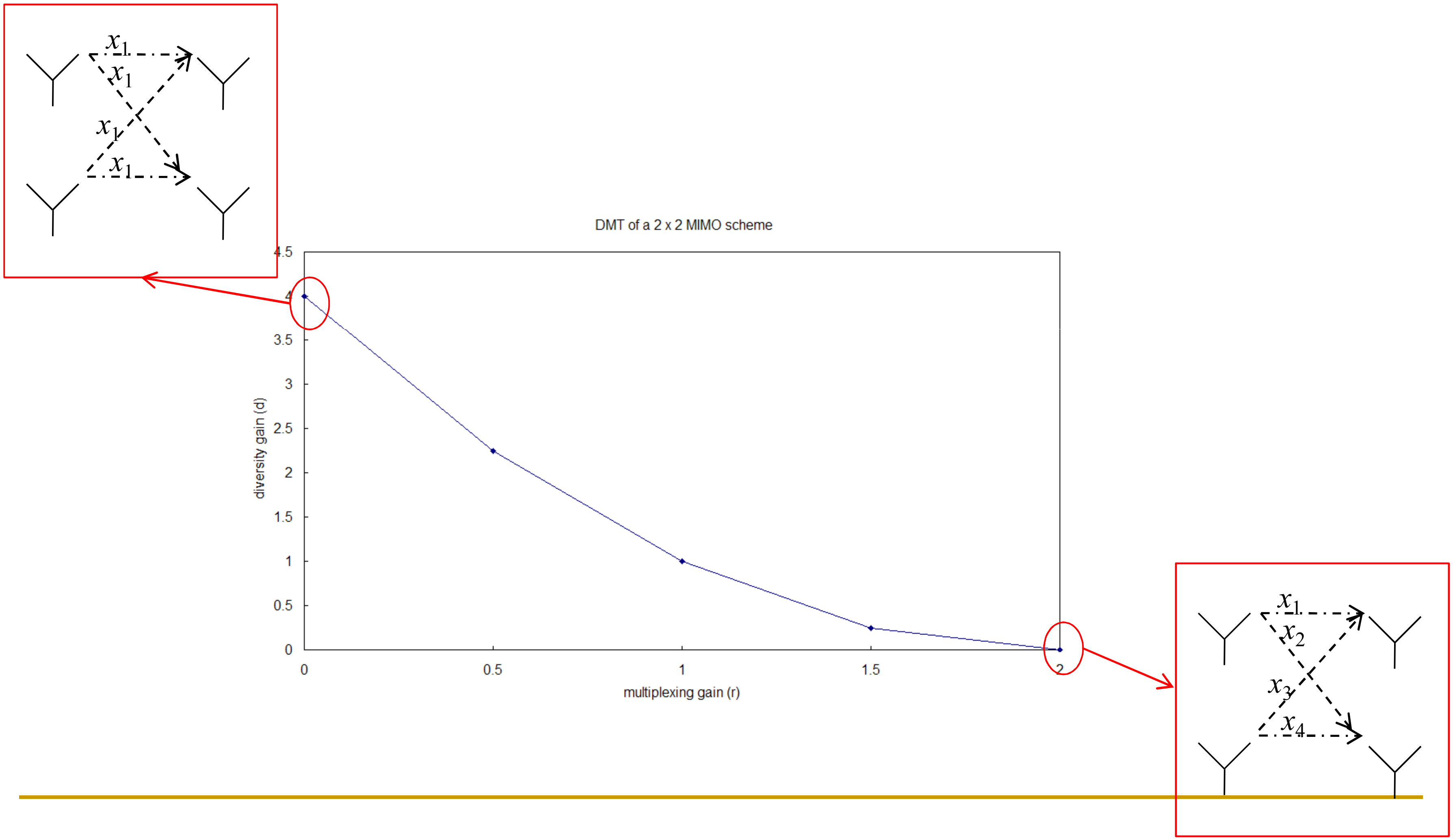
- A comparison between a MIMO system and a SISO system

MIMO		SISO
$R(\rho) \doteq r\log\rho$	vs.	$R(\rho) \doteq \log\rho$
$P_E(\rho) \doteq \rho^{-d}$	vs.	$P_{\mathrm{E}}(\rho) \doteq \rho^{-1}$

- d – a metric describing the system performance;
  r – a metric describing the system transmission rate (data rate);

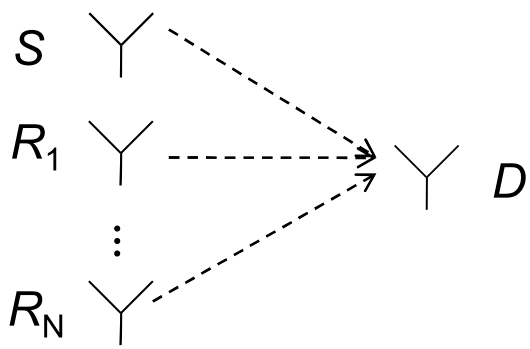
DMT Analysis

- Pursuing both *d* and *r* is a tradeoff problem → *d*(*r*)



DMT Analysis

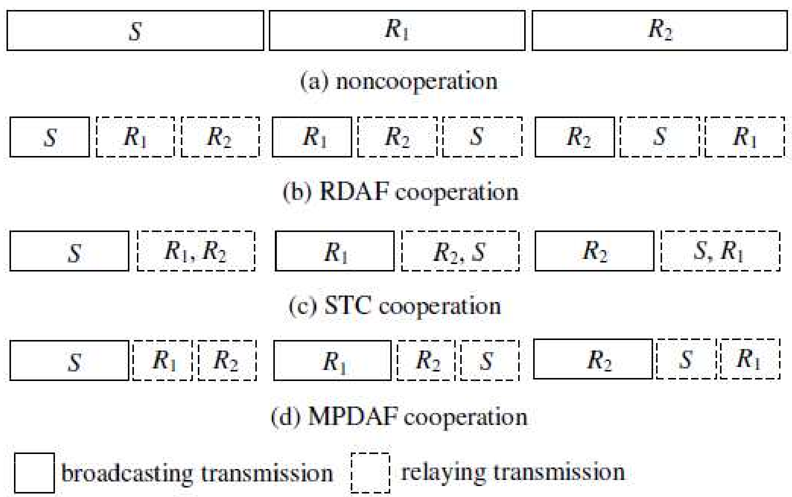
- A cooperative scheme can be treated as a MISO scheme (n = 1)



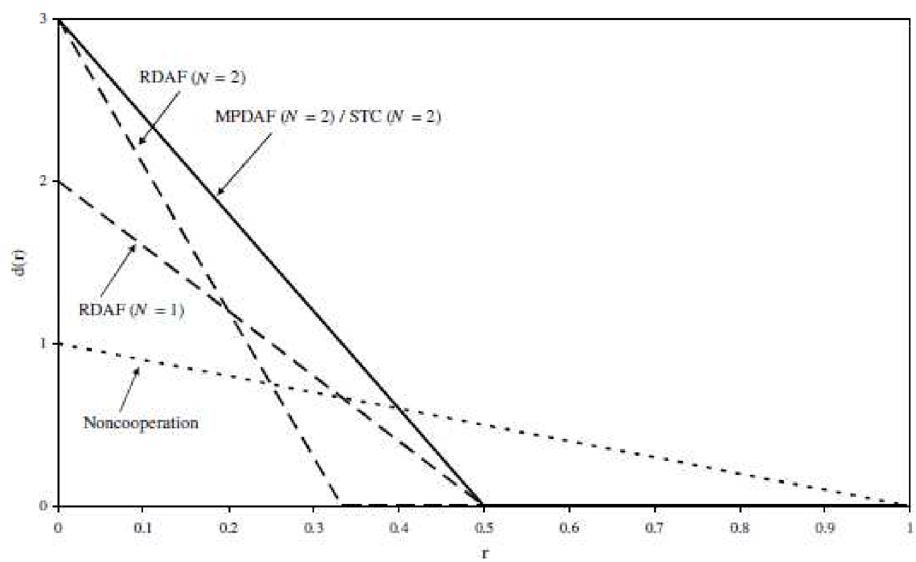
- $r_{max} = 1$, $d_{max} = N + 1$

- Due to the orthogonal time transmission between broadcasting and relaying, the achievable multiplexing gain will be a fraction of 1.

DMT Analysis



Remark: For protocols A and B, if $d_A(r) > d_B(r)$ for all r, protocol A has an outage performance gain over protocol B.



For a MPDAF scheme with N relays, $\underline{d(r) = (N + 1)(1 - 2r)^+}$

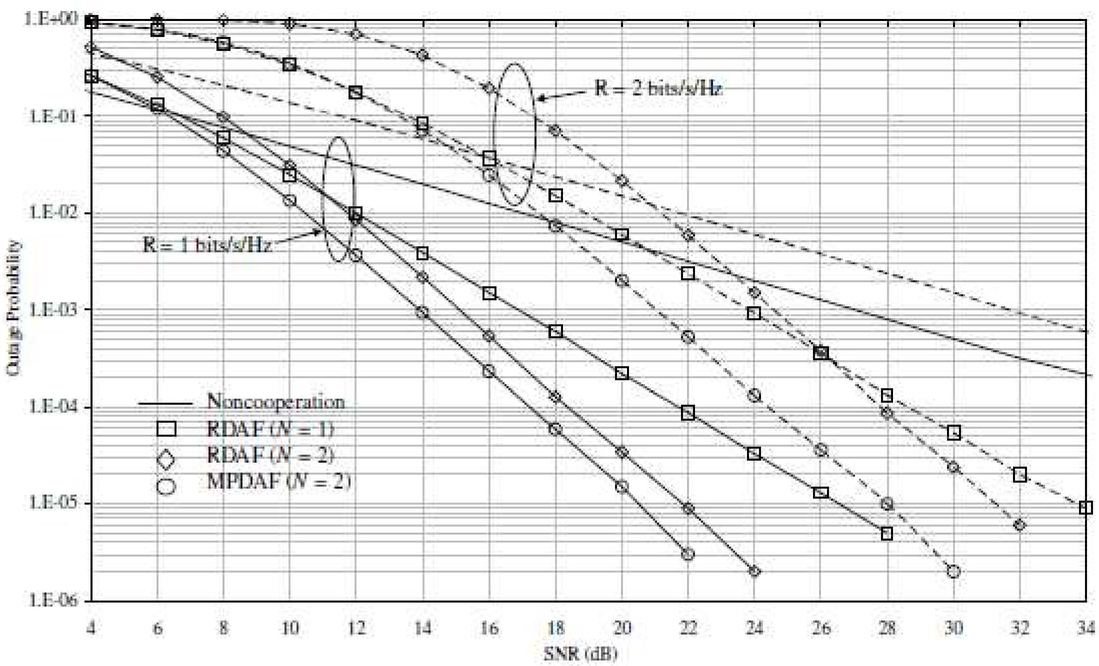
How to prove this DMT performance bound is achievable?

DMT Analysis

- Outage probability validation
- MPDAF (N = 2),

$$P_O = \Pr[\prod_{t=1}^{2}(1 + |\alpha_0|^2\rho + f(|\alpha_t|^2\rho, |\gamma_t|^2\rho)) < 2^{4R}].$$

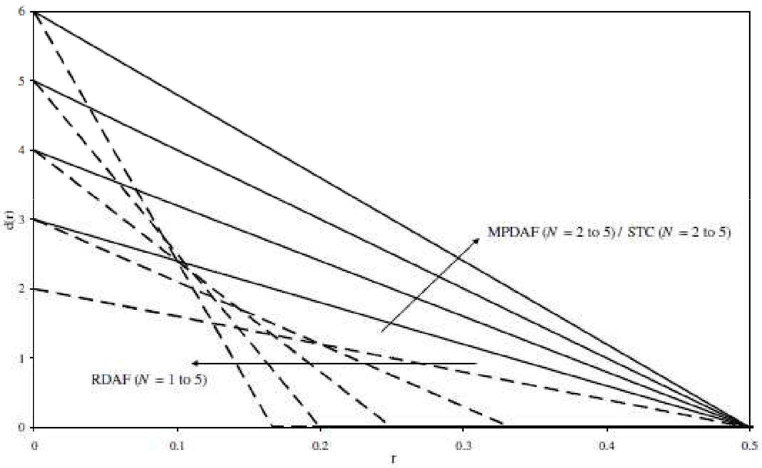
α_{SD} α_{RtD} α_{SRt}

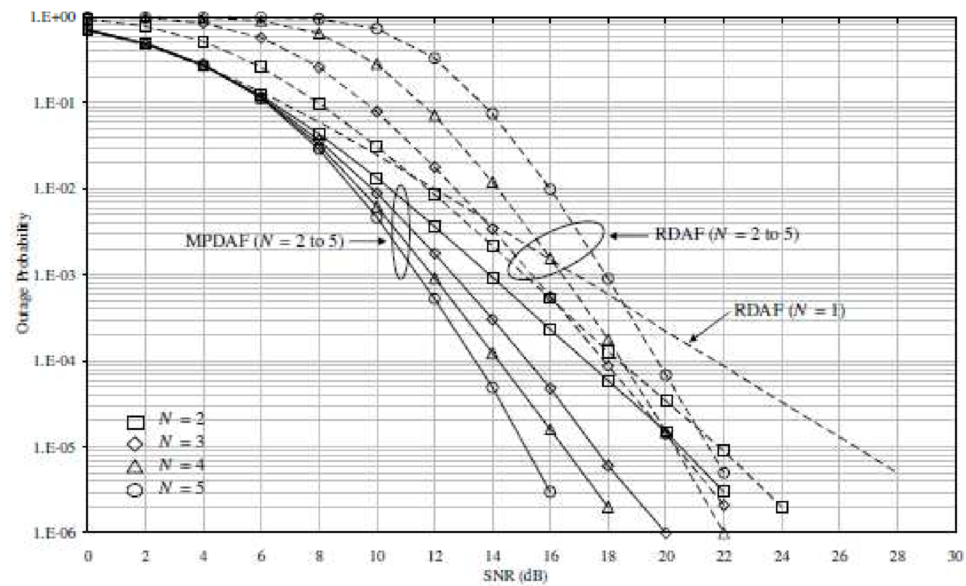


Note: $f(u, v) = uv / (u + v + 1)$

DMT Analysis

- MPDAF (N = 2 to 5)
- $$P_O = \Pr[\prod_{t=1}^{N}(1 + |\alpha_0|^2\rho + f(|\alpha_t|^2\rho, |\gamma_t|^2\rho)) < 2^{2NR}].$$





DMT Analysis

- How to prove the DMT performance of $d(r) = (N + 1)(1 - 2r)^+$ can be achieved?

- The DMT upper bound calculation:

$$d(r) \leq d_0, \;\; d_0 = \inf_{(\delta_0, \delta_1, \ldots, \delta_N) \in \mathbf{O}^+} \sum_{j=0}^{N} \delta_j.$$

  O is the set of outage events.

  δ is the exponential order of fading coefficient α, defined as:

$$\delta = -\lim_{\rho \to \infty} \frac{\log(|\alpha|^2)}{\log \rho},$$

- $d_0(r)$ can be determined from analysing the asymptotic behavior of P_O with $\rho \to \infty$, and <u>$d_0(r) = (N + 1)(1 - 2r)^+$</u>

- $P_O \doteq \rho^{-d0(r)}$

DMT Analysis

- We need to further analyse whether $d_0(r)$ also characterises the lower bound of $d(r)$, such that

$$d_0(r) \leq d(r) \leq d_0(r) \rightarrow d(r) = d_0(r)$$

- Recall ***Definition III***, $d(r)$ is defined by the error probability $P_E(\rho)$ as:

$$P_E(\rho) \doteq \rho^{-d(r)}$$

- $$\left.\begin{array}{l} P_O \doteq \rho^{-d0(r)} \\ P_E(\rho) \doteq \rho^{-d(r)} \end{array}\right\} \rightarrow P_E(\rho) \;\dot{\leq}\; P_O \rightarrow d_0(r) \leq d(r)$$

DMT Analysis

- A DMT lower bound proof, assisted by the calculation of P_E and P_{PE}
- Proving logic:

Exact calculation

$$P_E(\rho) = P_{E|O}P_O + P_{E,O^c}$$

Error probability in outage events (cond.)

Outage probability

Error probability in non-outage events (non-cond.)

↓

Upper bound

$$P_E(\rho) \dot{\le} P_O + P_{E,O^c}$$

↓

Condition

$$P_{E,O^c} \dot{\le} P_O$$

Prove the establishment of such a condition!

↓

Conditional Upper bound

$$P_E(\rho) \dot{\le} P_O \longrightarrow d_0(r) \le d(r)$$

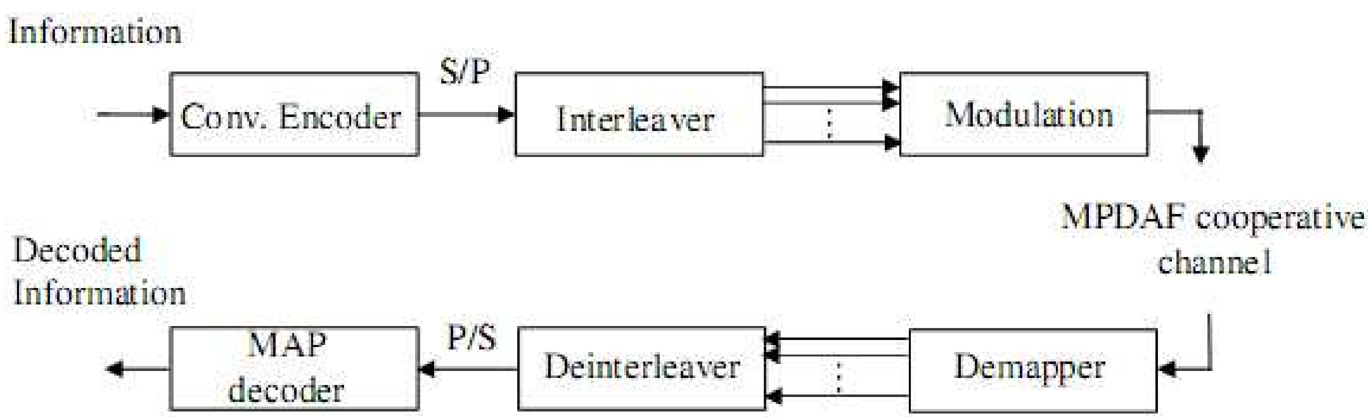
Coded MPDAF system

- Can we realise the promised diversity gain? How?
- Can we realise the spectral efficiency advantage? How?
- **How can we realise the information theoretical analysis in a practical coded system?**
- **Solution:**
  - Integrate the MPDAF scheme with an error-correction code;
  - Analyse the impact of such a cooperative scheme on the error-correction performance;
  - Simulation results.

Coded MPDAF system

- The bit-interleaved coded modulation (BICM) is deployed
- It is a spectrally efficiency error-correction scheme
- Its nature of 'bit-interleaving' enables the diversity gain provided by the MPDAF scheme to be exploited.

- BICM + MPDAF system model



Coded MPDAF system

- ***Remark:*** For a trellis decoding, it is important to introduce the diversity into the trellis transition branches, so that the diversity gain provided by the MPDAF scheme can be realised by the coded system.

- **A work example:** rate ½ conv. code, QPSK and MPDAF (N = 2)

$m_1 m_2 m_3 m_4 m_5 m_6$ → **Conv. Enc** → $c_1^1\ c_1^2\ c_2^1\ c_2^2\ c_3^1\ c_3^2\ c_4^1\ c_4^2\ c_5^1\ c_5^2\ c_6^1\ c_6^2$

S/P Converter →

Interleaver →

c_3^1	c_1^1	c_2^1	c_6^1	c_4^1	c_5^1
c_5^2	c_4^2	c_2^2	c_3^2	c_6^2	c_1^2

Modulation → $x[1]$ $x[2]$ $x[3]$ $x[4]$ $x[5]$ $x[6]$

Coded MPDAF system

Work example cont…

Mod. output → $x[1]\ \ x[2]\ \ x[3]\ \ x[4]\ \ x[5]\ \ x[6]$

MPDAF channel $\alpha_0,\ \alpha_1\beta_1\gamma_1$ | $\alpha_0,\ \alpha_2\beta_2\gamma_2$

Channel output → $y[1]\ \ y[2]\ \ y[3]\ \ y[4]\ \ y[5]\ \ y[6]$

$$\Pr[c_3^1 = \vartheta|y[1]], \Pr[c_1^1 = \vartheta|y[2]], \Pr[c_2^1 = \vartheta|y[3]], \Pr[c_6^1 = \vartheta|y[4]], \Pr[c_4^1 = \vartheta|y[5]], \Pr[c_5^1 = \vartheta|y[6]];$$

$$\Pr[c_5^2 = \vartheta|y[1]], \Pr[c_4^2 = \vartheta|y[2]], \Pr[c_2^2 = \vartheta|y[3]], \Pr[c_3^2 = \vartheta|y[4]], \Pr[c_6^2 = \vartheta|y[5]], \Pr[c_1^2 = \vartheta|y[6]].$$

Deinterleaver →

$$\Pr[c_1^1 = \vartheta|y[2]], \Pr[c_2^1 = \vartheta|y[3]], \Pr[c_3^1 = \vartheta|y[1]], \Pr[c_4^1 = \vartheta|y[5]], \Pr[c_5^1 = \vartheta|y[6]], \Pr[c_6^1 = \vartheta|y[4]];$$

$$\Pr[c_1^2 = \vartheta|y[6]], \Pr[c_2^2 = \vartheta|y[3]], \Pr[c_3^2 = \vartheta|y[4]], \Pr[c_4^2 = \vartheta|y[2]], \Pr[c_5^2 = \vartheta|y[1]], \Pr[c_6^2 = \vartheta|y[5]].$$

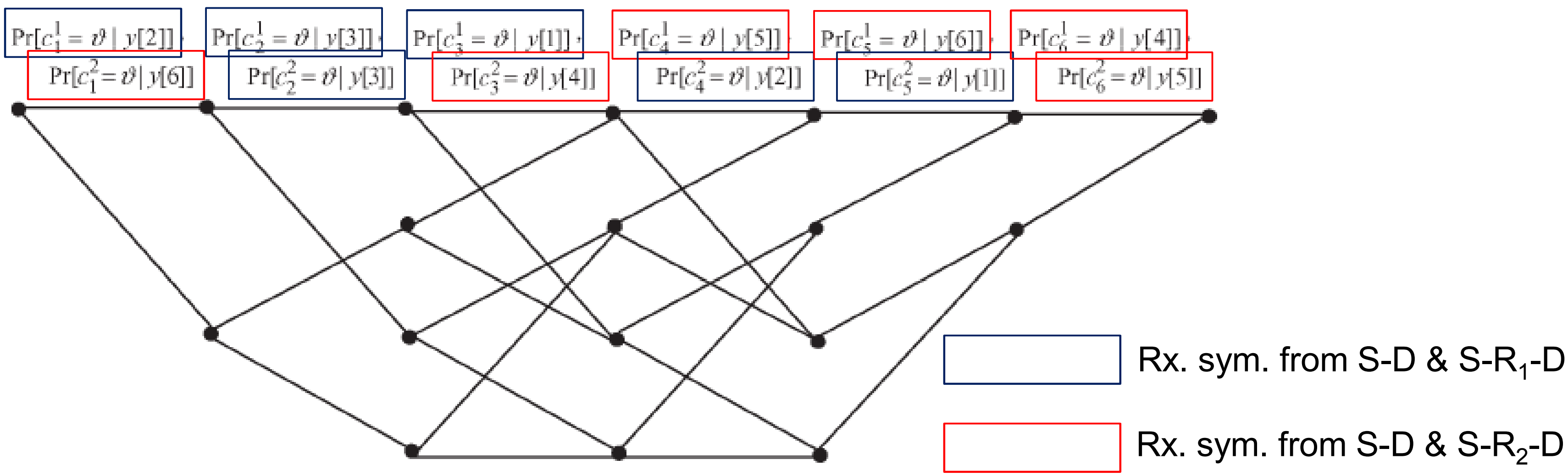
Coded MPDAF system

Deintlv. output (MAP decoder input):

$$\Pr[c_1^1=\vartheta|y[2]], \Pr[c_2^1=\vartheta|y[3]], \Pr[c_3^1=\vartheta|y[1]], \Pr[c_4^1=\vartheta|y[5]], \Pr[c_5^1=\vartheta|y[6]], \Pr[c_6^1=\vartheta|y[4]];$$

$$\Pr[c_1^2=\vartheta|y[6]], \Pr[c_2^2=\vartheta|y[3]], \Pr[c_3^2=\vartheta|y[4]], \Pr[c_4^2=\vartheta|y[2]], \Pr[c_5^2=\vartheta|y[1]], \Pr[c_6^2=\vartheta|y[5]].$$

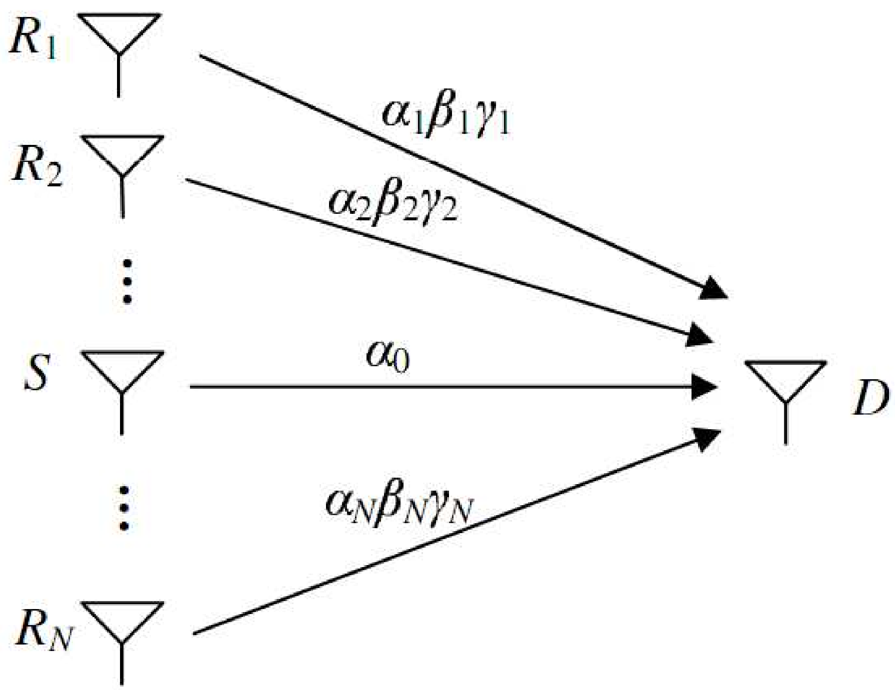
<u>Diversity within the trellis transition branches</u>



The decoding metrics (prob. or Eucl. dist.) are calculated in an accumulated fashion. It is better to spread out the diversity effect and reduce the risk of a 'deeply faded path' dominating the decoding event.

Coded MPDAF system

- System performance assessment – find the practical diversity gain!
- Proposition: MPDAF → MISO interpretation



Coded MPDAF system

- Tx.: $\mathbf{x} = \{x[1], x[2], ..., x[l/2], x[l/2+1], x[l/2+2], ..., x[l]\}.$

  Rx.: $\mathbf{y} = \{y[1], y[2], ..., y[l/2], y[l/2+1], y[l/2+2], ..., y[l]\}.$

  Det.: $\mathbf{e} = \{e[1], e[2], ..., e[l/2], e[l/2+1], e[l/2+2], ..., e[l]\}.$

- Channel vector: $\Omega = \begin{bmatrix} \alpha_0 & \alpha_1\beta_1\gamma_1 & \alpha_2\beta_2\gamma_2 \end{bmatrix}$

- Distance matrix: $\Lambda = \begin{bmatrix} \sum_{k=1}^{l} |x[k]-e[k]|^2 & 0 & 0 \\ 0 & \sum_{k=1}^{l/2} |x[k]-e[k]|^2 & 0 \\ 0 & 0 & \sum_{k=l/2+1}^{l} |x[k]-e[k]|^2 \end{bmatrix}.$

- Pairwise error probability: $P(\mathbf{x} \to \mathbf{e} \mid \alpha_0, \alpha_t, \beta_t, \gamma_t(t=1,2)) \leq \exp(-\Omega\Lambda\Omega^H \rho/4).$

- Assuming noiseless inter-user channel, e.g. $\beta_t = 1/\gamma_t$ and $\alpha_t\beta_t\gamma_t = \alpha_t$
  This is an assumption of genius exist in the relays, so that relays have the exact estimation of **x**.

Coded MPDAF system

- The rank of Λ is 3;
- The pairwise error probability can be further upper bounded by:

$$\begin{aligned} P(\mathbf{x} \to \mathbf{e} \mid \alpha_0, \alpha_t, \beta_t, \gamma_t(t=1,2)) &\leq [\prod_{i=1}^{3}(1+\lambda_i\rho/4)]^{-1} \\ &\leq (\prod_{i=1}^{3}\lambda_i)^{-1}(\rho/4)^{-3}. \end{aligned}$$

- Generalising the result into a MPDAF scheme with an arbitrary number of relays *N*:

$$P(\mathbf{x} \to \mathbf{e} \mid \alpha_0, \alpha_t, \beta_t, \gamma_t(t=1,2,...,N)) \leq (\prod_{i=1}^{N+1}\lambda_i)^{-1}(\rho/4)^{-(N+1)}.$$

- Note, this analysis demonstrates the achievable diversity for a practical coded system in the ideal situation.

Coded MPDAF system

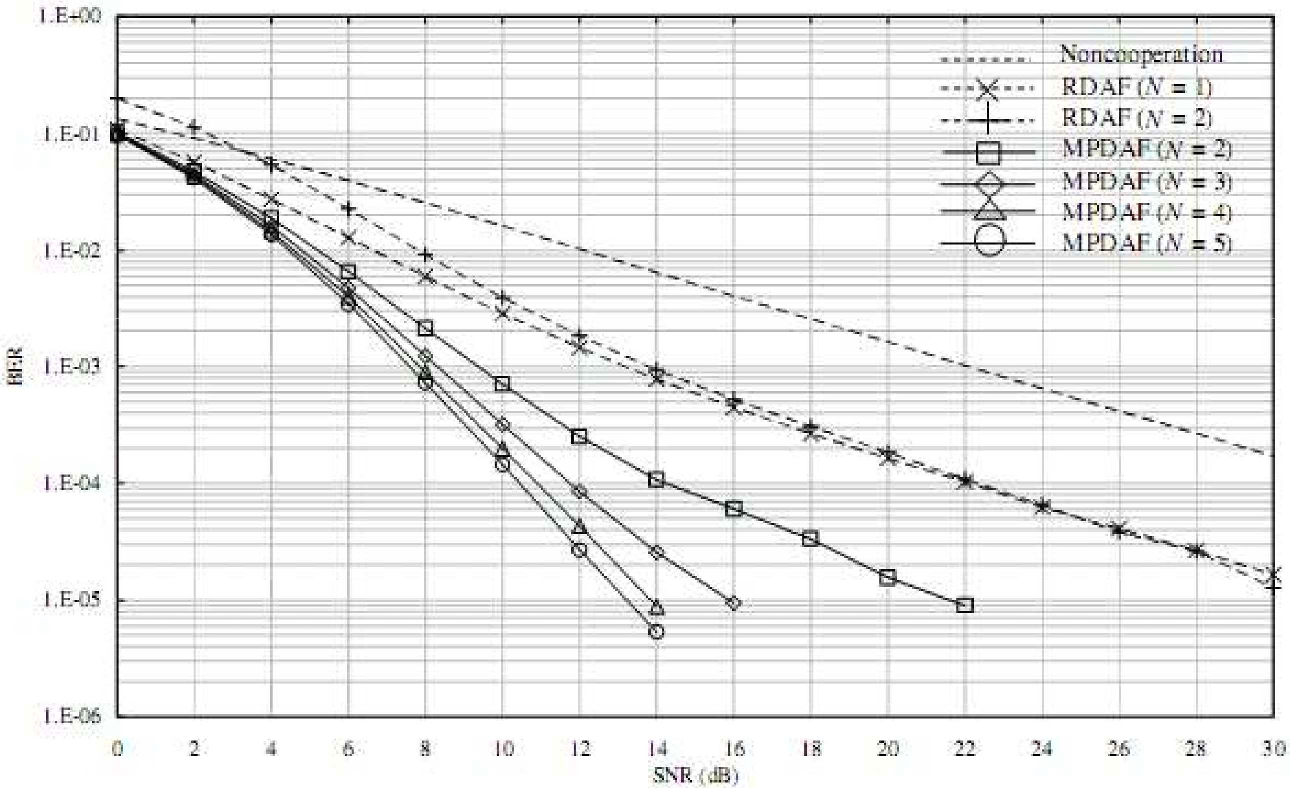
- A couple of BICM + MPDAF systems;
- Comparison with the RDAF scheme is based on achieving the same spectral efficiency.
- System I

TABLE I
SYSTEM PARAMETERS OF THE BICM CODED MPDAF SCHEME WITH $\Gamma = 0.5$ BITS/SYMBOL

Schemes	Code	Modulation	Spectral efficiency (Γ)
noncooperation	Conv $(15, 17)_8$	QPSK	1
RDAF $(N = 1)$		QPSK	0.5
RDAF $(N = 2)$		8PSK	0.5
MPDAF		QPSK	0.5

Coded MPDAF systems

- Performance of system I



Coded MPDAF system

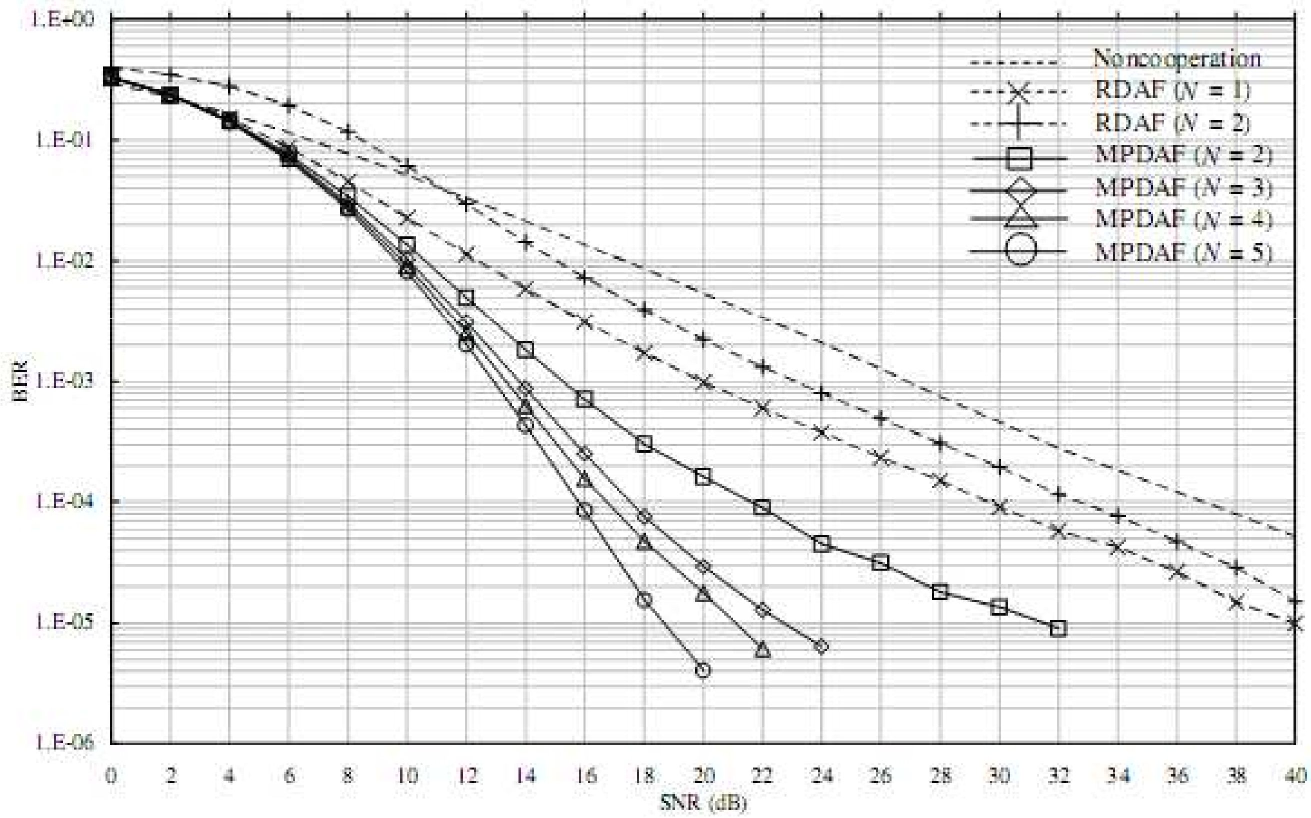
- System II

TABLE II
SYSTEM PARAMETERS OF THE BICM CODED MPDAF SCHEME WITH $\Gamma = 1$ BITS/SYMBOL

Schemes	Code	Modulation	Spectral efficiency (Γ)
noncooperation	Conv $(15, 17)_8$	16QAM	2
RDAF $(N = 1)$		16QAM	1
RDAF $(N = 2)$		64QAM	1
MPDAF		16QAM	1

Coded MPDAF systems

- Performance of system II



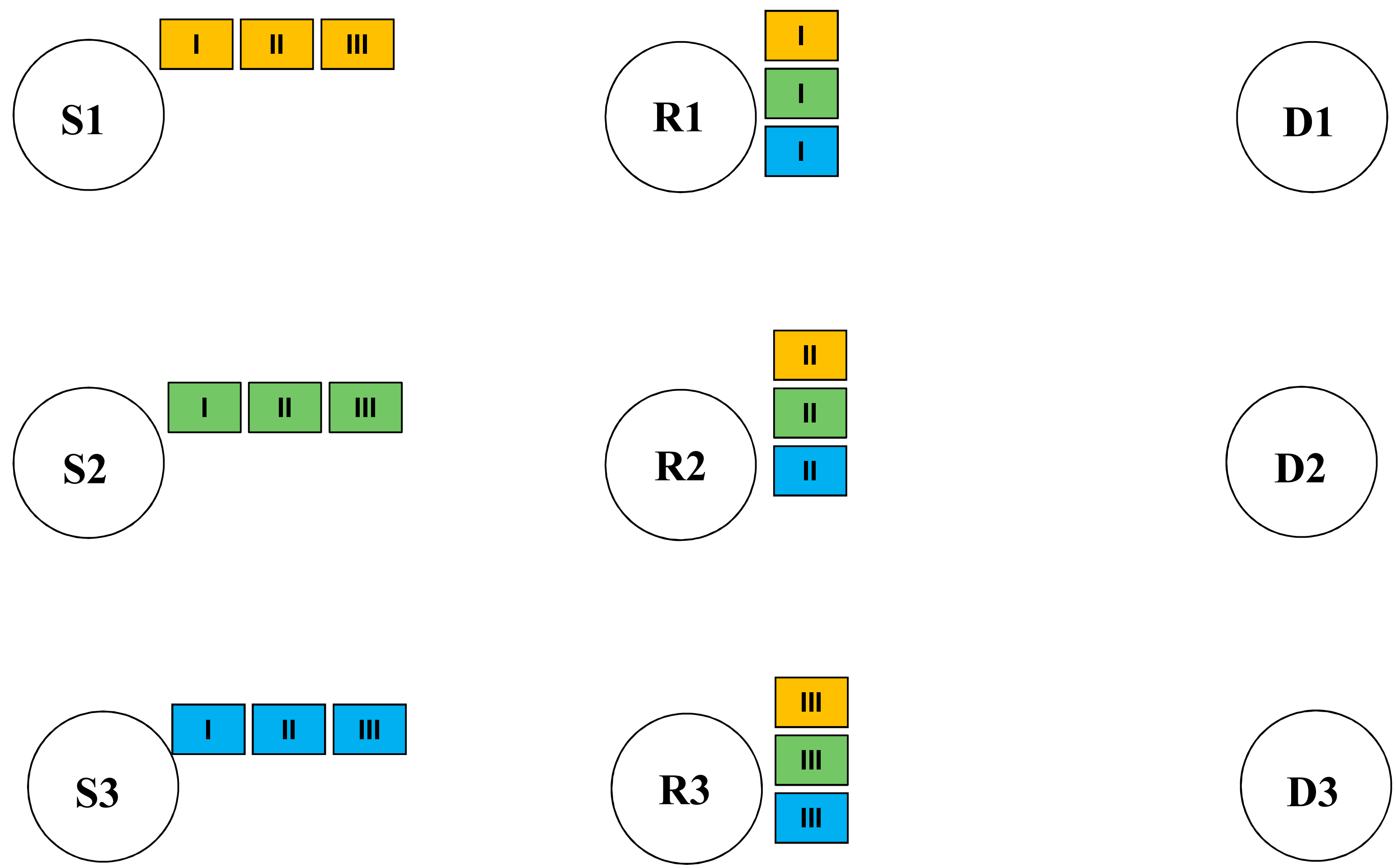
Conclusions and future work

- MPDAF scheme, a dist. coop. scheme that can achieve diversity without affecting its multiplexing gain;
- It also maintains a constant spectral efficiency;
- A practical demonstration on BICM + MPDAF system;
- MPDAF requires simple implementation effort, but for signal recognition and user time synchronisation.
- The beginning of an end …

  (1) MPDAF's application in a multicast communication scenario;

  (2) Code designed for the MPDAF channel.

Conclusions and future work



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