Signal processing in the upcoming wireless networks:

Untangling signals in space, in spectrum, and network coded

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creating and sharing knowledge for telecommunications

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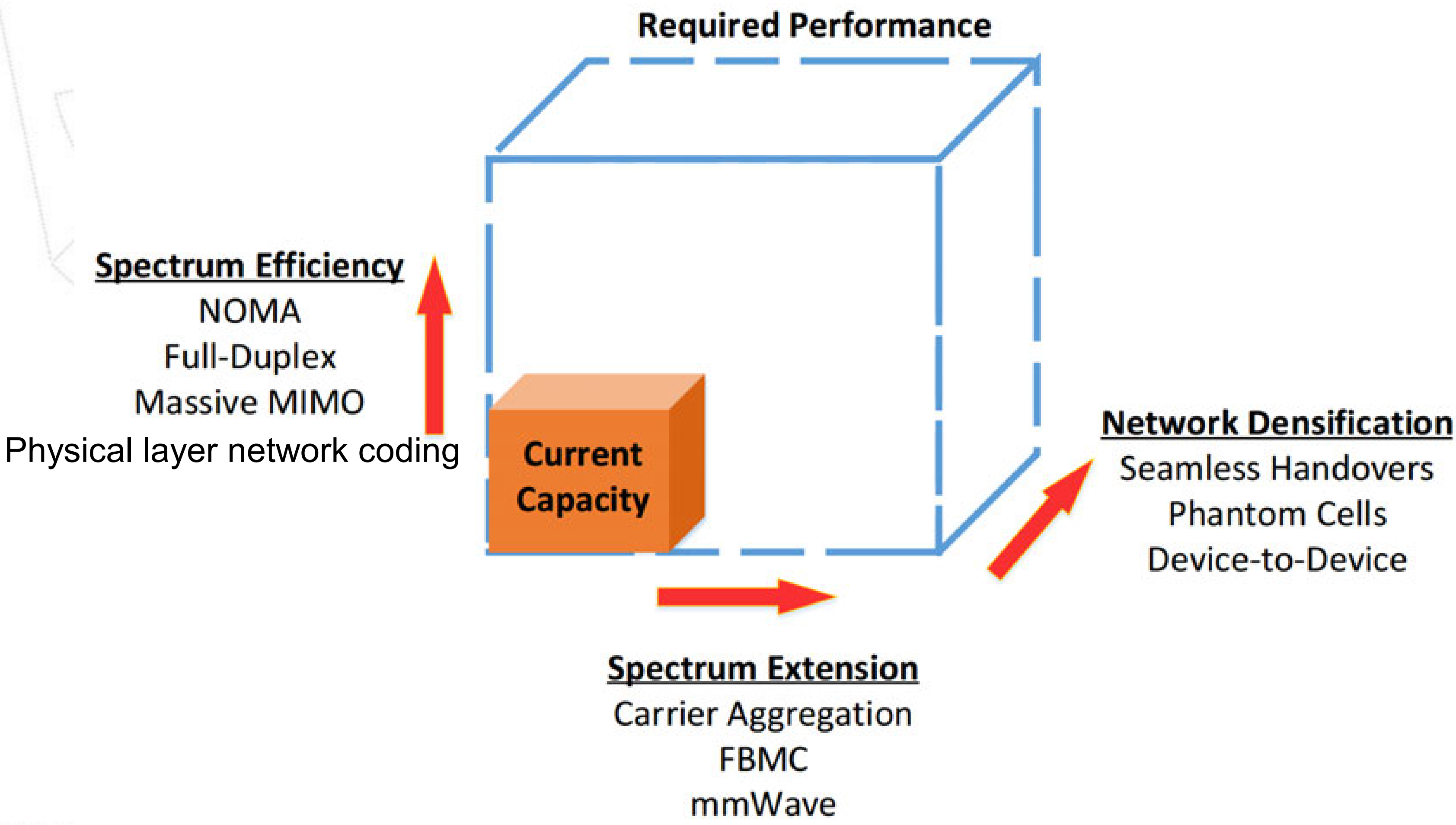
How to offer more?



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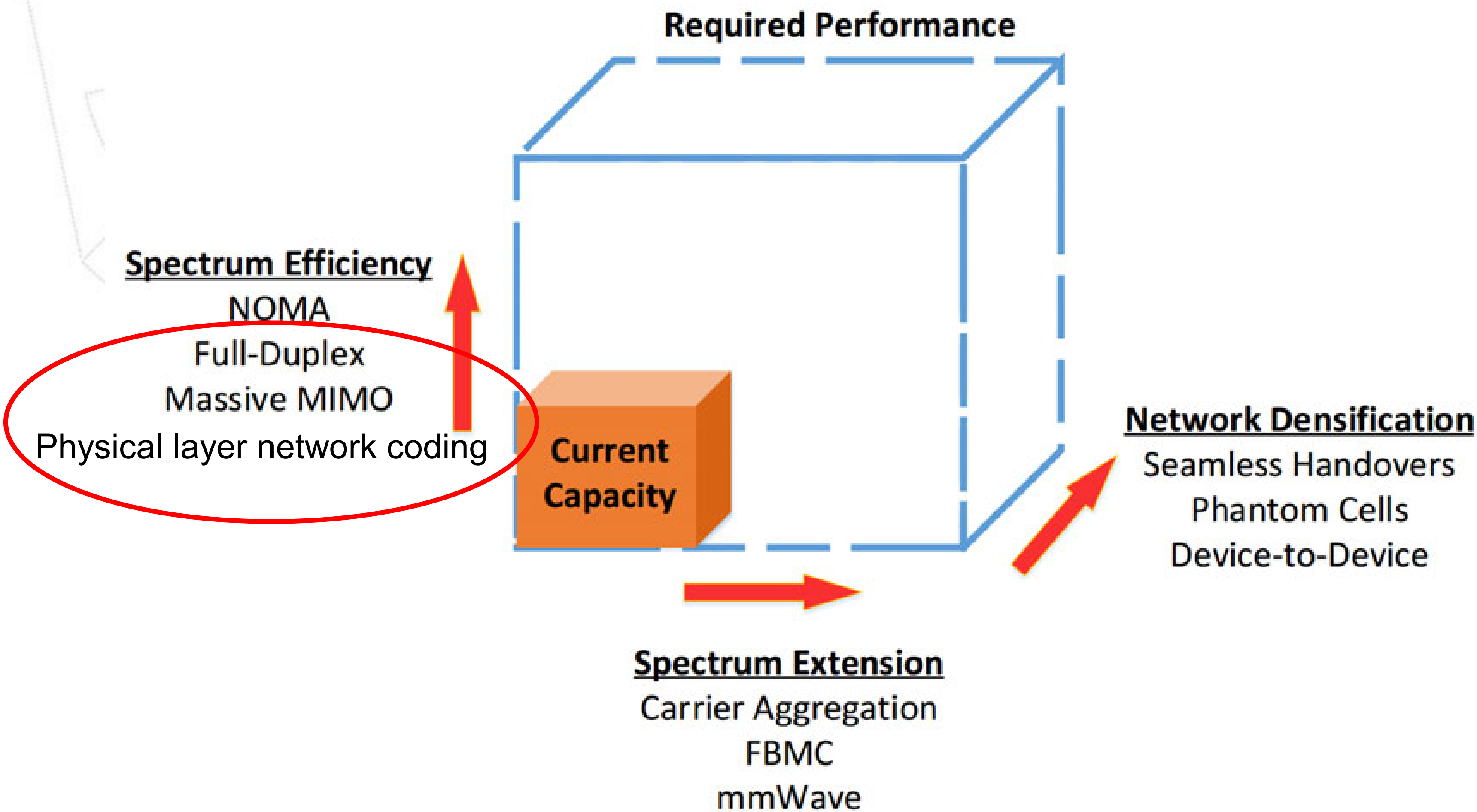

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1- Spatial multiplexing (MIMO)

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4- TWRC and the Y-network

5- Full-duplex + massive MIMO + PLNC

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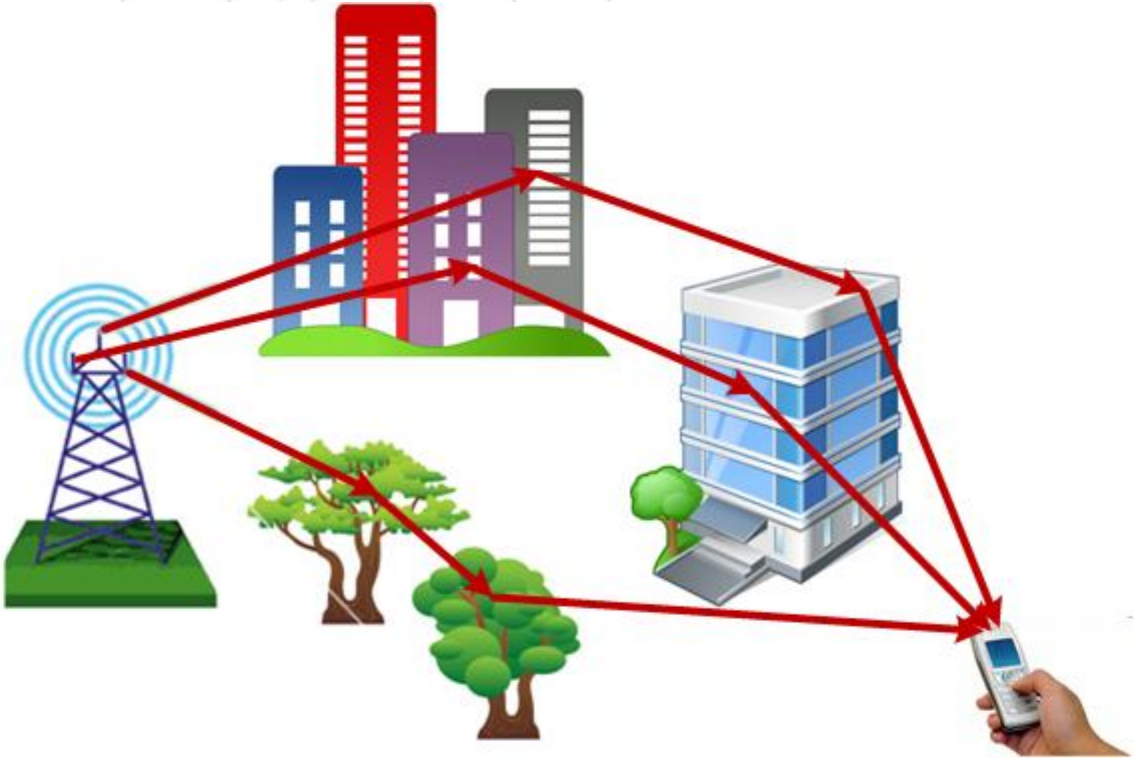
Multipath Fading



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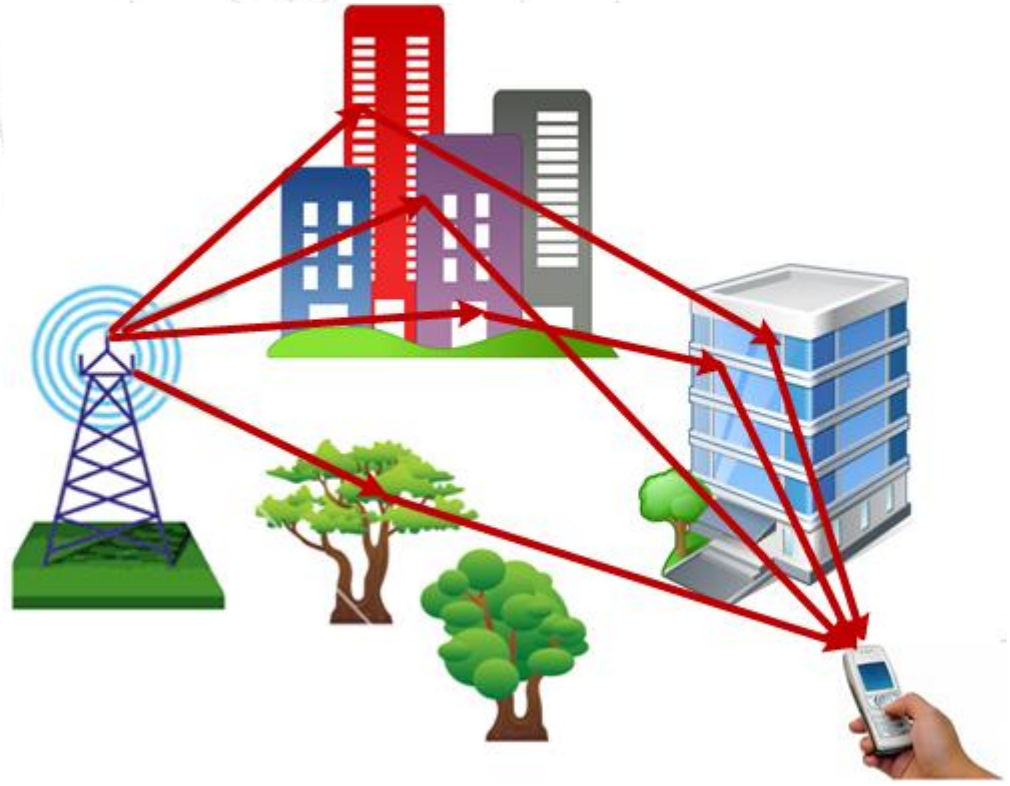

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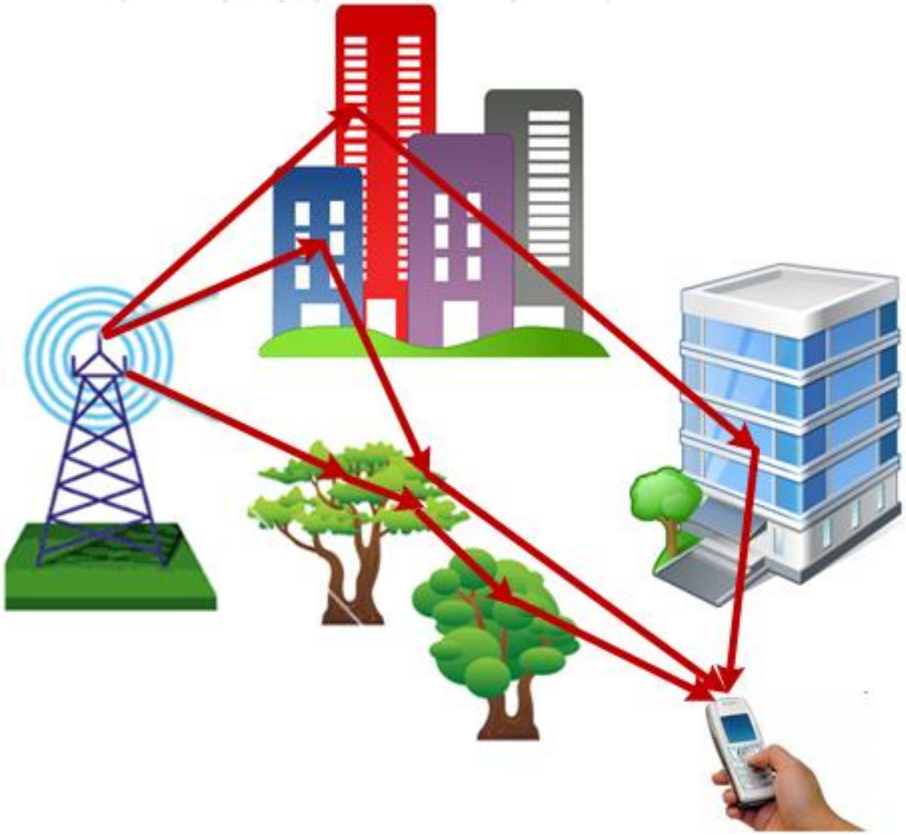

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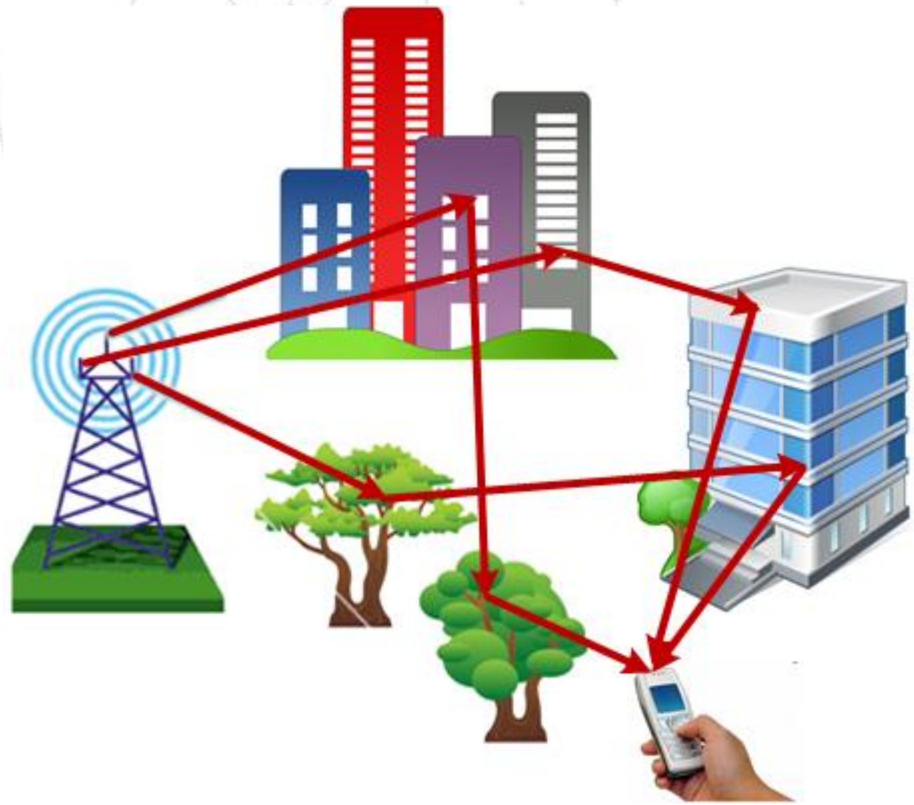
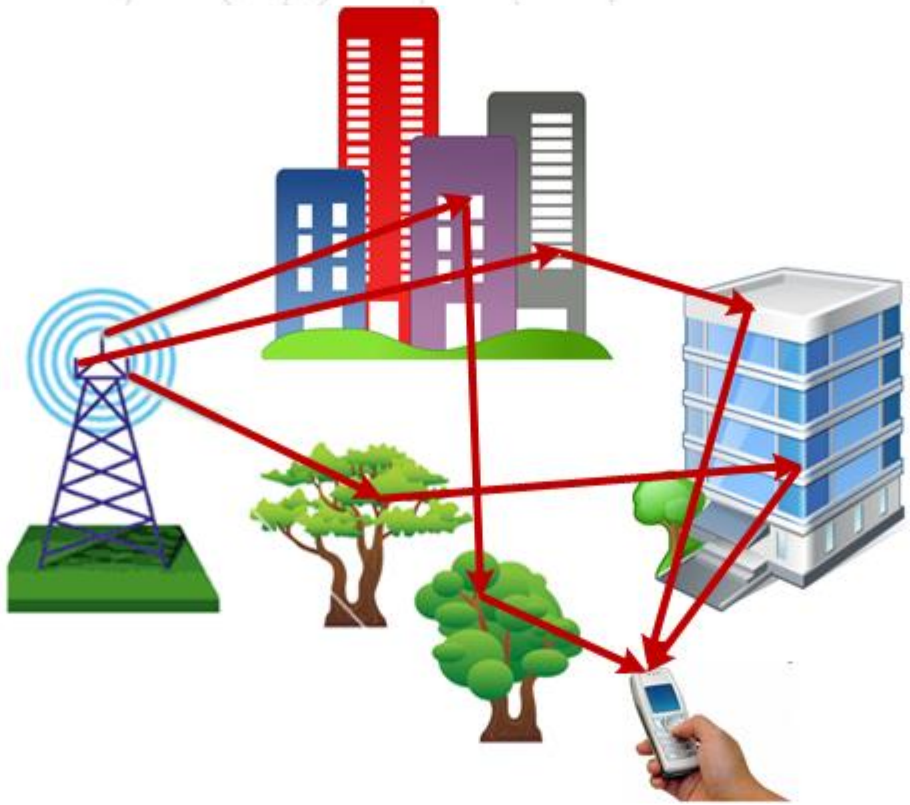
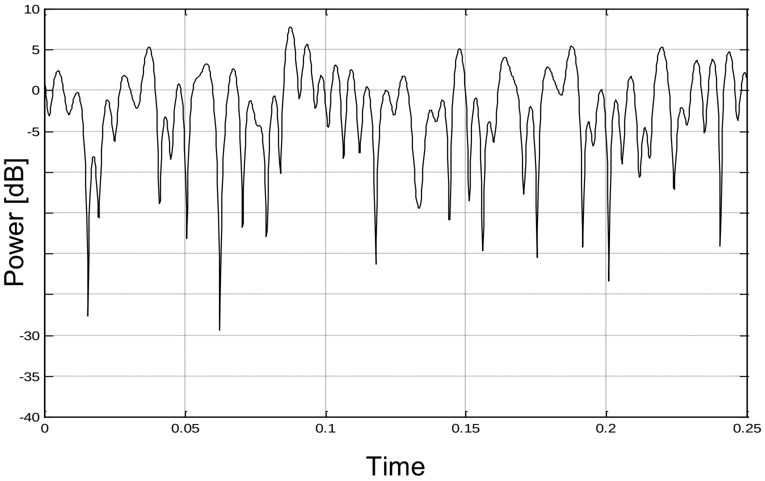
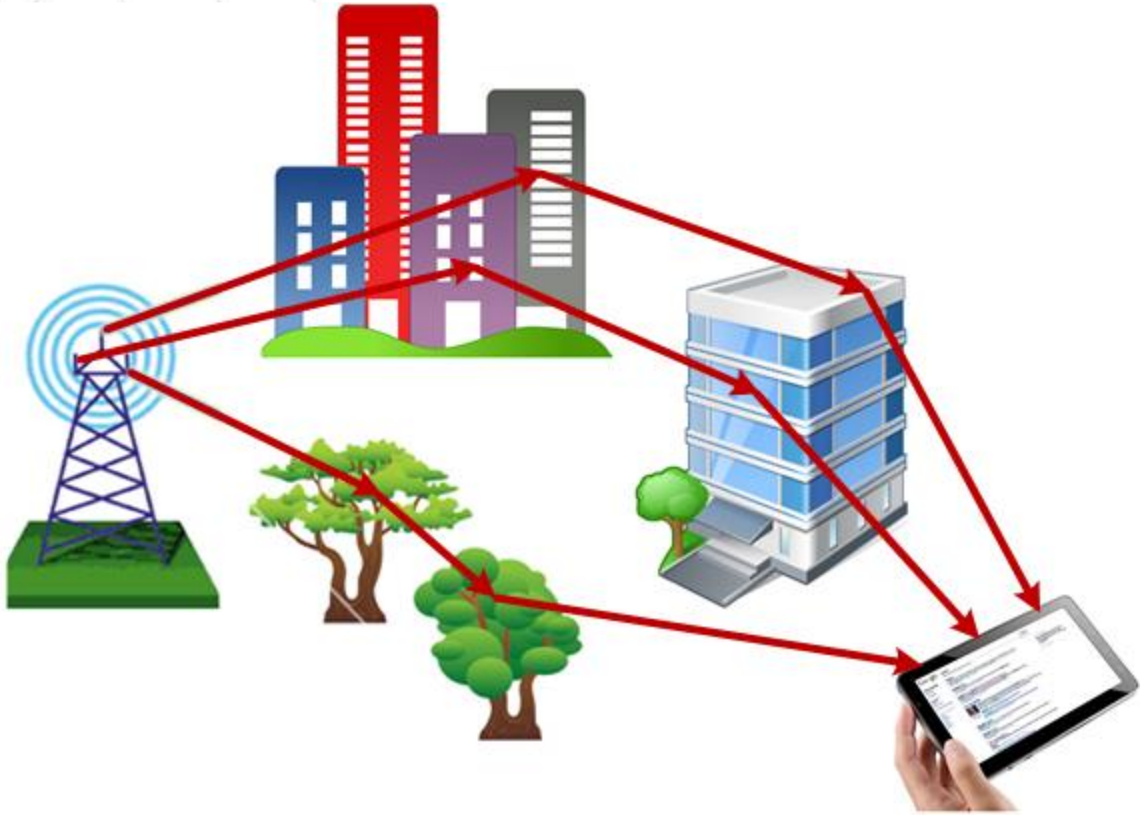


Multipath Fading





It turns out that this can be made equivalent to…



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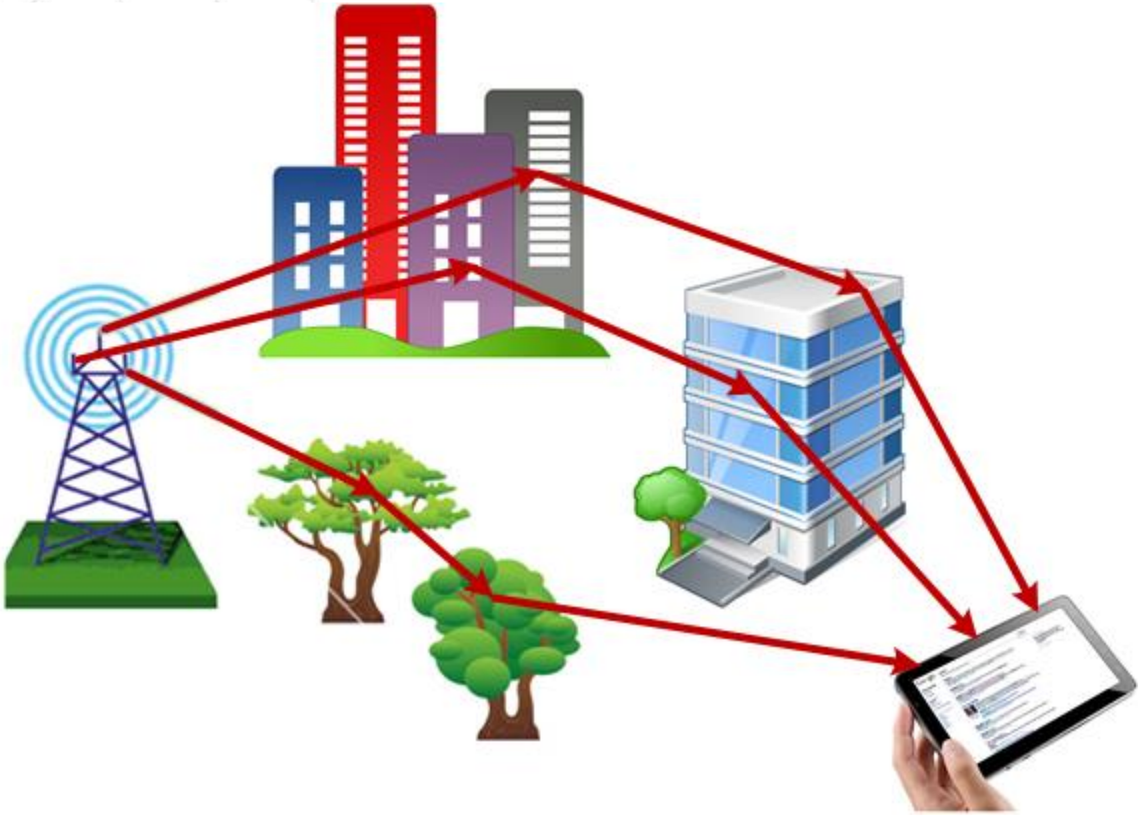


How?

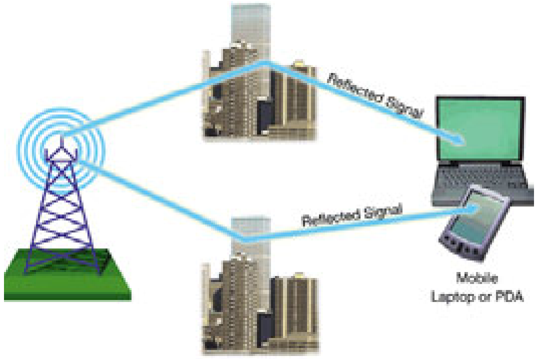
Beyond Shannon's capacity

Gerard Foschini

(Bell Labs, NJ)

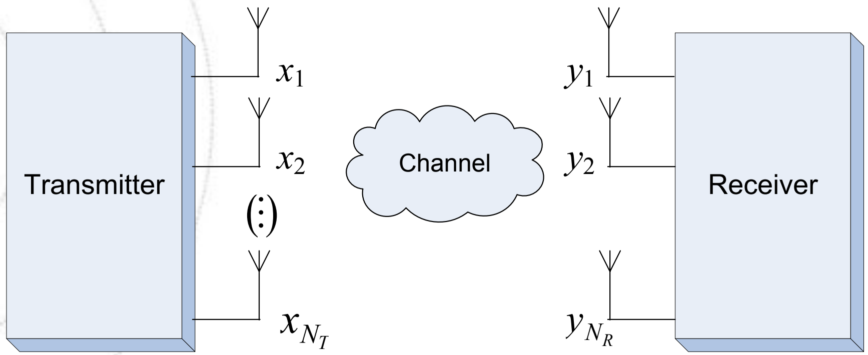
1993 - 1998:

- Paulraj et al. research on MIMO (Stanford, CA).
- Gerard Foschini deduced the theoretical capacity for MIMO and proved it experimentally (@ Bell Labs, NJ).



- Multipath can be beneficial by opening simultaneous channels.
- Multiple-input multiple-output (MIMO) was born.
- After 15 years of academic research → standards:
  802.11n and 4G (LTE-A, WiMax).

Multiple-input multiple-output (MIMO) detection

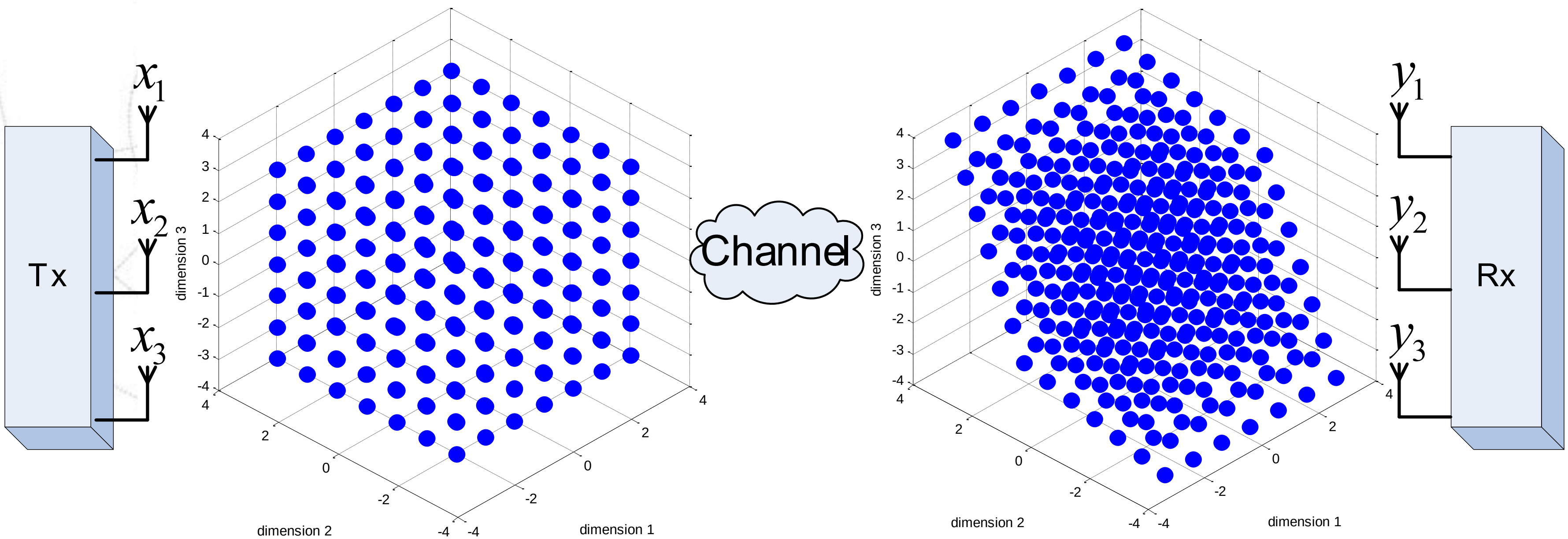


$$\begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \\ \vdots \\ \mathbf{y}_{N_R} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N_T} \\ h_{21} & h_{22} & \cdots & h_{2N_T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_R 1} & h_{N_R 2} & \cdots & h_{N_R N_T} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \vdots \\ \mathbf{x}_{N_T} \end{bmatrix} + \begin{bmatrix} \mathbf{n}_1 \\ \mathbf{n}_2 \\ \vdots \\ \mathbf{n}_{N_R} \end{bmatrix}$$

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

$$\hat{\mathbf{x}}_{ML} = \min_{\mathbf{x}} \left\{ \left\| \mathbf{y} - \mathbf{H}\mathbf{x} \right\|^2 \right\}$$

MIMO channel is a linear transformation



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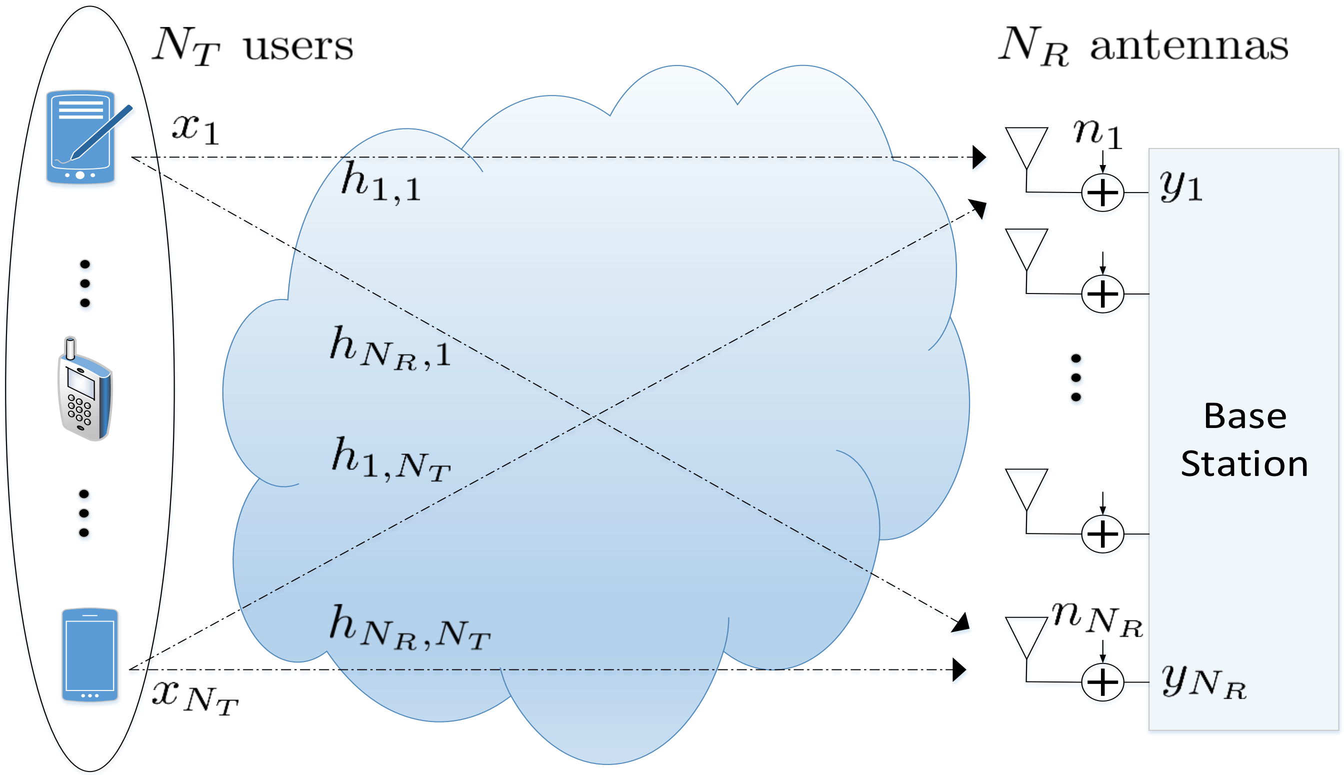
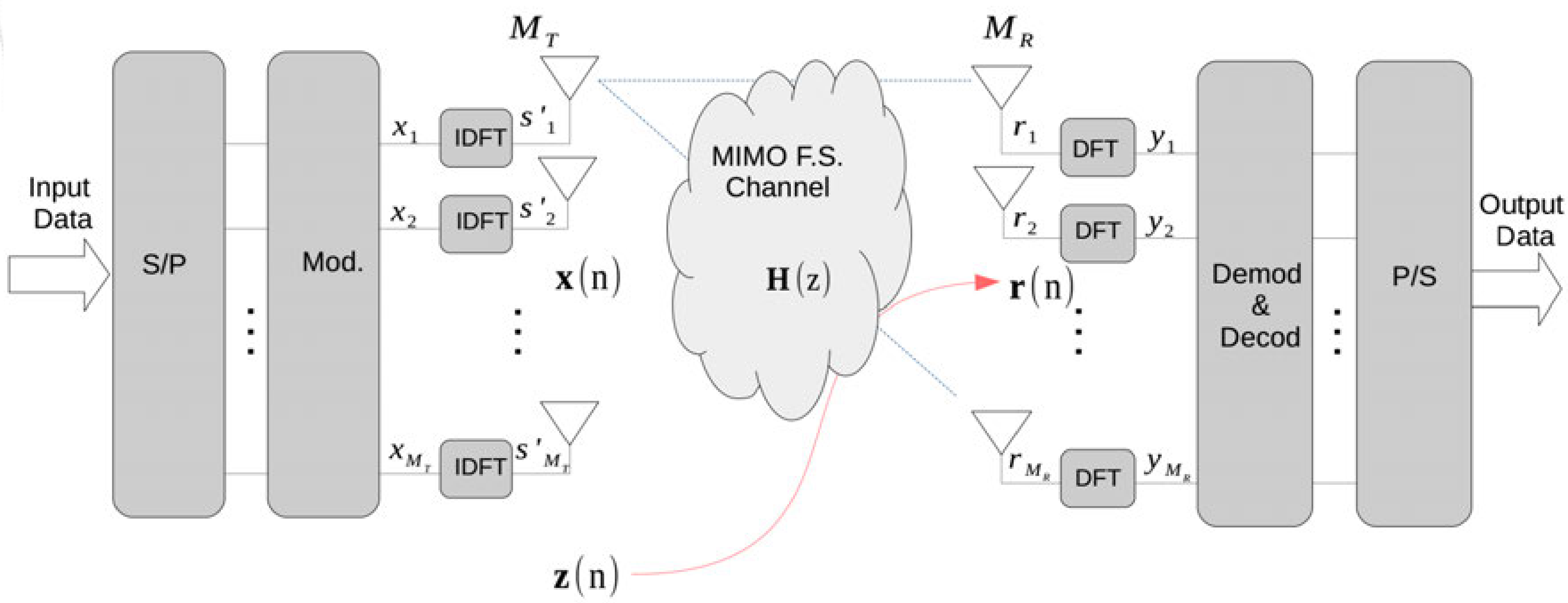
$$\hat{\mathbf{x}}_{ML} = \min_{\mathbf{x}} \left\{ \left\| \mathbf{y} - \mathbf{H}\mathbf{x} \right\|^2 \right\}$$

Example: 3 dimensions (3 antennas using PAM).

Virtual MIMO (non co-located antennas)



Orthogonal frequency division multiplexing MIMO (OFDM-MIMO)



"A rose by any other name would smell as sweet"

	MIMO	Equalisation for ISI channels	Multi-user Communication
Inversion (linear)	• Zero-forcing (ZF) • Channel inversion • Decorrelation	Zero-forcing (ZF) equalisation	Decorrelating
Minimum mean squared error (MMSE)	MMSE	MMSE filtering	MMSE detection
Interference cancellation	• Nulling and cancelling • Successive interference cancellation (SIC) • V-BLAST detection	Decision feedback equalisation (DFE)	• Iterative multi-user detection MUD) • Successive interference cancellation (SIC)
Optimum detection	• Maximum likelihood detection (MLD) • Exhaustive search	Maximum likelihood sequence detection (MLSD)	• ML detection • Brute force • Sphere decoding (near optimum)
Precoding	• Multiuser-MIMO • Broadcast channel (BC)	• ISI Precoding • Costas precoding • Tomlinson-Harashima precoding (THP)	Dirty paper coding (DPC)
Parallel subchannels	• Closed loop SU-MIMO • Singular value decomposition (SVD) and water filling • Communication over eigen- modes • Eigen-beam spatial division multiplexing • Precoding • Beamforming	• OFDM • Multi-tone modulation • Filter bank multicarrier	Not defined

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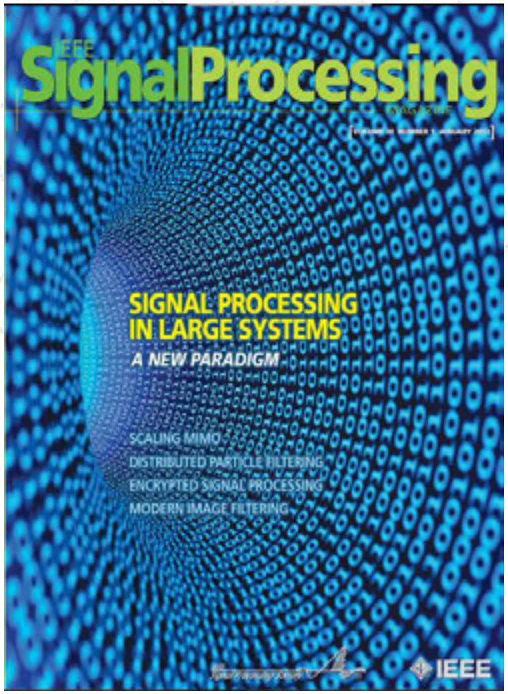
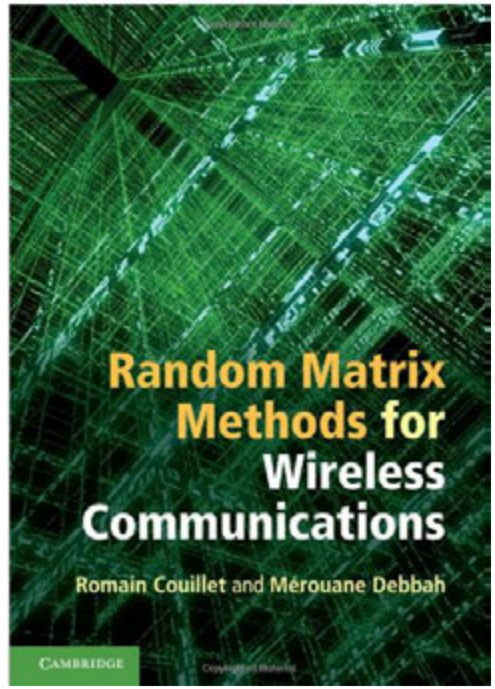
Massive MIMO





F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors, and F. Tufvesson, *“Scaling up MIMO: Opportunities and Challenges with Very Large Arrays”*, IEEE Signal Procesessing Magazine, **January, 2013**.

Efficient Linear Processing (for tall H matrices)

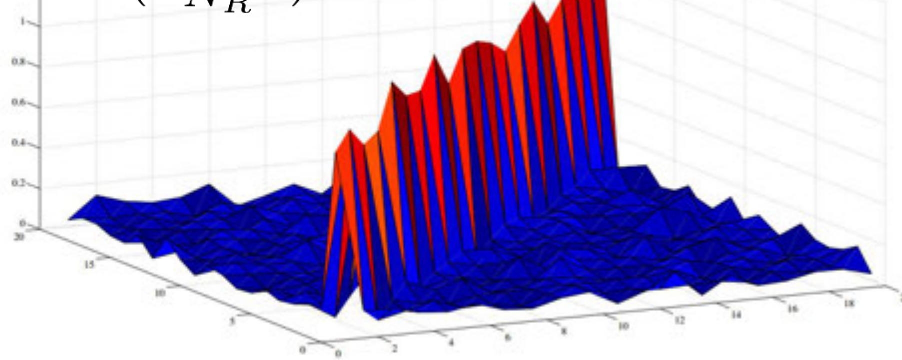
- Zero-forcing (or MMSE): $$(\underbrace{\mathbf{H}^H\mathbf{H}}_{\mathbf{Z}})^{-1}\mathbf{H}^H\mathbf{y} = \mathbf{H}^\dagger\mathbf{y}$$

- Near optimal diversity: $$N_R - N_T + 1 \approx N_R$$

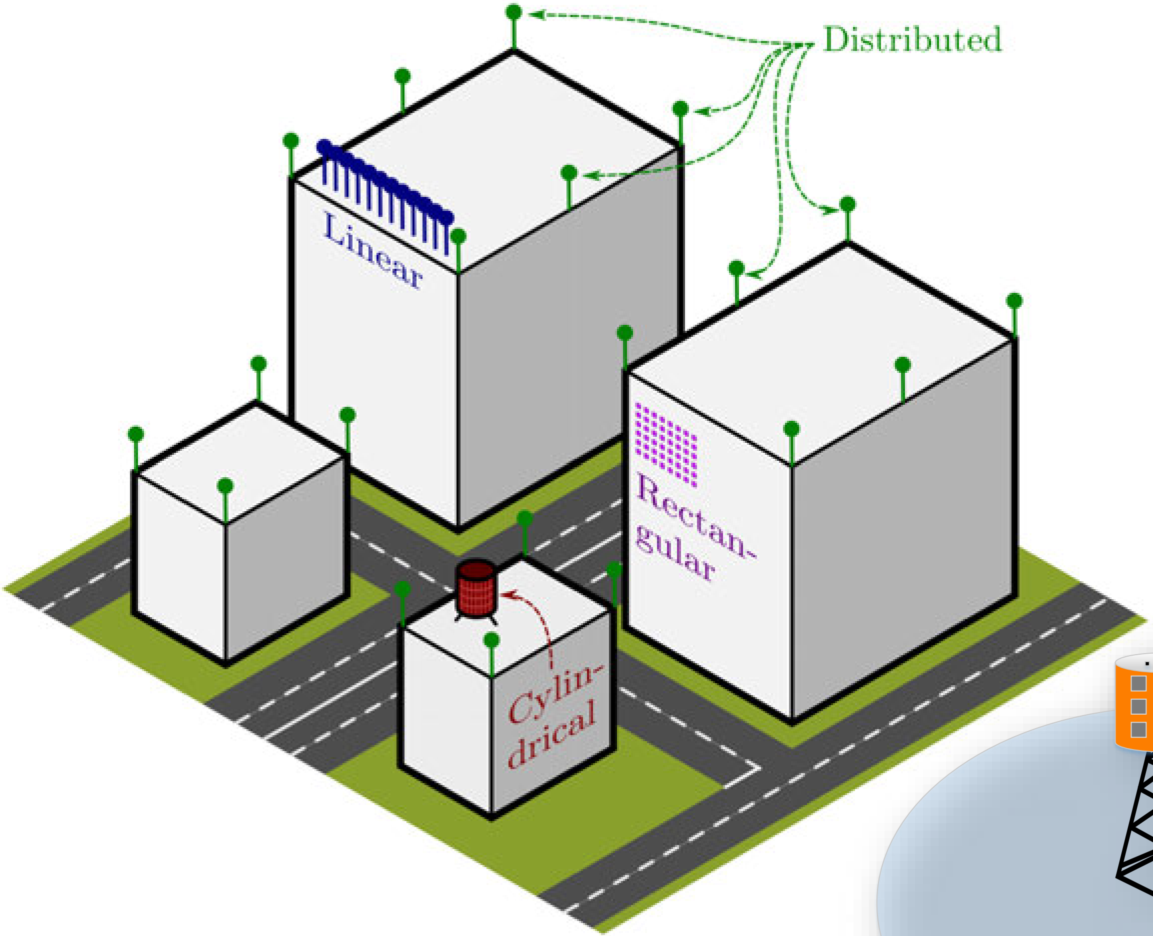
- Low complexity
    - But requires inverse ($\mathcal{O}(N_T^3)$)

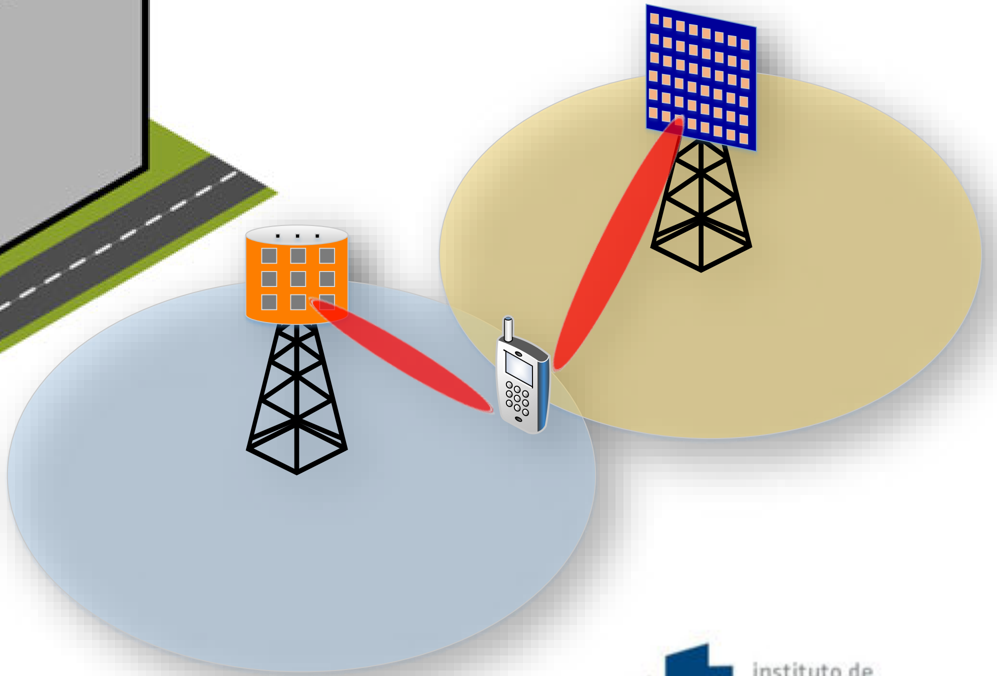
- It is possible to use:
    - Neumann series (approximation)
    - Matrix inversion lemma

$$\left(\frac{\mathbf{H}^H\mathbf{H}}{N_R}\right) \xrightarrow{\text{a.s.}} \mathbf{D}$$



Massive MIMO: antenna arrays





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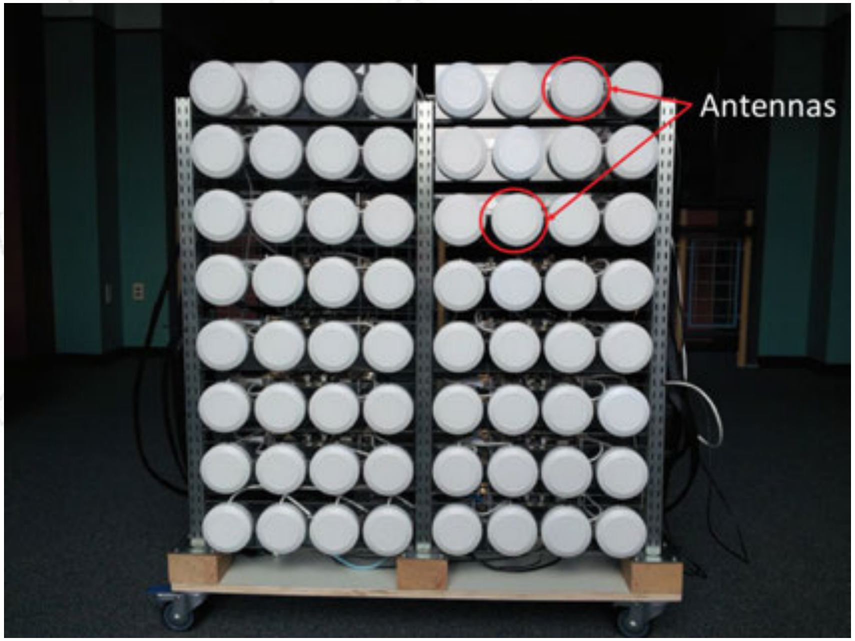
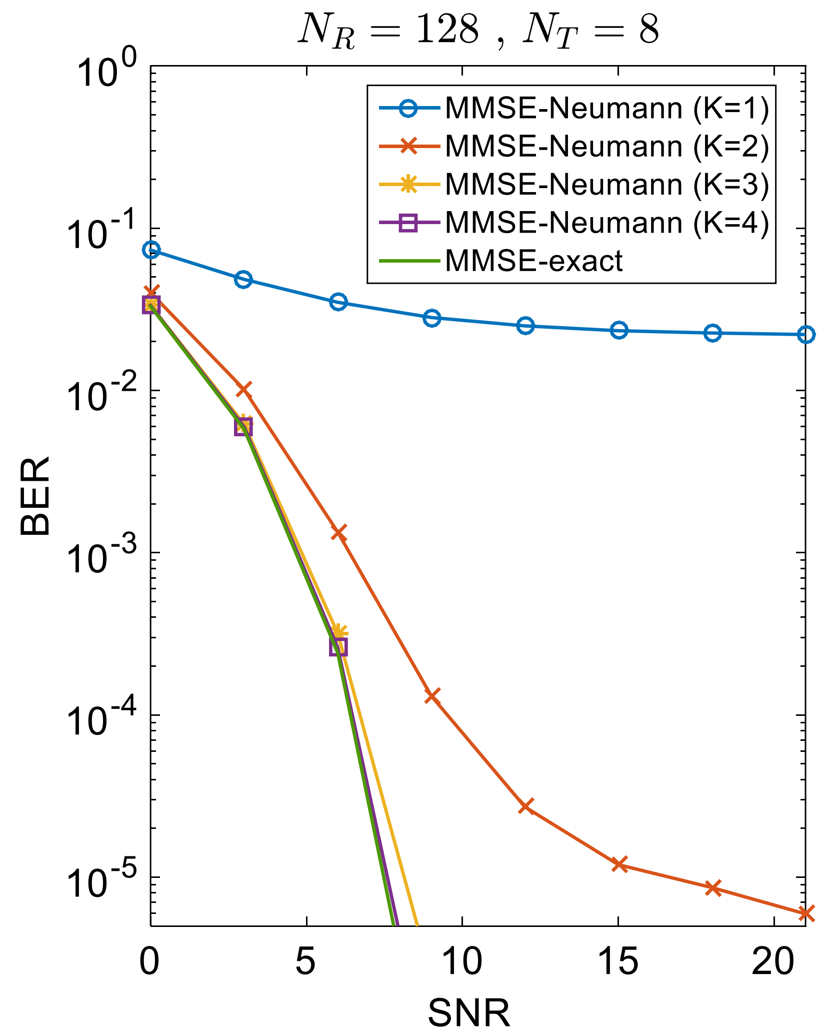


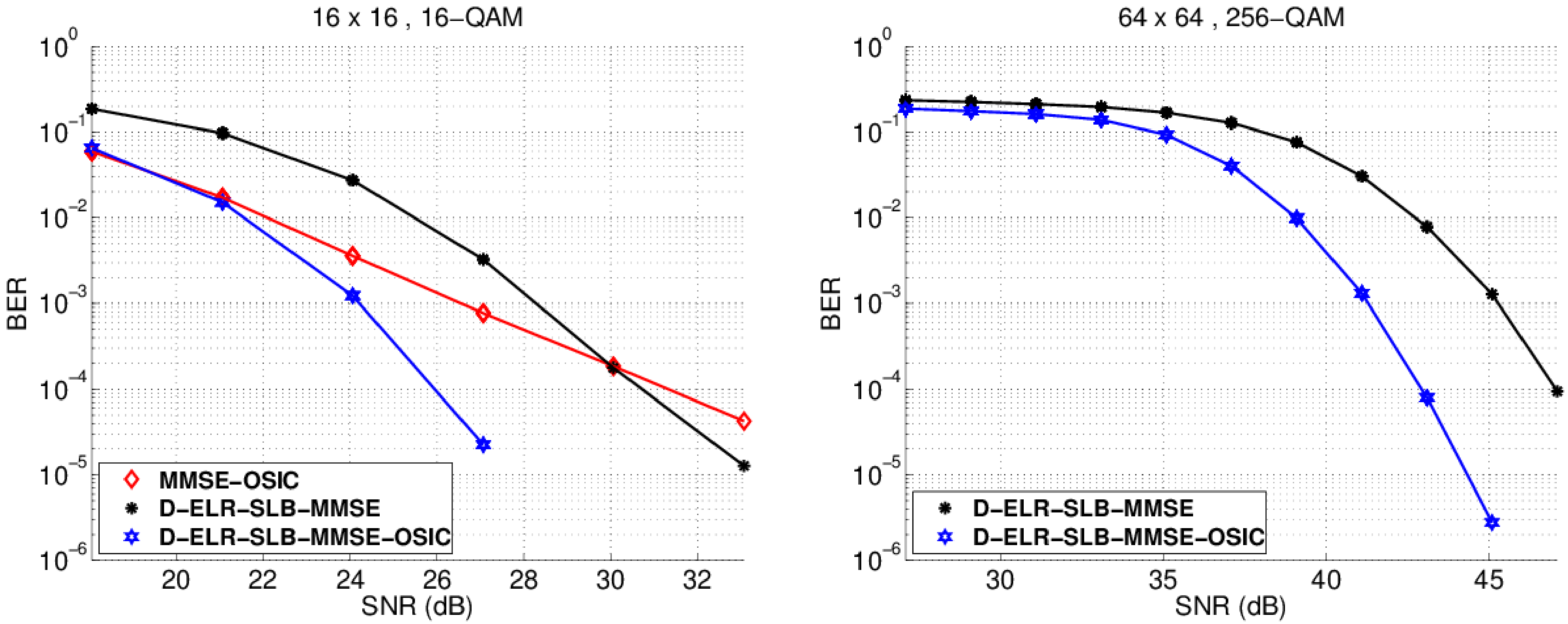
(Images: from Lund Univ., EU METIS and ARGOS projects)

Neumann series (approximation)



The Neumann series provides an efficient, hardware-realisable, method to compute the inverse required to perform linear processing.

Large (symmetric) MIMO



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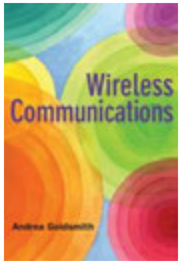
Recent state-of-the-art in radio science

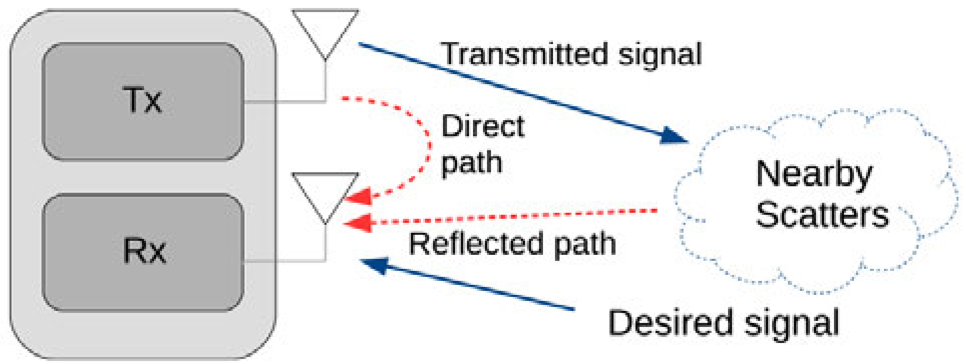
"It is generally not possible for radios to receive and transmit on the same frequency band because of the interference that results."

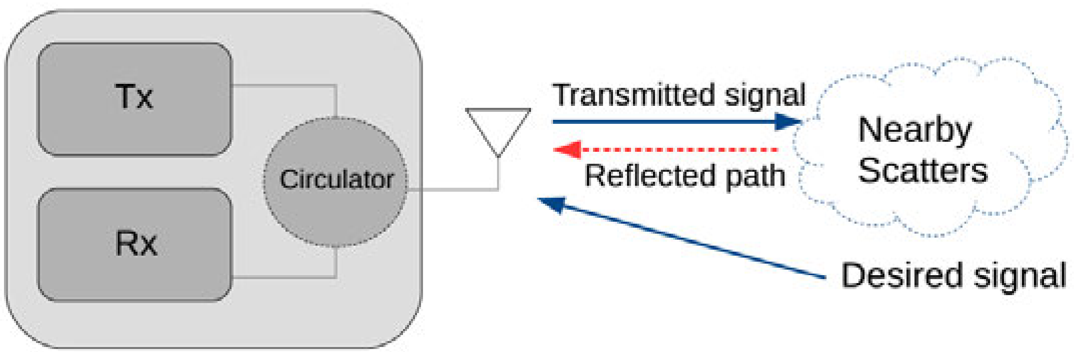


Andrea Goldsmith,

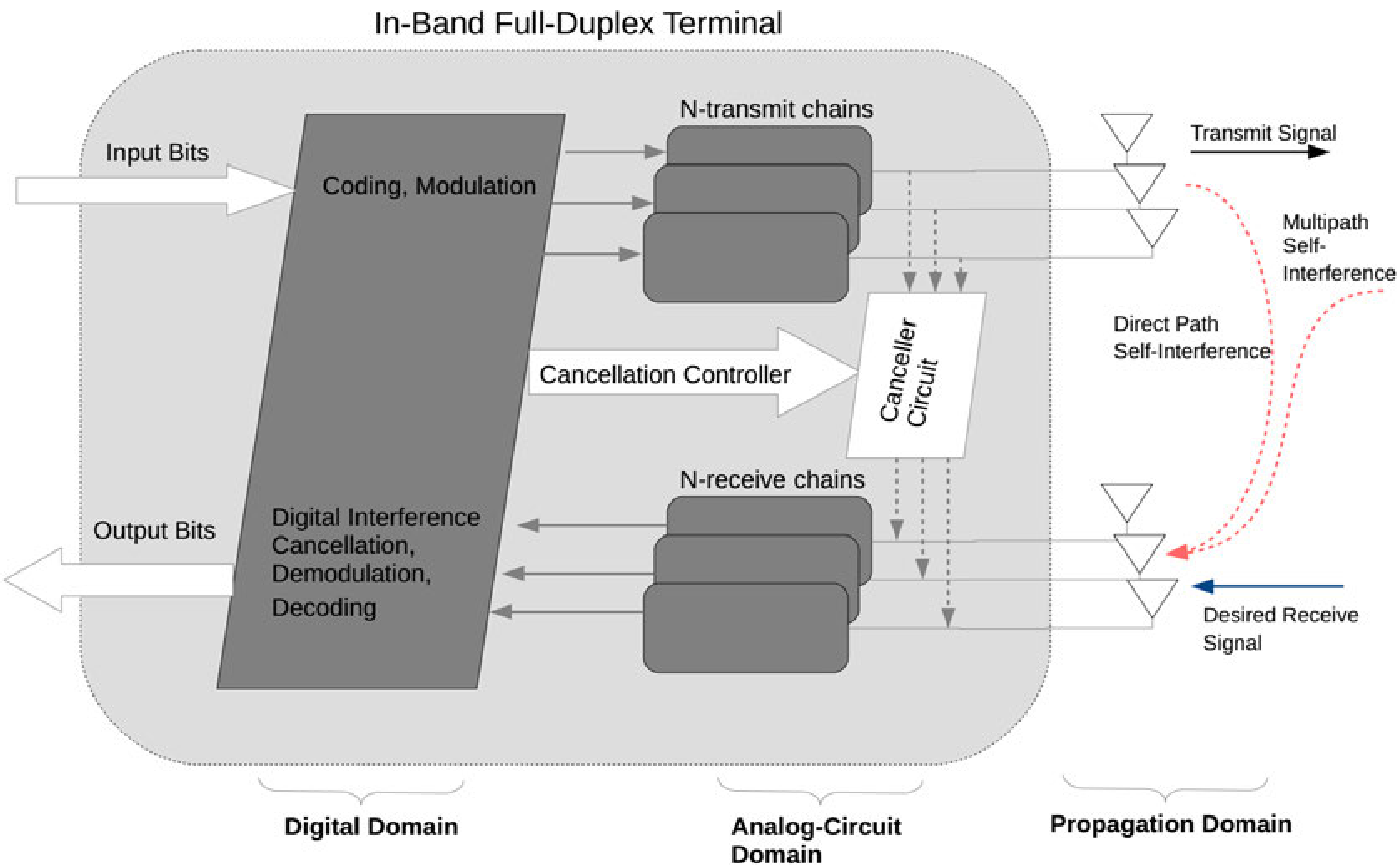
In *Wireless Communications*, Cambridge University Press, p. 454, 2003

Two possible antenna setups

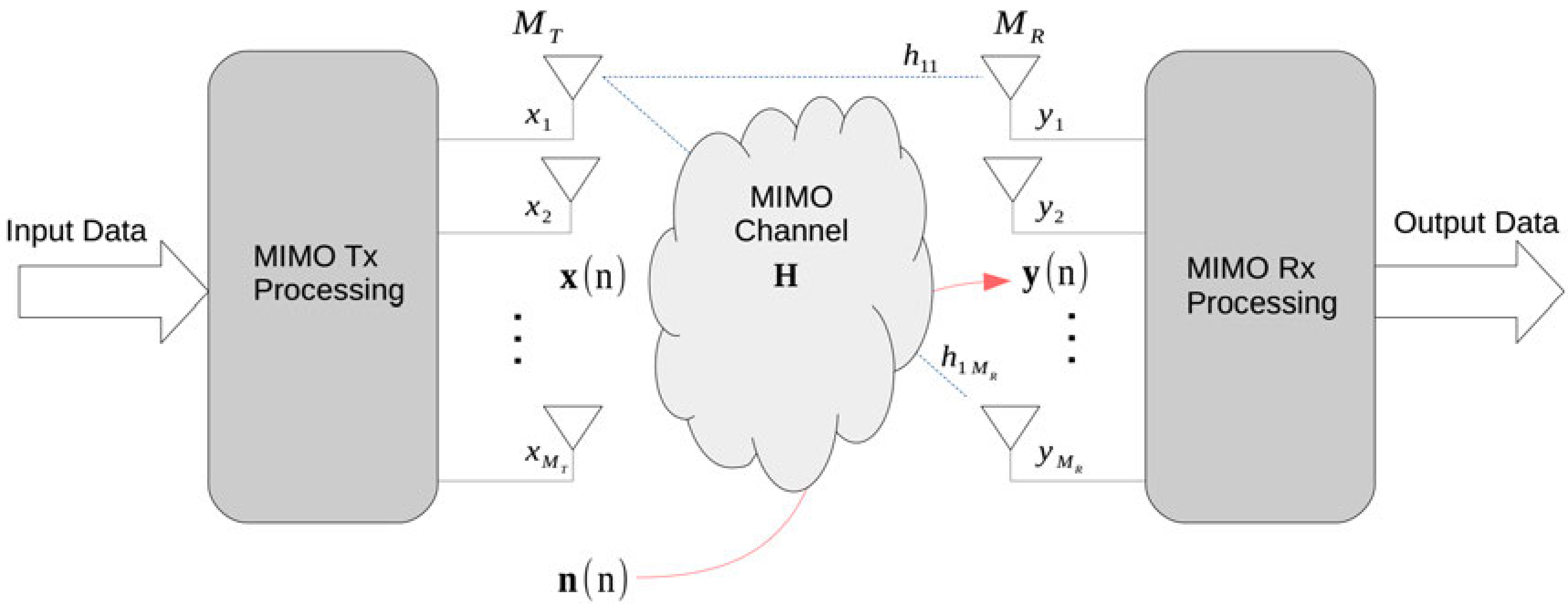




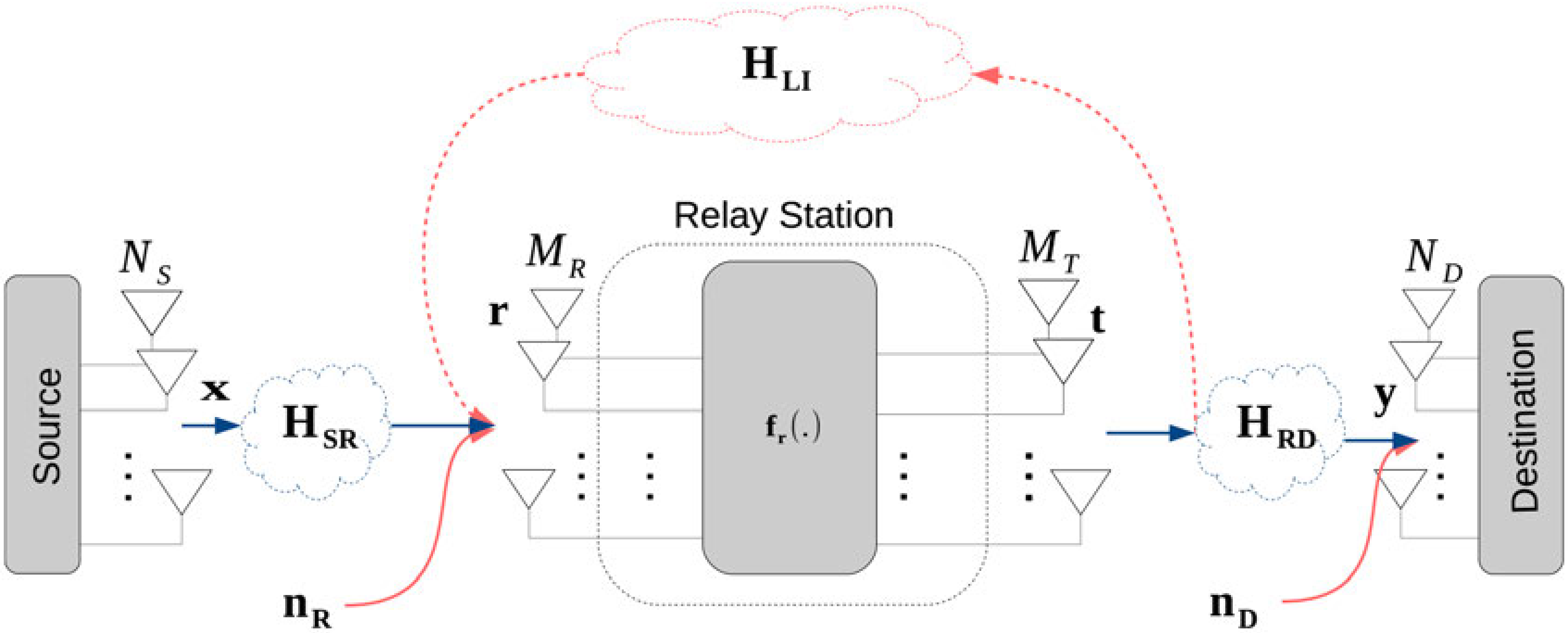
MIMO full-duplex device



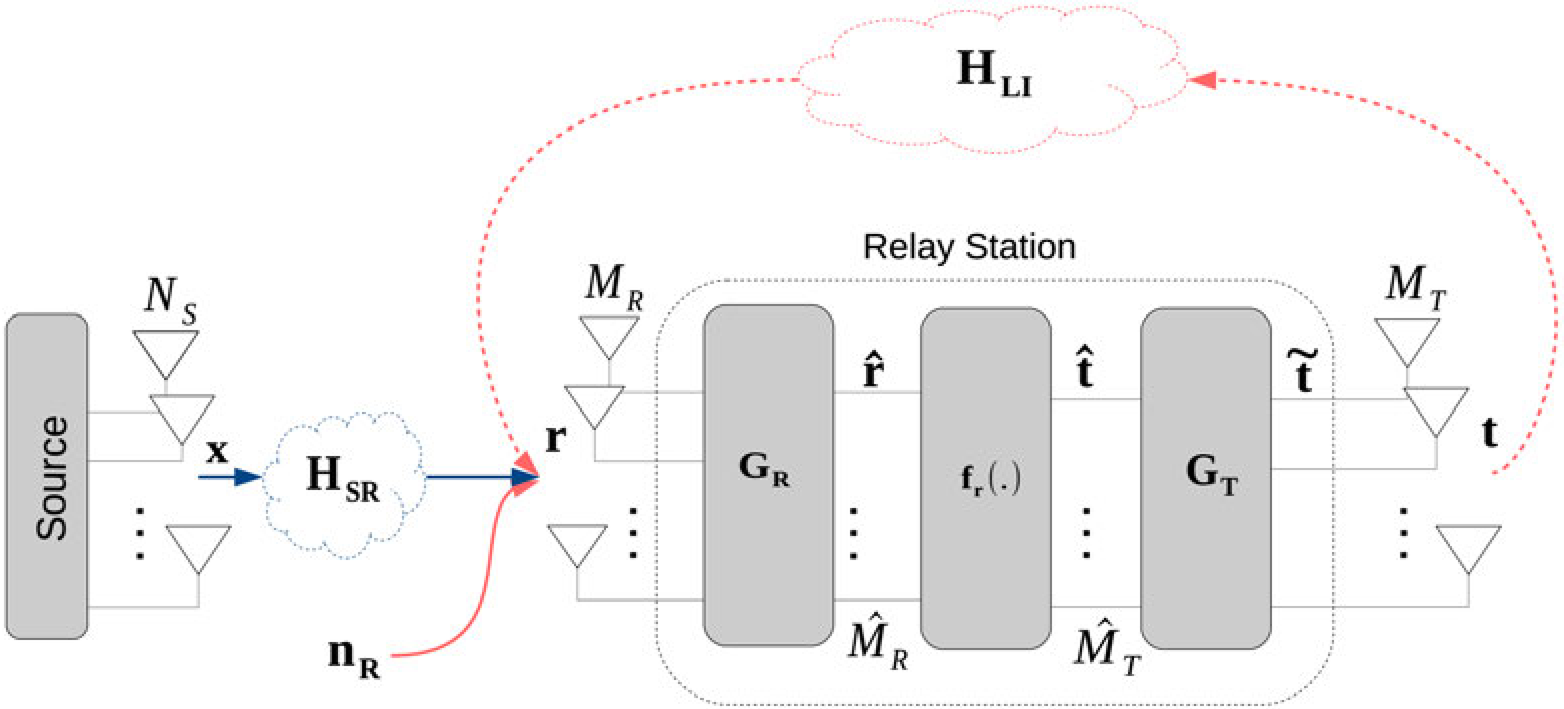
Multiple-input multiple-output (i.e., multi-antenna)



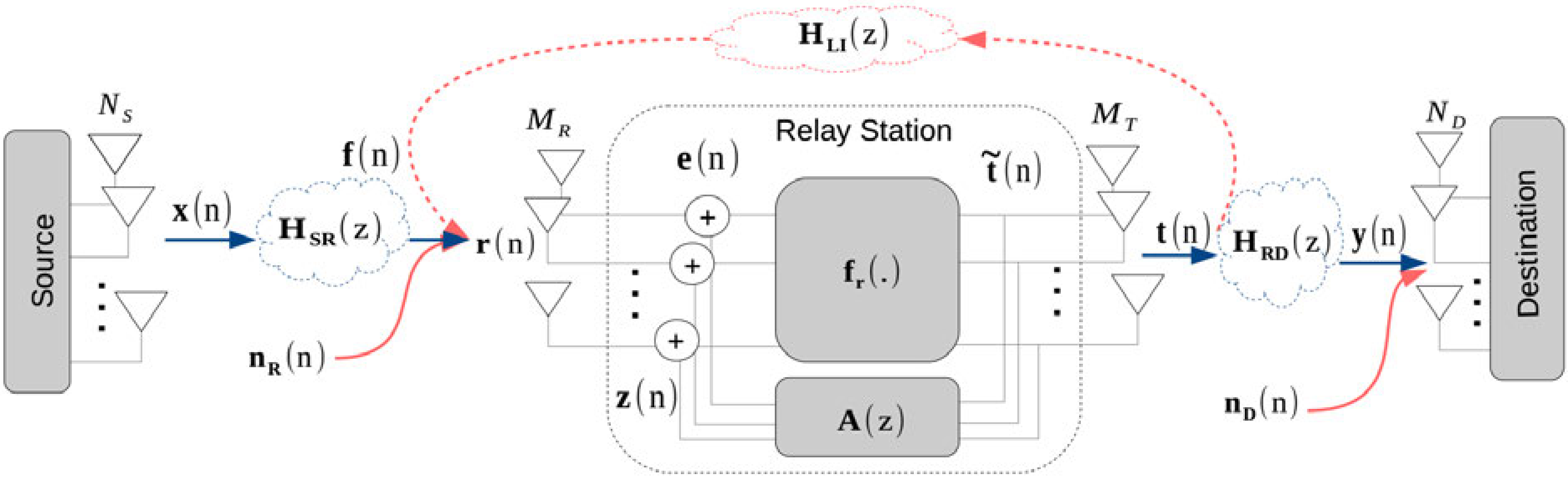
In-band full-duplex relay station



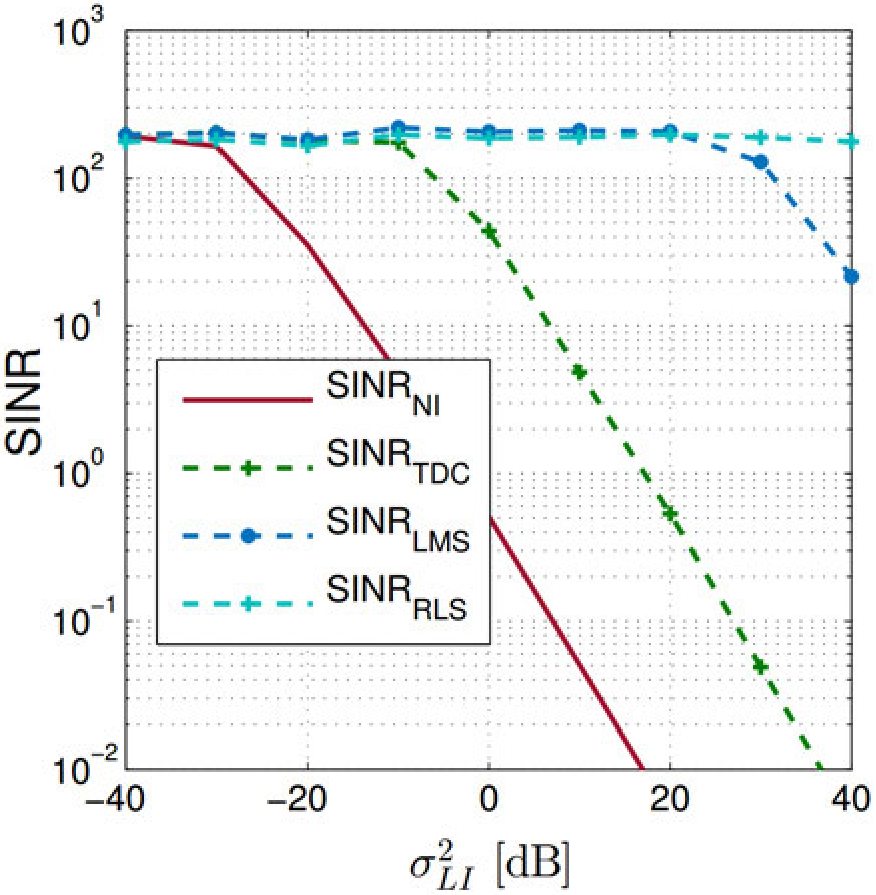
Filter design: receive filters and transmit filters



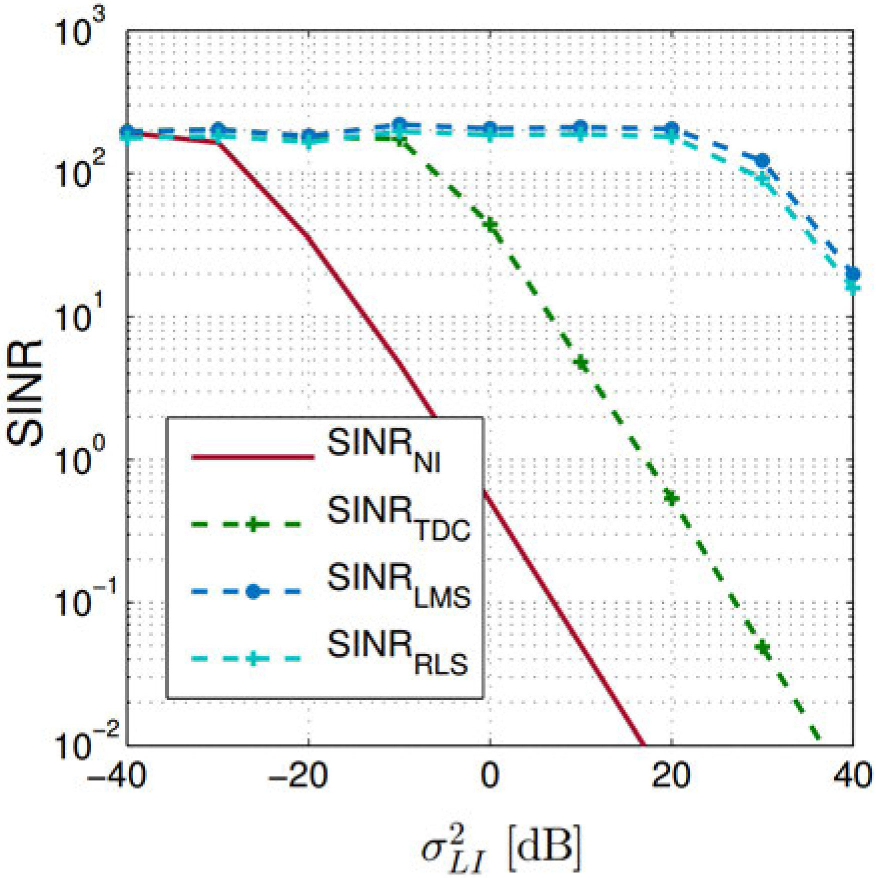
Feedback filter for interference cancellation



How loopback interference impacts on SINR

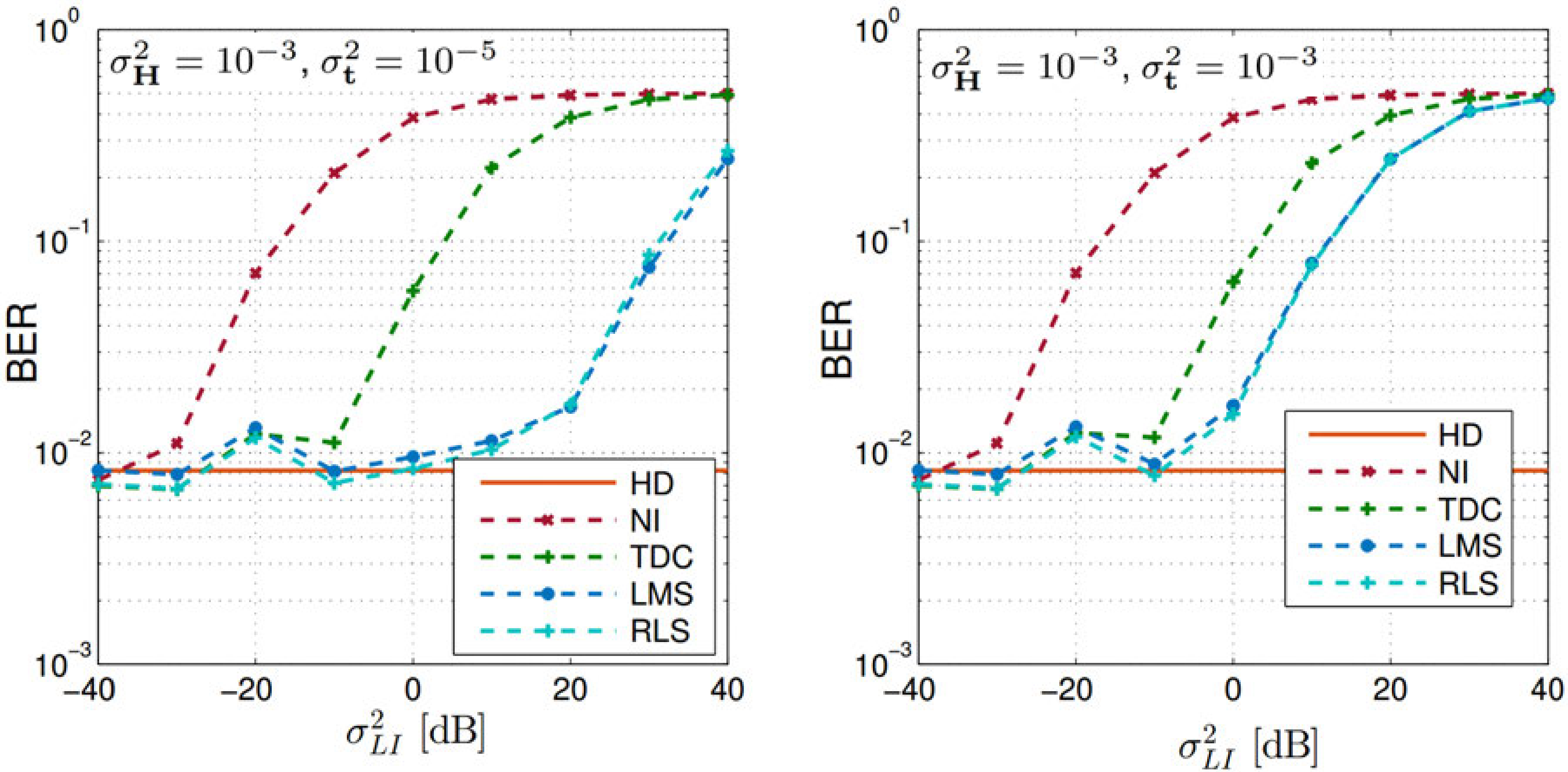


(a) $\sigma^2_{\mathbf{H}} = 10^{-3}$, $\sigma^2_{\mathbf{t}} = 10^{-5}$.



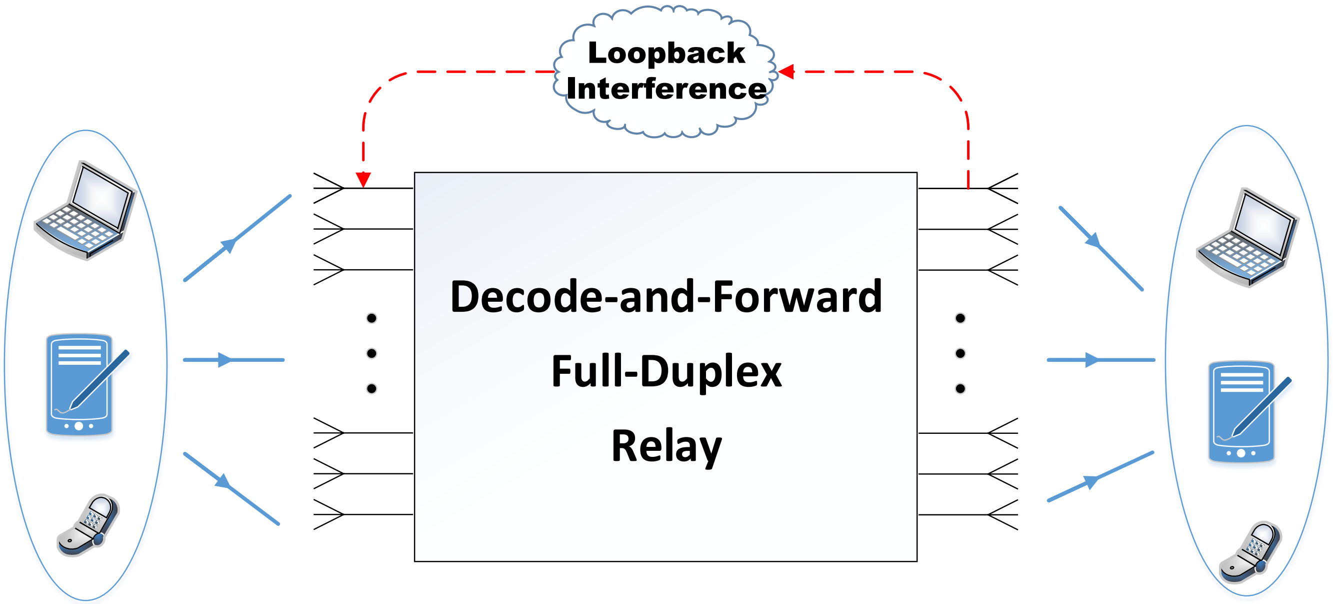
(b) $\sigma^2_{\mathbf{H}} = 10^{-3}$, $\sigma^2_{\mathbf{t}} = 10^{-3}$.

Protection to self interference gain

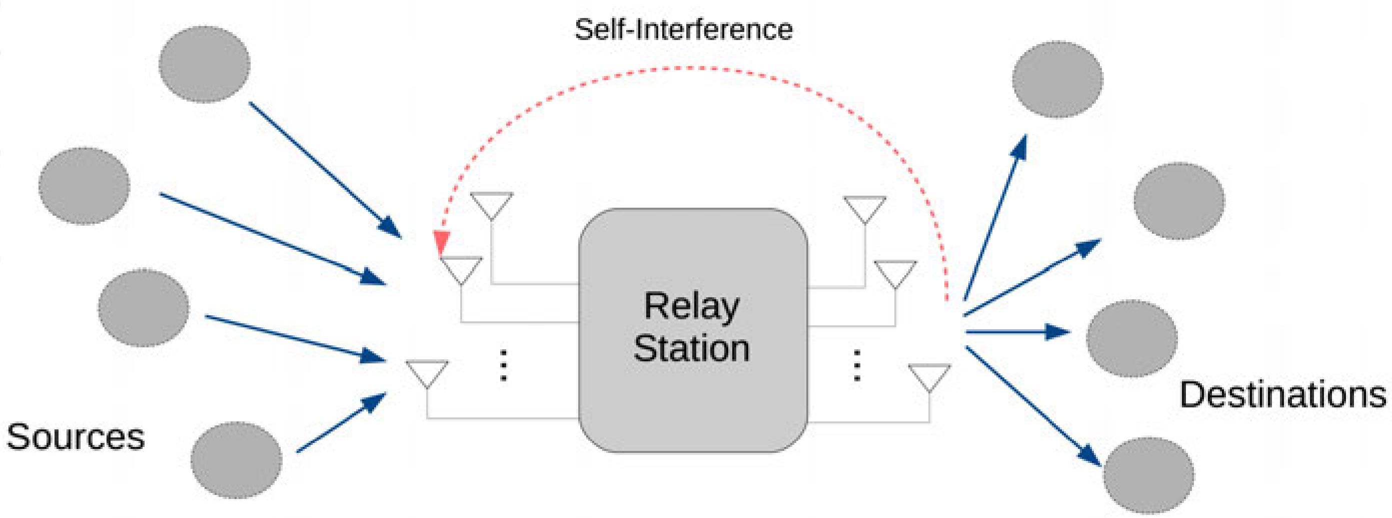


Technique	Gain
Natural Isolation	Reference (0 dB)
NSP	-20 dB
MMSE	-25 dB
LMS	-30 to -40 dB
RLS	-30 to -40 dB
Perfect Cancellation	$-\infty$ dB

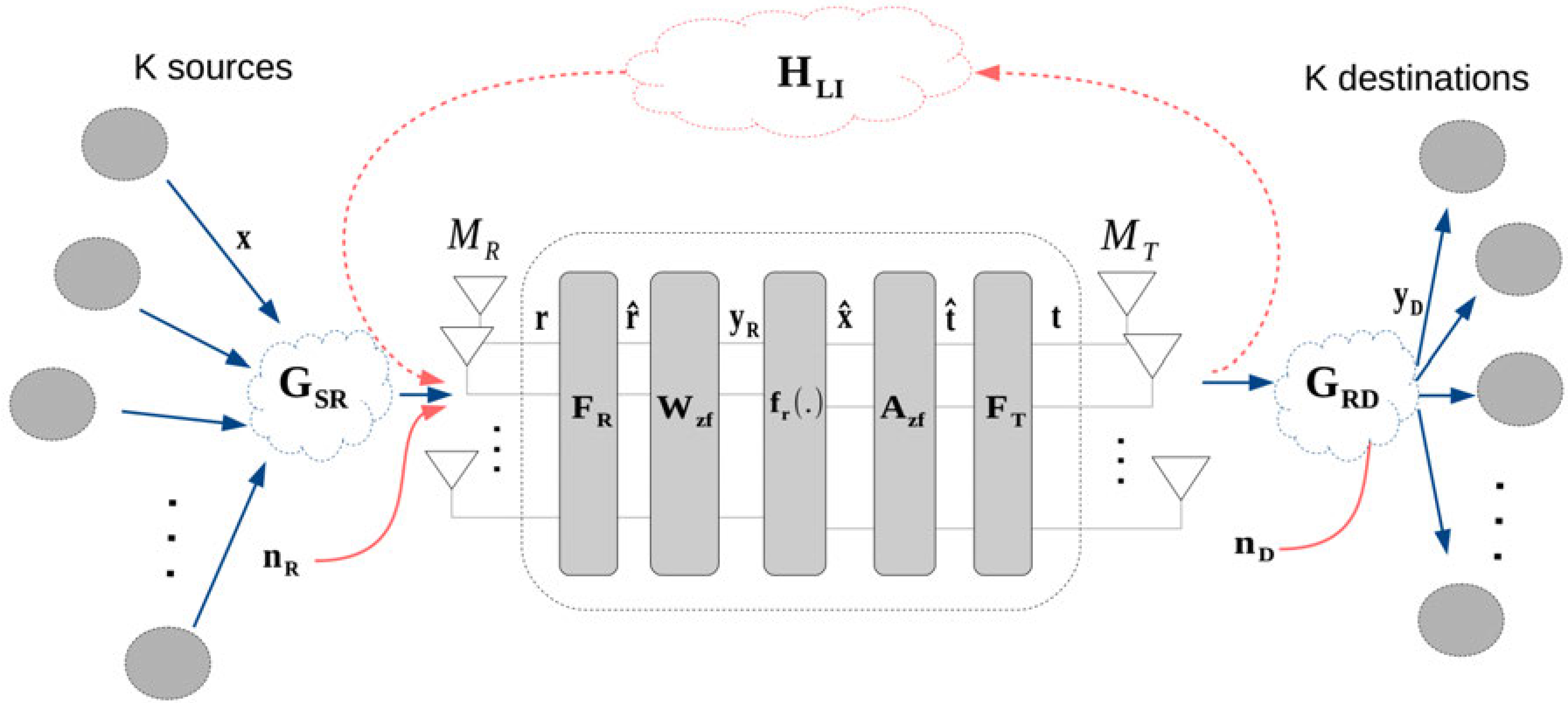
Multi-pairs using virtual MIMO



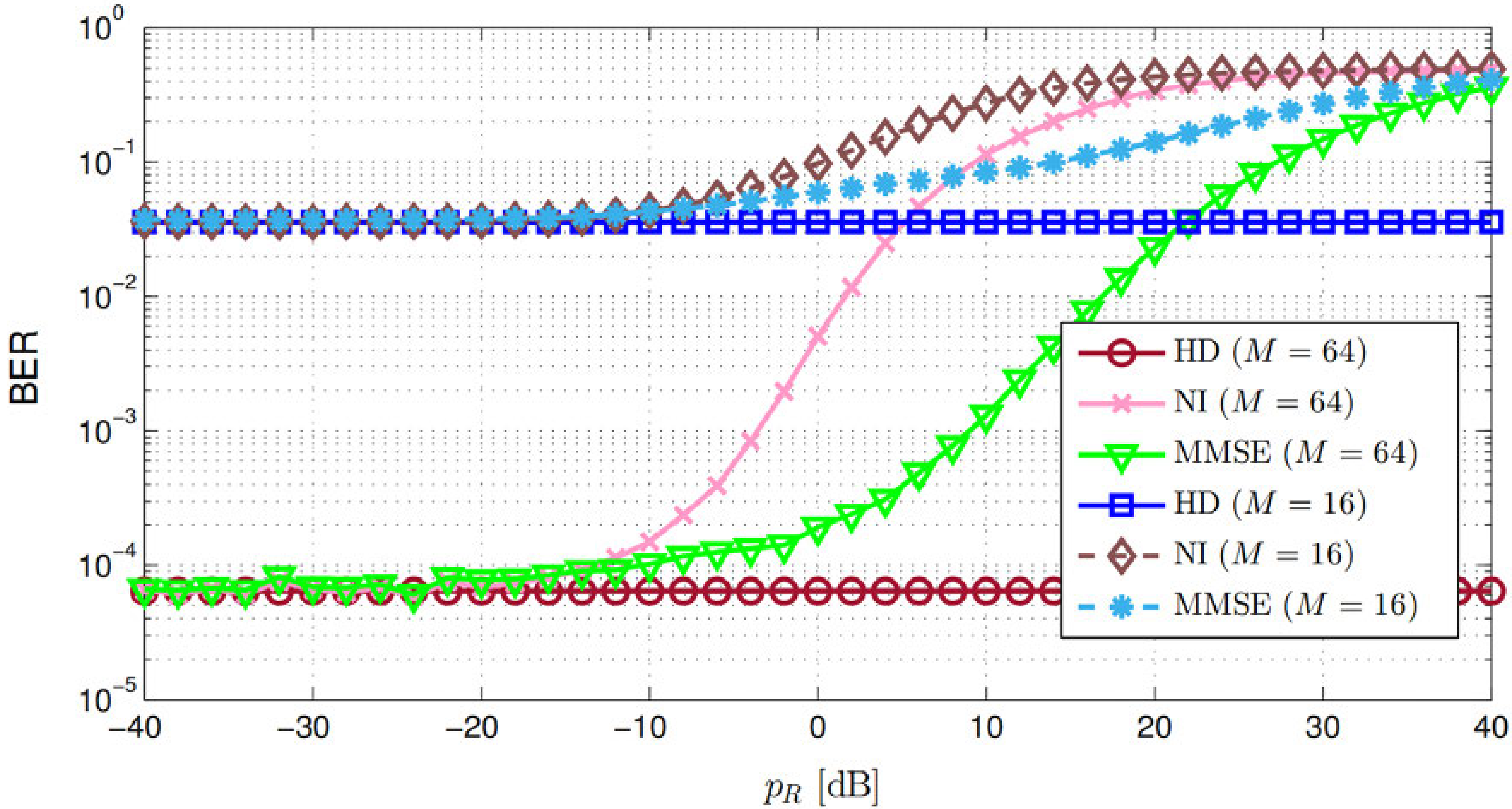
Multi-pairs with a full-duplex relay (1)



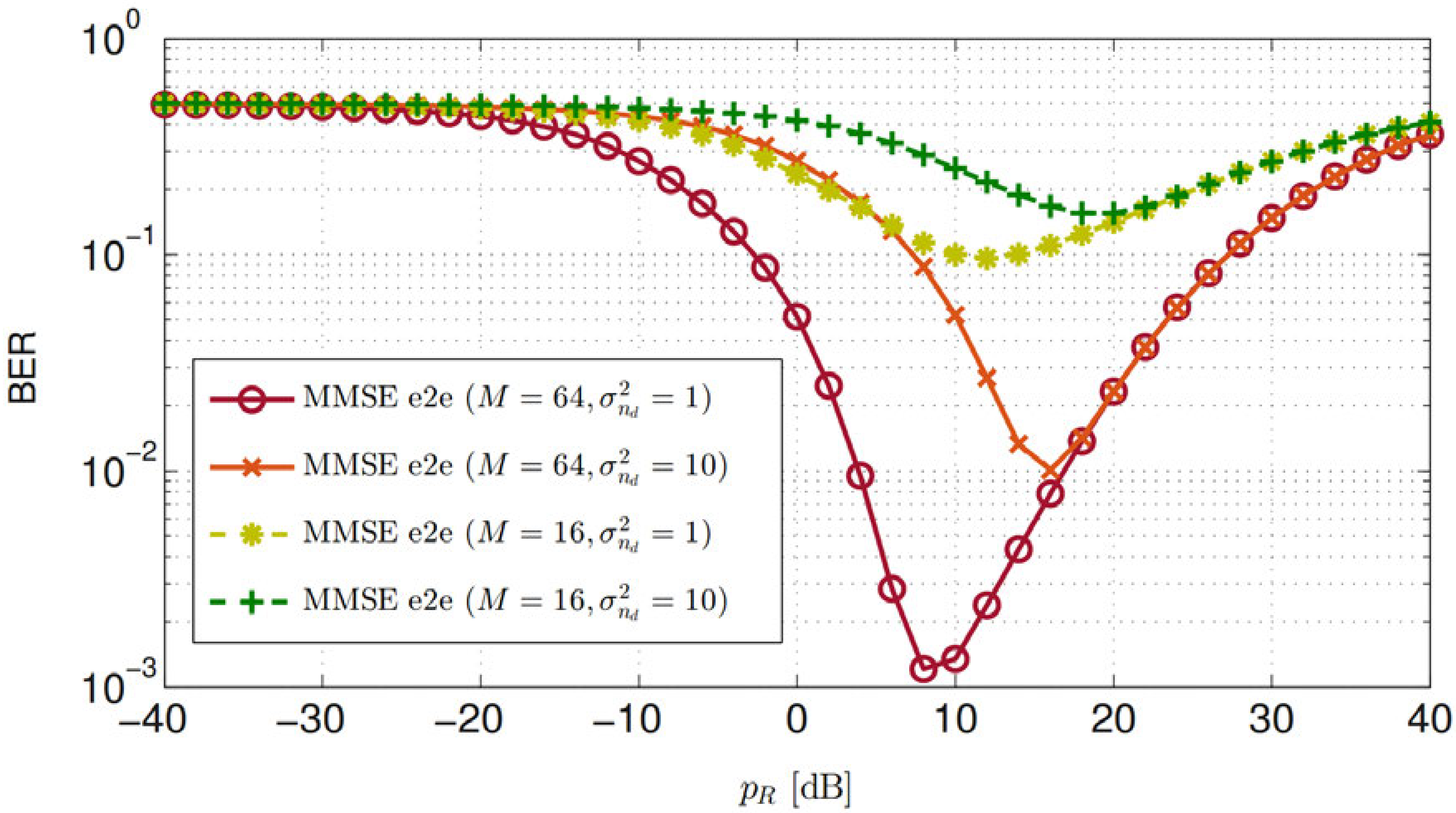
Multi-pairs with a full-duplex relay (2)



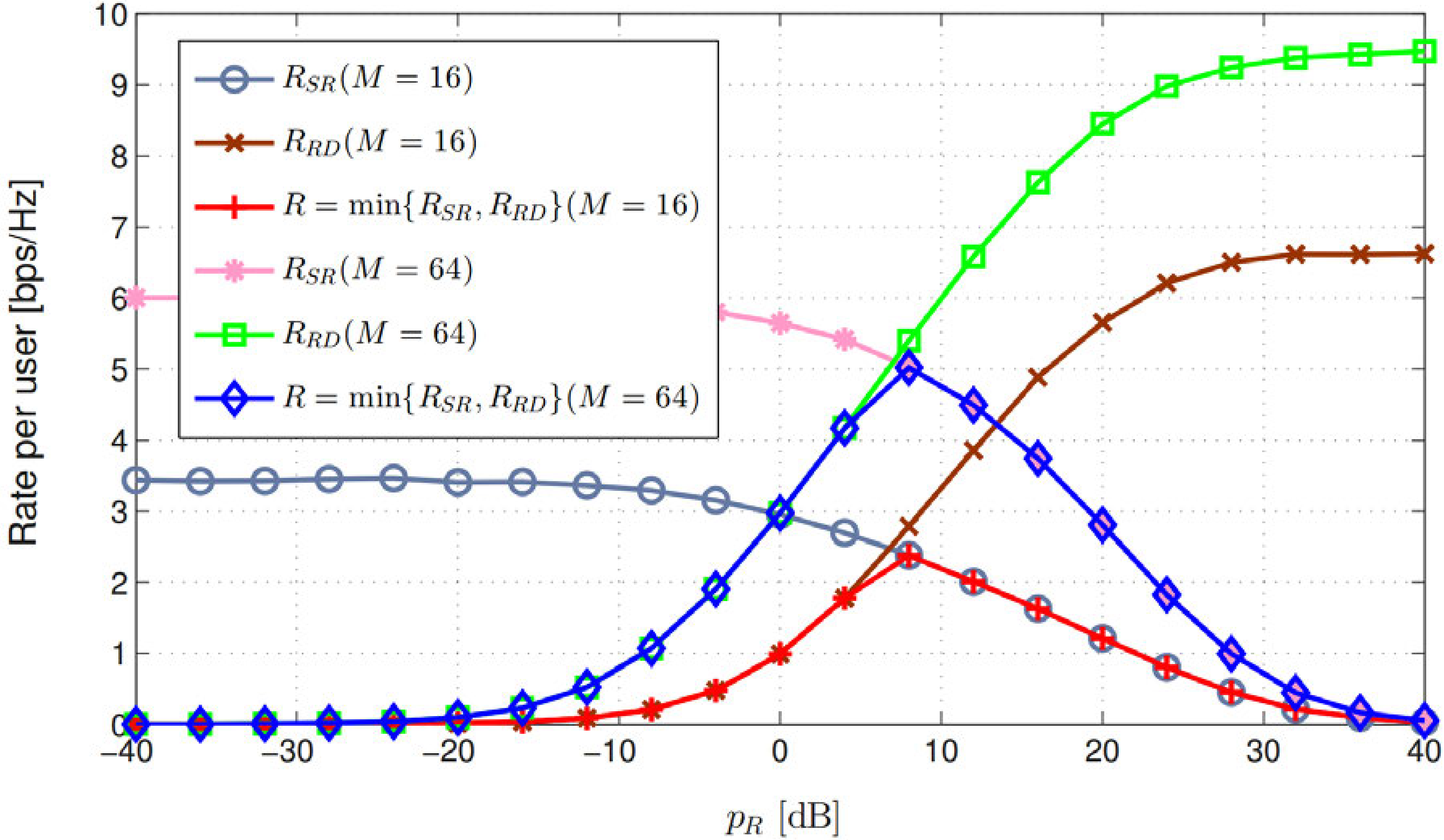
Multi-pairs with a full-duplex relay: loop interference gain



Multi-pairs with a full-duplex relay: effect of the relay power on the performance



Multi-pairs with a full-duplex relay: effect of the relay power on the rates



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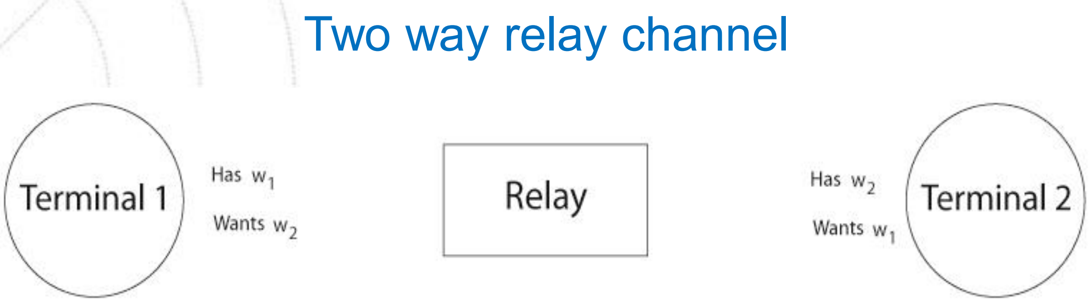
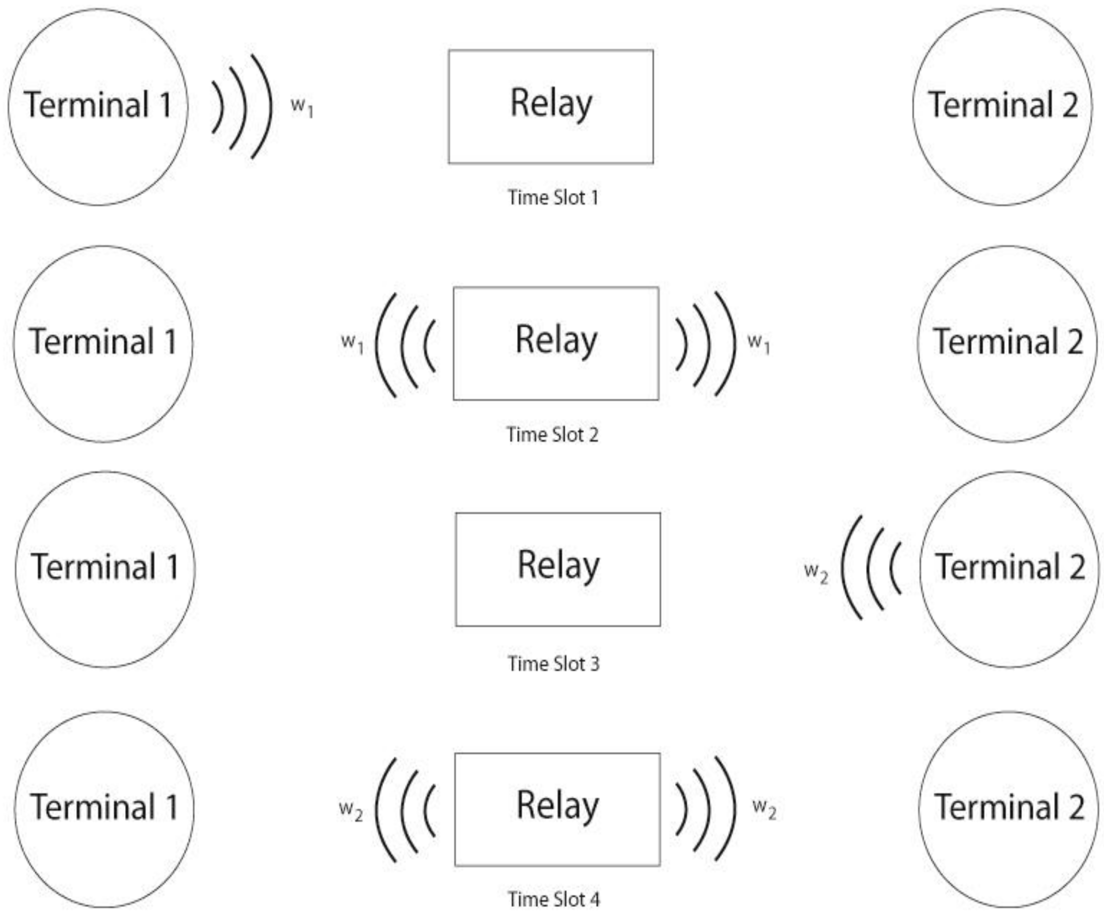
Two way relay channel



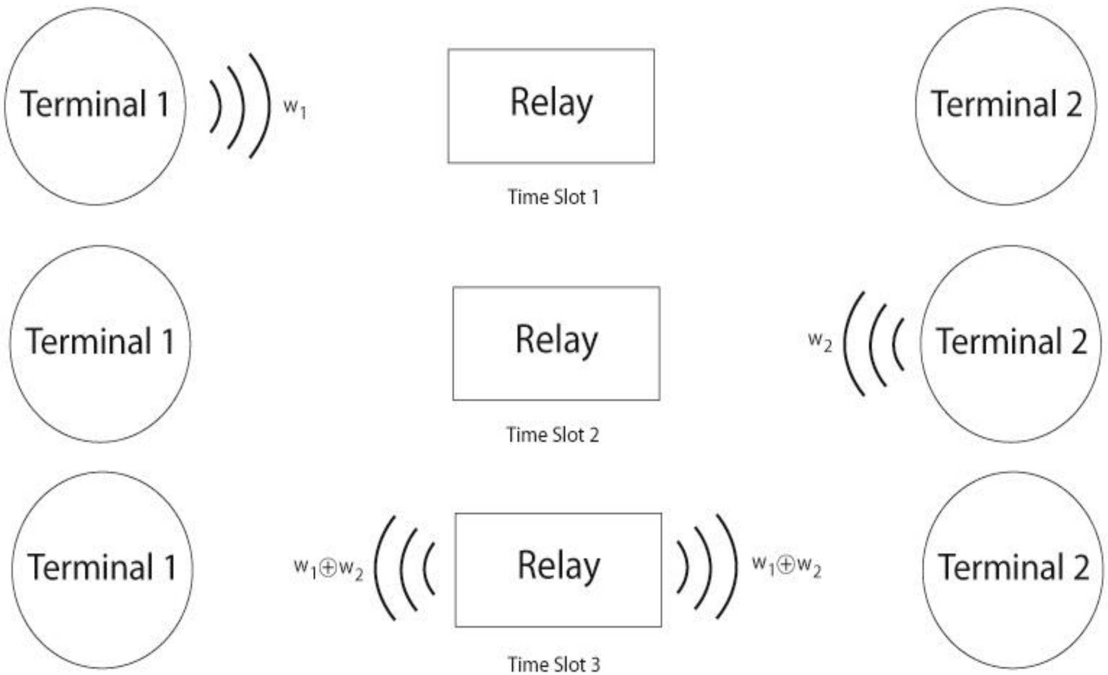
Two way relay channel

TDMA



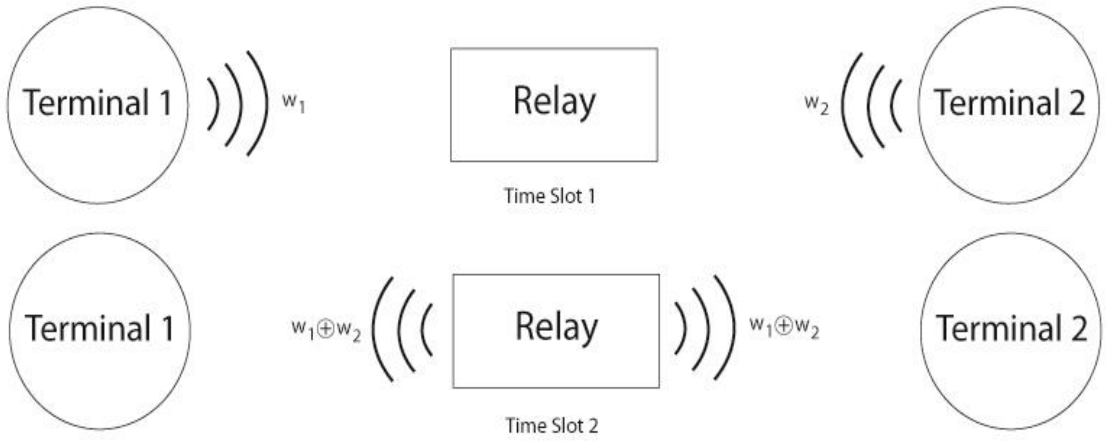
Two way relay channel

Network Coding



Two way relay channel

Physical layer Network Coding



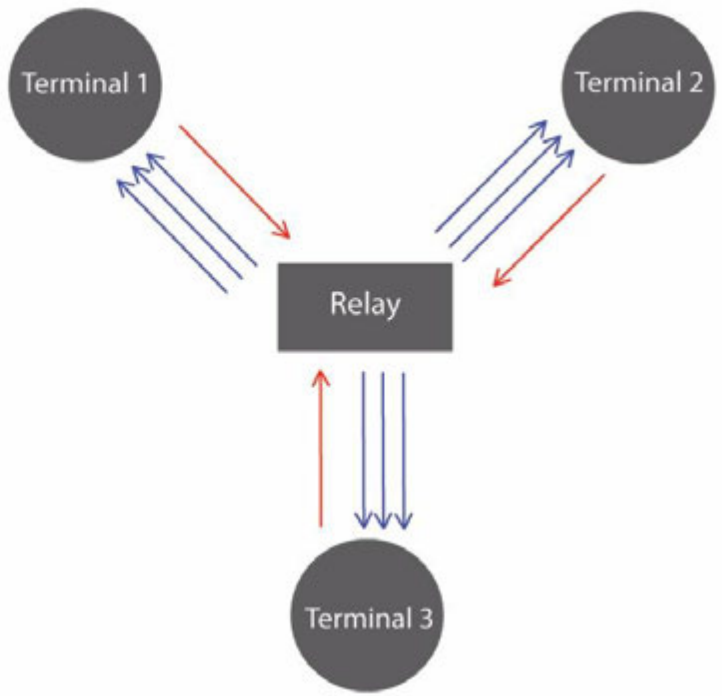
Two time-slots. Can we do better?

$\Rightarrow$ Merge both stages $\Leftrightarrow$ in-band full-duplex.

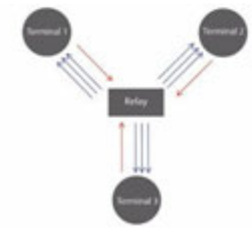
Multi-way channels. The Y-network with TDMA:

Six time-slots.

Can we do better?



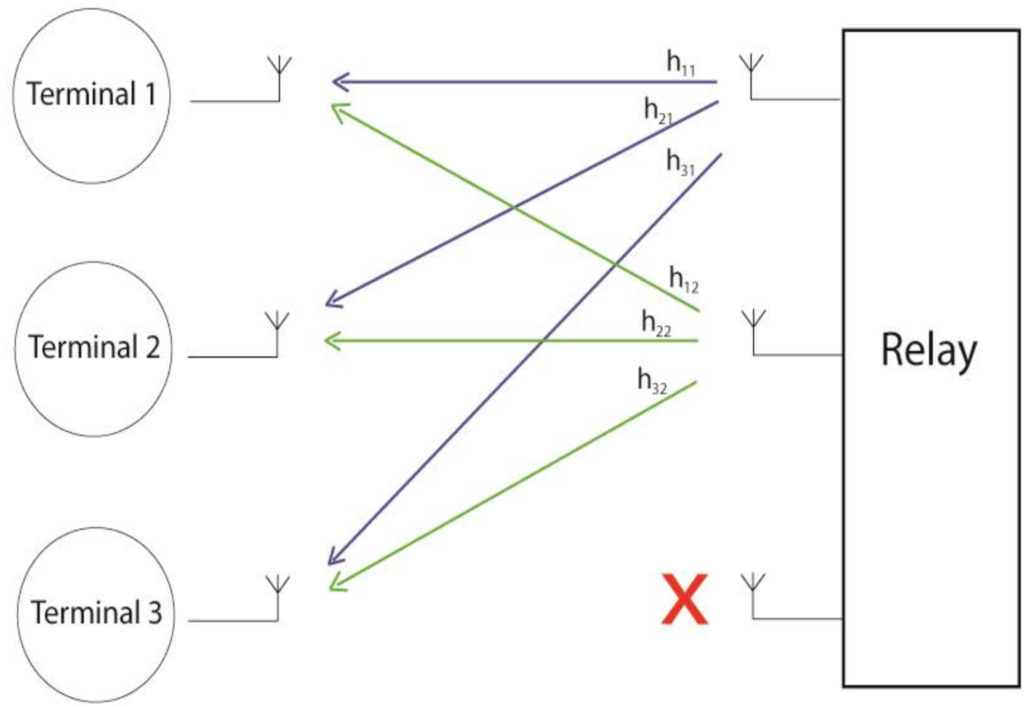
Three time slots: a protocol with SISO (1)



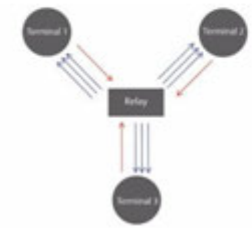
$$y_1[2] = h_{11}x_1 + h_{12}x_2 + n$$

$$y_2[2] = h_{21}x_1 + h_{22}x_2 + n$$

$$y_3[2] = h_{31}x_1 + h_{32}x_2 + n$$



Three time slots: a protocol with SISO (1)



$$y_1[2] = \cancel{h_{11}x_1} + h_{12}x_2 + n$$

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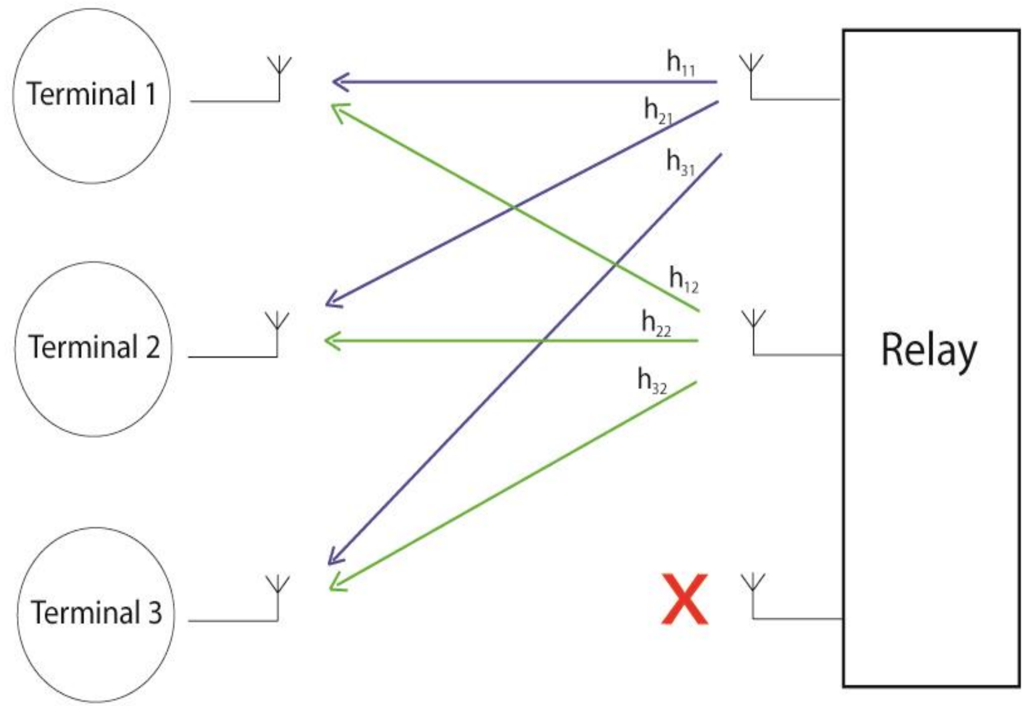
$$y_3[2] = h_{31}x_1 + h_{32}x_2 + n$$



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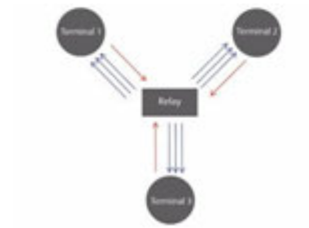
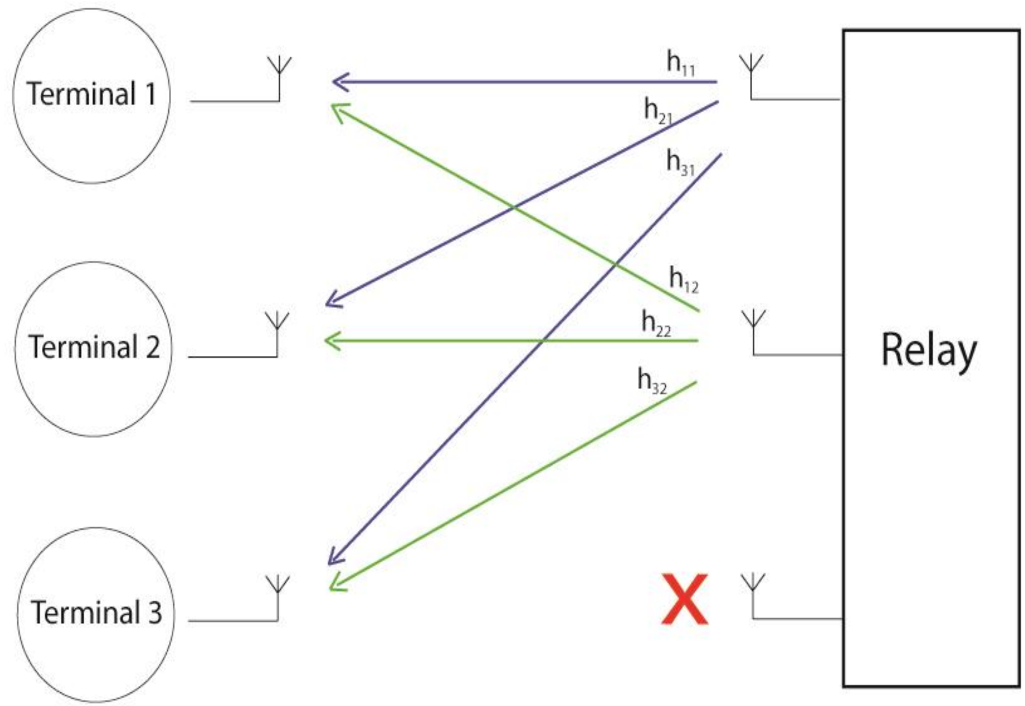


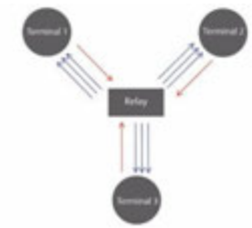
$$y_1[2] = \cancel{h_{11}x_1} + h_{12}x_2 + n \qquad \color{blue}{\hat{x}_2}$$

$$y_2[2] = h_{21}x_1 + \cancel{h_{22}x_2} + n \qquad \color{blue}{\hat{x}_1}$$

$$y_3[2] = h_{31}x_1 + h_{32}x_2 + n \qquad \color{blue}{y_3[2]}$$



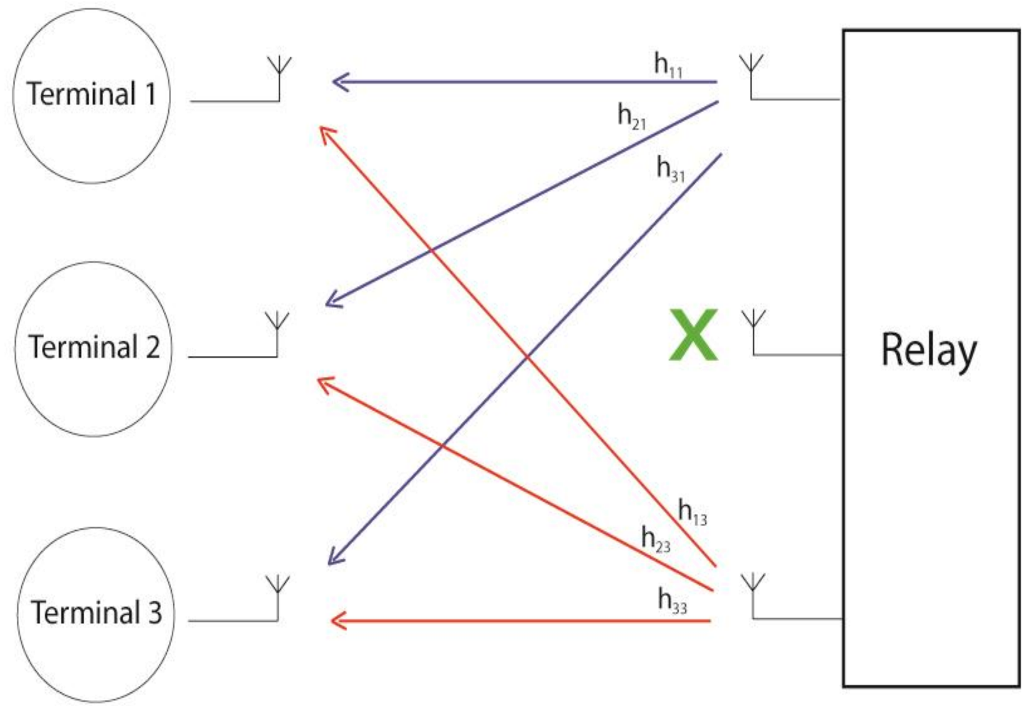
Three time slots: a protocol with SISO (2)



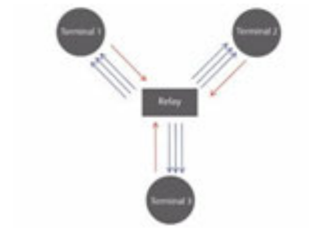
$$y_1[3] = h_{11}x_1 + h_{13}x_3 + n \qquad \hat{x}_2$$

$$y_2[3] = h_{21}x_1 + h_{23}x_3 + n \qquad \hat{x}_1$$

$$y_3[3] = h_{31}x_1 + h_{33}x_3 + n \qquad y_3[2]$$



Three time slots: a protocol with SISO (2)



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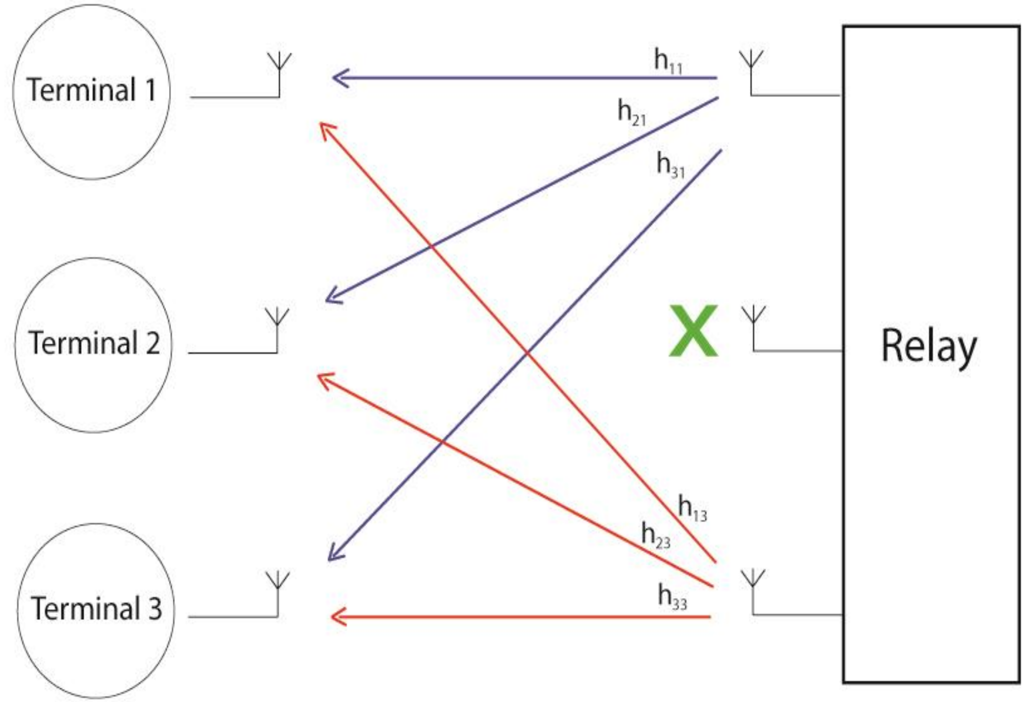
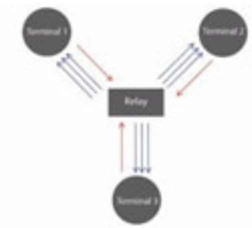


Three time slots: a protocol with SISO (2)



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$\hat{x}_2$

$\hat{x}_3$

$$y_2[3] = \cancel{h_{21}x_1} + h_{23}x_3 + n$$

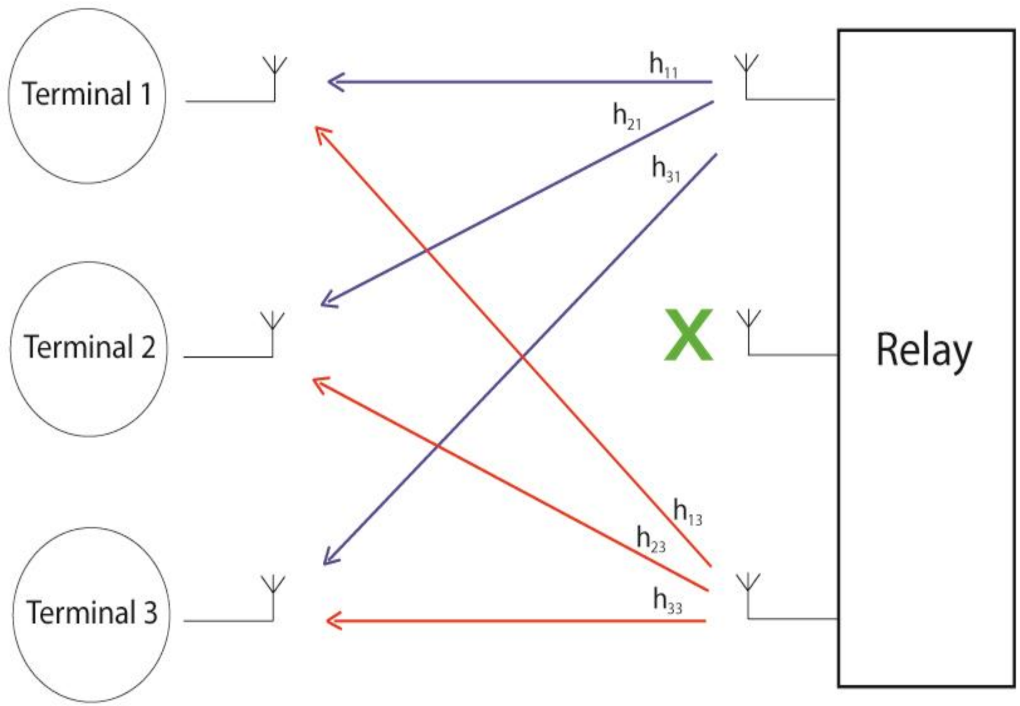
$\hat{x}_1$

$\hat{x}_3$

$$y_3[3] = h_{31}x_1 + \cancel{h_{33}x_3} + n$$

$y_3[2]$

$\hat{x}_1$



Three time slots: a protocol with SISO (2)

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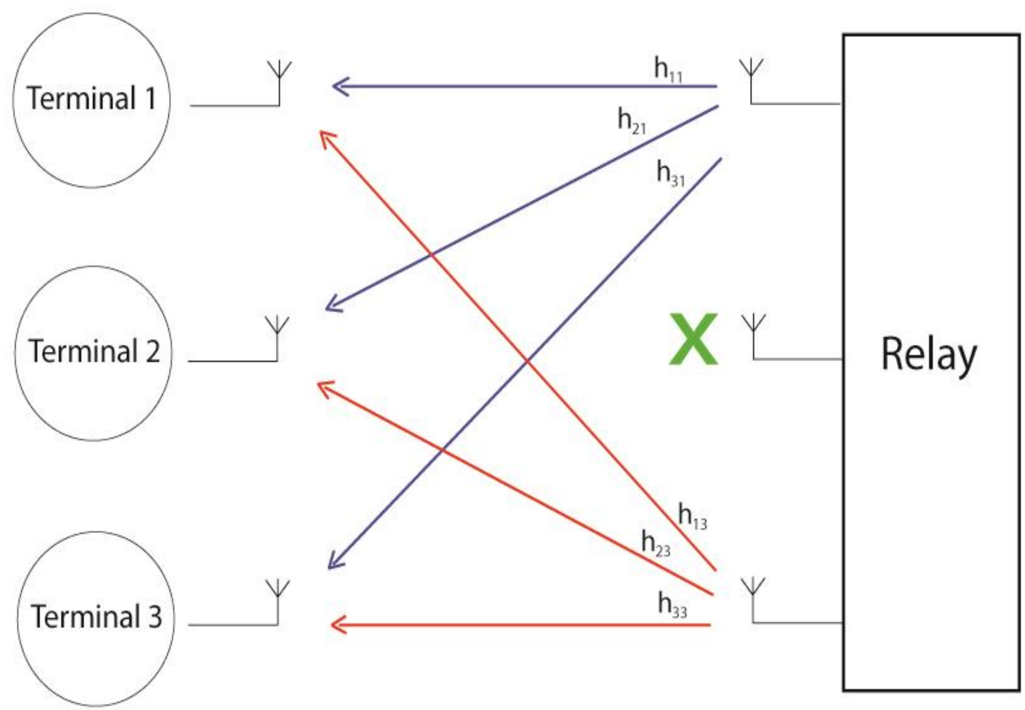
$\hat{x}_1$

$\hat{x}_3$

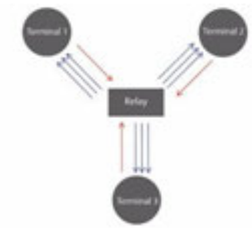
$$y_3[3] = h_{31}x_1 + \cancel{h_{33}x_3} + n$$

$\hat{x}_1$

$$y_3[2] = h_{31}x_1 + h_{32}x_2 + n$$



Three time slots: a protocol with SISO (2)



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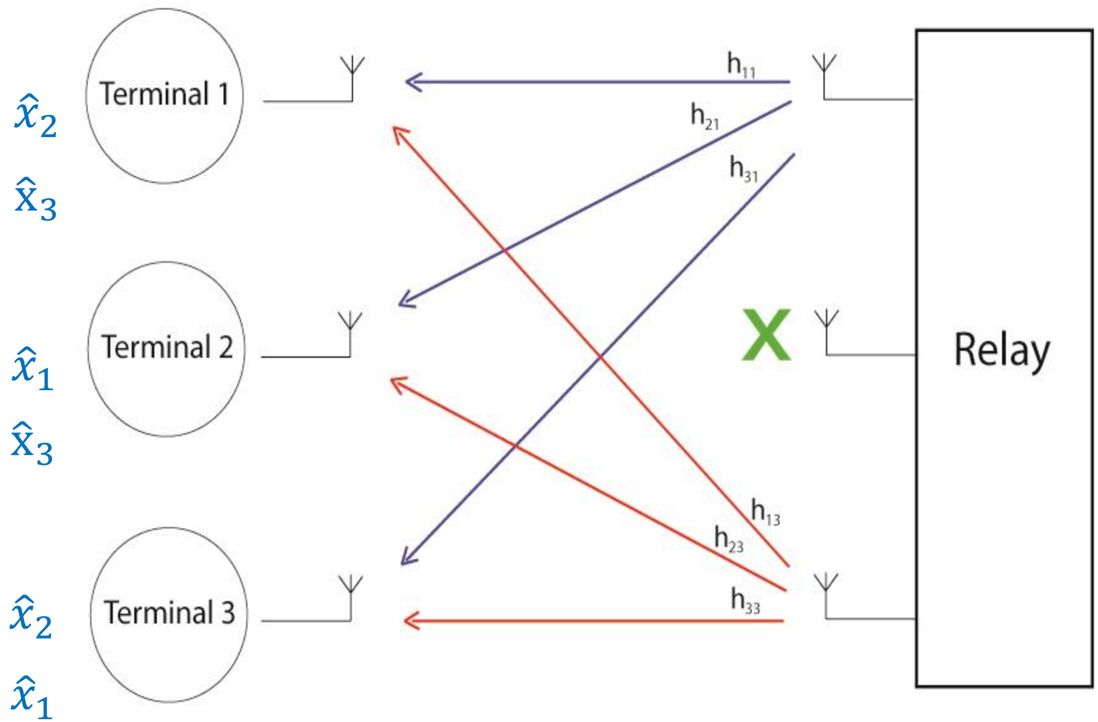
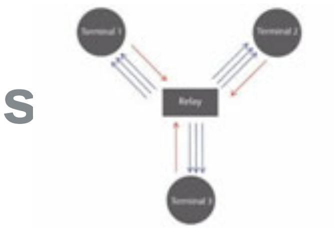


Two time slots: a protocol with SISO terminals

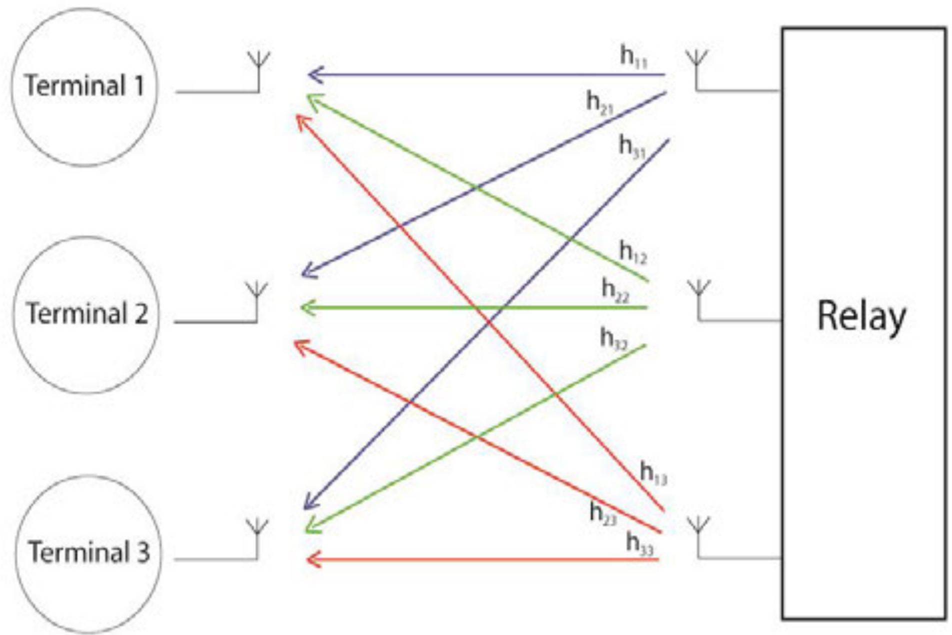


- Terminals have CSIR

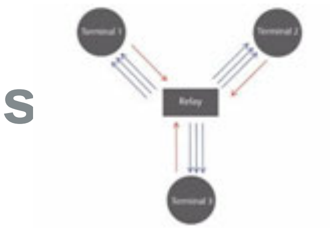
$$y_1 = h_{11}\mathrm{x}_1 + h_{12}\mathrm{x}_2 + h_{13}x_3 + n$$

$$y_2 = h_{21}\mathrm{x}_1 + h_{22}\mathrm{x}_2 + \mathrm{h}_{23}\mathrm{x}_3 + n$$

$$y_3 = h_{31}x_1 + h_{32}x_2 + h_{33}x_3 + n$$



Two time slots: a protocol with SISO terminals

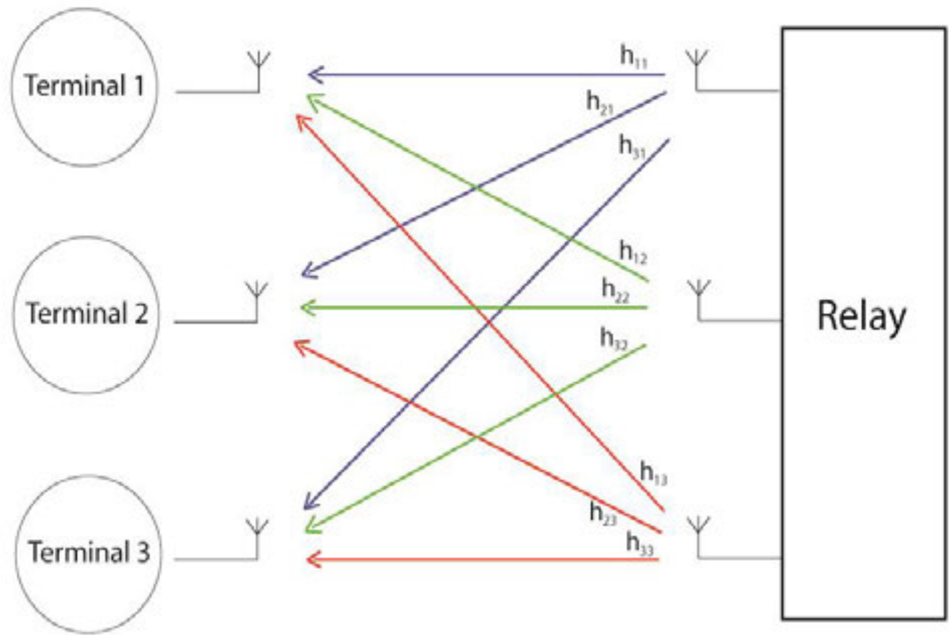


- Each terminal cancels its own message

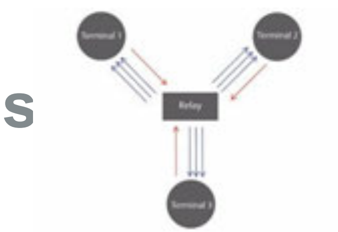
$$y_1 = \cancel{h_{11}x_1} + h_{12}x_2 + h_{13}x_3 + n$$

$$y_2 = h_{21}x_1 + \cancel{h_{22}x_2} + h_{23}x_3 + n$$

$$y_3 = h_{31}x_1 + h_{32}x_2 + \cancel{h_{33}x_3} + n$$



Two time slots: a protocol with SISO terminals

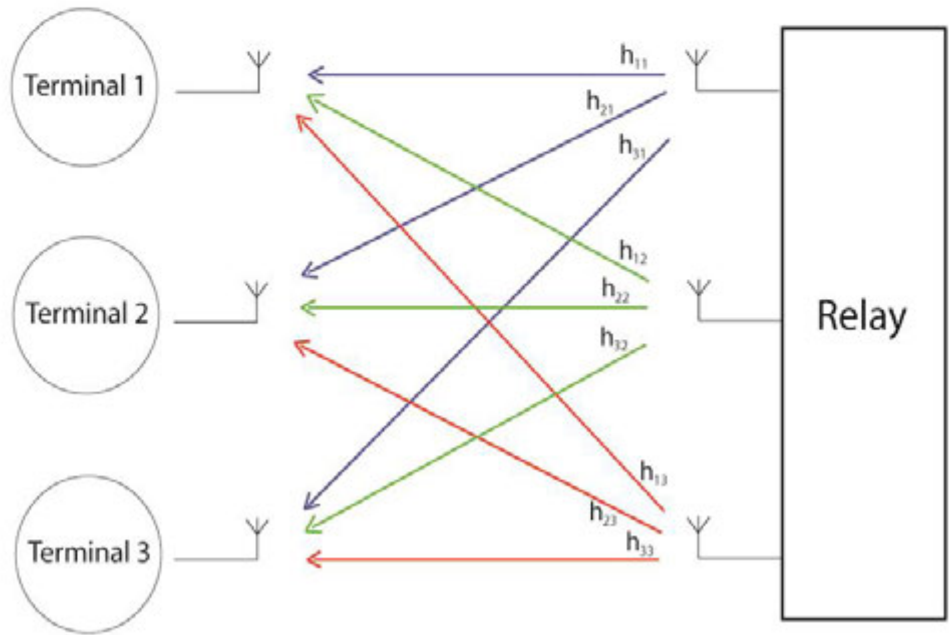


- Joint detection (ML) to detect the last two messages

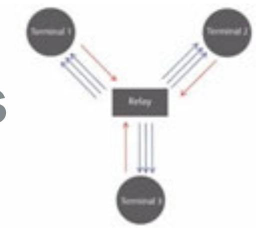
$$y_1' = y_1 - h_{11}x_1$$

$$y_2' = y_2 - h_{22}x_2$$

$$y_3' = y_3 - h_{33}x_3$$



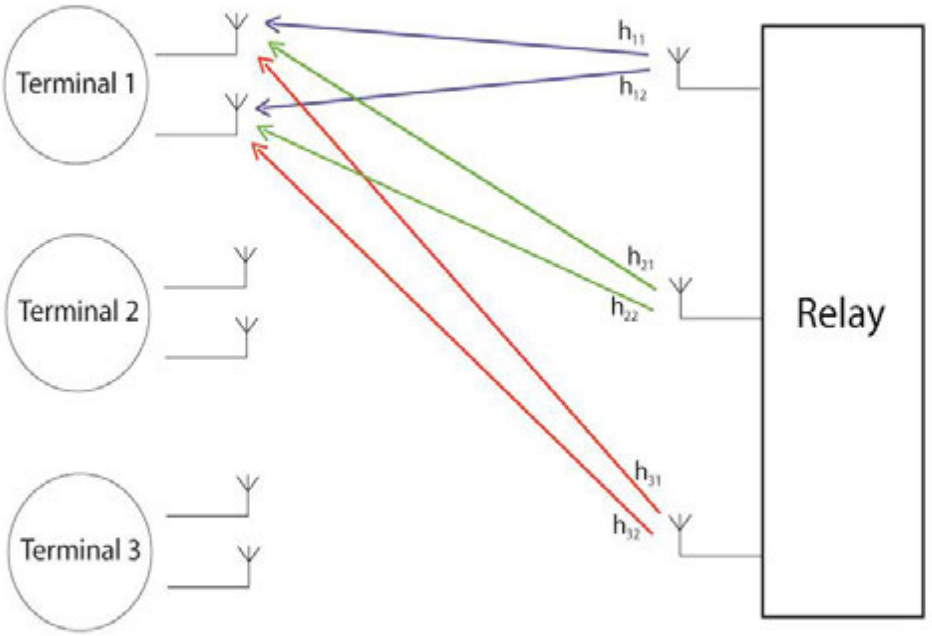
Two time slots: a protocol with MIMO terminals



Each terminal cancels its own message and the remaining two are MIMO detected.

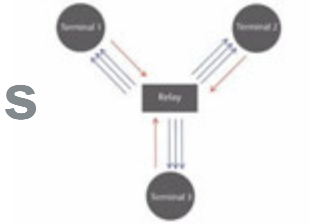
$$y_{11} = h_{11}x_1 + h_{21}x_2 + h_{31}x_3 + n$$

$$y_{12} = h_{12}x_1 + h_{22}x_2 + \mathrm{h}_{32}x_3 + n$$



Two time-slots only: Can we do better?

Two time slots: a protocol with MIMO terminals



Each terminal cancels its own message and the remaining two are MIMO detected.

$$y_{11} = \cancel{h_{11}}x_1 + h_{21}x_2 + h_{31}x_3 + n$$

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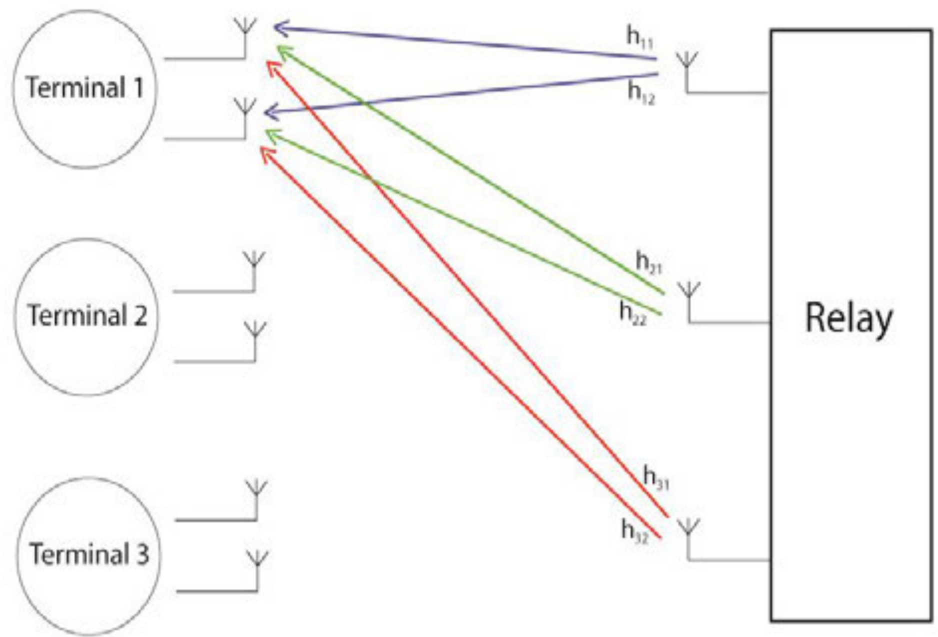
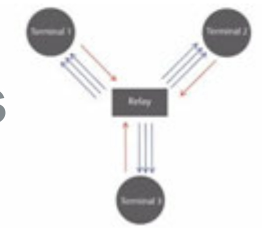


Two time-slots only: Can we do better?

Two time slots: a protocol with MIMO terminals



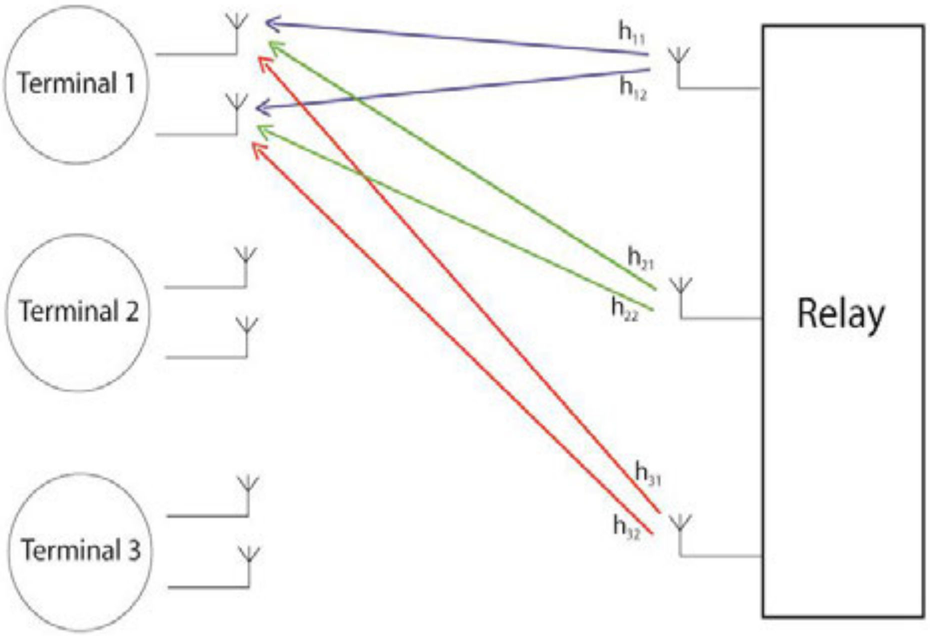
Each terminal cancels its own message and the remaining two are MIMO detected.

$$y_{11} = \cancel{h_{11}} x_1 + h_{21}x_2 + h_{31}x_3 + n$$

$$y_{12} = \cancel{h_{12}} x_1 + h_{22}x_2 + \mathrm{h}_{32}x_3 + n$$

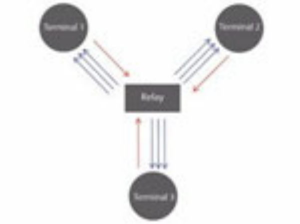
- A 2x2 MIMO detection problem:

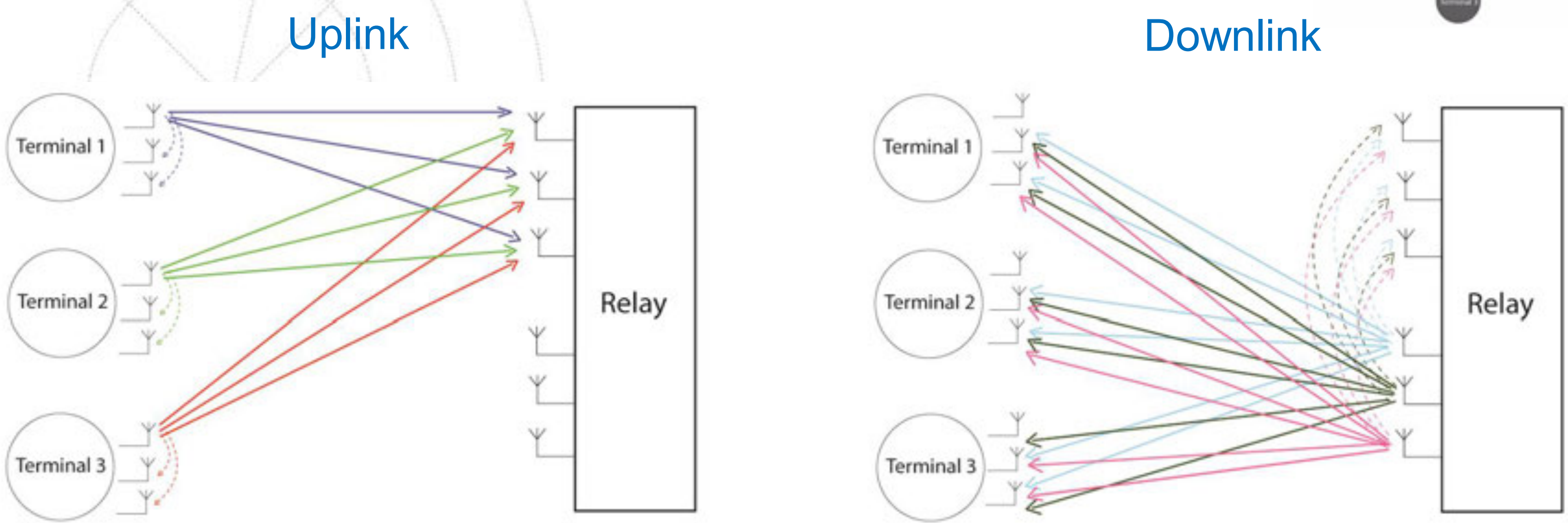
$$\begin{bmatrix} y'_{11} \\ y'_{12} \end{bmatrix} = \begin{bmatrix} h_{21} & h_{31} \\ h_{22} & h_{32} \end{bmatrix} \begin{bmatrix} x_2 \\ x_3 \end{bmatrix} + [\mathbf{n}]$$

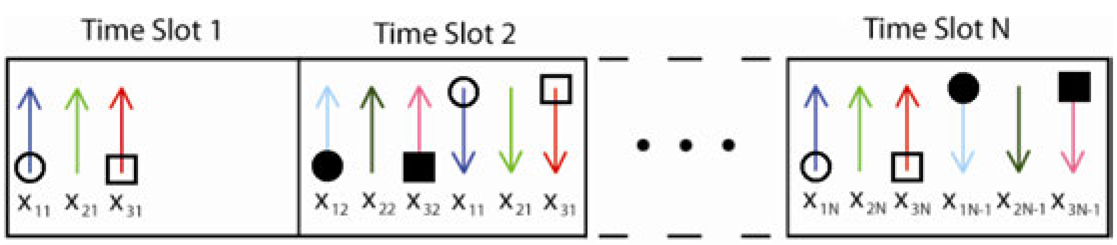


Two time-slots only: Can we do better?

Full-duplex in the Y-channel: how it can work

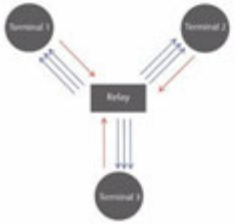


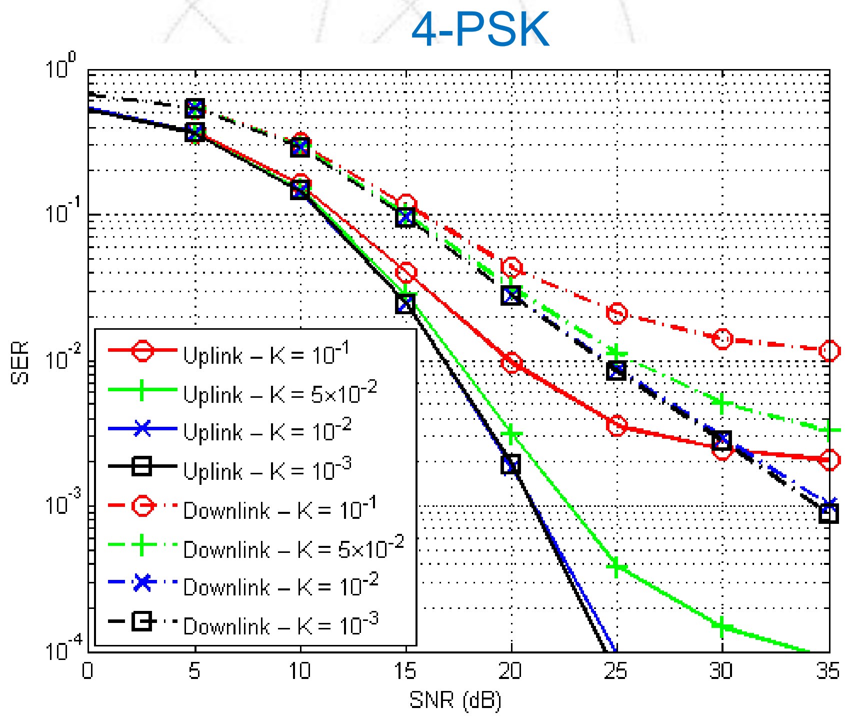


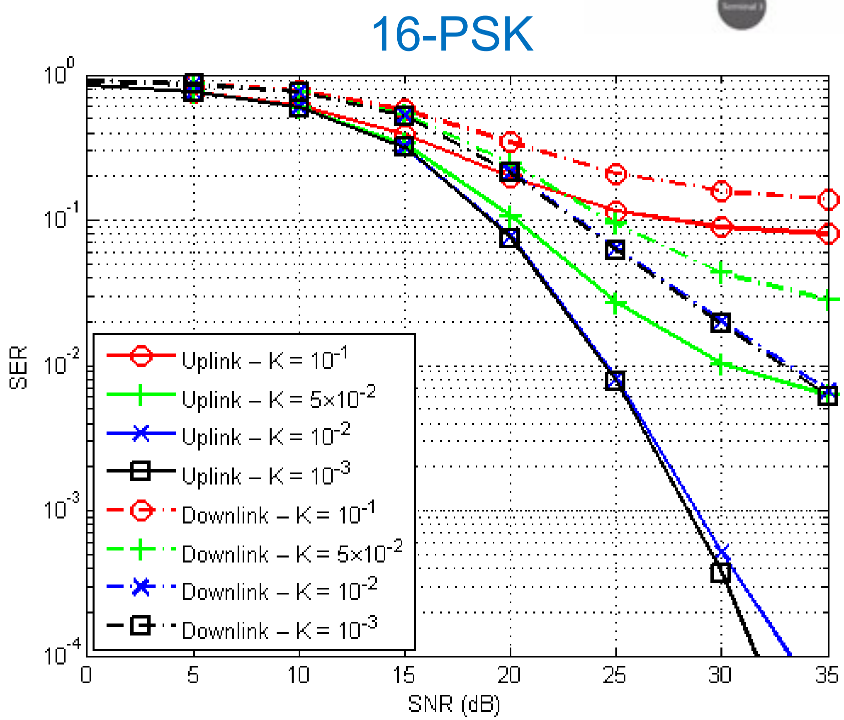


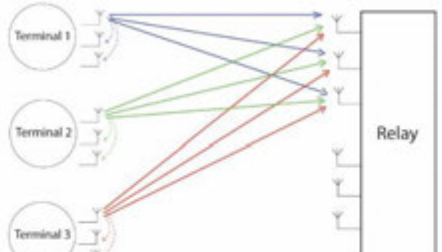
One time slot only on average as the number of messages exchanges increases!

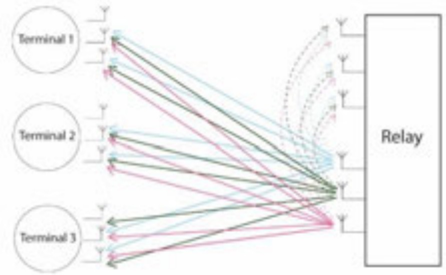
Full-duplex in the Y-channel: Performance











1- Spatial multiplexing (MIMO)

2- Massive MIMO

3- In-band full-duplex

4- TWRC and the Y-network

5- Full-duplex + massive MIMO + PLNC

Signal processing in the upcoming wireless networks:

Untangling signals in space, in spectrum, and network coded

1- Spatial multiplexing (MIMO)

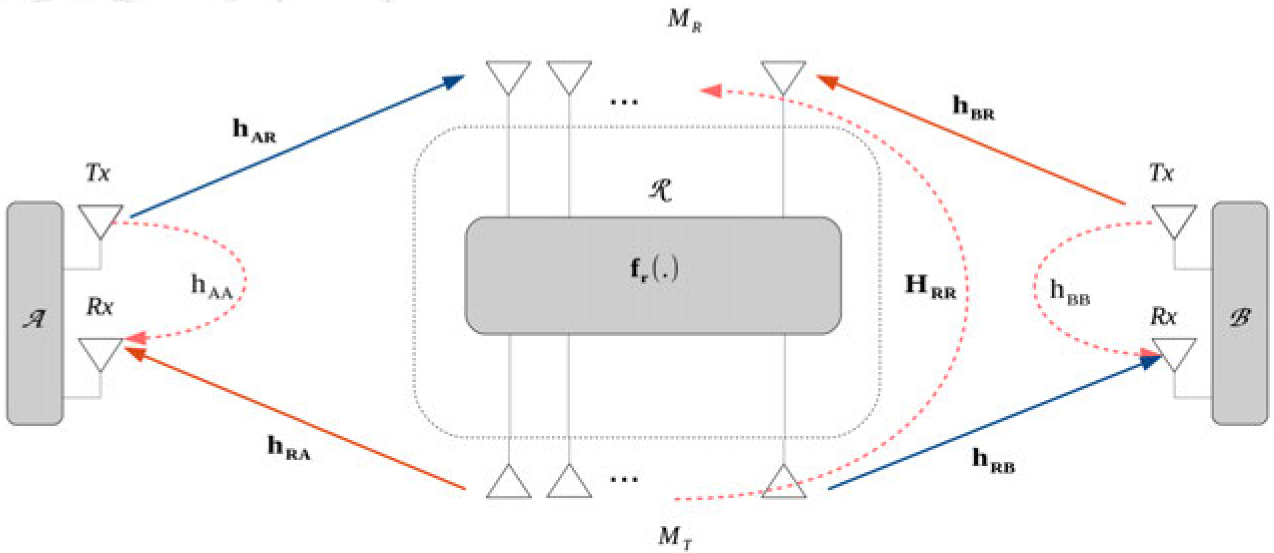
2- Massive MIMO

3- In-band full-duplex

4- TWRC and the Y-network

$\boxed{\textbf{5- Full-duplex + massive MIMO + PLNC}}$

Full-duplex with a massive MIMO relay and PLNC

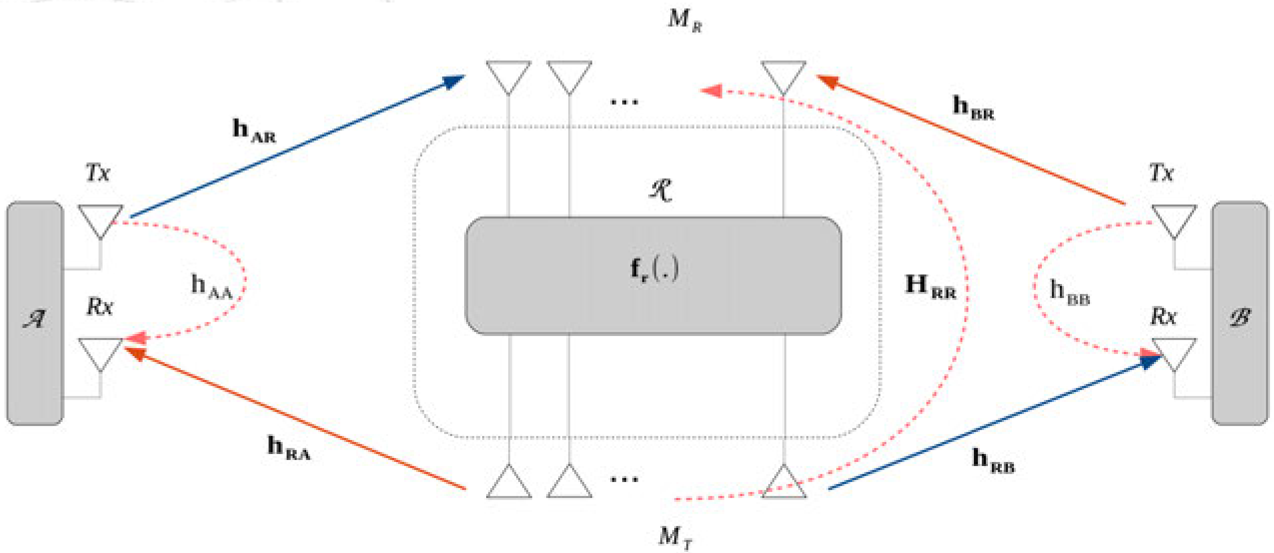


$$\mathbf{y}_{\mathbf{R}}(n) = \sqrt{p_A}\mathbf{h}_{\mathbf{AR}}x_A(n) + \sqrt{p_B}\mathbf{h}_{\mathbf{BR}}x_B(n) + \sqrt{p_R}k_R\mathbf{H}_{\mathbf{RR}}\mathbf{x}_{\mathbf{R}}(n) + \mathbf{n}_{\mathbf{R}}(n)$$

$$y_A(n) = \sqrt{p_R}\mathbf{h}_{\mathbf{RA}}\mathbf{x}_{\mathbf{R}}(n) + \sqrt{p_A}k_A h_{AA}x_A(n) + n_A(n)$$

$$y_B(n) = \sqrt{p_R}\mathbf{h}_{\mathbf{RB}}\mathbf{x}_{\mathbf{R}}(n) + \sqrt{p_B}k_B h_{BB}x_B(n) + n_B(n)$$

Self-interference model



$$\mathbf{H_{RR}x_R}(n) - \widehat{\mathbf{H_{RR}x_R}}(n)$$
$$= \left(\tilde{\mathbf{H}}_{\mathbf{RR}} + \mathcal{E}_{\mathbf{H_{RR}}}\right)\left(\tilde{\mathbf{x}}_{\mathbf{R}}(n) + \mathcal{E}_{\mathbf{x_R}}(n)\right) - \widehat{\mathbf{H_{RR}x_R}}(n)$$
$$\triangleq k_R \mathbf{H_{RR}x_R}(n)$$

$$h_{AA}x_A(n) - \widehat{h_{AA}x_A}(n) \triangleq k_A h_{AA} x_A(n)$$
$$h_{BB}x_B(n) - \widehat{h_{BB}x_B}(n) \triangleq k_B h_{BB} x_B(n)$$

	(k_A, k_B, k_R)
Natural isolation	Reference (0 dB)
Conventional time-domain cancellation	-20 dB
Recursive least squares cancellation	-30 to -40 dB
Perfect cancellation	$-\infty$ dB

Denoise and forward with QPSK in the TWRC

$\mathcal{M} : \mathbb{Z}_Q \rightarrow \mathcal{D}_Q$ $\quad S \in \mathbb{Z}_Q = \{0, 1, \ldots, Q-1\}$

QPSK modulation uses: $\mathbb{Z}_4 = \{0, 1, 2, 3\}$

Decision at the relay:

$$(\hat{S}_A, \hat{S}_B) = \underset{(s_1, s_2) \in \mathbb{Z}_Q^2}{\text{argmin}} \| \mathbf{y_R}(n) - (\mathbf{h_{AR}} \mathcal{M}(s_1) + \mathbf{h_{BR}} \mathcal{M}(s_2)) \|^2$$

Decisions at the terminals:

$$\hat{S}'_B = \underset{s \in \mathbb{Z}_Q}{\text{argmin}} \| \mathbf{y_A}(n) - \mathbf{h_{RA}} \mathcal{M}_R(\mathcal{C}(S_A, s)) \|^2$$

$$\hat{S}'_A = \underset{s \in \mathbb{Z}_Q}{\text{argmin}} \| \mathbf{y_B}(n) - \mathbf{h_{RB}} \mathcal{M}_R(\mathcal{C}(S_B, s)) \|^2$$

Two mappings: GF(2) and GF(4)

$\mathcal{C}(s_1, s_2) \neq \mathcal{C}(s'_1, s_2)$ for any $s_1 \neq s'_1 \in \mathbb{Z}_Q$ and $s_2 \in \mathbb{Z}_Q$

$\mathcal{C}(s_1, s_2) \neq \mathcal{C}(s_1, s'_2)$ for any $s_1 \in \mathbb{Z}_Q$ and $s_2 \neq s'_2 \in \mathbb{Z}_Q$

$$\mathcal{C} : \mathbb{Z}_Q^2 \rightarrow \mathbb{Z}_Q, \; \mathcal{C}(S_1, S_2) = S_1 \oplus S_2$$

$$\mathcal{C} : \mathbb{Z}_Q^2 \rightarrow \mathbb{Z}_Q, \; \mathcal{C}(S_1, S_2) = [S_1 + S_2] \text{mod } Q$$

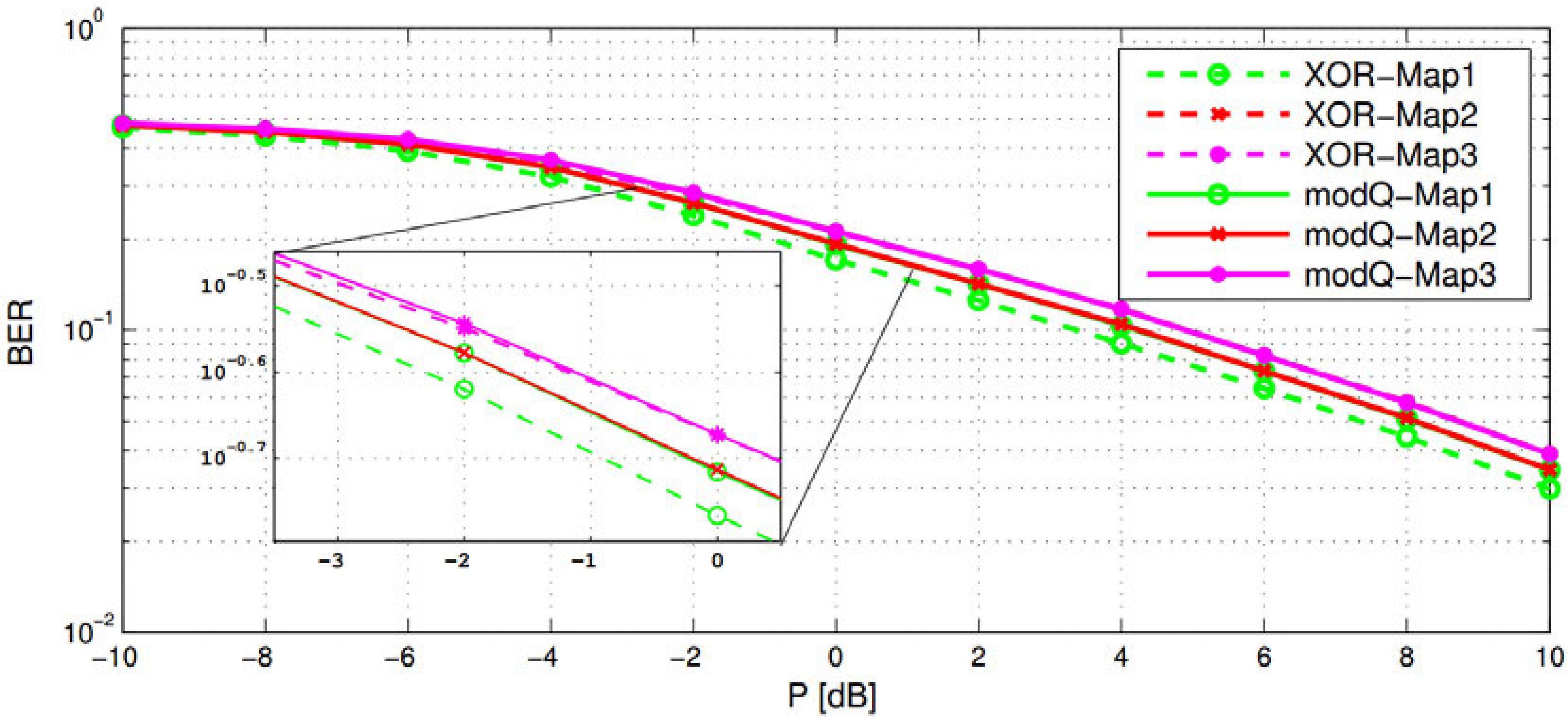
Two mappings: GF(2) and GF(4)

	$\mathcal{C}(S_1, S_2) = S_1 \oplus S_2$				$\mathcal{C}(S_1, S_2) = [S_1 + S_2]\text{mod}Q$			
Pair message (S_A, S_B)	(0,0) (1,1) (2,2) (3,3)	(0,1) (1,0) (2,3) (3,2)	(0,2) (1,3) (2,0) (3,1)	(0,3) (1,2) (2,1) (3,0)	(0,0) (1,3) (2,2) (3,1)	(0,1) (1,0) (2,3) (3,2)	(0,2) (1,1) (2,0) (3,3)	(0,3) (1,2) (2,1) (3,0)
Code $S_R = \mathcal{C}(S_A, S_B)$	0	1	2	3	0	1	2	3
Mapping $\mathcal{M}_{R,4}$: 1) 2) 3)	$+1+j$ $+1+j$ $+1+j$	$+1-j$ $-1-j$ $+1-j$	$-1+j$ $+1-j$ $-1-j$	$-1-j$ $-1+j$ $-1+j$	$+1+j$ $+1+j$ $+1+j$	$+1-j$ $-1-j$ $+1-j$	$-1+j$ $+1-j$ $-1-j$	$-1-j$ $-1+j$ $-1+j$

Bit error probability

$$
\begin{aligned}
P_{BER,\mathcal{A}} = P(\hat{S}_2' \neq S_2) &= \sum_{S_1 \in \mathbb{Z}_Q} P(S_1) \Big[\frac{1}{Q \log_2 Q} \sum_{X \in \mathcal{D}_Q} \sum_{\tilde{X} \neq X \in \mathcal{D}_Q} P(X \to \tilde{X}) \\
&\times d_H(B_Q(x: \mathcal{M}_{R,Q}(\mathcal{C}(S_1, x)) = X), B_Q(x: \mathcal{M}_{R,Q}(\mathcal{C}(S_1, x)) = \tilde{X})) \Big] \\
&= \frac{1}{Q \log_2 Q} \sum_{X \in \mathcal{D}_Q} \sum_{\tilde{X} \neq X \in \mathcal{D}_Q} P(X \to \tilde{X}) \times \\
&\underbrace{\Big[\sum_{S_1 \in \mathbb{Z}_Q} P(S_1) \times d_H(B_Q(x: \mathcal{M}_{R,Q}(\mathcal{C}(S_1, x)) = X), B_Q(x: \mathcal{M}_{R,Q}(\mathcal{C}(S_1, x)) = \tilde{X})) \Big]}_{\triangleq N_B(X \to \tilde{X})} \\
&= \frac{1}{Q \log_2 Q} \sum_{X \in \mathcal{D}_Q} \sum_{\tilde{X} \neq X \in \mathcal{D}_Q} P(X \to \tilde{X}) N_B(X \to \tilde{X}).
\end{aligned}
$$

Bit error probability



$k_R = k_A = k_B = -20$ dB $\qquad \sigma_{\mathbf{n}}^2 = -10$ dB $\qquad M_R = 4$

Nested lattice coding

Lattice: $\Lambda = \{\mathbf{x} = \mathbf{M}\mathbf{z},\ \mathbf{z} \in \mathbb{Z}\}$

$a\mathbf{x} + b\mathbf{y} \in \Lambda$, for $\mathbf{x}, \mathbf{y} \in \Lambda$ and $a, b \in \mathbb{Z}$

Quantiser: $\mathrm{Q}_\Lambda(\mathbf{x}) = \text{argmin}_{\lambda \in \Lambda} \parallel \mathbf{x} - \lambda \parallel$

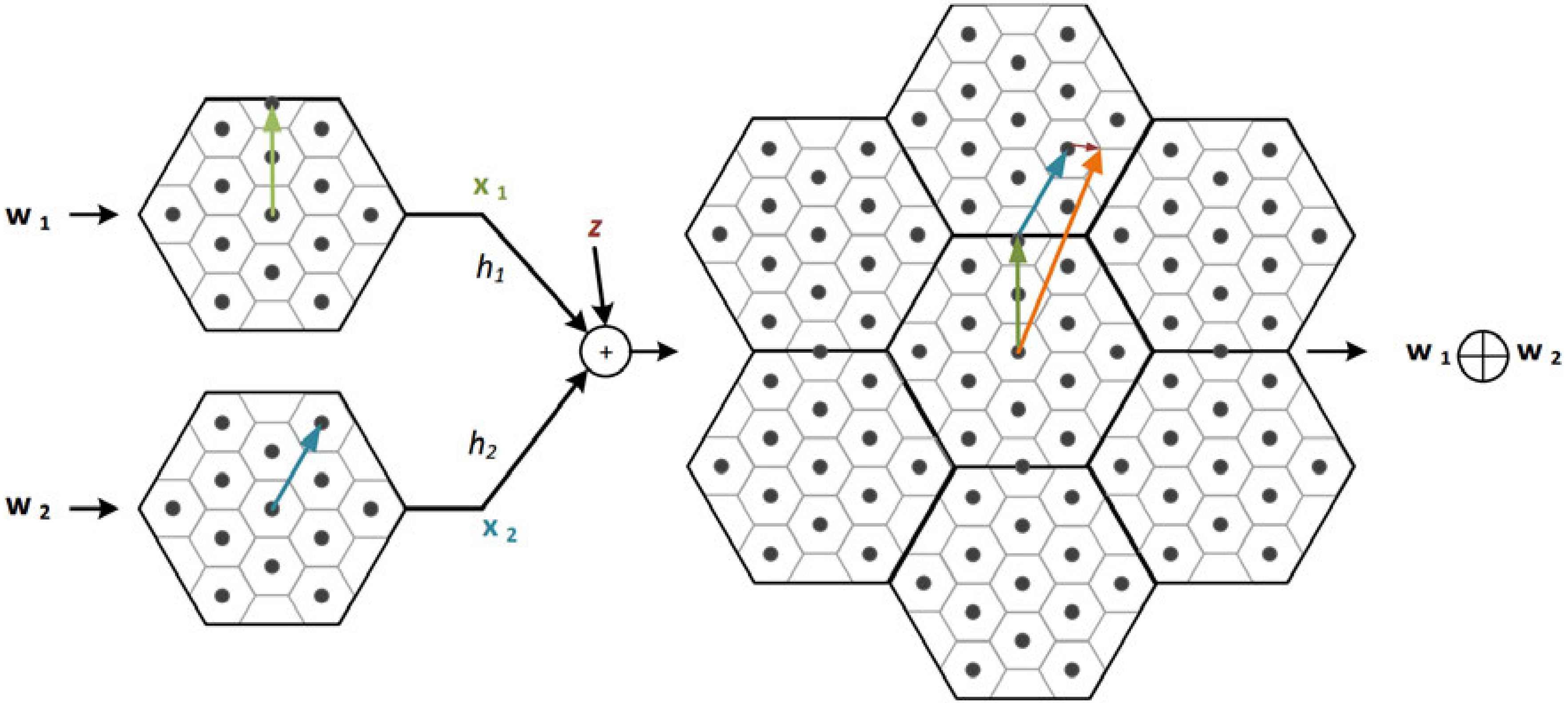
Nested lattice code:

$$\mathcal{L} = \Lambda_\mathsf{F} \cap \mathcal{V}_{\Lambda_\mathsf{C}}, \in \mathbb{R}^n = \{\lambda = [\lambda_\mathsf{F}]\text{mod}_{\Lambda_\mathsf{C}}, \lambda_\mathsf{F} \in \Lambda_\mathsf{F}\}$$

Isomorphism: $\phi : \mathbb{F}_Q^n \to \mathcal{L} = \Lambda_\mathsf{F} \cap \mathcal{V}_{\Lambda_\mathsf{C}} (\in \mathbb{R}^n)$

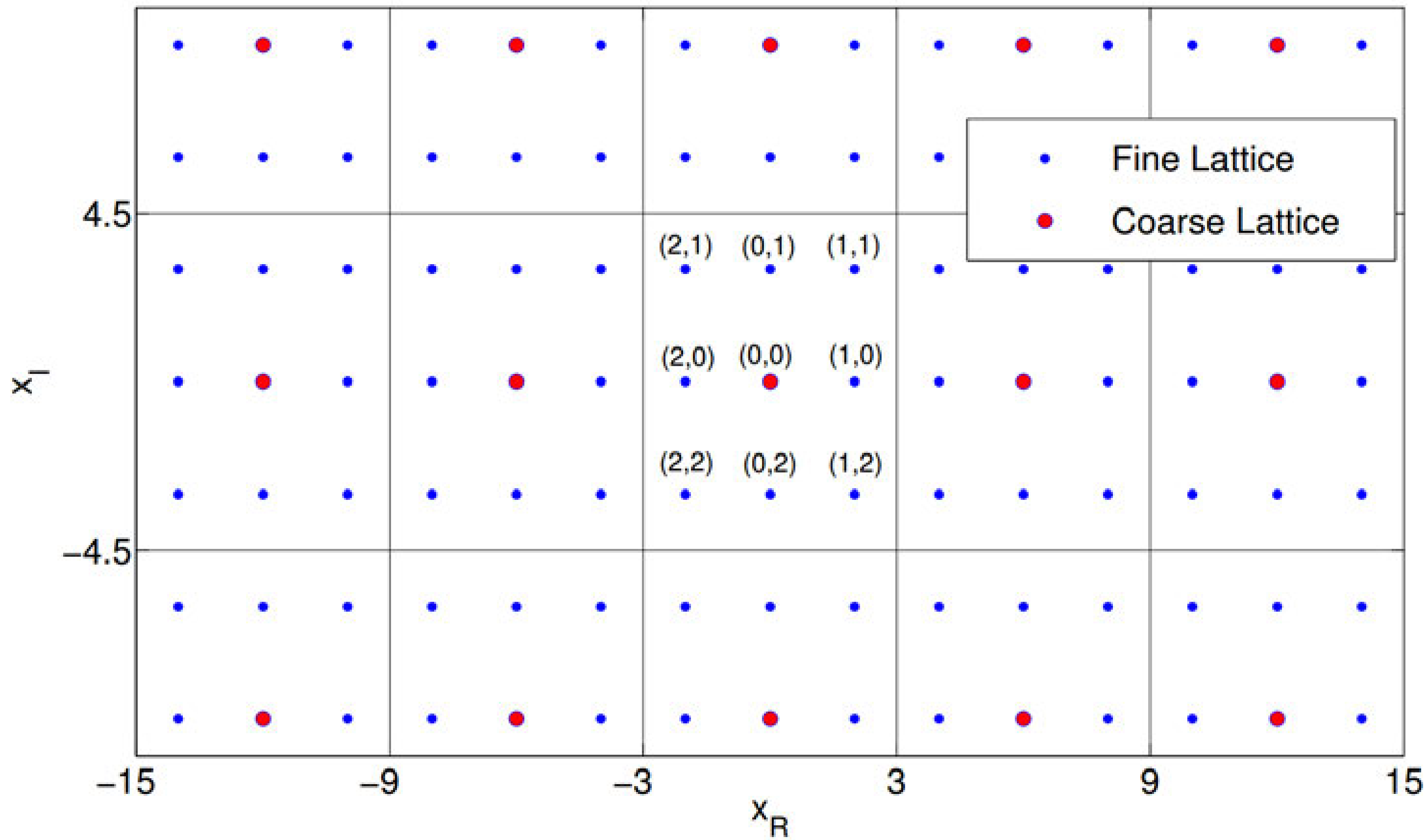
$$S_A, S_B \to \mathbf{x}_\mathbf{A}, \mathbf{x}_\mathbf{B}$$

Lattice-based physical layer NC



Gaussian lattice

$$\mathbb{Z}^2_{Q=3} \to \mathbb{C}: \; x = \phi(S)$$



Relay reception

$$\mathbf{y_R}(n) = \sqrt{p_A}\mathbf{h_{AR}}x_A(n) + \sqrt{p_B}\mathbf{h_{BR}}x_B(n) + \sqrt{p_R}k_R\mathbf{H_{RR}}\mathbf{x_R}(n) + \mathbf{n_R}(n)$$

Relay (receiver):

$$y_R(n) = h_{AR}\Big(\frac{h^*_{AR}}{< h_{AR} >}x_A(n)\Big) + h_{BR}\Big(\frac{h^*_{BR}}{< h_{BR} >}x_B(n)\Big) + \tilde{n}(n)$$

$$= g_{AR}\cdot\phi(S_A) + g_{BR}\cdot\phi(S_B) + \tilde{n}(n)$$

$$g_{AR} = \left(\frac{h_{AR}h^*_{AR}}{<h_{AR}>}\right) \qquad g_{BR} = \left(\frac{h_{BR}h^*_{BR}}{<h_{BR}>}\right)$$

$$v = [a_A \cdot x_A + a_B \cdot x_B]\text{mod}_{\Lambda_C} \qquad x_A, x_B \in \mathcal{L}_G$$

Processing Stage at the Relay for each $y_R(n)$:

1) Scale the received relay signal, using the MMSE scaling factor: $\tilde{y}_R = \alpha \cdot y_R$;

2) Quantize $\tilde{y}_R$ to the closest fine lattice point: $\mathrm{Q}_{\Lambda_F}(\tilde{y}_R)$;

3) Perform modulo operation with respect to the coarse lattice to obtain back a point in the nested lattice code: $x_R = [\mathrm{Q}_{\Lambda_F}(\tilde{y}_R)]\text{mod}_{\Lambda_C}$.

Terminal's reception

Processing Stage at Terminal $\mathcal{A}$ (similar for $\mathcal{B}$):

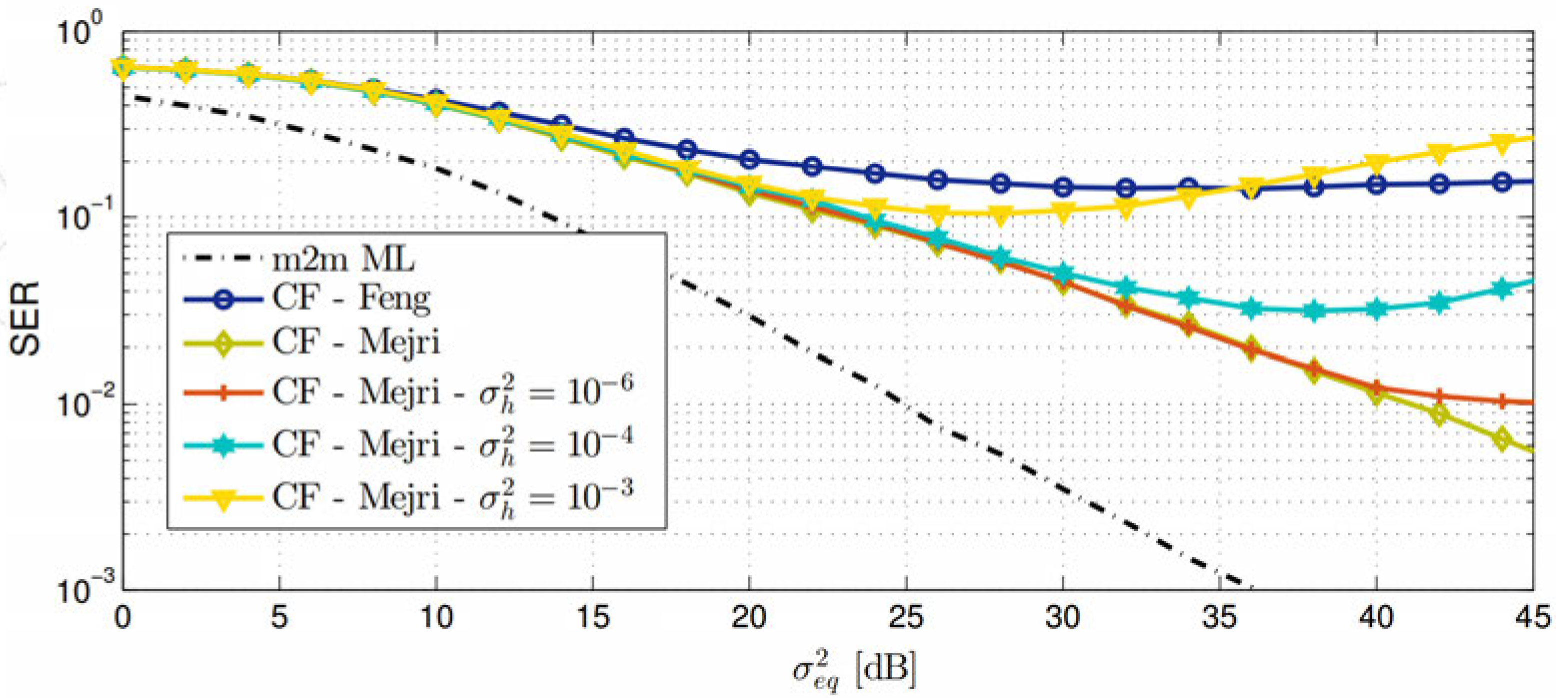
1) Decode the relay transmitted signal, taking into consideration the complex channel effect, using the ML detector for the nested lattice code: $\hat{x}_R = \arg\min_{\lambda \in \Lambda_F \cap \mathcal{V}_{\Lambda_C}} \parallel y_A - h_{RA}\lambda \parallel$;

2) Map the received information back to the finite field:
First component $u_1 = \phi^{-1}(\mathcal{R}\{\hat{x}_R\}) = [q_A S_{A,1} + q_B S_{B,1}]\text{mod}_Q$ and second component $u_2 = \phi^{-1}(\mathcal{I}\{\hat{x}_R\}) = [q_A S_{A,2} + q_B S_{B,2}]\text{mod}_Q$ (where the coefficients q_A, q_B are naturally given by $q_A = [a_A]\text{mod}_Q$ and $q_B = [a_B]\text{mod}_Q$);

3) Subtract own information: $w_{A,1} = [u_1 - q_A S_{A,1}]\text{mod}_Q = q_B S_{B,1}$ and $w_{A,2} = [u_2 - q_A S_{A,2}]\text{mod}_Q = q_B S_{B,2}$;

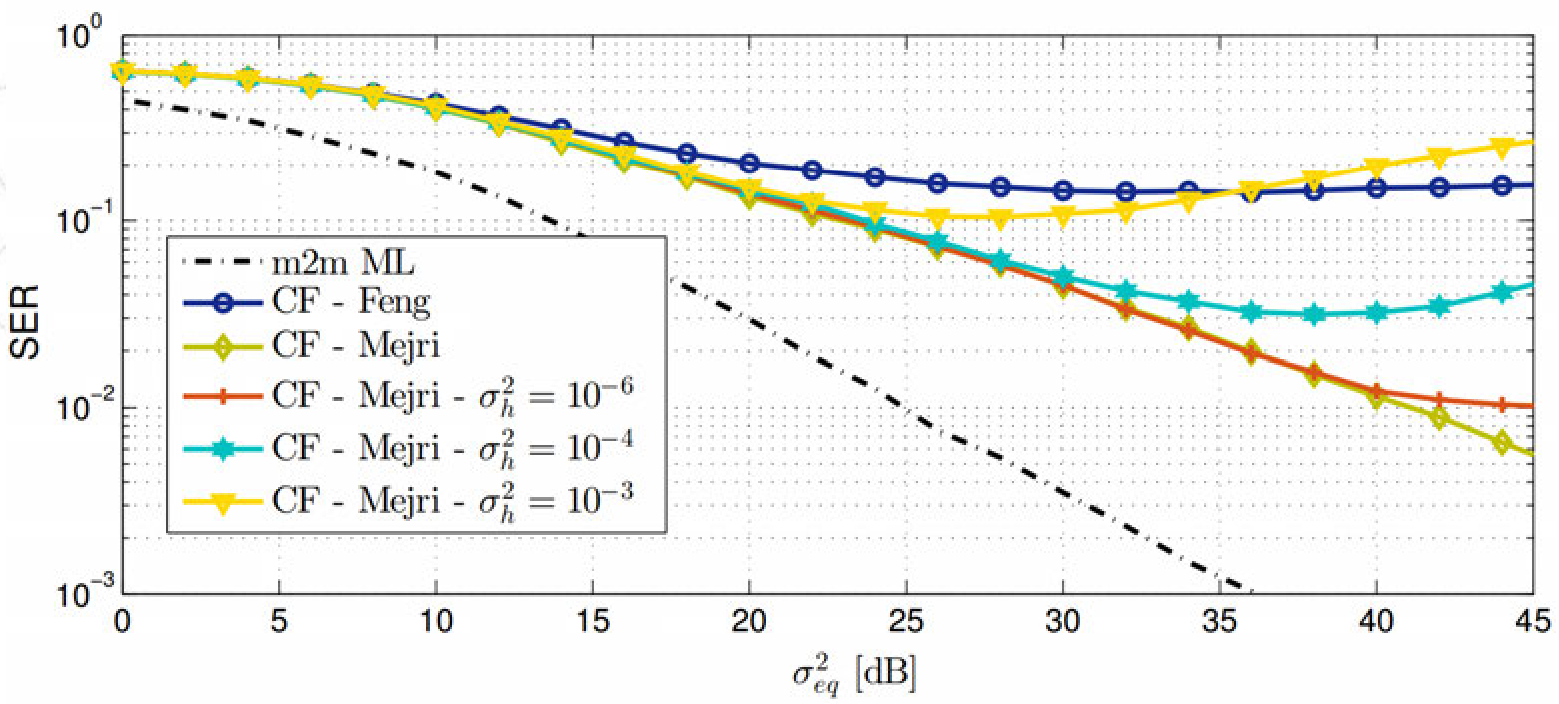
4) Remove channel integer effect over the finite field, q_B, to obtain $\hat{S}_B = (\hat{S}_{B,1}; \hat{S}_{B,2})$.

TWRC with lattice-based PLNC



MMSE scale factor: $\alpha = \dfrac{\gamma \cdot \mathbf{g}\mathbf{a}^H}{1 + \gamma \cdot \mathbf{g}\mathbf{g}^H}$

TWRC with lattice-based PLNC



From an engineering perspective the scheme has a very poor performance.

How to improve it?

Equivalent noise is composed of:

Cross-terms interference:

$$(\mathbf{H_{BR}}^{\dagger}\mathbf{H_{AR}}\mathbf{x_A}(n)+\mathbf{H_{AR}}^{\dagger}\mathbf{H_{BR}}\mathbf{x_B}(n))$$

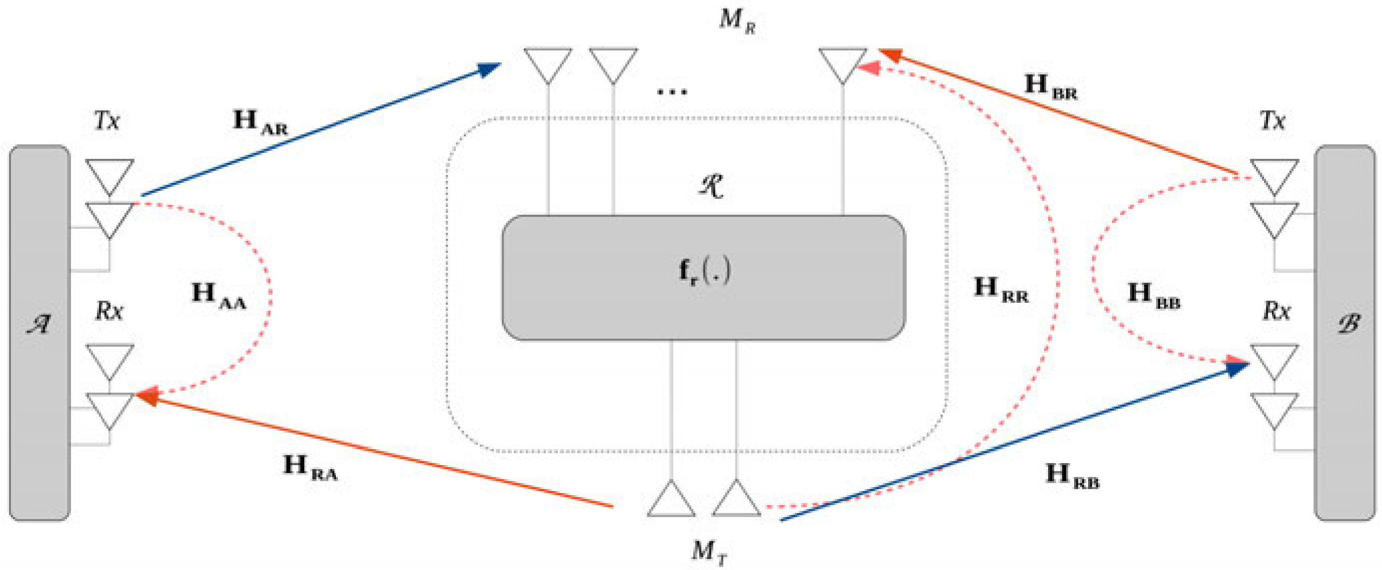
Self-interference: $(\mathbf{H_{BR}}^{\dagger} + \mathbf{H_{AR}}^{\dagger})k_R\mathbf{H_{RR}}\mathbf{x_R}(n)$

Noise term: $(\mathbf{H_{BR}}^{\dagger} + \mathbf{H_{AR}}^{\dagger})\mathbf{n_R}(n)$

But, given the massive MIMO effect:

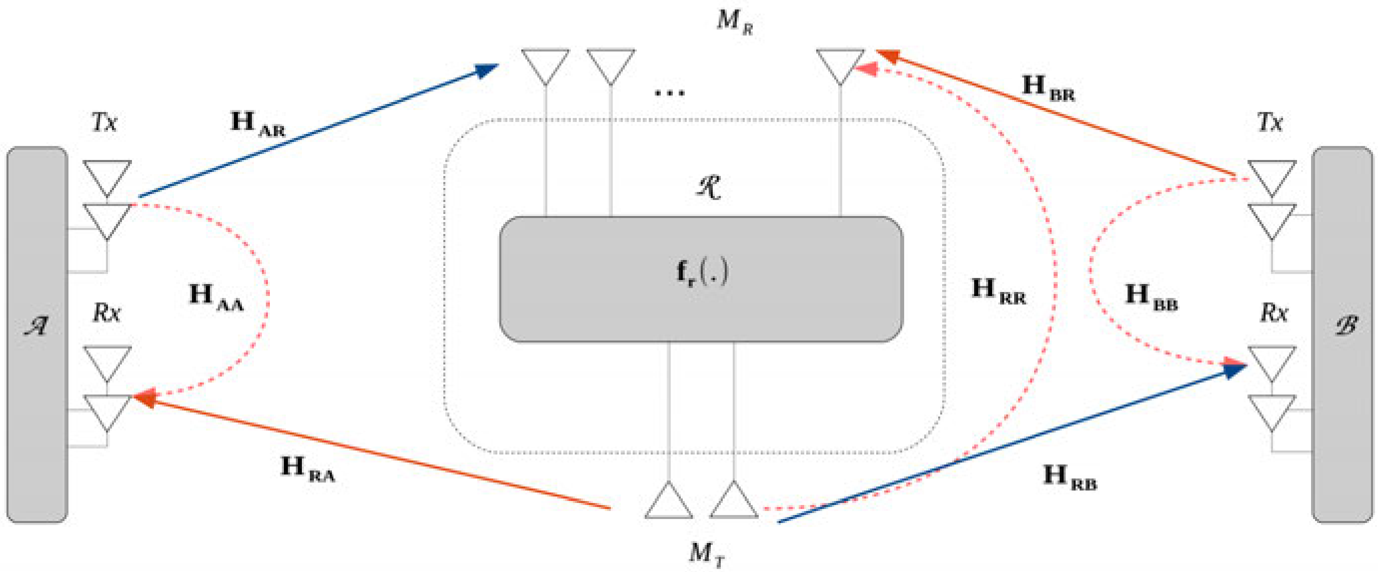
$$\mathbf{H_{BR}}^{\dagger}\mathbf{H_{AR}} \to \mathbf{0}, \mathbf{H_{AR}}^{\dagger}\mathbf{H_{BR}} \to \mathbf{0},\ \text{as } M_R \to \infty$$

Taking advantage of massive MIMO



$$
\begin{aligned}
\mathbf{y}_{\mathbf{R}}(n) &= \mathbf{H}_{\mathbf{AR}}\mathbf{x}_{\mathbf{A}}(n) + \mathbf{H}_{\mathbf{BR}}\mathbf{x}_{\mathbf{B}}(n) + k_R\mathbf{H}_{\mathbf{RR}}\mathbf{x}_{\mathbf{R}}(n) + \mathbf{n}_{\mathbf{R}}(n) \\
&= \mathbf{H}_{\mathbf{AR}}\mathbf{x}_{\mathbf{A}}(n) + \mathbf{H}_{\mathbf{BR}}\mathbf{x}_{\mathbf{B}}(n) + \tilde{\mathbf{n}}_{\mathbf{R}}(n)
\end{aligned}
$$

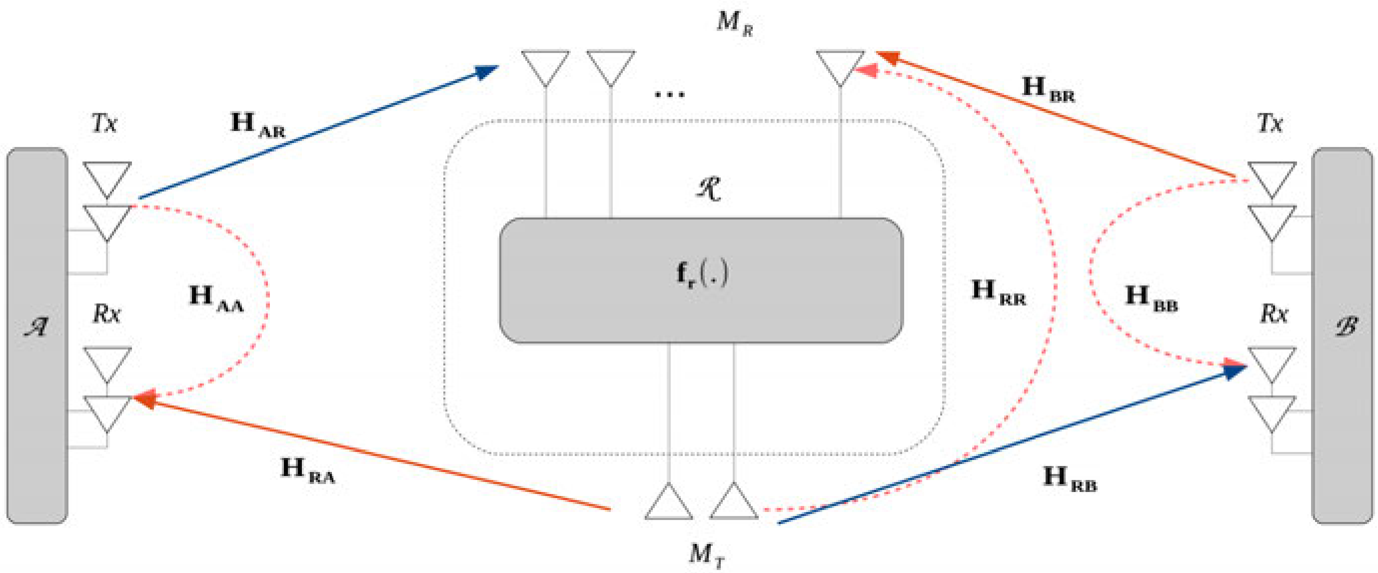
Taking advantage of massive MIMO



$$
\begin{aligned}
\mathbf{y_P}(n) =& \mathbf{H_{AR}}'\mathbf{y_R}(n) + \mathbf{H_{BR}}'\mathbf{y_R}(n) \\
=& (\mathbf{H}_{\mathbf{AR}}^H\mathbf{H_{AR}})^{-1}\mathbf{H}_{\mathbf{AR}}^H\mathbf{y_R}(n) + (\mathbf{H}_{\mathbf{BR}}^H\mathbf{H_{BR}})^{-1}\mathbf{H}_{\mathbf{BR}}^H\mathbf{y_R}(n) \\
=& (\mathbf{H_{AR}}^\dagger\mathbf{H_{AR}}\mathbf{x_A}(n) + \mathbf{H_{BR}}^\dagger\mathbf{H_{BR}}\mathbf{x_B}(n)) \\
& + (\mathbf{H_{BR}}^\dagger\mathbf{H_{AR}}\mathbf{x_A}(n) + \mathbf{H_{AR}}^\dagger\mathbf{H_{BR}}\mathbf{x_B}(n)) + (\mathbf{H_{BR}}^\dagger + \mathbf{H_{AR}}^\dagger) \\
=& \underbrace{\mathbf{D_A}\mathbf{x_A}(n) + \mathbf{D_B}\mathbf{x_B}(n)}_{\text{desired component}} + \underbrace{\tilde{\mathbf{n}}_{\mathbf{R}}^\star(n)}_{\text{equivalent total noise}}
\end{aligned}
$$

$$
\left[\mathbf{D_A}\mathbf{x_A}(n) + \mathbf{D_B}\mathbf{x_B}(n)\right] \text{mod}_{\Lambda_C}
$$

Reception at both terminals



$$\mathbf{y_A}(n) = \mathbf{H_{RA}x_R}(n) + \tilde{\mathbf{n}}_\mathbf{A}(n) \qquad \mathbf{y_B}(n) = \mathbf{H_{RB}x_R}(n)$$

Reception at the relay and at both terminals

Procedure 3 PLNC Scheme for Massive MIMO Relaying

Processing stage at the relay for each $\mathbf{y_R}(n)$:

1) Zero forcing process of the received signal: $\mathbf{y_P}(n) = \mathbf{H_{AR}}^{\dagger}\mathbf{y_R}(n) + \mathbf{H_{BR}}^{\dagger}\mathbf{y_R}(n)$;

for $i = 1, \cdots, N_T$ **do**

2) Scale the processed relay signal, using the MMSE scaling factor $y_{P,i}$: $\tilde{y}_{P,i} = \alpha_i \cdot y_{P,i}$;

3) Quantize $\tilde{y}_{P,i}$ to the closest fine lattice point: $\mathrm{Q}_{\Lambda_\mathsf{F}}(\tilde{y}_{P,i})$;

4) Perform modulo operation with respect to the coarse lattice to obtain back a point of the nested lattice code: $x_{R,i} = [\mathrm{Q}_{\Lambda_\mathsf{F}}(\tilde{y}_{P,i})]\mathrm{mod}_{\Lambda_\mathsf{C}}$;

end for

5) Transmit the signal $\mathbf{x_R}(n) = [x_{R,1}, \cdots, x_{R,N_T}]$;

Processing stage at terminal $\mathcal{A}$ (similar for $\mathcal{B}$):

1) Decode the relay transmitted signal using the ML detector for the nested lattice code: $\hat{\mathbf{x}}_\mathbf{R} = \arg\min_{\lambda \in (\Lambda_\mathsf{F} \cap \mathcal{V}_{\Lambda_\mathsf{C}})^{N_T}} \parallel \mathbf{y_A} - \mathbf{H_{RA}}\lambda \parallel$;

for $i = 1, \cdots, N_T$ **do**

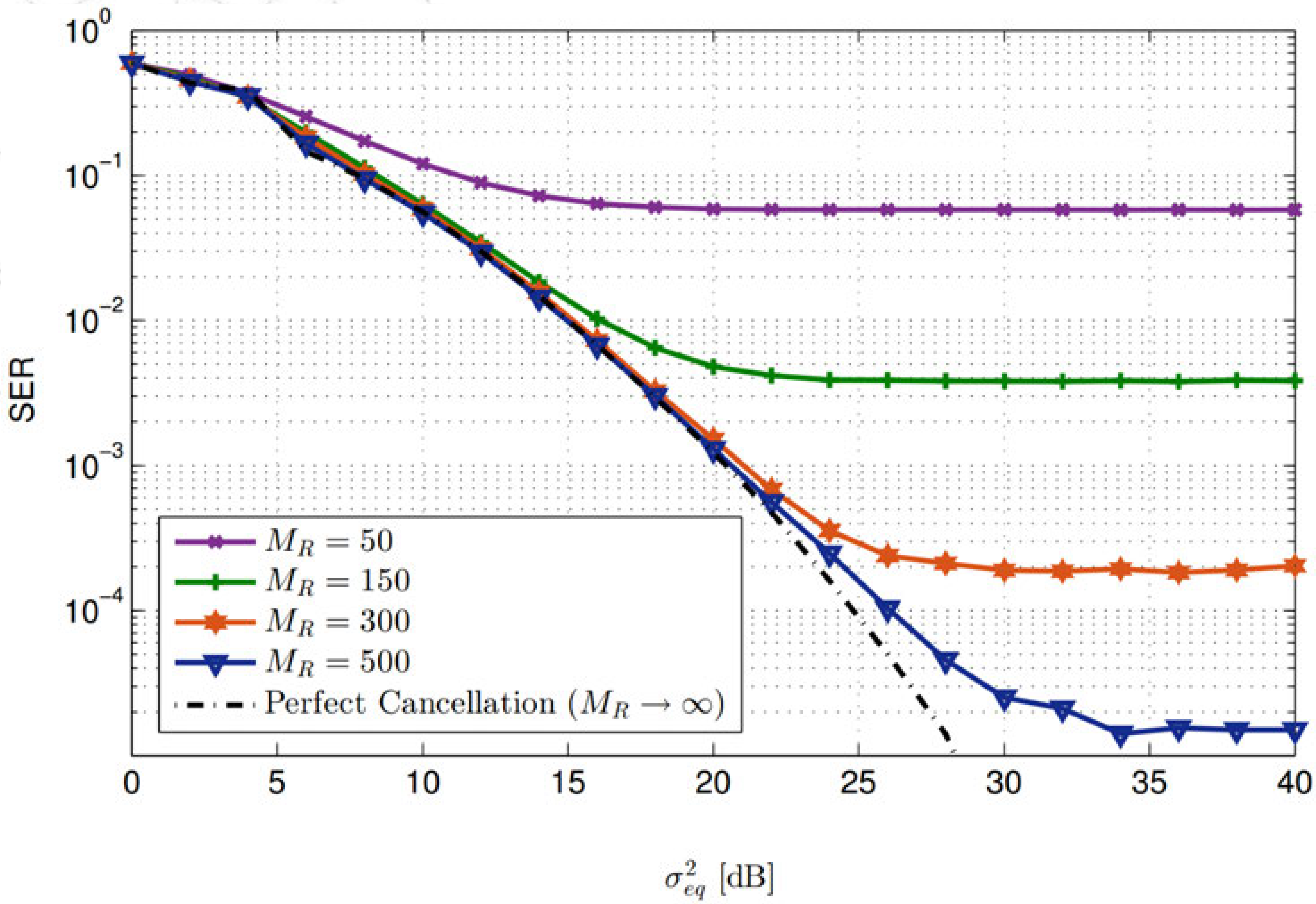
2) Map the received information back to the finite field: $u_{1,i} = \phi^{-1}(\mathcal{R}\{\hat{x}_{R,i}\}) = [S_{A,1,i} + S_{B,1,i}]\mathrm{mod}Q$ and $u_{2,i} = \phi^{-1}(\mathcal{I}\{\hat{x}_{R,i}\}) = [S_{A,2,i} + S_{B,2,i}]\mathrm{mod}Q$ (where here $q_A = 1, q_B = 1$);

3) Subtract own information to obtain: $\hat{S}_{B,1,i} = [u_{1,i} - S_{A,1,i}]\mathrm{mod}Q$ and $\hat{S}_{B,2,i} = [u_{2,i} - S_{A,2,i}]\mathrm{mod}Q$;

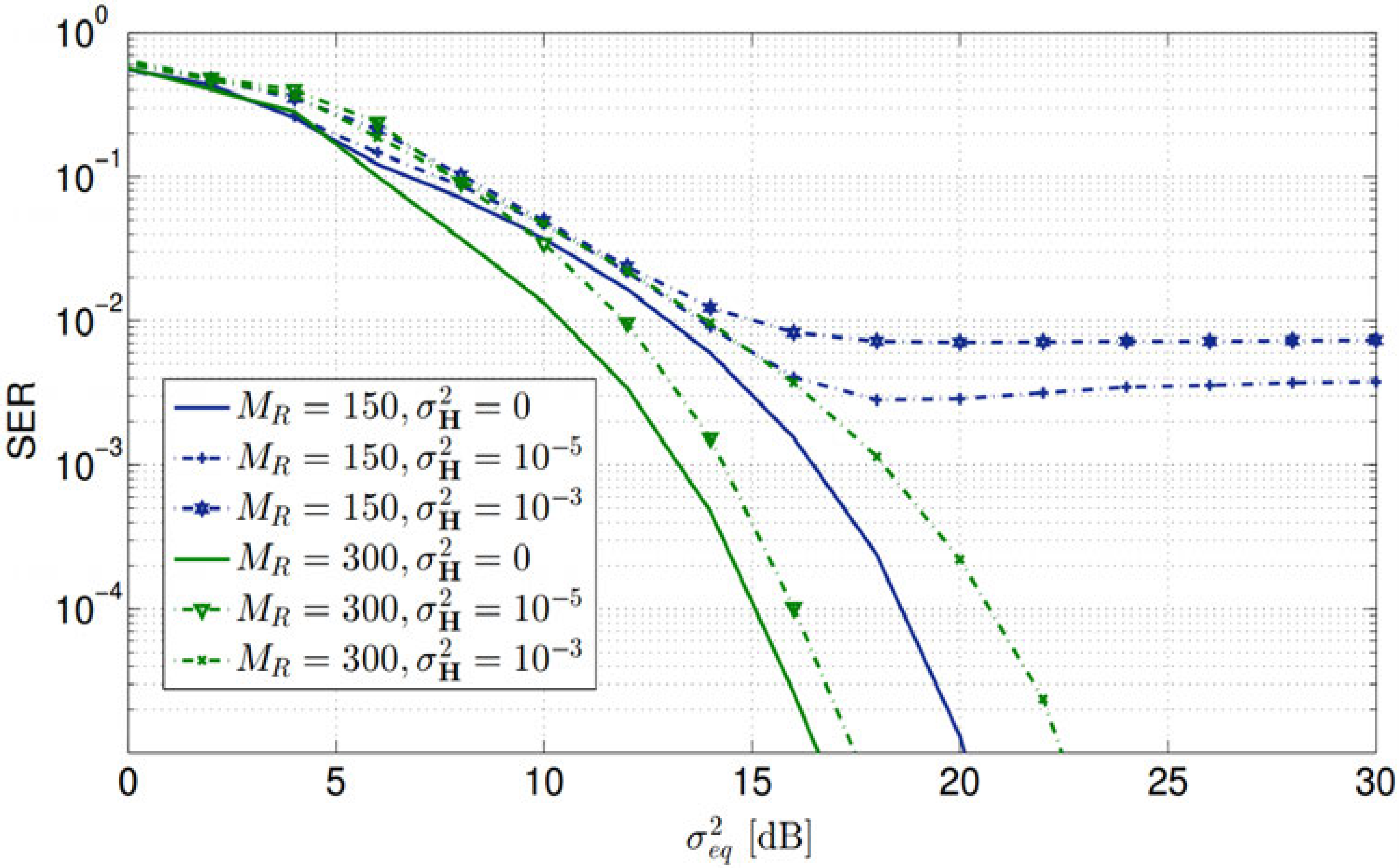
end for

4) Obtain $\hat{S}_{B,i} = (\hat{S}_{B,1,i}; \hat{S}_{B,2,i})$ for $i = 1, \cdots, N_T$.

Results: massive MIMO + full-duplex + PLNC

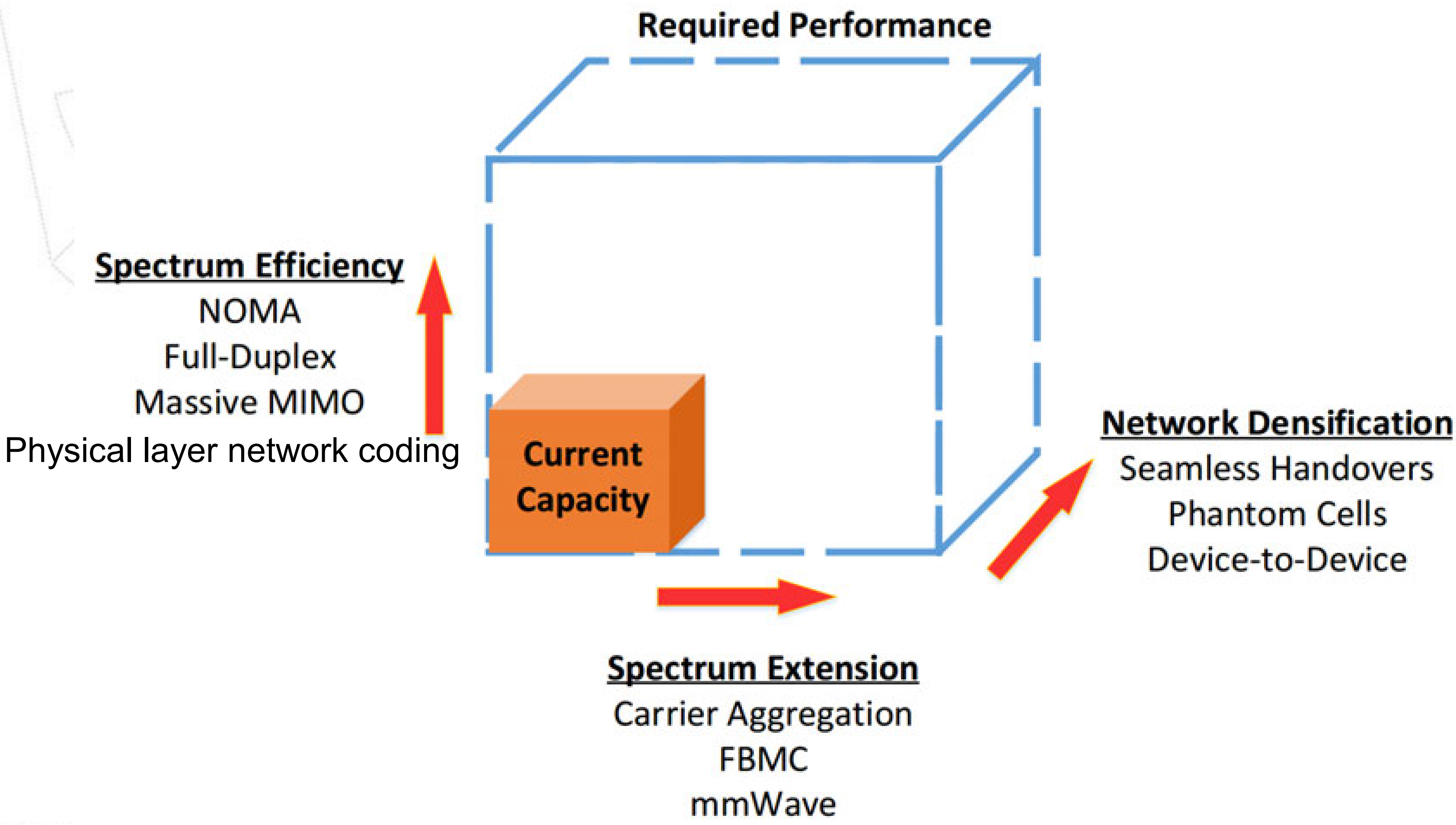


Effect of channel estimation errors

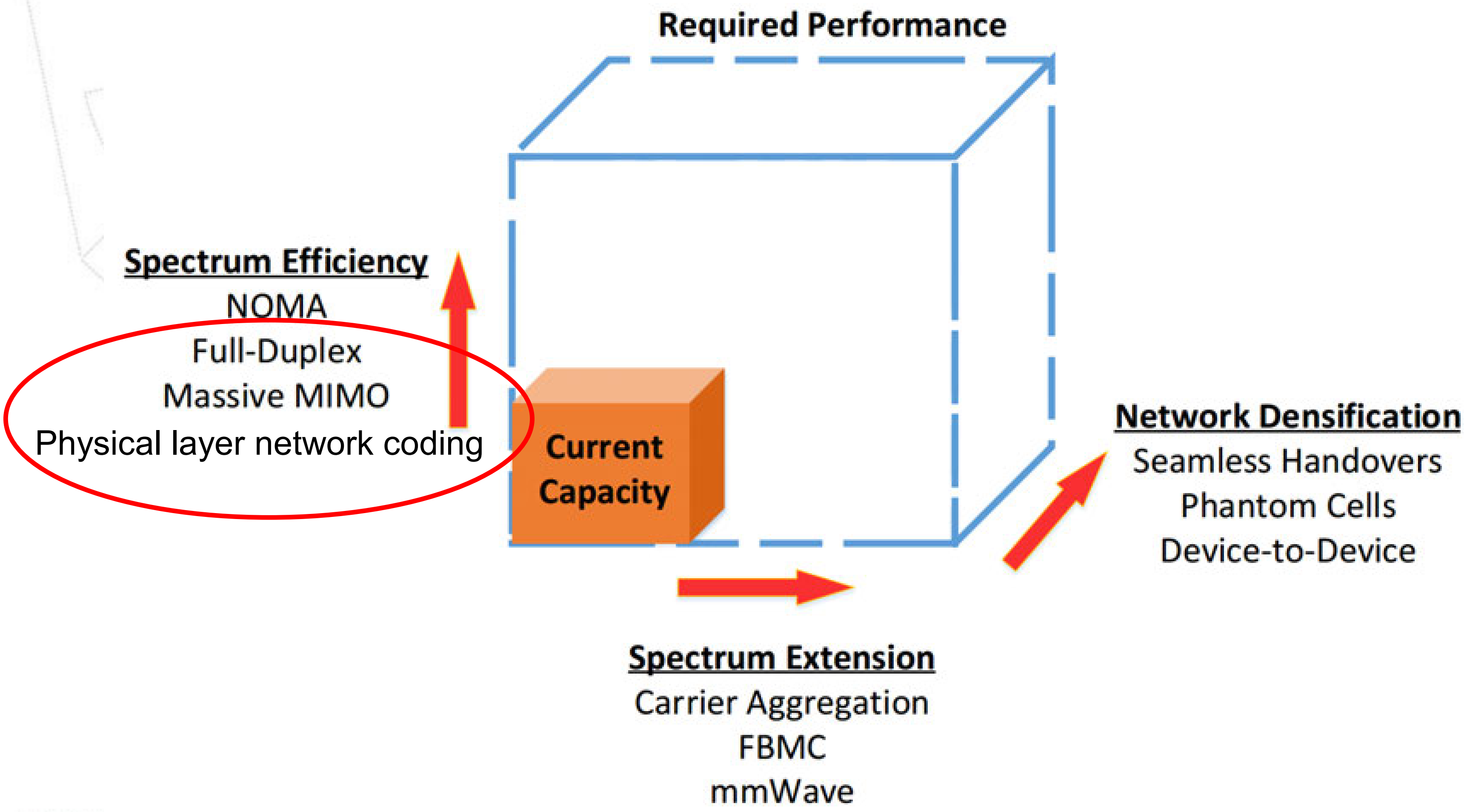


Channel state information accuracy is crucial !

How to offer more?



How to offer more?



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Graduate Students:

Francisco Rosário

João Sande Lemos

Thank you

Back up slides

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“Lattice are everywhere*”

Current growing/hot topics:

• Physical Layer Network Coding

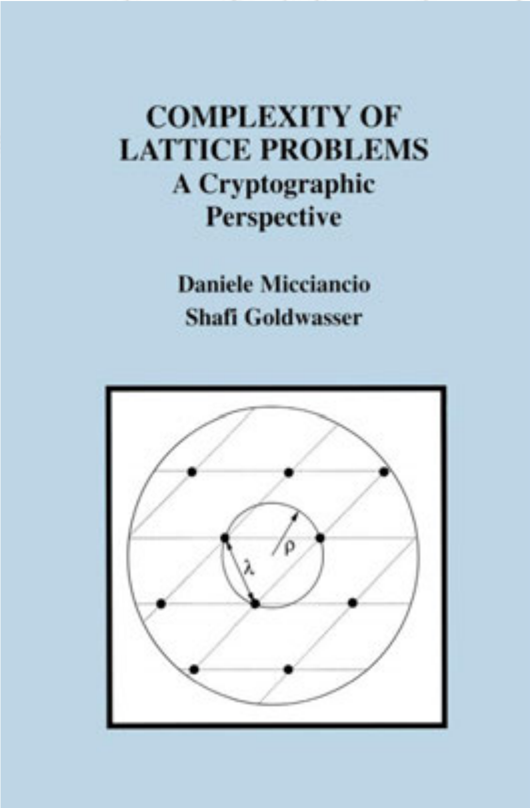
[Gastpar, Nazer, Proc. of the IEEE, 2011];

•Lattice-based cryptography for physical layer security.

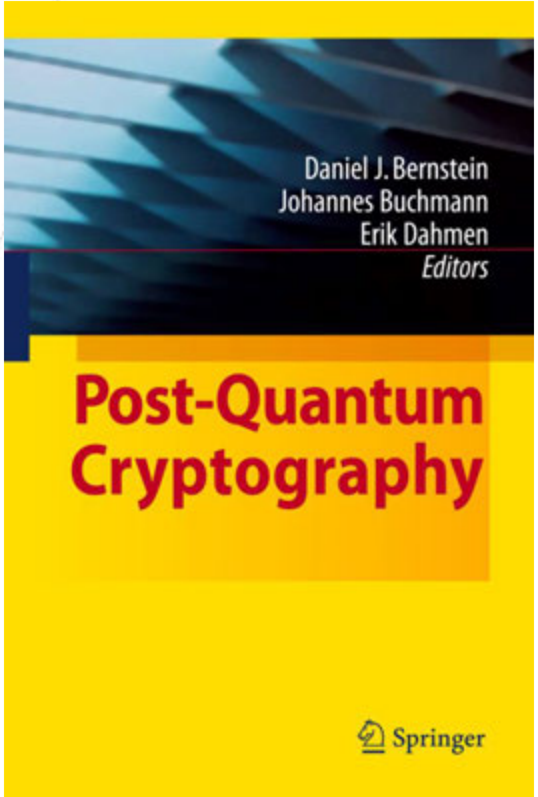
•R. Zamir, ``Lattices are Everywhere'', *talk at the Information Theory and Applications Workshop (ITA09)*, University of California at San Diego, February 2009.

- U. Erez, S. Litsyn and R. Zamir, "Lattices which are good for (almost) everything“, *IEEE Transactions on Information Theory*, pp. 3401-3416 Oct. 2005.

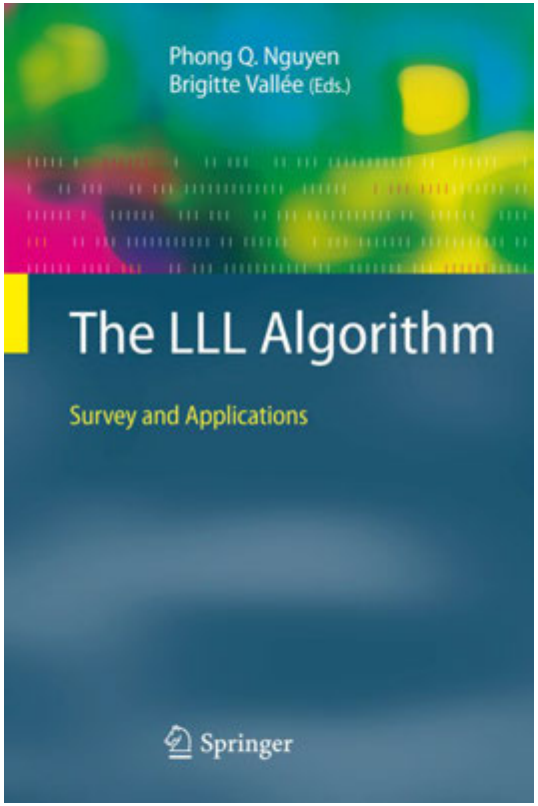
Lattices in Cryptography



2002

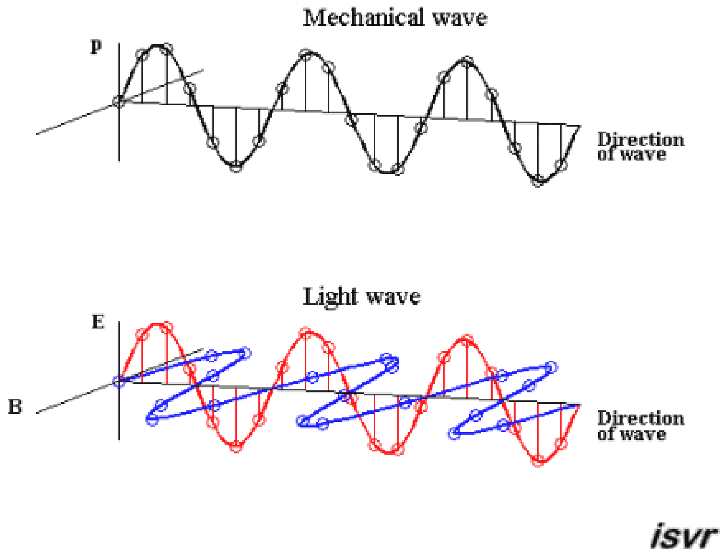


2009

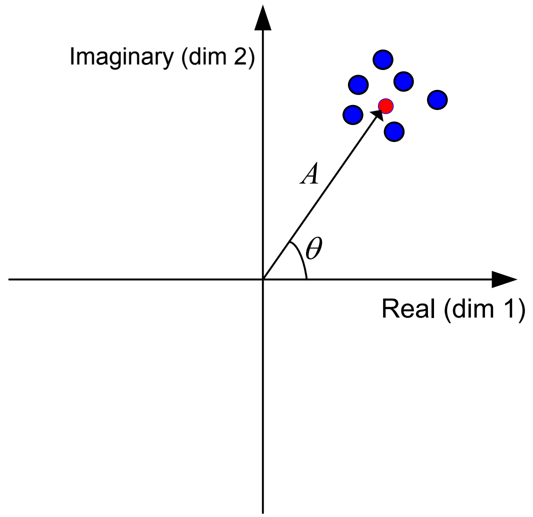


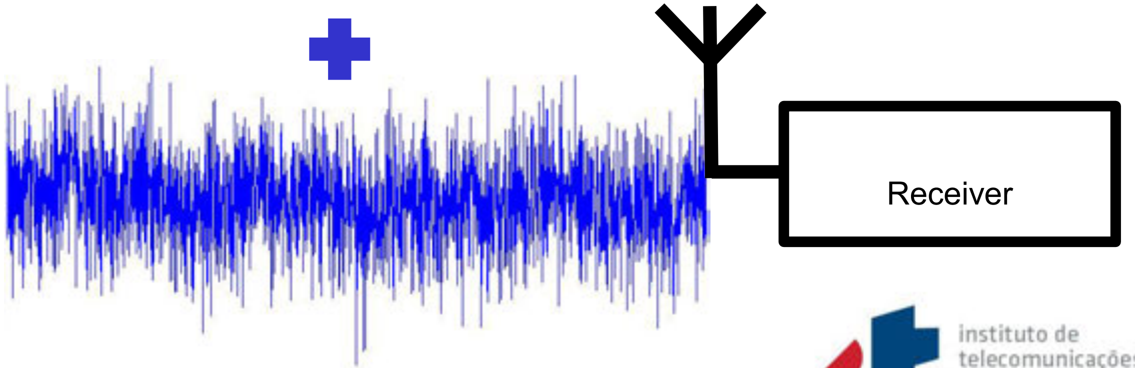
2009

Radio waves as symbols



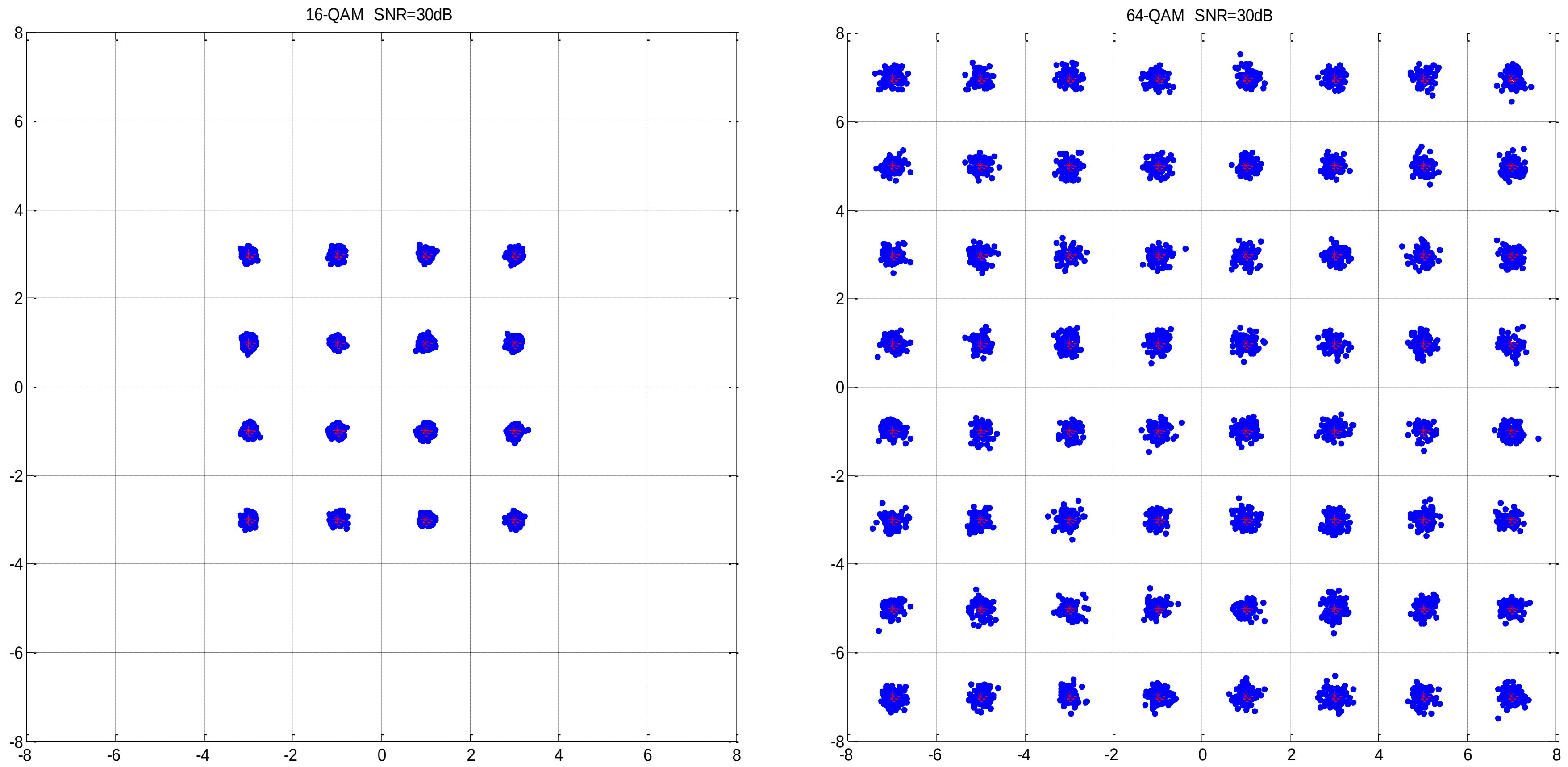
[Picture from the Institute of Sound and Vibration, University of Southampton, UK]





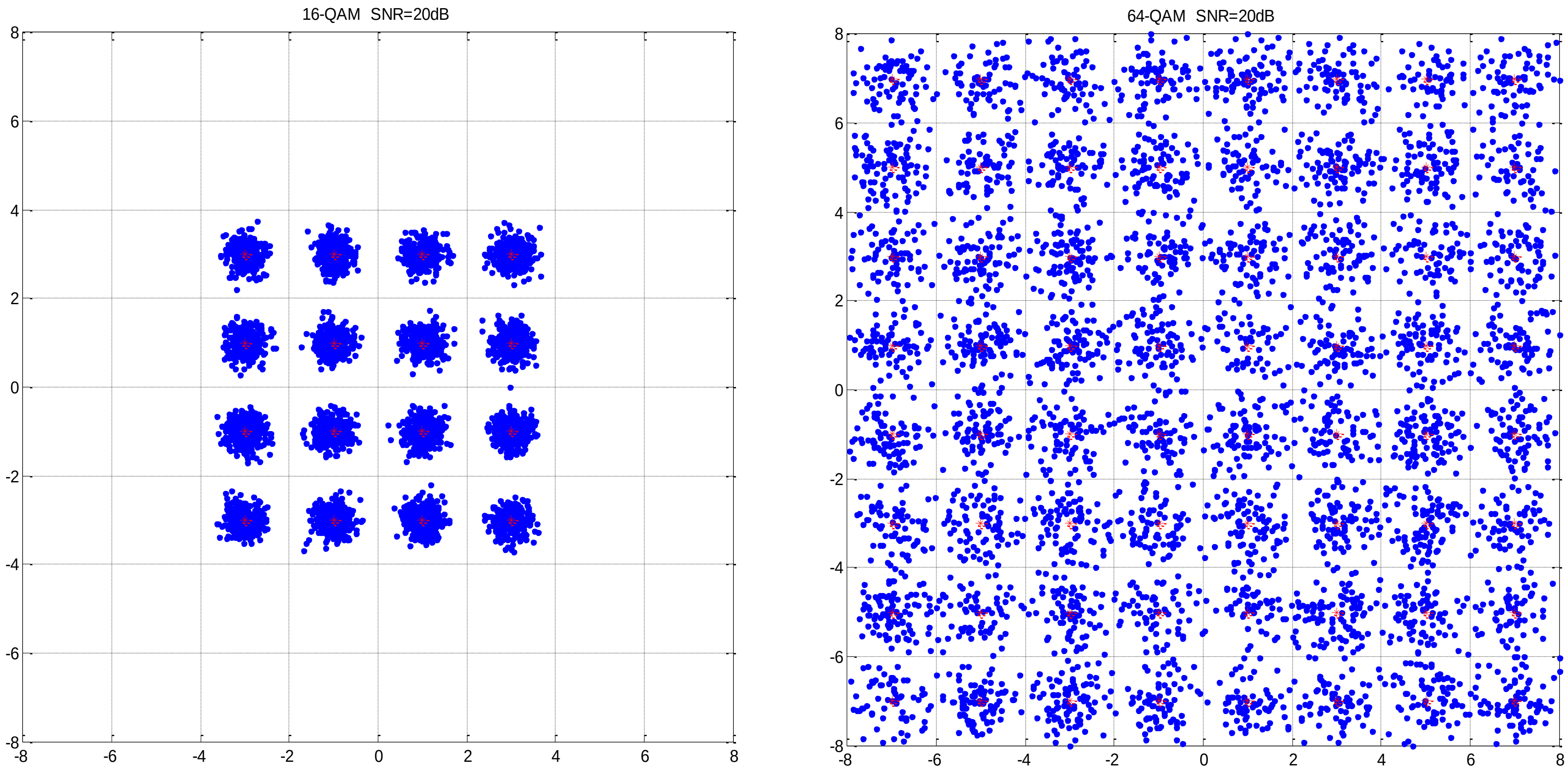
2D orthogonal lattices in SISO

30 dB



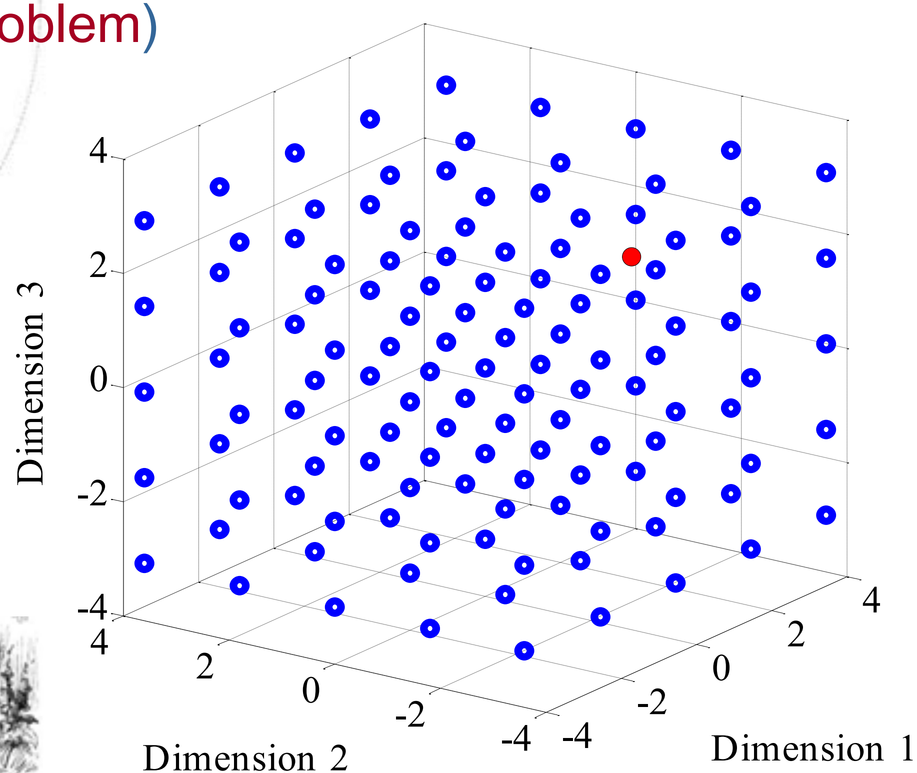
2D orthogonal lattices in SISO

20 dB



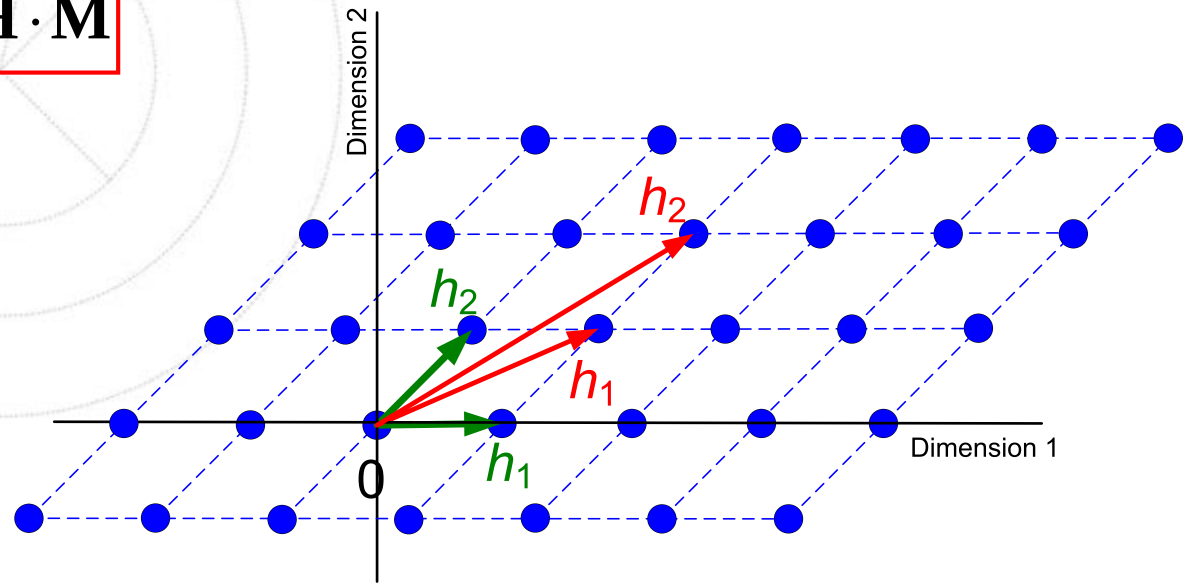
CVP in lattices in 8 dimensions (or more)

Closest vector problem (CVP) in a lattice
(NP-hard problem)



Equivalent basis: reduced and not reduced

$$\boxed{\mathbf{H}_{eq} = \mathbf{Q} \cdot \mathbf{H} \cdot \mathbf{M}}$$



- Almost orthogonal vectors
- Short vectors

LLL reduction

- Reduction in polynomial time Lenstra,Lentra,Lovász (1982)
- The Gauss algorithm (1801) is LLL in 2D

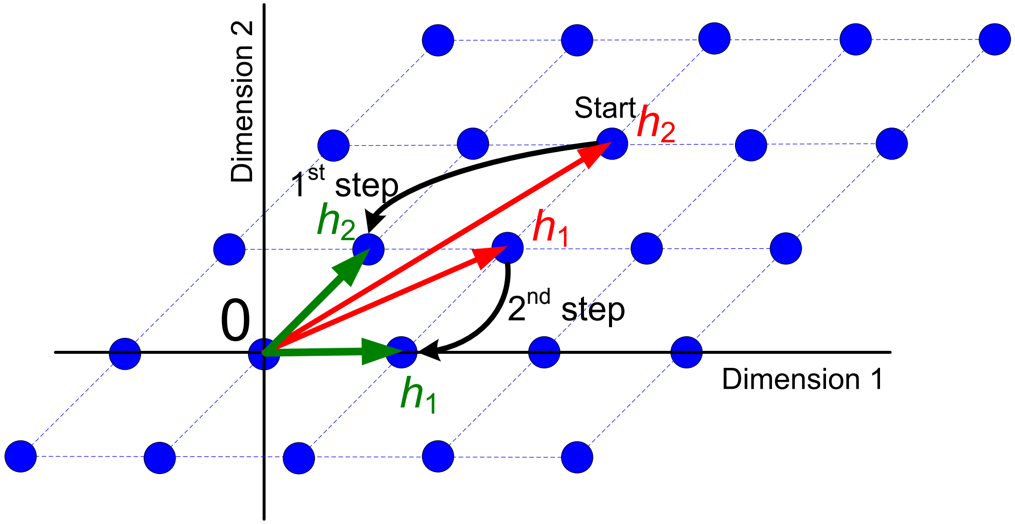
Arjen Klaas Lenstra

Hendrik Willem Lenstra

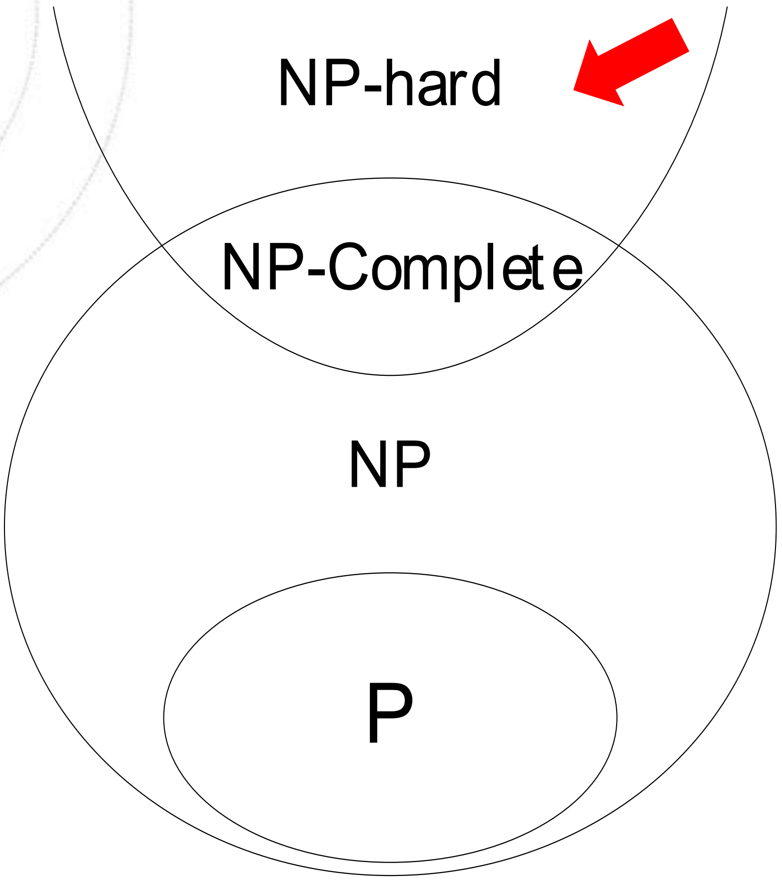
László Lovász

1st step: replace h_2 by $h_2 - h_1$ which gives us h_2

2st step: replace h_1 by $h_1 - h_2$ which gives us h_1



NP Hard Problems: the worst



Linear receivers

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

Zero Forcing (ZF)

$$\hat{\mathbf{x}} = \mathrm{slice}(\mathbf{H}^{-1}\mathbf{y})$$

$$\mathbf{y} \Rightarrow \boxed{\mathbf{W}_{ZF} = \mathbf{H}^{-1}} \Rightarrow \boxed{\text{Slicing}} \Rightarrow \hat{\mathbf{x}}$$

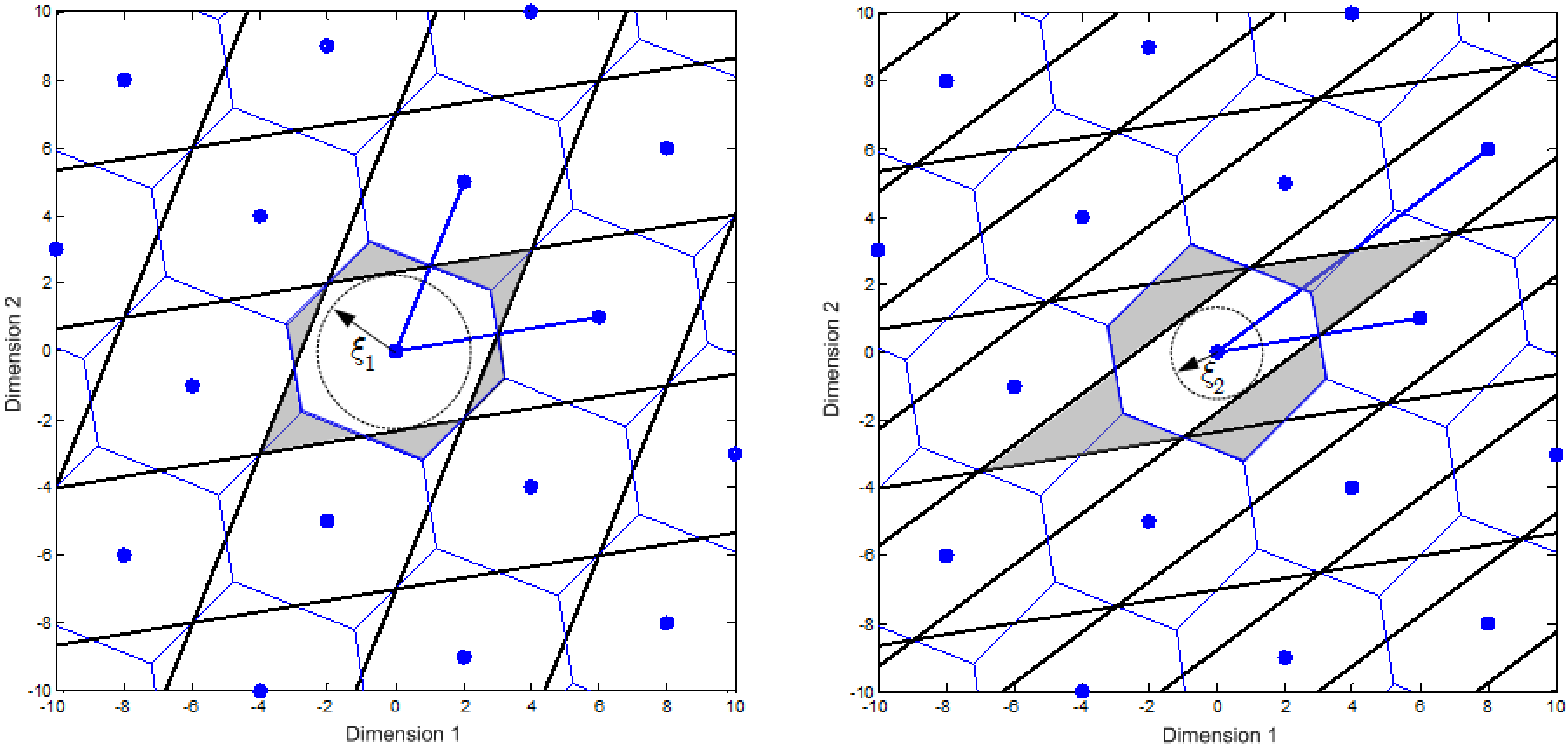
(or pseudo-inverse $\mathbf{H}^{+} = \left(\mathbf{H}^{H}\mathbf{H}\right)^{-1}\mathbf{H}^{H}$

Minimum Mean Squared Error (MMSE)

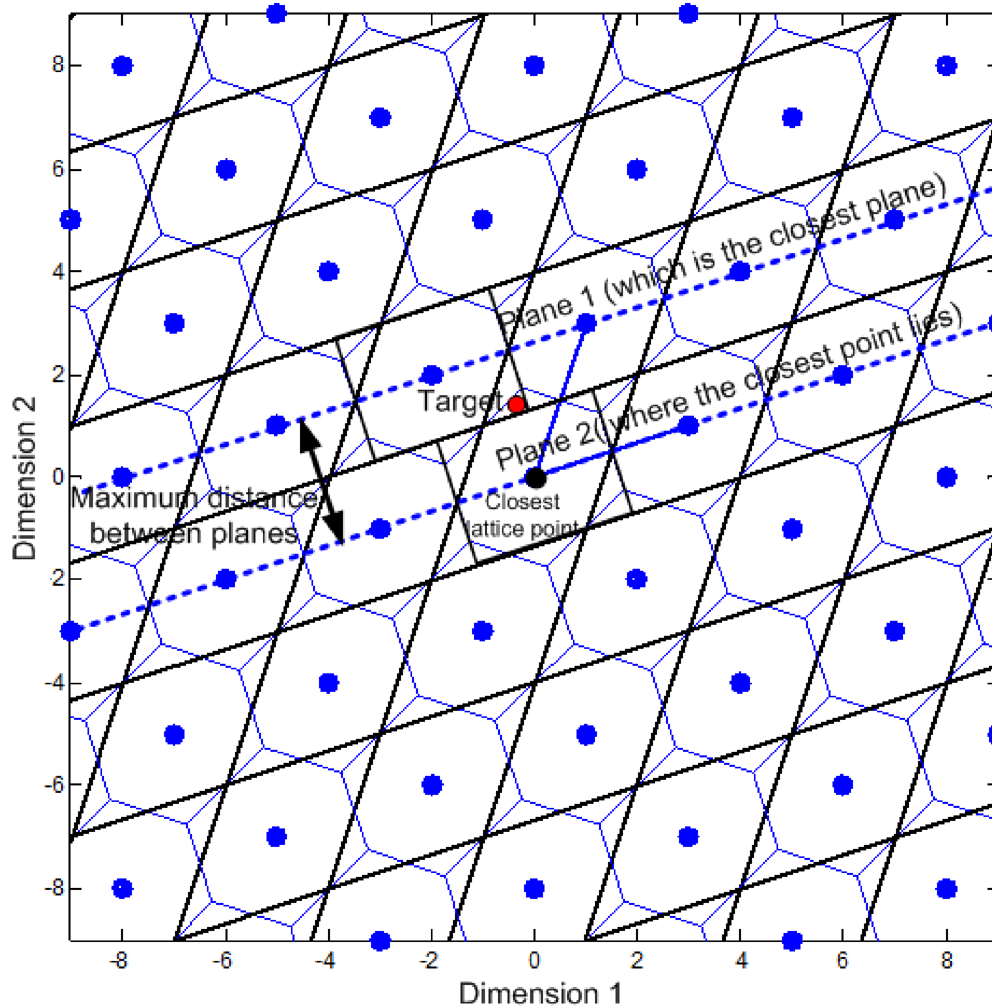
$$\mathrm{E}\left[\left\|\mathbf{W}\mathbf{y} - \mathbf{x}\right\|^{2}\right]$$

$$\mathbf{y} \Rightarrow \boxed{\mathbf{W}_{MMSE} = \left(\mathbf{H}^{H}\mathbf{H} + \frac{1}{SNR}\mathbf{I}_{N_T}\right)^{-1}\mathbf{H}^{H}} \Rightarrow \boxed{\text{Slicing}} \Rightarrow \hat{\mathbf{x}}$$

The geometry of zero-forcing



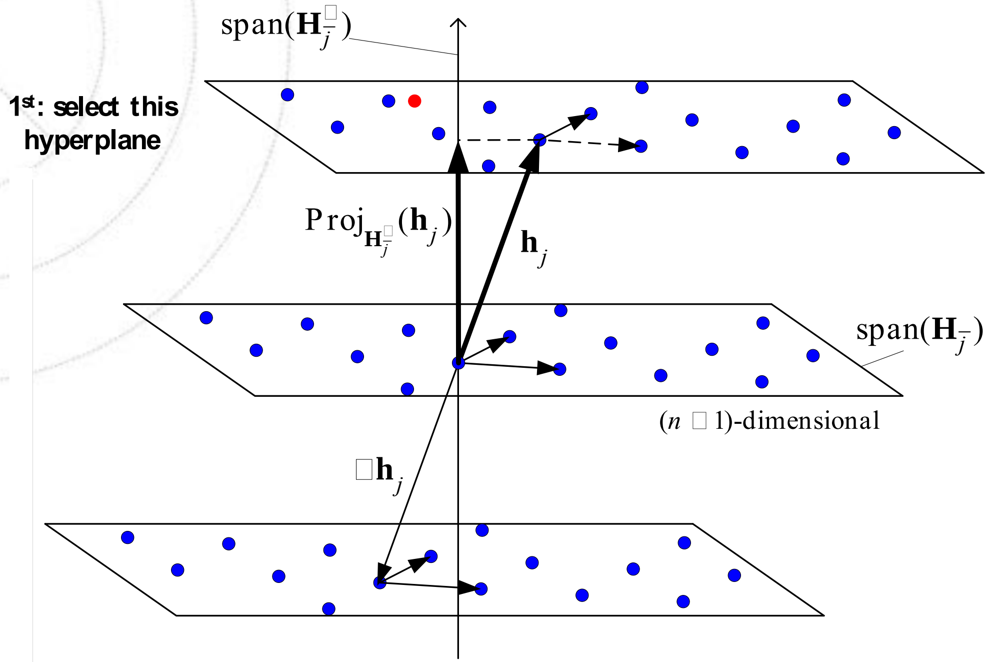
The geometry of successive interference cancelation



$$\mathbf{H} = \mathbf{QR}$$

$$\begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \\ \mathbf{y}_3 \end{bmatrix} = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ 0 & r_{22} & r_{23} \\ 0 & 0 & r_{33} \end{pmatrix} \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \mathbf{x}_3 \end{bmatrix} + \begin{bmatrix} \mathbf{n}_1 \\ \mathbf{n}_2 \\ \mathbf{n}_3 \end{bmatrix}$$

V-BLAST - vertical Bell Labs space-time [1999]
or… SIC: successive interference cancelation
or… Babai's algorithm or the nearest plane algorithm [1986]



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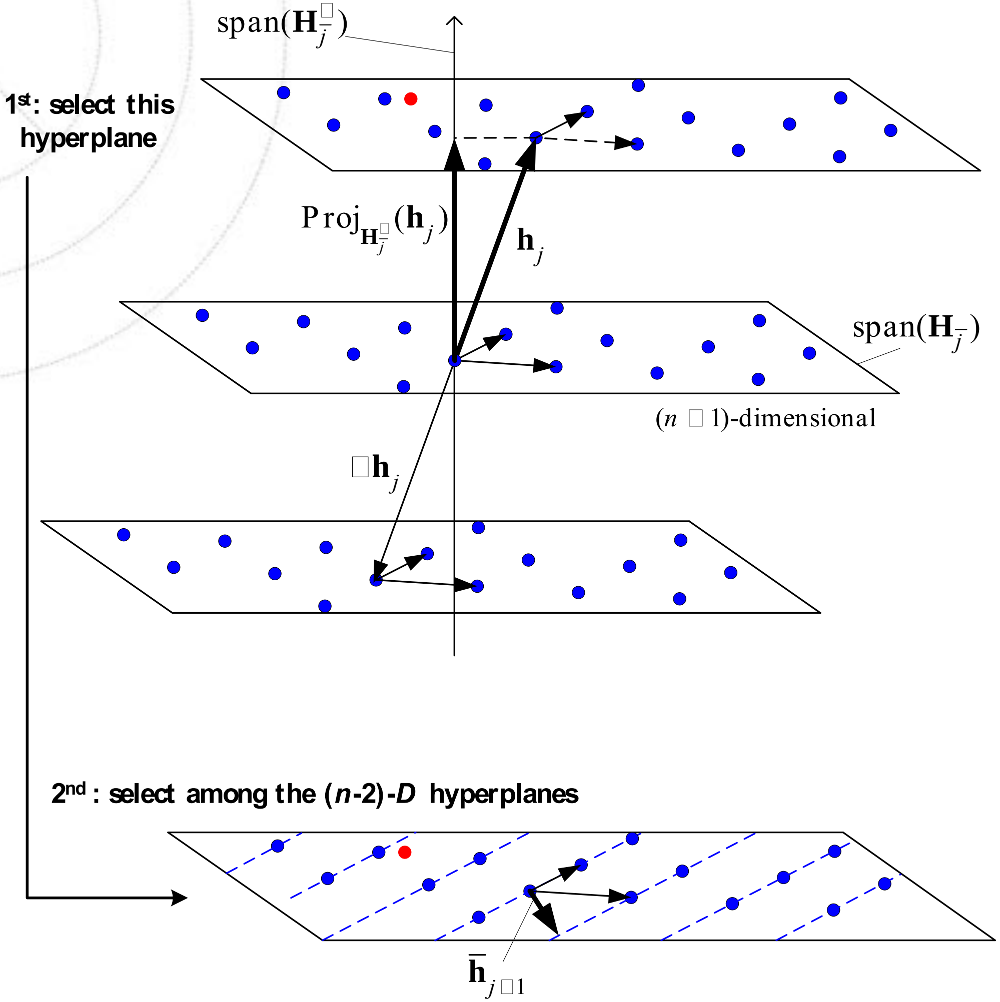
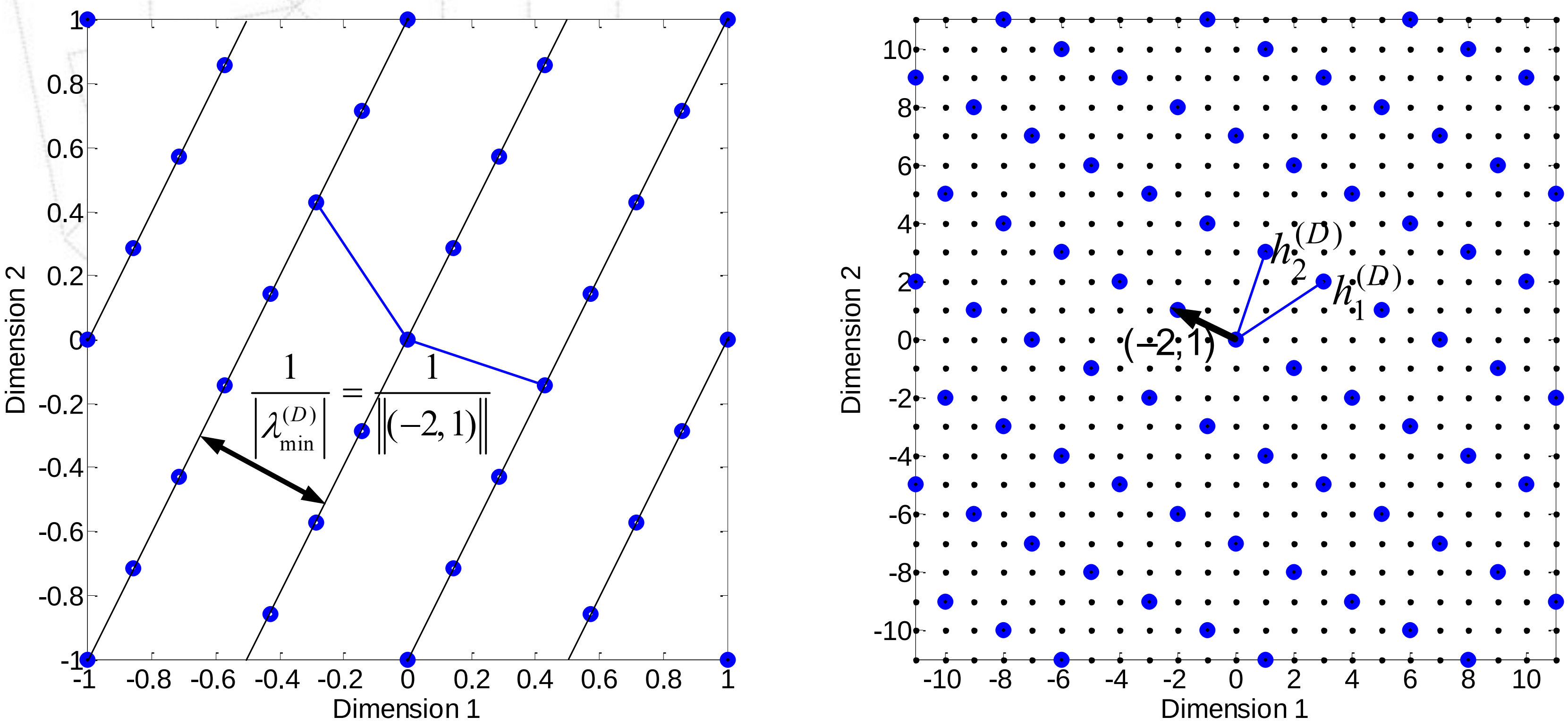
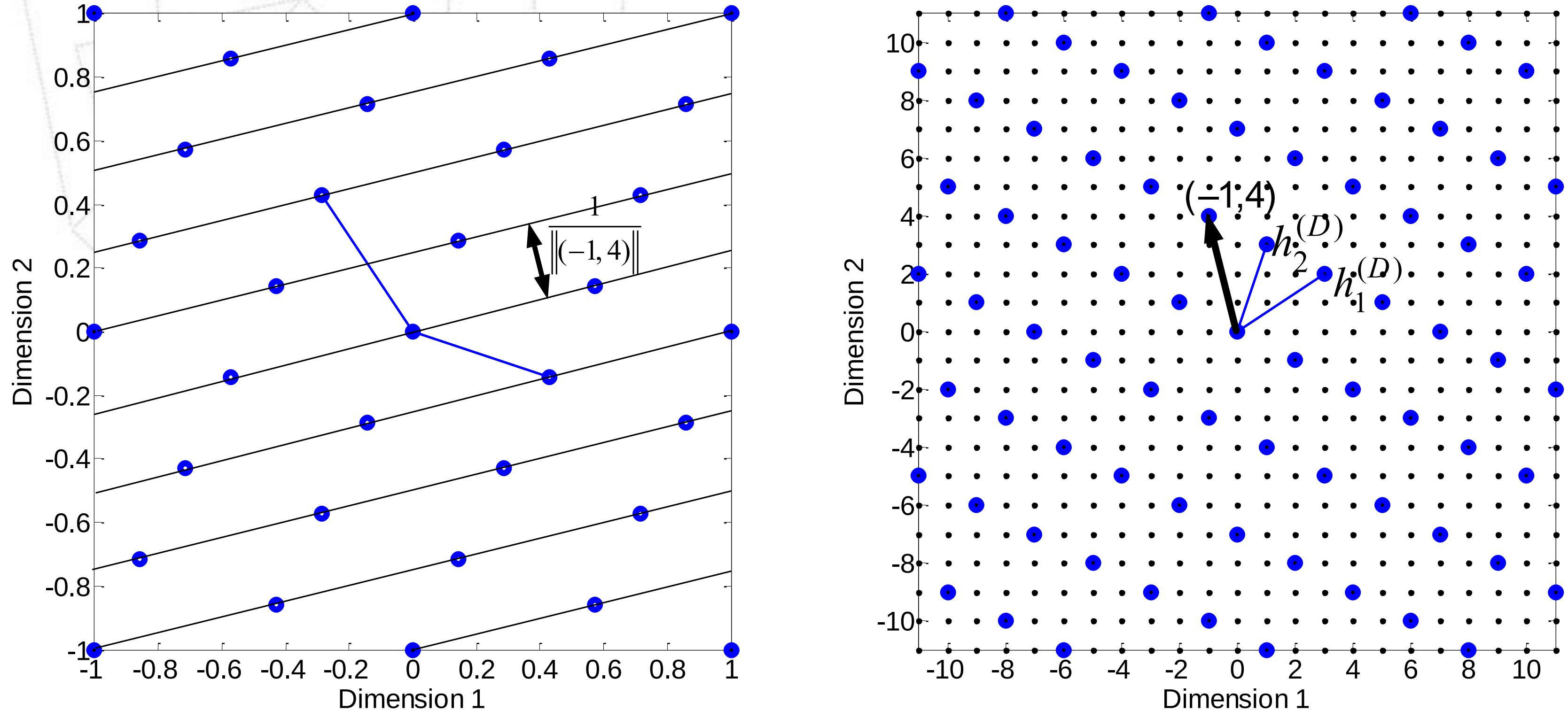


Vectors in the Dual Lattice define hyperplanes (1/2)



(a) Selection of (–2,1) in the dual lattice.

Vectors in the Dual Lattice define hyperplanes (2/2)

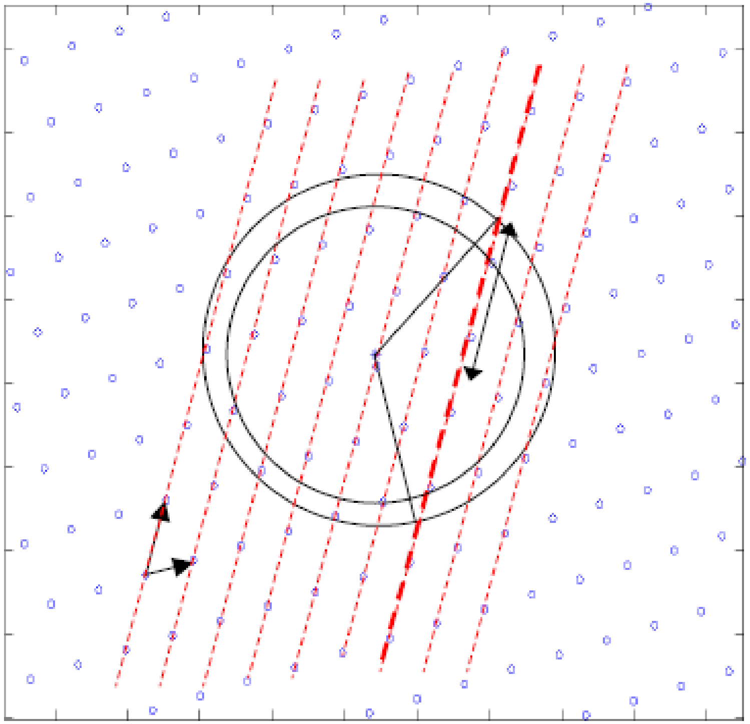


(b) Selection of (−1,4) in the dual lattice.

The geometry of sphere decoding

$$\|\mathbf{y} - \mathbf{H}\mathbf{x}\|^2 \leq \chi^2$$

$$\begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \\ \mathbf{y}_3 \end{bmatrix} = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ 0 & r_{22} & r_{23} \\ 0 & 0 & r_{33} \end{pmatrix} \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \mathbf{x}_3 \end{bmatrix} + \begin{bmatrix} \mathbf{n}_1 \\ \mathbf{n}_2 \\ \mathbf{n}_3 \end{bmatrix}$$



[Figure by Dr. Wai Ho Mow, Univ. of hong Kong]

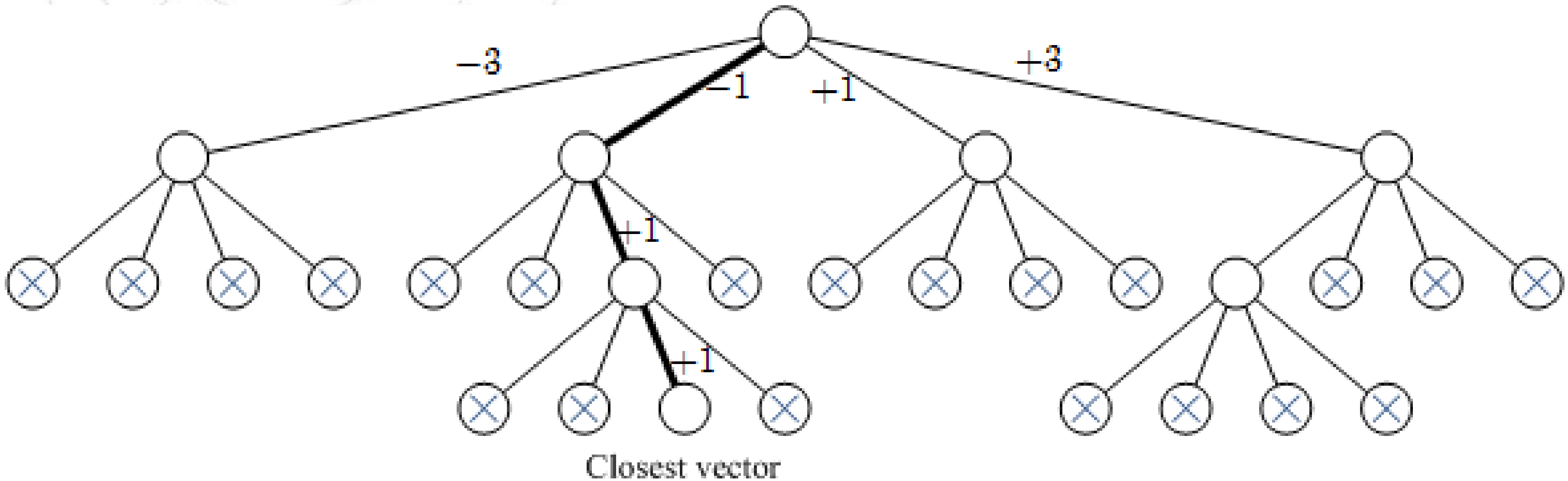
$$\mathbf{y} \Rightarrow \boxed{\mathbf{H} = \mathbf{Q}\mathbf{R}} \Rightarrow \boxed{\text{Tree exploration}} \Rightarrow \hat{\mathbf{x}}$$

Unitary matrix (Rigid rotation)

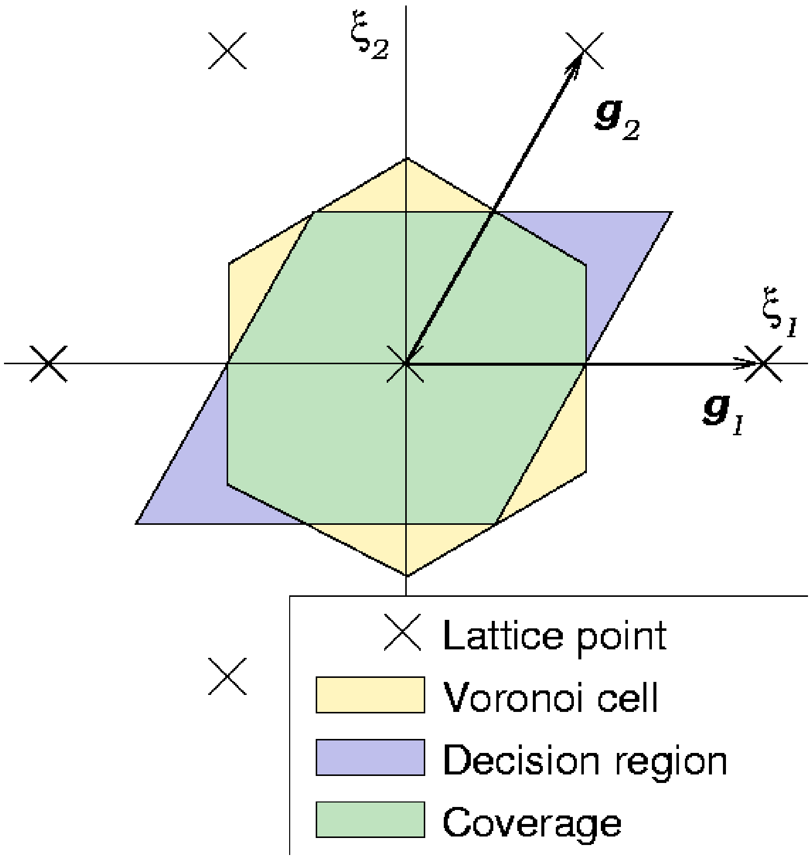
Upper triangular

$$\sum_{i=1}^{m} \left(y'_i - \sum_{j=i}^{m} r_{ij} x(j) \right)^2 \leq \chi'^2$$

Sphere decoding or… tree decoding



The notion of *coverage* (1/2)



[Figure by Dr. Karen Su, University of Cambridge]

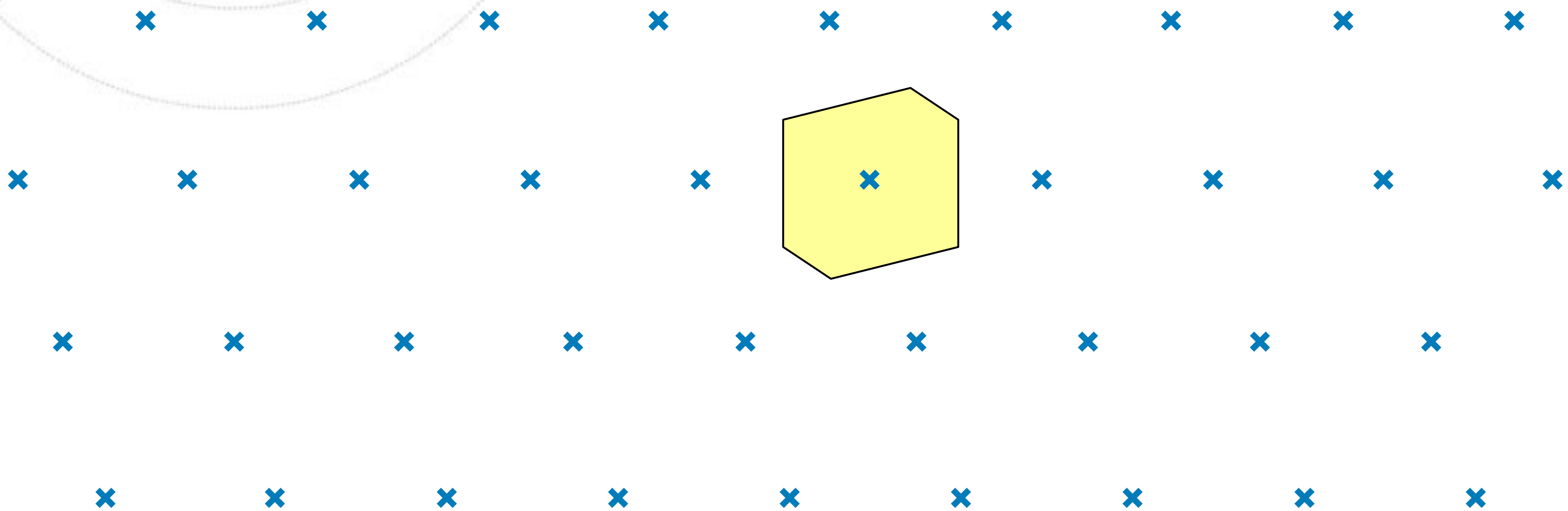
The notion of *coverage* (2/2)

Improves coverage of Voronoi cell by increasing the inradius of the decision region

(Figure co-authored with Dr. Karen Su, University of Cambridge)

The notion of *coverage* (2/2)

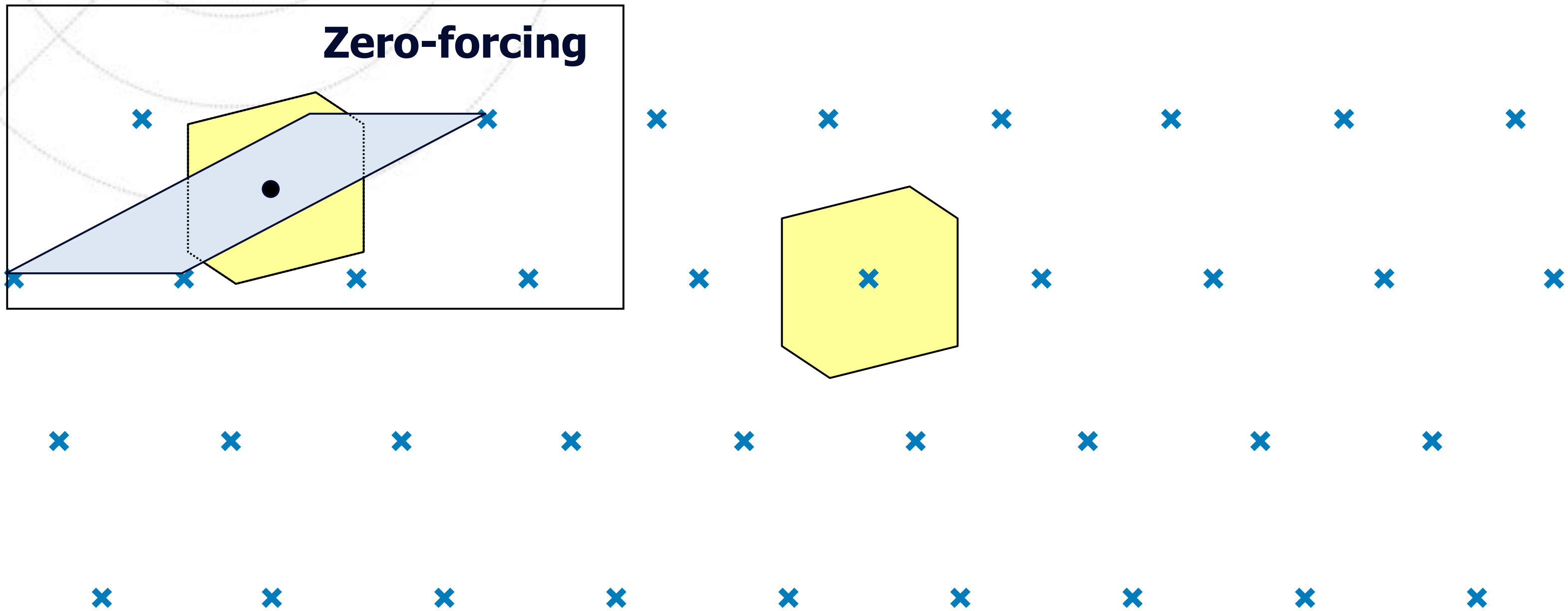
Improves coverage of Voronoi cell by increasing the inradius of the decision region



(Figure co-authored with Dr. Karen Su, University of Cambridge)

The notion of *coverage* (2/2)

Improves coverage of Voronoi cell by increasing the inradius of the decision region



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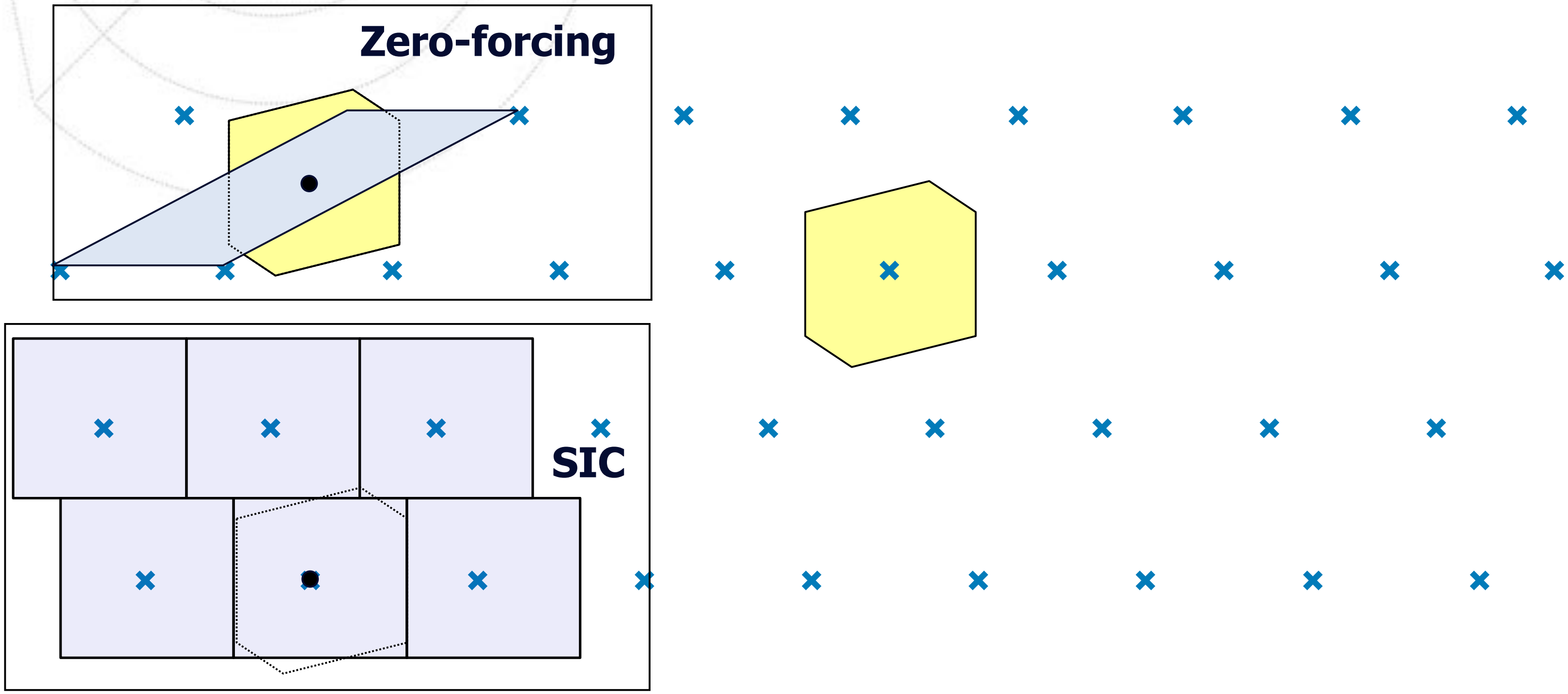

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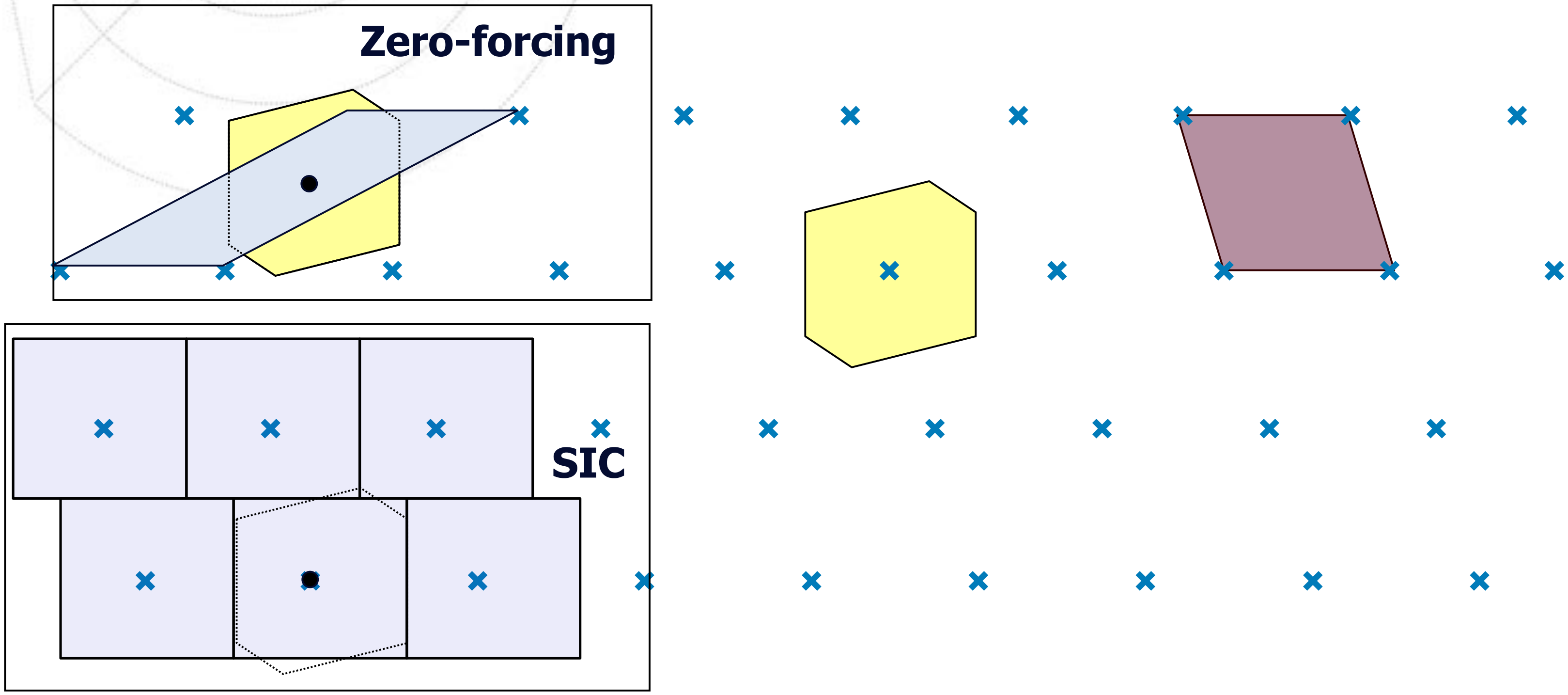

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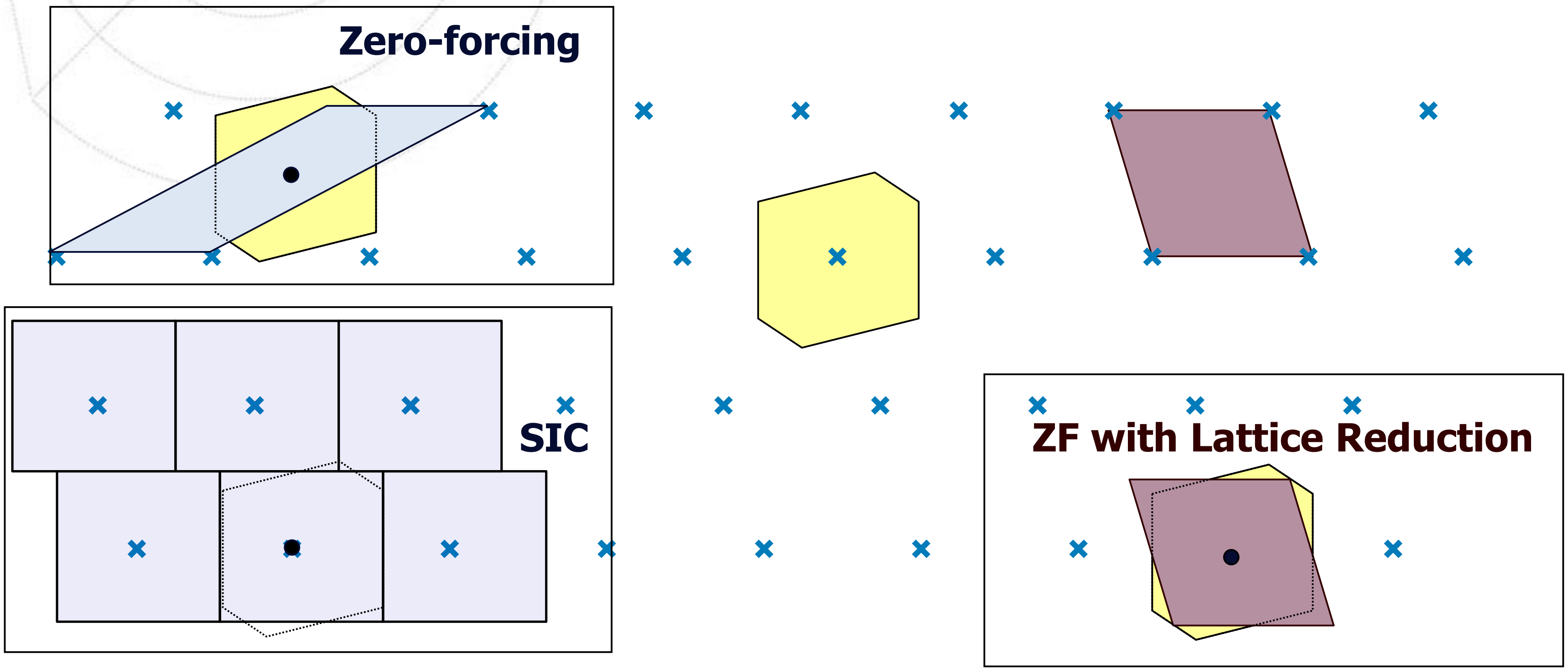

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Two approaches for MIMO

Space-Time Coding

- Increase diversity (slope of the BER curves).

Spatial-multiplexing

- Increase spectral efficiency. Preferable to aim at SM [Lozano & Jindal 2010]

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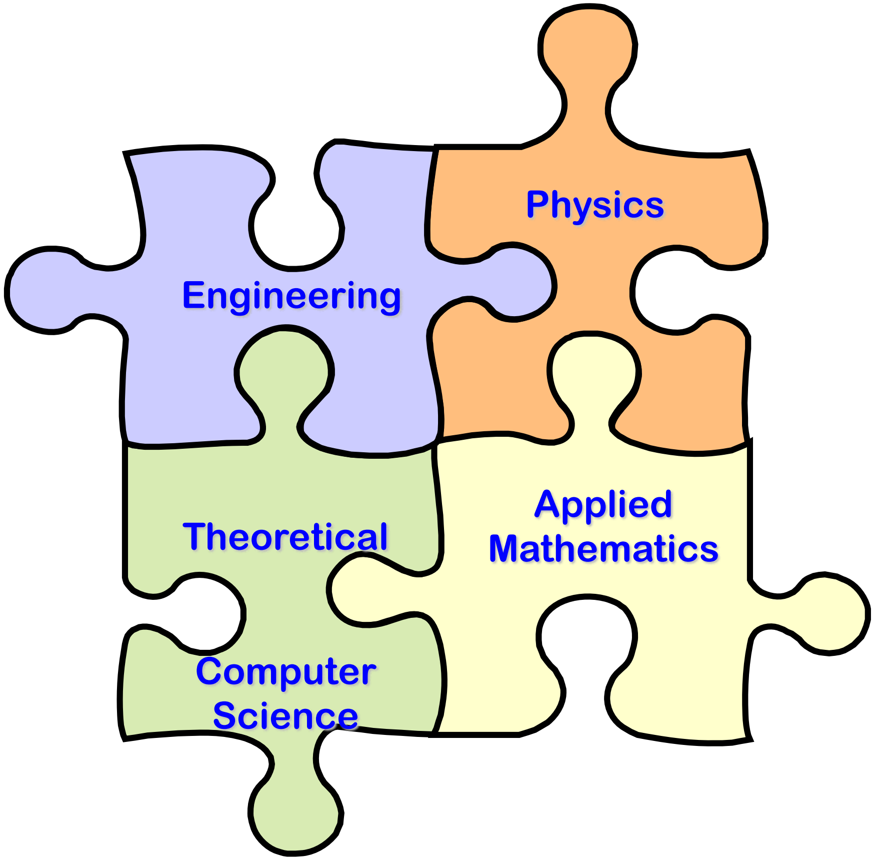
MIMO detection brings together…

- *Information Theory*
- *Coding Theory*
- *Detection and Estimation Theory*
- *Statistical signal processing*
- *Algorithms*
- *Optimization*
- *Pattern Recognition*
- *Machine Learning*
- *Cryptography*



Most used techniques

Linear

- Zero Forcing (ZF)
- Minimum Mean Squared Error (MMSE)

Non- Linear

- V-BLAST (OSIC with ZF criterion)
- V-BLAST (OSIC with MMSE criterion)
- Lattice Reduction Aided (with ZF criterion)
- Lattice Reduction Aided (with MMSE criterion)
- Sphere decoder (with different enumerations)
- Maximum Likelihood (ML)

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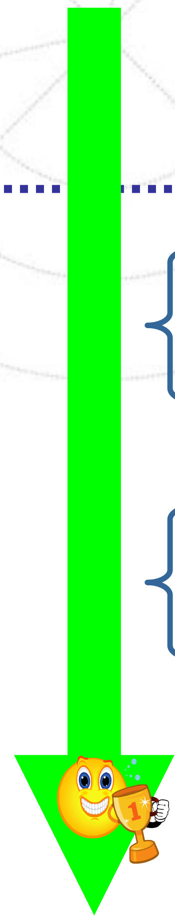

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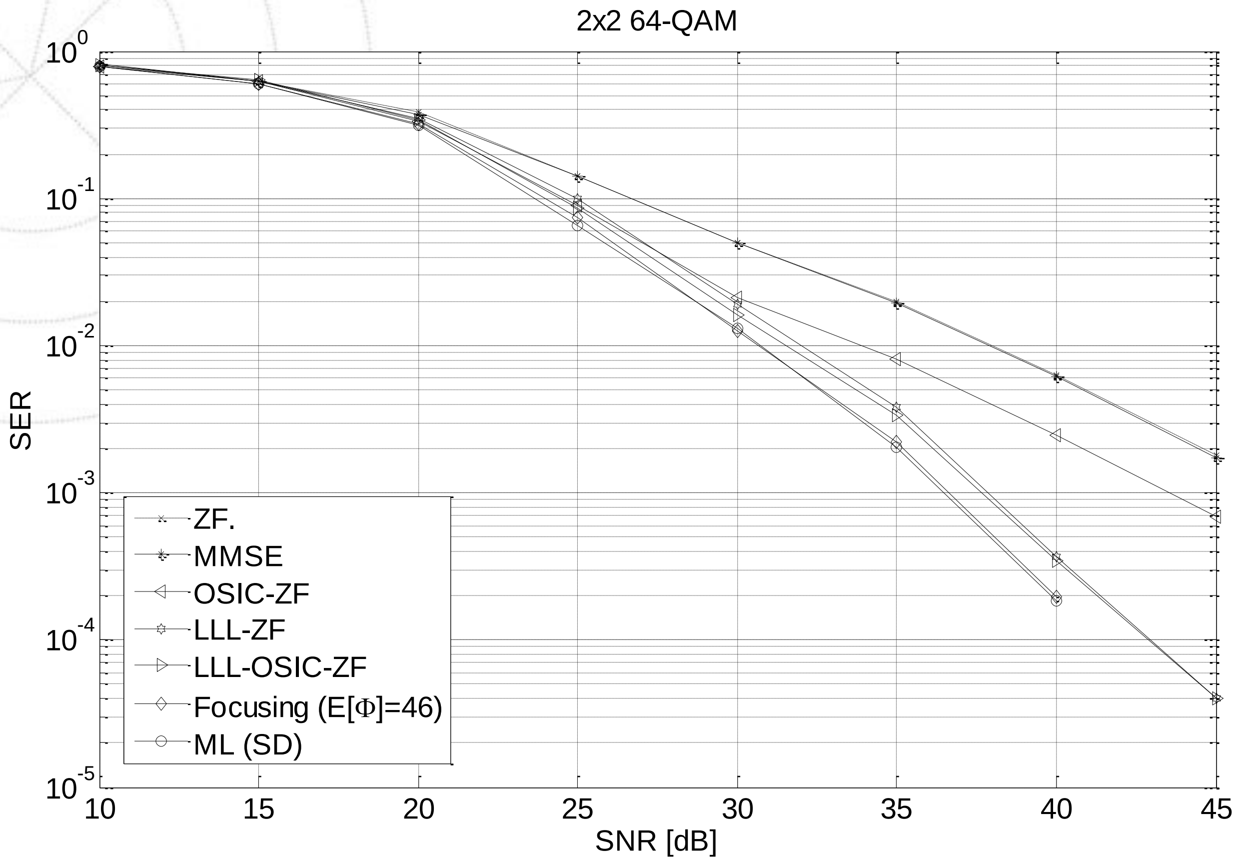

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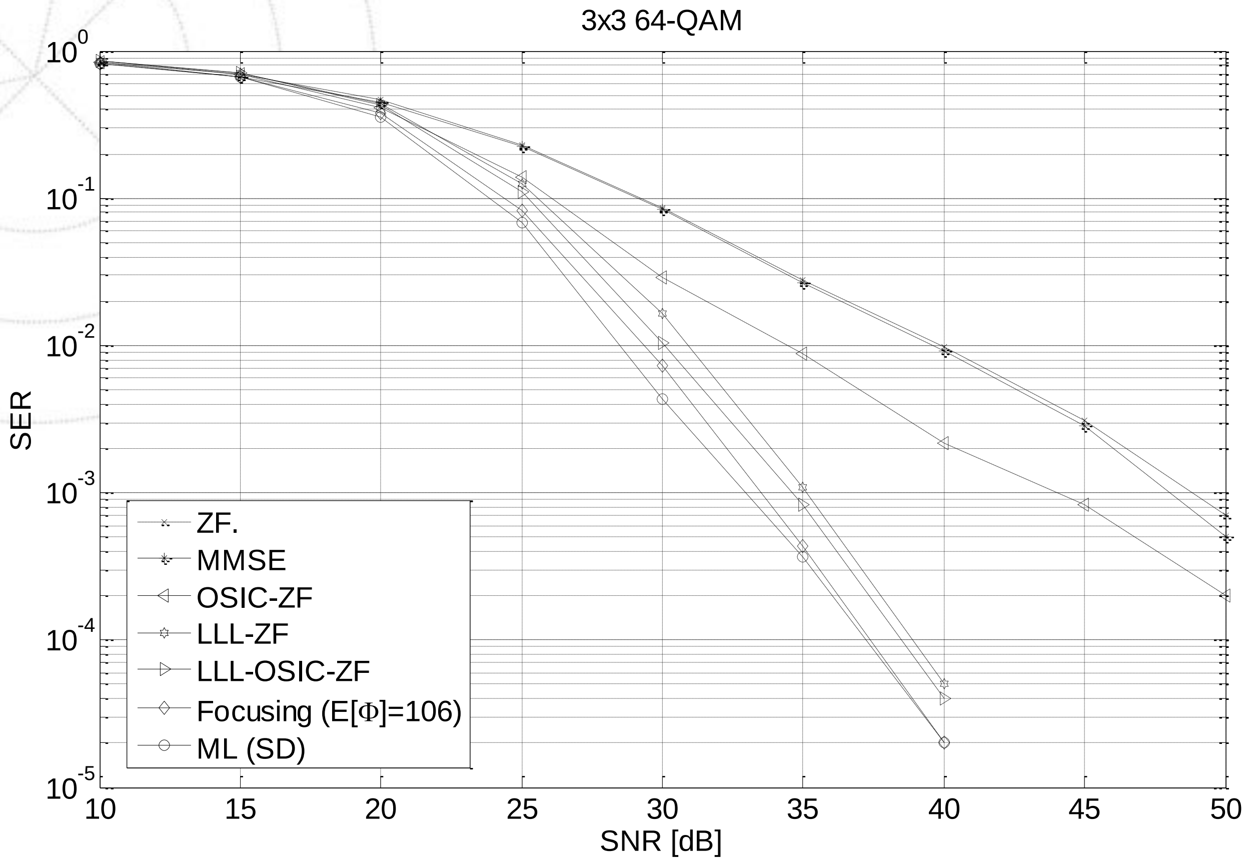

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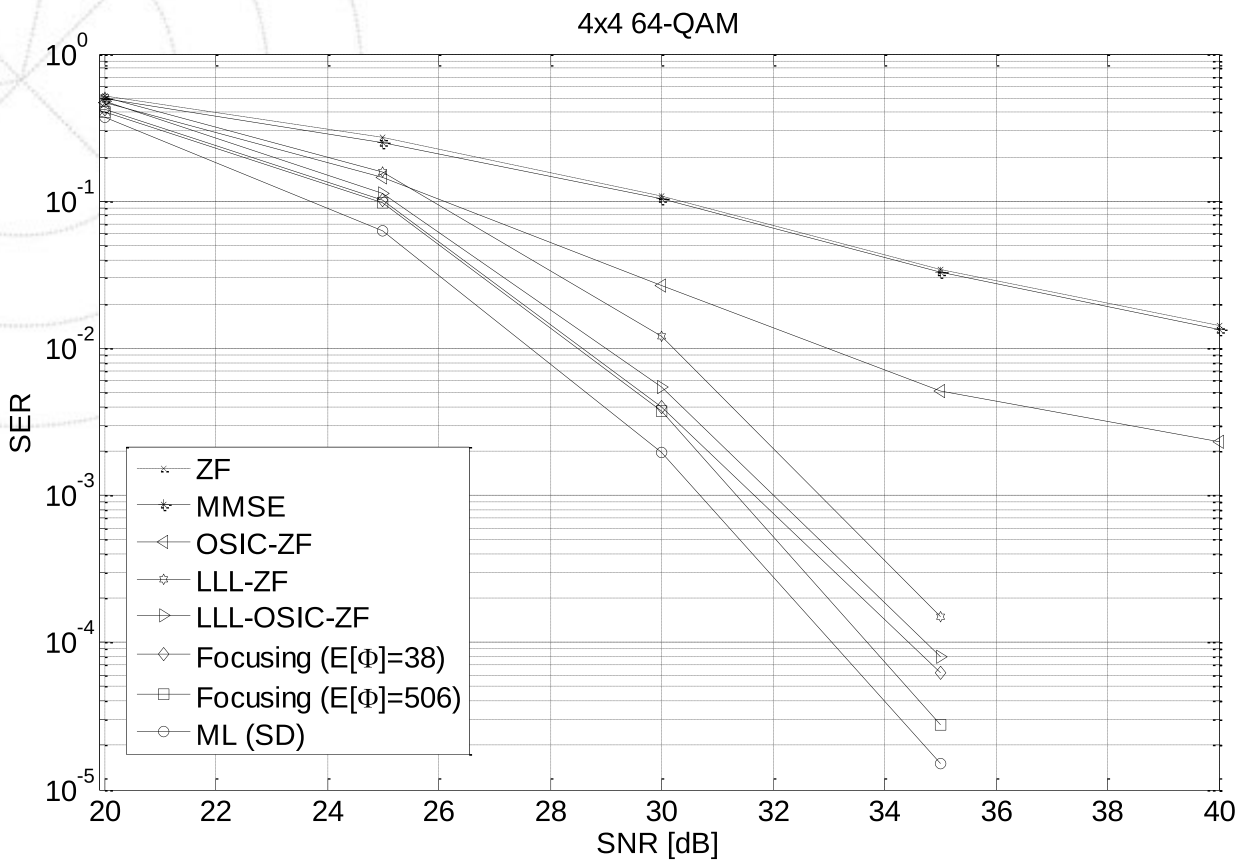

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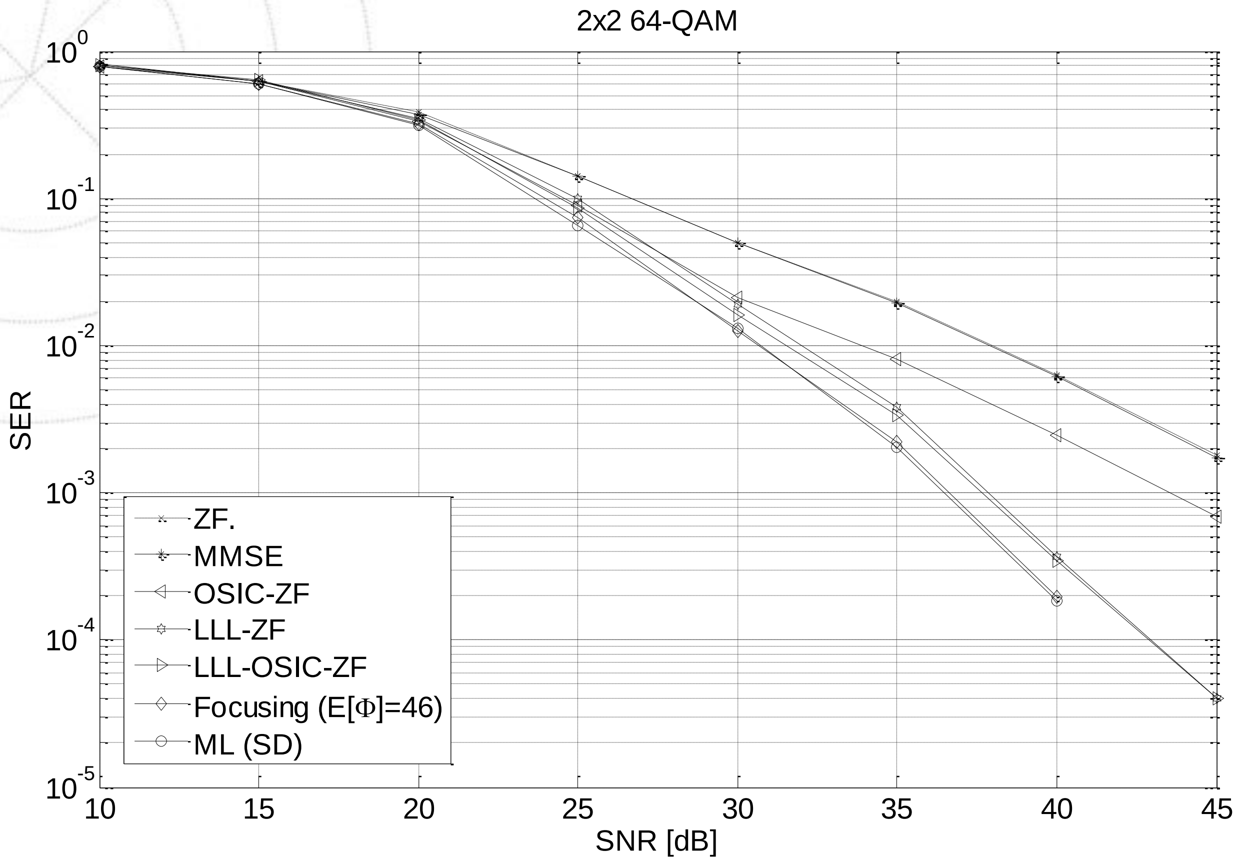

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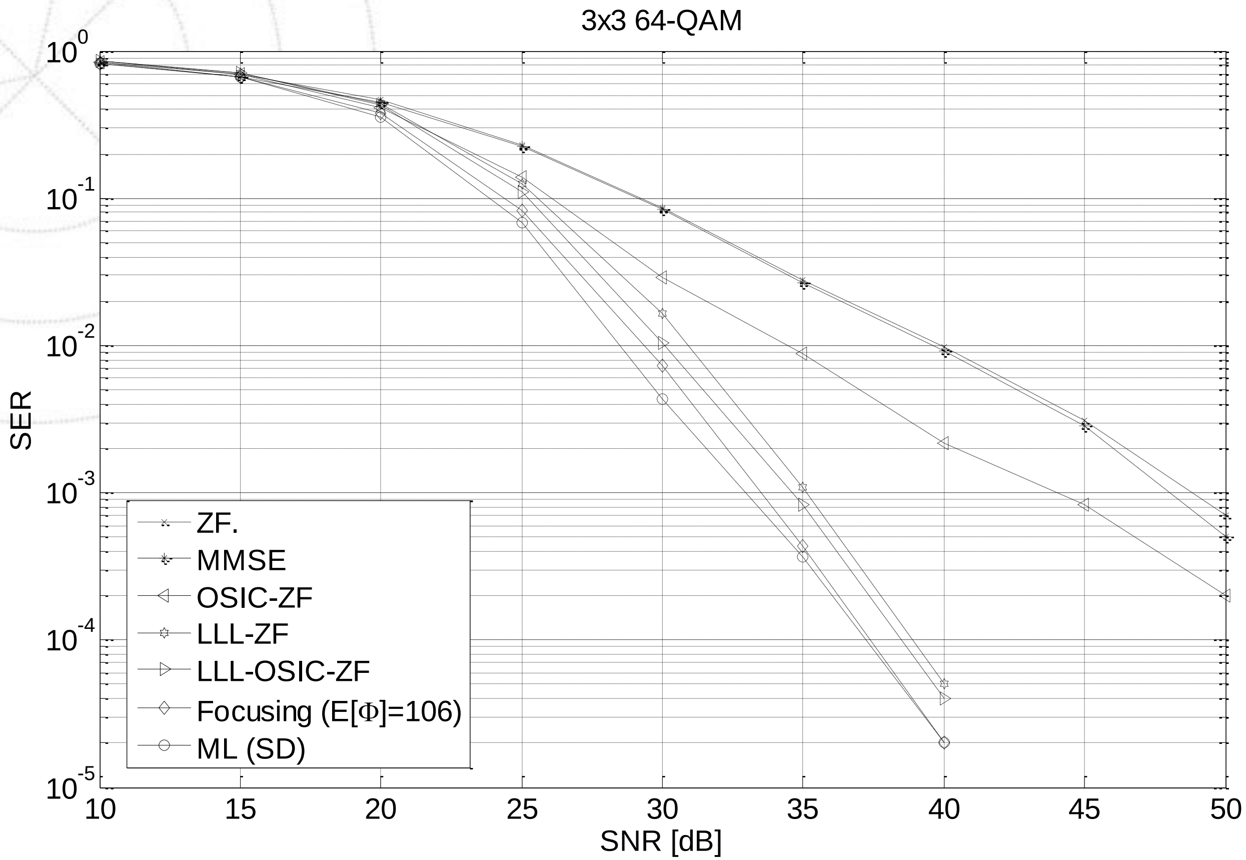

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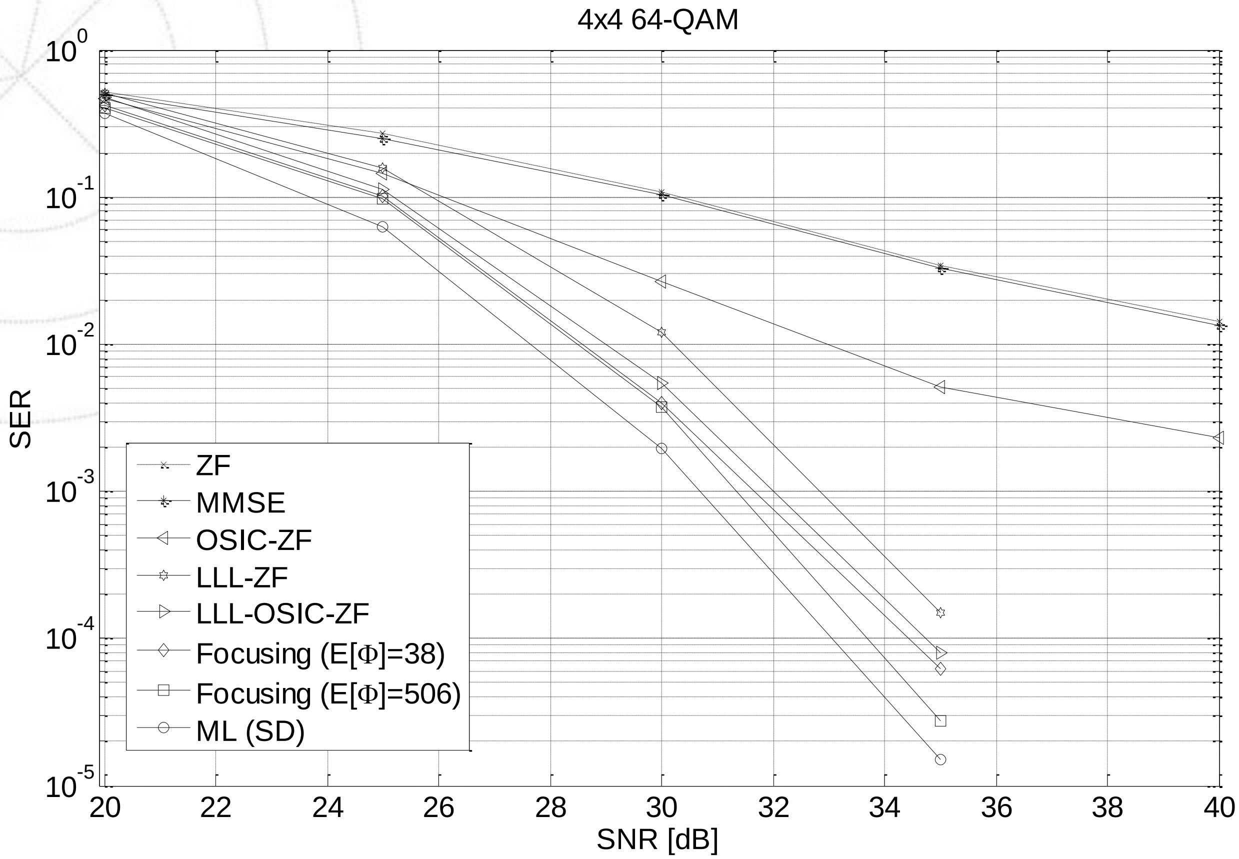

LTE-Advanced user Equipment categories

3GPP Release	UE Category	Downlink rate	MIMO Layers	Uplink rate
Release 8	Category 1	10.3 Mbit/s	1	5.2 Mbit/s
Release 8	Category 2	51.0 Mbit/s	2	25.5 Mbit/s
Release 8	Category 3	102.0 Mbit/s	2	51.0 Mbit/s
Release 8	Category 4	150.8 Mbit/s	2	51.0 Mbit/s
Release 8	Category 5	299.6 Mbit/s	4	75.4 Mbit/s
Release 10	Category 6	301.5 Mbit/s	2 or 4	51.0 Mbit/s
Release 10	Category 7	301.5 Mbit/s	2 or 4	102.0 Mbit/s
Release 10	Category 8	2998.6 Mbit/s	8	1497.8 Mbit/s

State of the art in 2015

- LTE-Advanced: 30 b/s/Hz
- Using 8x8 (8 antennas on each side of the link).
- Efficient detection was still an open problem until 2013.

[e.g., IEEE Comms Mag Feb. 2012]

•“ Randomised SIC”. MCMC: Gibbs sampling is a surprisingly near-optimal solution. Perhaps a revolution.

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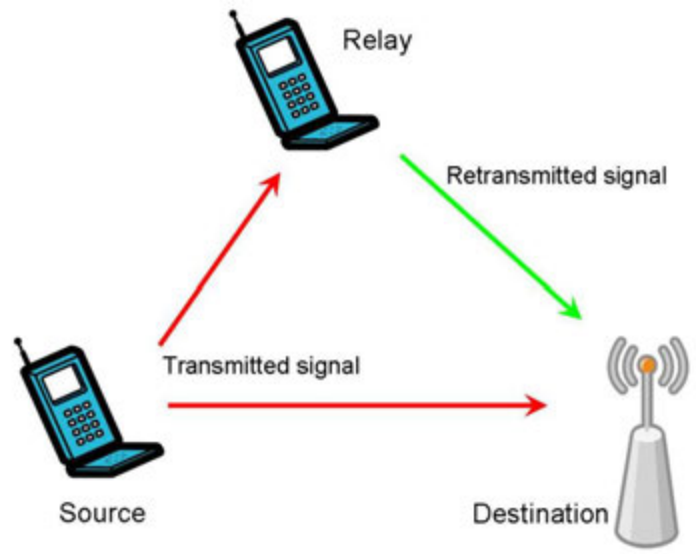
(In convencional symmetric MIMO)

Under development

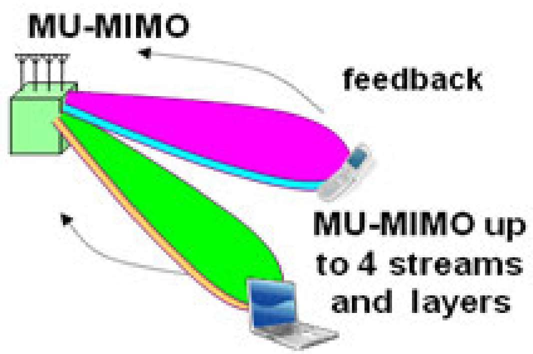
- Co-operative relay networks

(Started with Laneman & Wornel, MIT 2003)



Broadcast channel Precoding (or MU-MIMO in the LTE jargon) is a dual concept to spatial multiplexing

- Is the reverse (*dual*) of Spatial Multiplexing
- Base station transmits to all and each terminal only sees its own signal
- Requires Channel knowledge at the transmitter (of course!)



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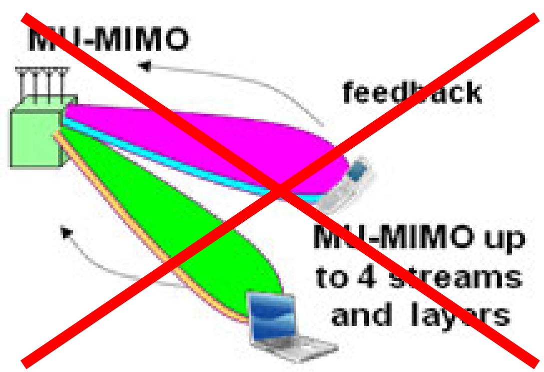

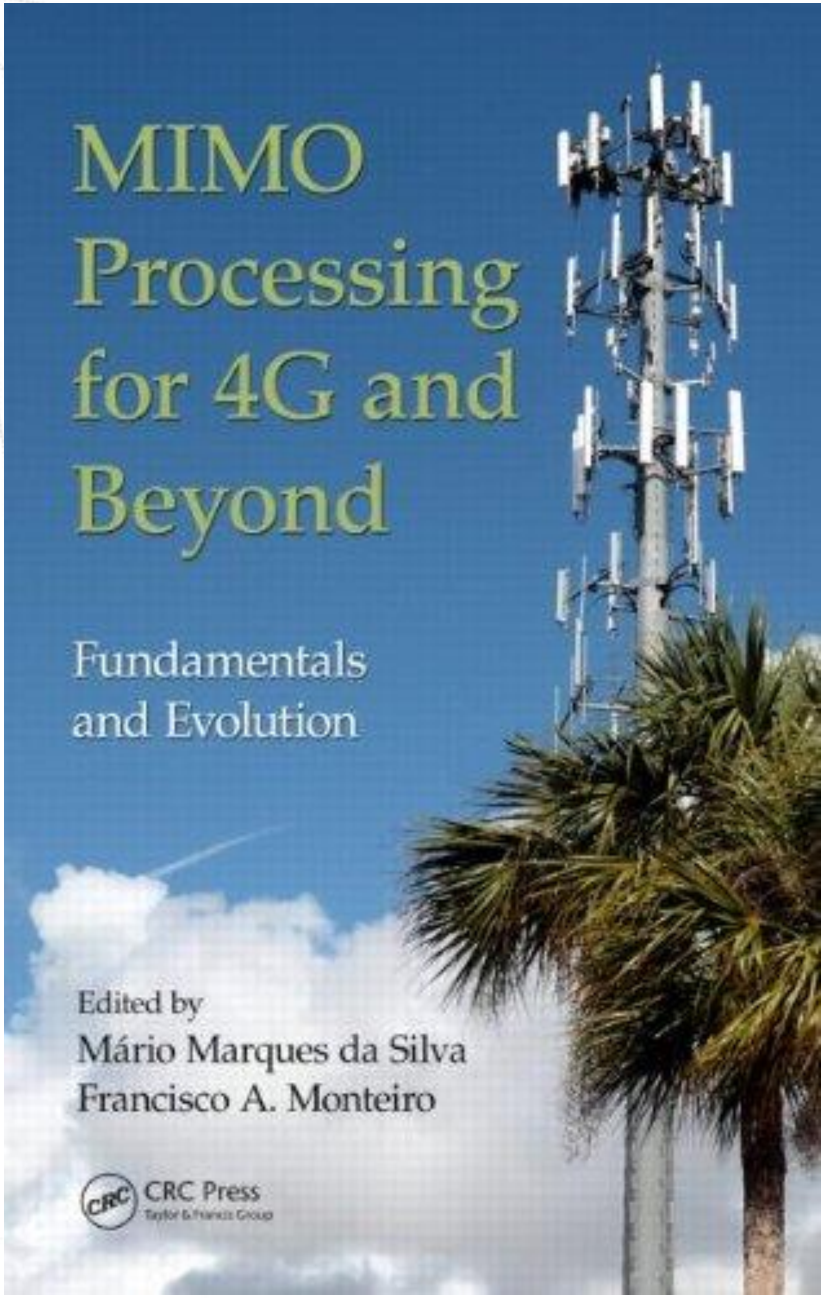

Includes an introduction to *MIMO detection techniques*

(CRC Press - Taylor and Francis, June 2014)