Advanced Hybrid-ARQ Receivers for Broadband MIMO Communications

Soutenance

Houda CHAFNAJI

pour Obtenir le grade de

DOCTEUR DE TELECOM BRETAGNE

en habilitation conjointe avec l'Université de Bretagne Sud

Advanced Hybrid-ARQ Receivers for Broadband MIMO Communications

Par

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Motivations and General Framework

Main objective:

How to efficiently combine multiple transmissions (diversity gain) while maintaining an affordable receiver complexity?

General Framework

- ✓ Chase-type ARQ
- ✓ Channel is short-term quasi-static block fading.
- ✓ Mutli-paths MIMO channels
- ✓ Cyclic-prefix (CP) transmissions to prevent inter-block interference (IBI).
- ✓ Frequency Domain Processing

Presentation Outline

- New Class of Turbo Packet Combiners
- Turbo Packet Combining for MIMO ARQ with Co-Channel Interference (CCI)
- Turbo Packet Combining for Broadband MIMO CDMA Systems
- Generalized ARQ for Broadband Cooperative Communications
- Conclusions and Future Work

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- **New Class of Turbo Packet Combiners**
- Turbo Packet Combining for MIMO ARQ with Co-Channel Interference (CCI)
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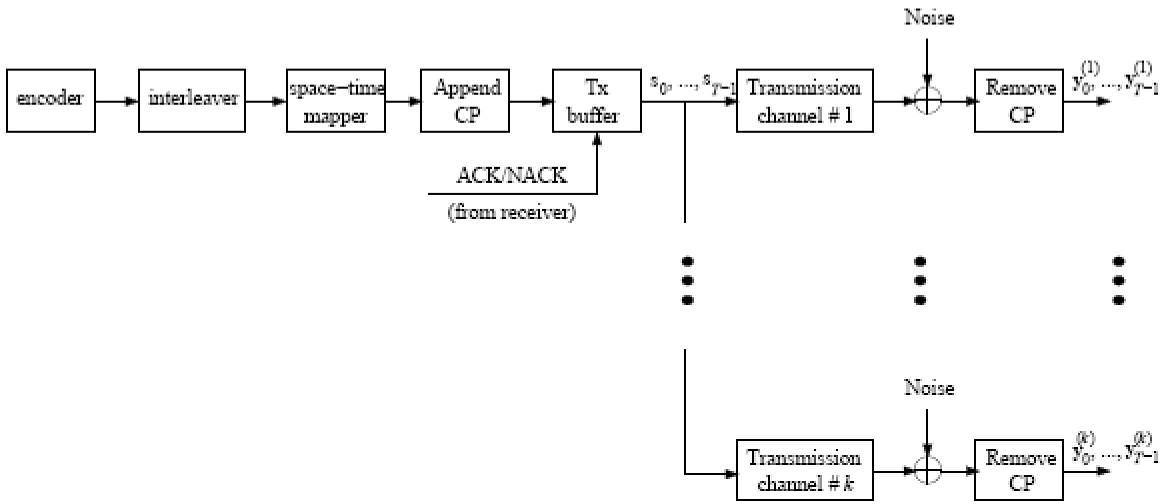
- Generalized ARQ for Single Carrier Broadband Cooperative Communications
- Conclusions and Future Work

New Class of Turbo Packet Combiners

Transmission Scheme

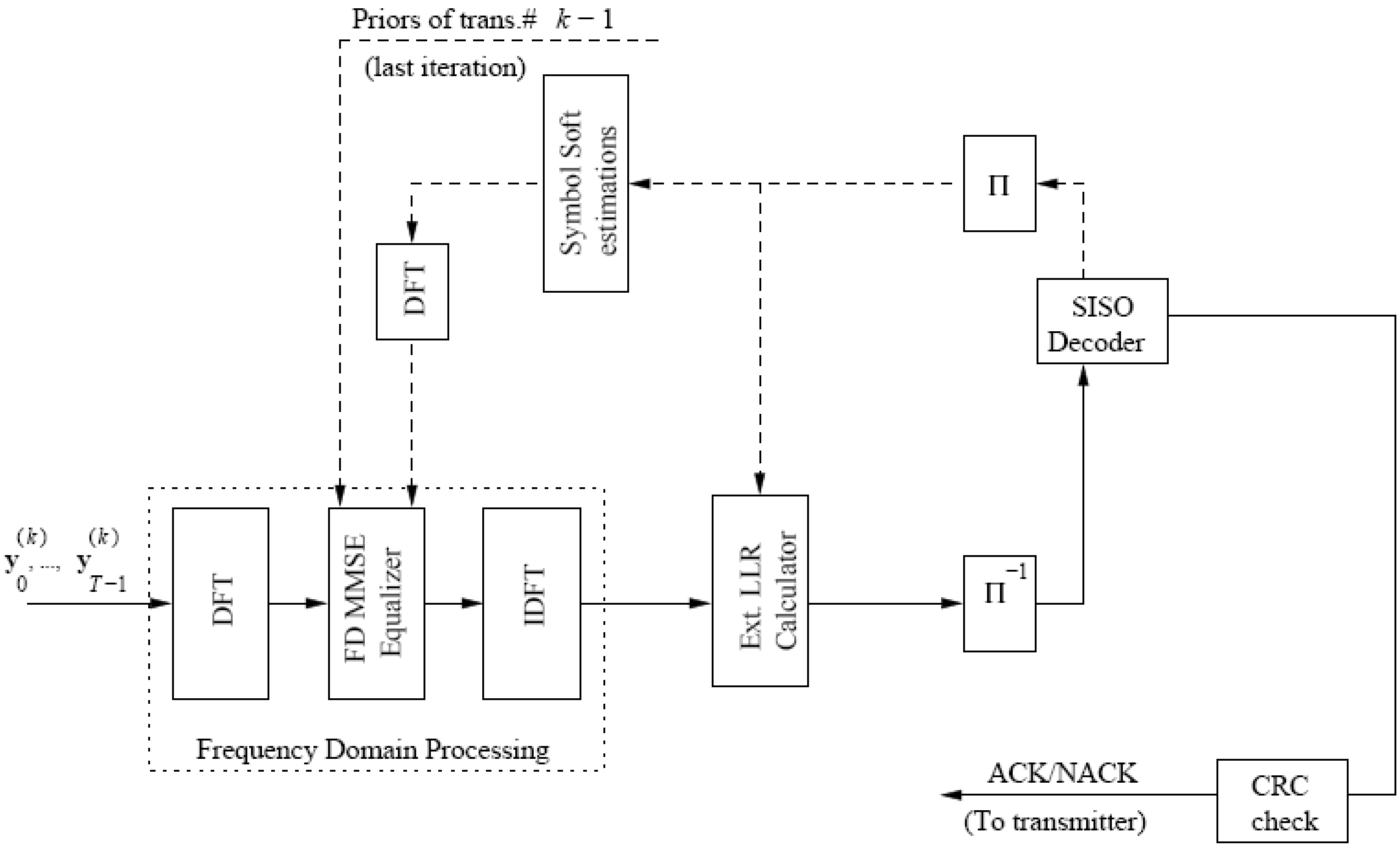


- At each transmission # *k*, a point to point MIMO link with N_T transmit and N_R receive antennas.
- $\mathbf{s}_0, \cdots, \mathbf{s}_{T-1} \in \mathcal{S}^{N_T}$ are the symbol vectors.
- *L* paths MIMO channel: $\mathbf{H}_0^{(k)}, \cdots, \mathbf{H}_{L-1}^{(k)} \in \mathbb{C}^{N_R \times N_T}$.

$$\mathbf{y}_i^{(k)} = \sum_{l=0}^{L-1} \mathbf{H}_l^{(k)} \mathbf{s}_{(i-l) \bmod T} + \mathbf{n}_i^{(k)} \quad (1)$$

New Class of Turbo Packet Combiners

Receiver Scheme with no Packet Combining



New Class of Turbo Packet Combiners

Virtual Receive Antenna Concept

- **Key idea:**

ARQ rounds ⇔ Virtual receive antennas
One (re)transmission ~ One set of N_R virtual Rx antennas.

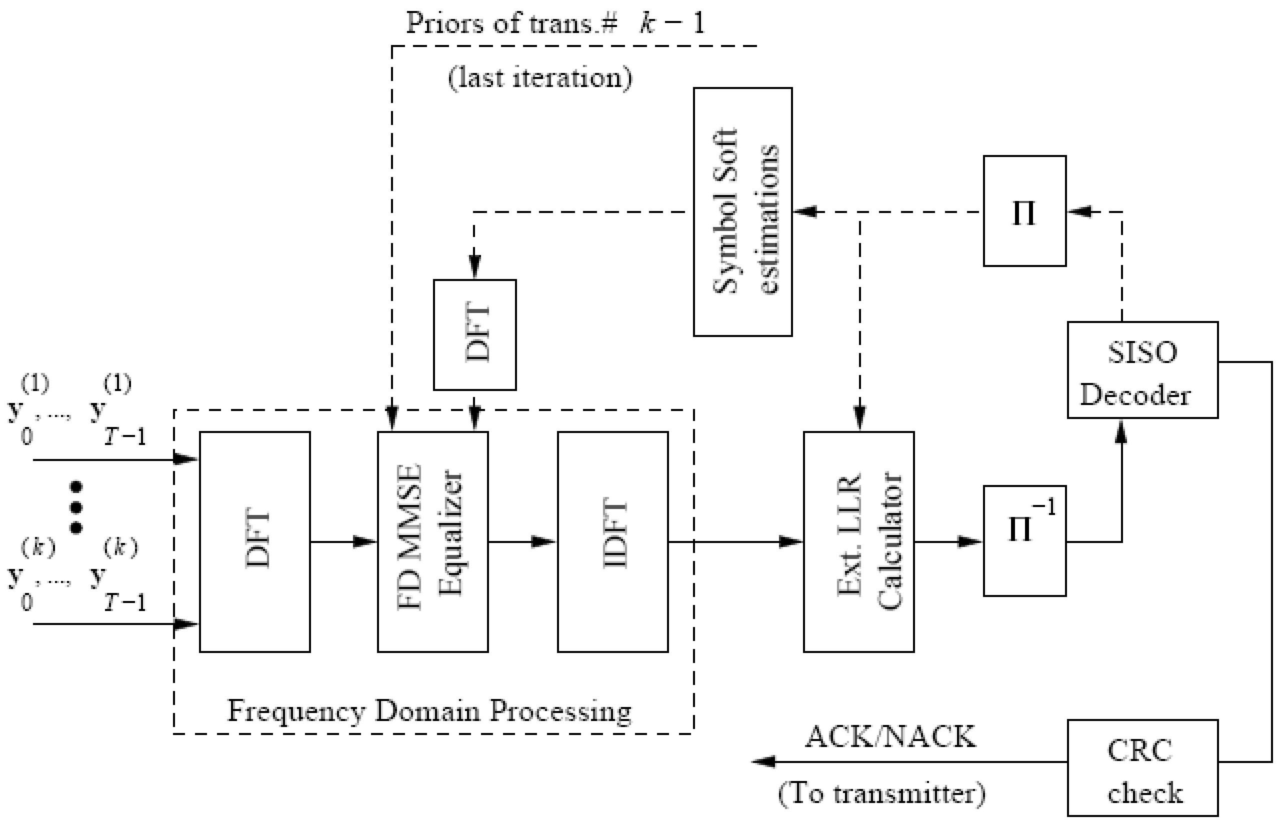
- **Dimensionality of the communication model at round k: kN_R receive and N_T transmit antennas.**
- **Transmissions translate into additional diversity branches.**

$$\begin{bmatrix} \mathbf{y}_i^{(1)} \\ \vdots \\ \mathbf{y}_i^{(k)} \end{bmatrix} = \sum_{l=0}^{L-1} \begin{bmatrix} \mathbf{H}_l^{(1)} \\ \vdots \\ \mathbf{H}_l^{(k)} \end{bmatrix} \mathbf{s}_{(i-l) \bmod T} + \begin{bmatrix} \mathbf{n}_i^{(1)} \\ \vdots \\ \mathbf{n}_i^{(k)} \end{bmatrix} \qquad (2)$$

New Class of Turbo Packet Combiners

Signal-Level Turbo Packet Combining Scheme

Receiver Architecture



T. Ait-Idir, **H. Chafnaji**, and S. Saoudi, "Joint Hybrid ARQ and Iterative Space-Time Equalization for Coded Transmission over MIMO-ISI Channel," ***IEEE WCNC 2008***, Las Vegas, NV, Mar-Apr. 2008.

New Class of Turbo Packet Combiners

Implementation Issues

- **The proposed combining strategy BOTTLENECK:**

Matrix inversion ⇔ complexity in order of $O\,(k^3 N_R^{\,3})$.

Store received signals and their channels ⇒ Memory size increases linearly with the number of retransmissions

- **Solution:**

Recursive Combining Strategy

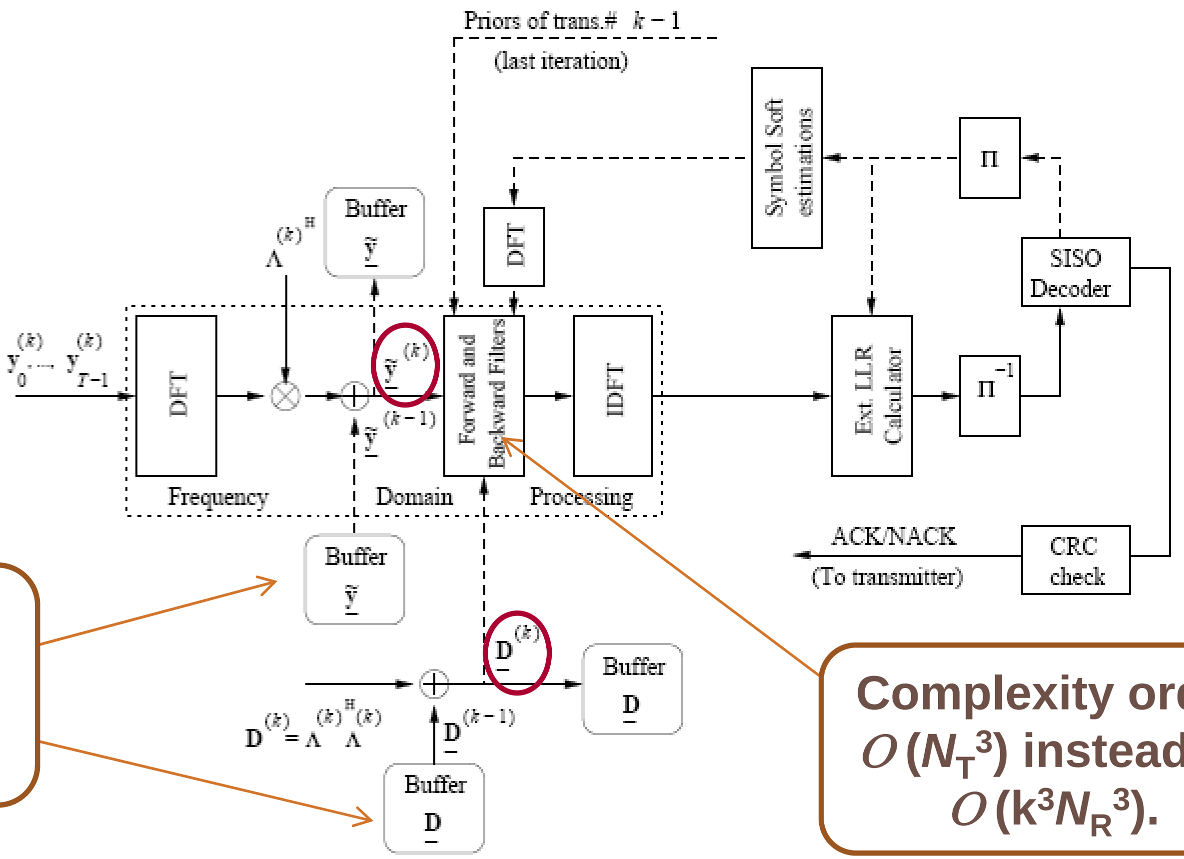
Translates the problem dimensionality from kN_R *into* N_T

H. Chafnaji, T. Ait-Idir, H. Yanikomeroglu, and S. Saoudi, “On the Design of Turbo Packet Combining Schemes for Relay-Assisted Systems over Multi-Antenna Broadband Channels,” ***IEEE 71st Semi-Annual VTC10Spring***, *Taipei, Taiwan*, May 2010.

New Class of Turbo Packet Combiners

Recursive Combining Scheme

New variables recursively computed ~ The packet combining algorithm remains identical from one



Memory size insensitive to kN_R

Complexity order $O(N_T^3)$ instead of $O(k^3N_R^3)$.

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New Class of Turbo Packet Combiners

Performance Evaluation (1/3)

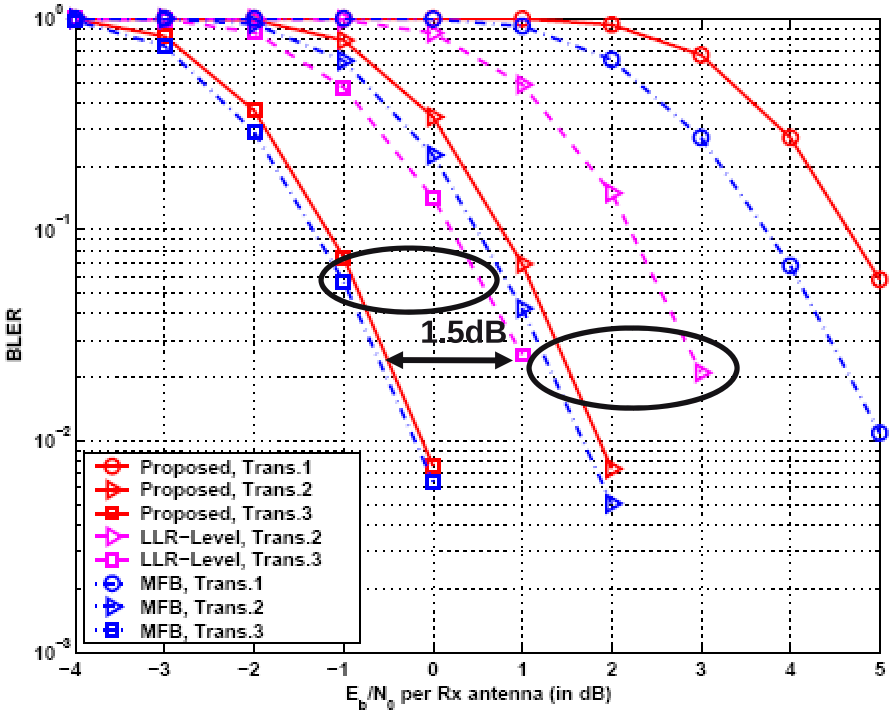
Simulation Settings

- $CC(35; 23)_8$, semi-random interleaving, and QPSK signaling.
- Coded block length: 1032 (including tails). EQual power taps channel profile.
- SISO decoding: Max-Log-MAP.
- Number of transmissions: $K = 3$.
- Number of channel paths: $L = 10$.
- Number of iterations: $N_{iter} = 3$.
- Performance evaluation: BLER and Throughput vs E_b/N_0 (/Rx antenna/info bit).
- Benchmark: Coded matched filter bound (MFB)
- Reference: Conventional LLR-level combining.

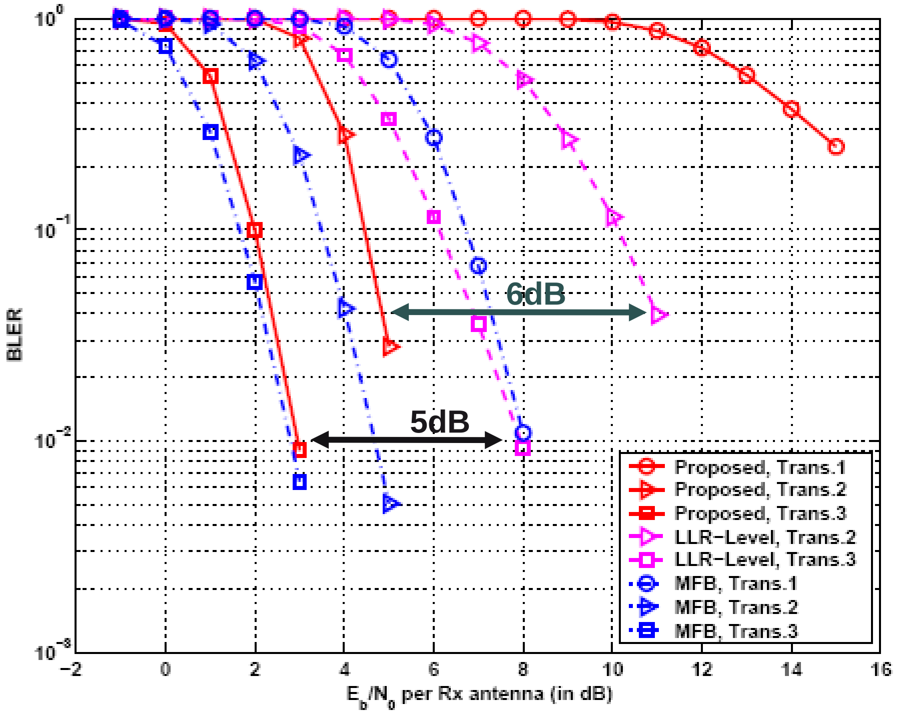
New Class of Turbo Packet Combiners

Performance Evaluation (2/3)

BLER Performances



$N_T = N_R = 2$

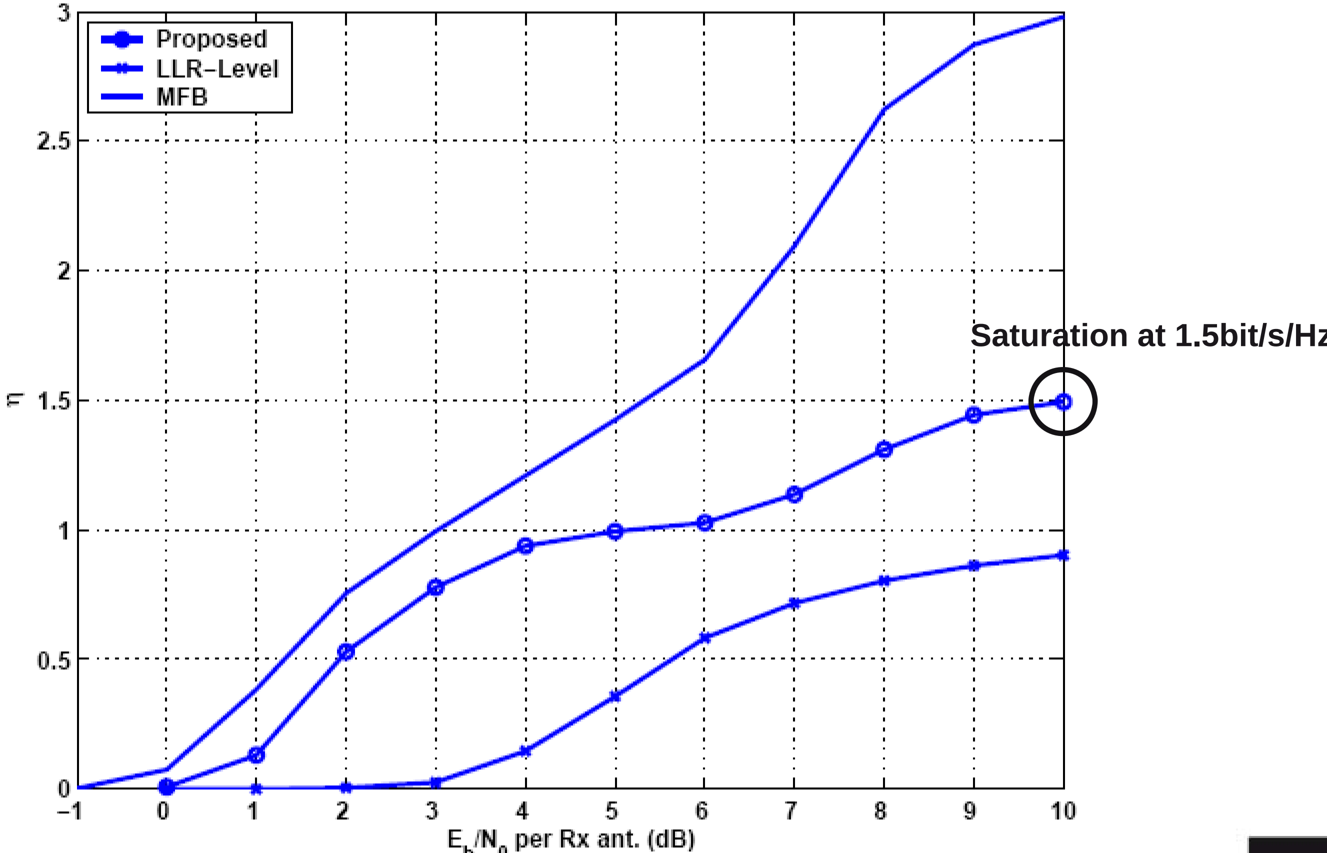


Overloaded system $N_T = 4,\ N_R = 2$

New Class of Turbo Packet Combiners

Performance Evaluation (2/3)

Throughput: Overloaded system $N_T = 3$, $N_R = 1$



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Presentation Outline

- New Class of Turbo Packet Combiners
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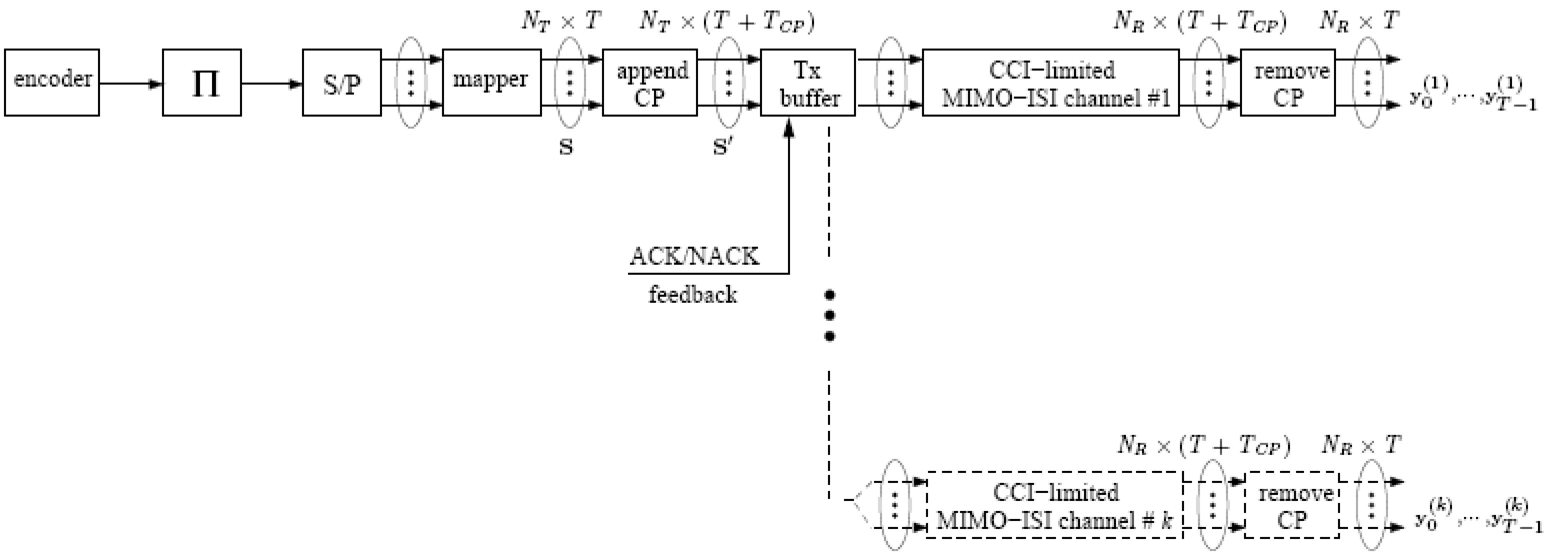
Turbo Packet Combining for MIMO ARQ with Co-Channel Interference (CCI)

General Framework:

Cyclic Prefix (CP)-aided single carrier transmission under the presence of CCI

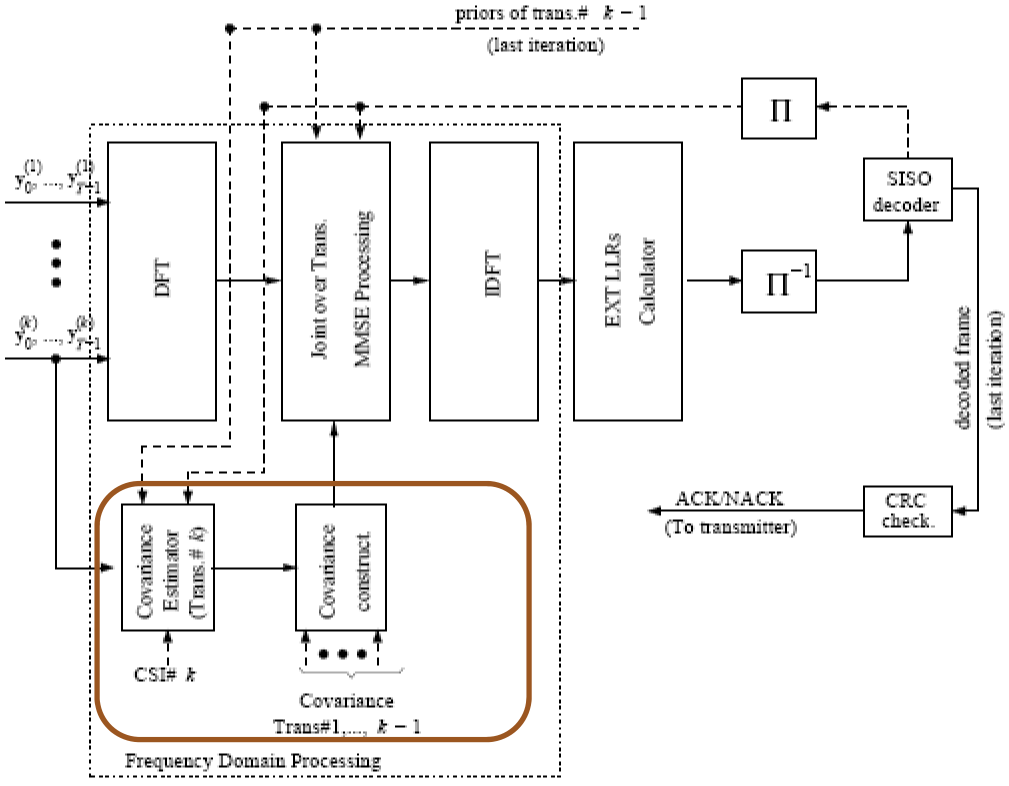


$$\mathbf{y}_i^{(k)} = \sum_{l=0}^{L-1} \mathbf{H}_l^{(k)} \mathbf{s}_{(i-l) \bmod T} + \underbrace{\sum_{l'=0}^{L'-1} \mathbf{H}_{l'}^{\mathrm{CCI}(k)} \mathbf{s}_{(i-l') \bmod T}^{\mathrm{CCI}(k)} + \mathbf{n}_i^{(k)}}_{\mathbf{w}_i^{(k)} = \mathrm{CCI} + \mathrm{noise}}, \qquad (3)$$

Turbo Packet Combining for MIMO ARQ with Co-Channel Interference (CCI)

Signal-Level Turbo Packet Combining Architecture:

Iterative turbo estimation of CCI covariance matrix in the frequency domain, together with packet combining.



Asymptotic Performance (1/2)

- We assume perfect LLR feedback from the SISO decoder.
- The interferer CSI is perfectly known
- ρ_k is the rank of CCI covariance matrix at round *k.*

Theorem: **We consider a CCI-limited MIMO ARQ system with N_T transmit and N_R receive antennas, and ARQ delay k. The signal-level packet combiner provides perfect CCI suppression for asymptotically high SNR if**

$$\sum_{u=1}^{k} \rho_u < kN_R - N_T. \qquad (4)$$

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Asymptotic Performance (2/2)

$$\sum_{u=1}^{k} \rho_u < kN_R - N_T. \qquad (4)$$

- **System Interpretations:**
  - **Impact of CCI fading channel: Interference is desired with users having low channel ranks.**
  - **Impact of the Nbr of Tx antennas and ARQ delay: Increase *K* and/or reduce N_T.**

T. Ait-Idir, **H. Chafnaji**, and S. Saoudi, "Turbo Packet Combining for Broadband Space-Time BICM Hybrid-ARQ Systems with Co-Channel Interference," ***IEEE Transactions on Wireless Communications***, vol. 9, no. 5, pp. 1686-1697, May 2010.

T. Ait-Idir, **H. Chafnaji**, and S. Saoudi, "Frequency Domain Hybrid-ARQ Chase Combining for Broadband MIMO Communication with Co-Channel Interference," ***IEEE GLOBECOM 2009***, Honolulu, Hawaii, Nov-Dec. 2009.

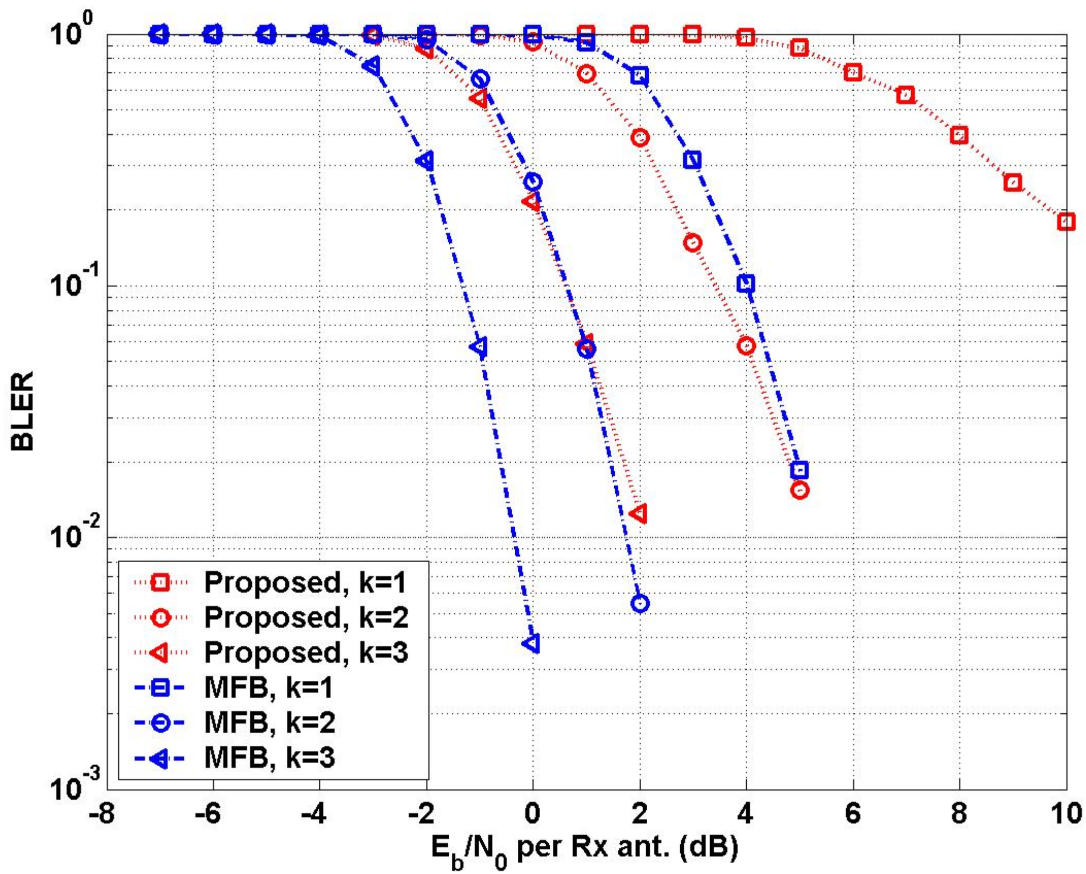
Performance Evaluation (1/2)

Simulation Settings

- $CC(35; 23)_8$, semi-random interleaving, and QPSK signaling.
- Coded block length: 1032 (including tails). EQual power taps channel profile.
- SISO decoding: Max-Log-MAP.
- Number of transmissions: K = 3.
- Number of channel paths: L = 2.
- Number of iterations: $N_{iter} = 3$.
- Performance evaluation: BLER vs E_b/N_0 (/Rx antenna/info bit).
- Benchmark: Coded matched filter bound (MFB).

Performance Evaluation (2/2)

$N_R = N_T = 4$, L=2, and SIR = 1dB



$N'_T = 2$, $L' = 1 \Rightarrow \rho = 2$

Asymptotic Analysis:
Perfect CCI cancellation for $k = 3$

Simulations:
Better CCI cancellation for $k = 3$

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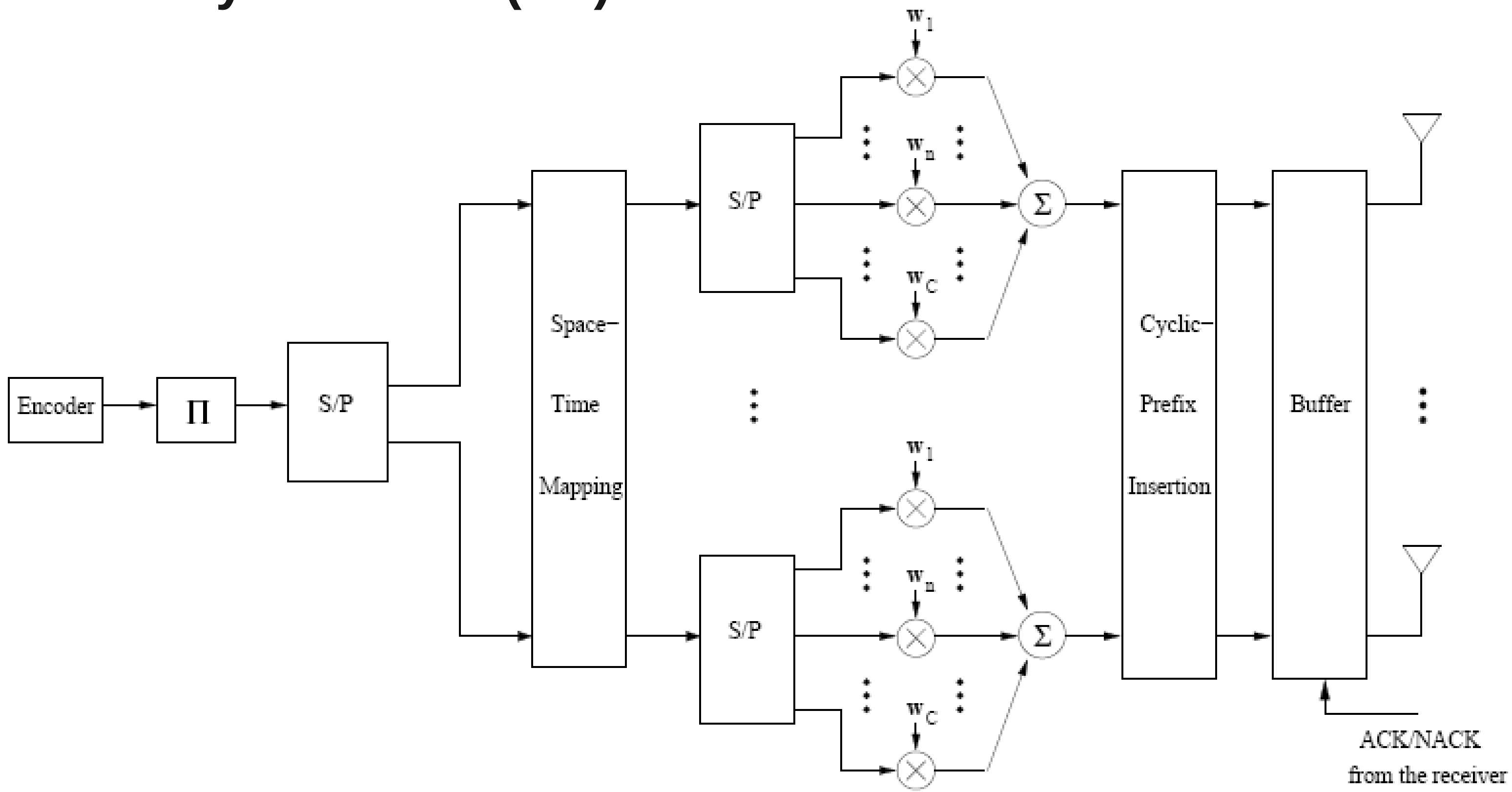
General Framework:

Cyclic Prefix (CP)-aided multi-code CDMA transmission



Iterative Receivers for Multi-Code CDMA ARQ

- **Chip-Level Turbo Packet Combiner: Straightforward extension of signal-level turbo packet combiner**
- **Symbol-Level Turbo Packet Combiner: Combining is performed jointly with the soft symbol demapper**

H. Chafnaji, T. Ait-Idir, and S. Saoudi, "Packet Combining and Chip Level Frequency Domain Turbo Equalization for Multi-Code Transmission over Multi-Antenna Broadband Channel," *19th Annual **IEEE Symposium PIMRC 2008***, Cannes, France, Sep. 2008.

H. Chafnaji, T.Ait-Idir, and S. Saoudi, "A comparative study of frequency domain HARQ Chase combining schemes for broadband single carrier MIMO CDMA systems," Accepted to ***IEEE GLOBECOM 2010***, Miami, Florida, USA , 6 December 2010.

Performance Evaluation (1/4)

Simulation Settings

- **$CC(35; 23)_8$, semi-random interleaving, QPSK signaling, and spreading factor *SF* = 16.**
- **Coded block length: 1024 (including tails). EQual power taps channel profile.**
- **SISO decoding: Max-Log-MAP.**
- **Number of transmissions: K = 3.**
- **Number of channel paths: L = 10.**
- **Number of iterations: $N_{iter} = 3$.**
- **Performance evaluation: BLER and Throughput vs E_c/N_0 (/Rx antenna/chip).**
- **Benchmark: Coded matched filter bound (MFB).**

Turbo Packet Combining for Broadband MIMO CDMA Systems

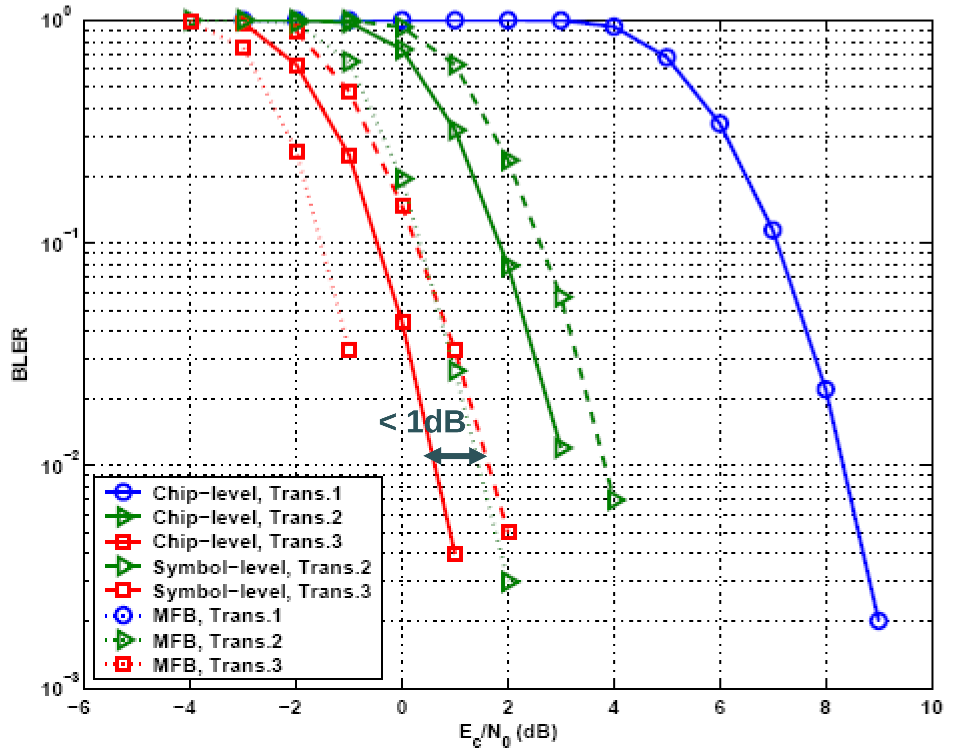
Performance Evaluation (2/4)

BLER Performances: $N_T = N_R = 4$ and $C = 16$

C_{memory}(Chip_Comb) = $5.C_{memory}$(Symbol_Comb)

Symbol-Level combining is the best candidate

with a low implementation cost and a small performance loss



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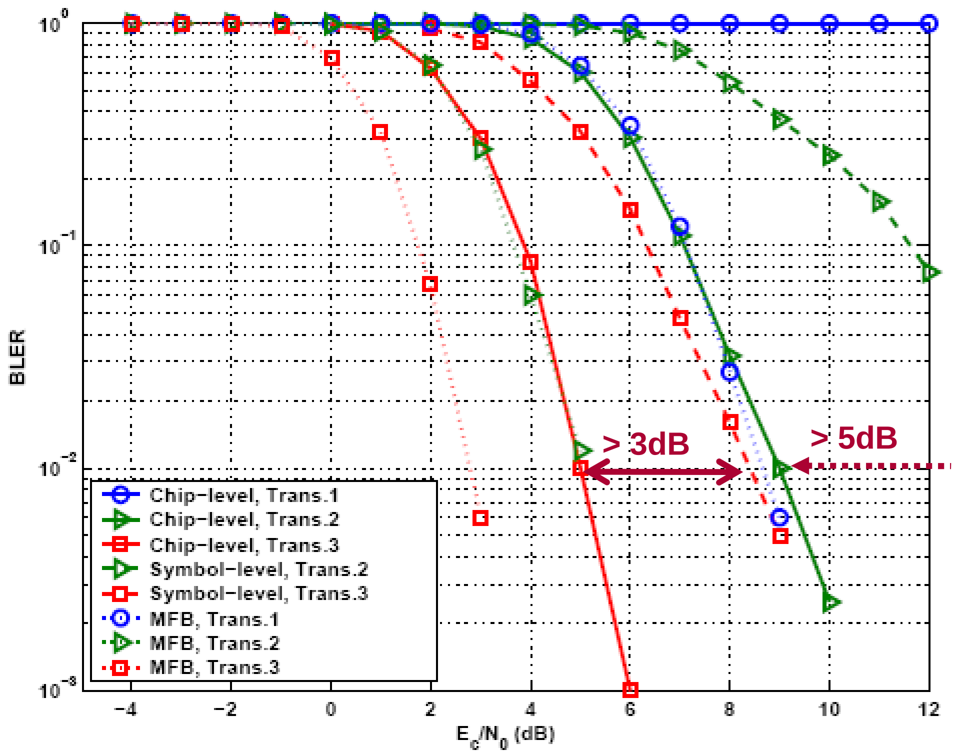
Turbo Packet Combining for Broadband MIMO CDMA Systems

Performance Evaluation (3/4)

BLER Performances: $N_T = 2$, $N_R = 1$, and $C = 16$



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Performance Evaluation (4/4)

Throughput Performances: $N_T = 2$, $N_R = 1$

High ICI: *C* = 16

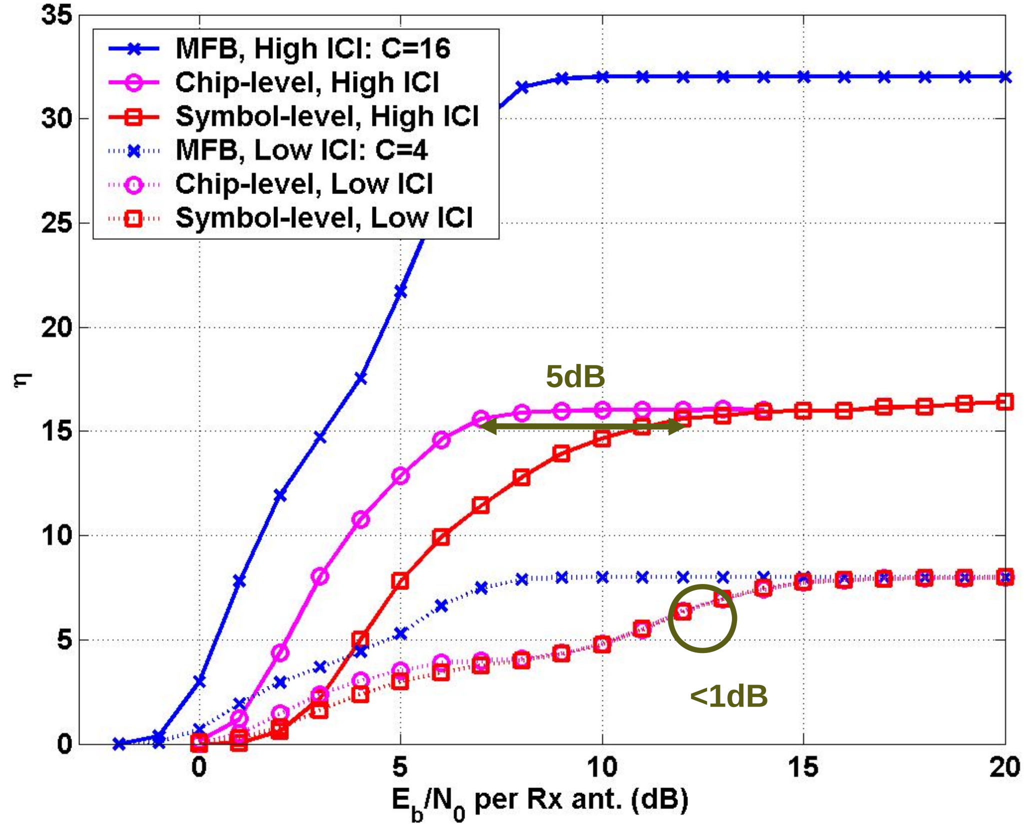
C_{memory}(Chip_Comb, C=16) = $1.5C_{memory}$(Symbol_Comb, C=16)

⇒ **Chip-Level Combining is the BEST**

Low ICI: *C* = 4

C_{memory}(Chip_Comb, C=4) = $12C_{memory}$(Symbol_Comb, C=4)

⇒ **Symbol-Level Combining is the BEST**



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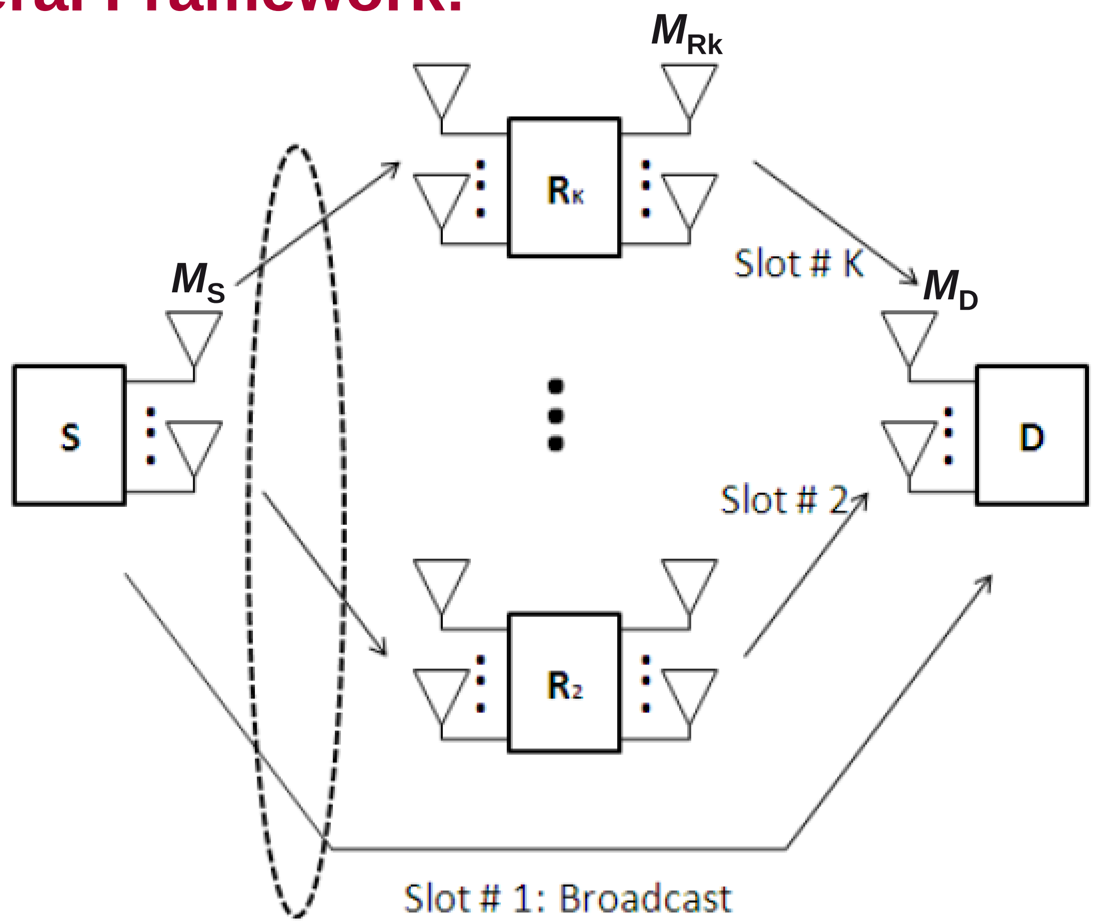
Generalized ARQ for Broadband Cooperative Communications

General Framework:



Generalized ARQ for Broadband Cooperative Communications

Problem

How to extend the proposed combining strategy to cooperative communications operating under the framework of multi-paths MIMO channels?

Main Concern

Build an appropriate system model to mask the cooperation and simplify the application of virtual antenna based combining

Generalized ARQ for Broadband Cooperative Communications

Relaying Schemes

- **Amplify-and-Forward scheme:**

  The relay simply amplifies the received signal and forwards it towards the destination during the allocated slot.

- **Decode-and-Forward schemes**
  - **Selective Decode-and-Forward scheme:**
    The relay only transmits when it can reliably decode the data packet.
  - **Modified Selective Decode-and-Forward scheme:**
    To prevent the occurring “silence", when the relay fails to correctly decode the packet, it sends back a NACK message to the source that directly transmits the packet to the destination during the allocated relay slot.

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Generalized ARQ for Broadband Cooperative Communications

Amplify-and-Forward scheme

- **Problem**

  Transmissions over relaying links in AF scheme suffer from colored noise as well as correlation between source-to-relay and relay-to-destination multi-path channels.

- **Solution to mask this cooperation problems**

  Perform whitening using Cholesky decomposition and derive an equivalent source-to-relay-to-destination channel

Generalized ARQ for Broadband Cooperative Communications

Decode-and-Forward scheme

- **Problem**

Heterogeneous nature of cooperative networks where the different nodes are equipped with different number of antennas.

- **Solution to mask this cooperation problems**

Derive a fixed rate equivalent multi-antenna system communication model where the multi-rate multi-node received signals can be viewed as direct retransmissions from a virtual node with a fixed transmission rate.

H. Chafnaji, T.Ait-Idir, H. Yanikomeroglu, and S. Saoudi, “Signal-level turbo packet combining for multi-rate relay-assisted systems over multi-antenna broadband channels,” Accepted to ***IEEE GLOBECOM 2010*****,** Miami, Florida, USA , 6-10 December 2010.

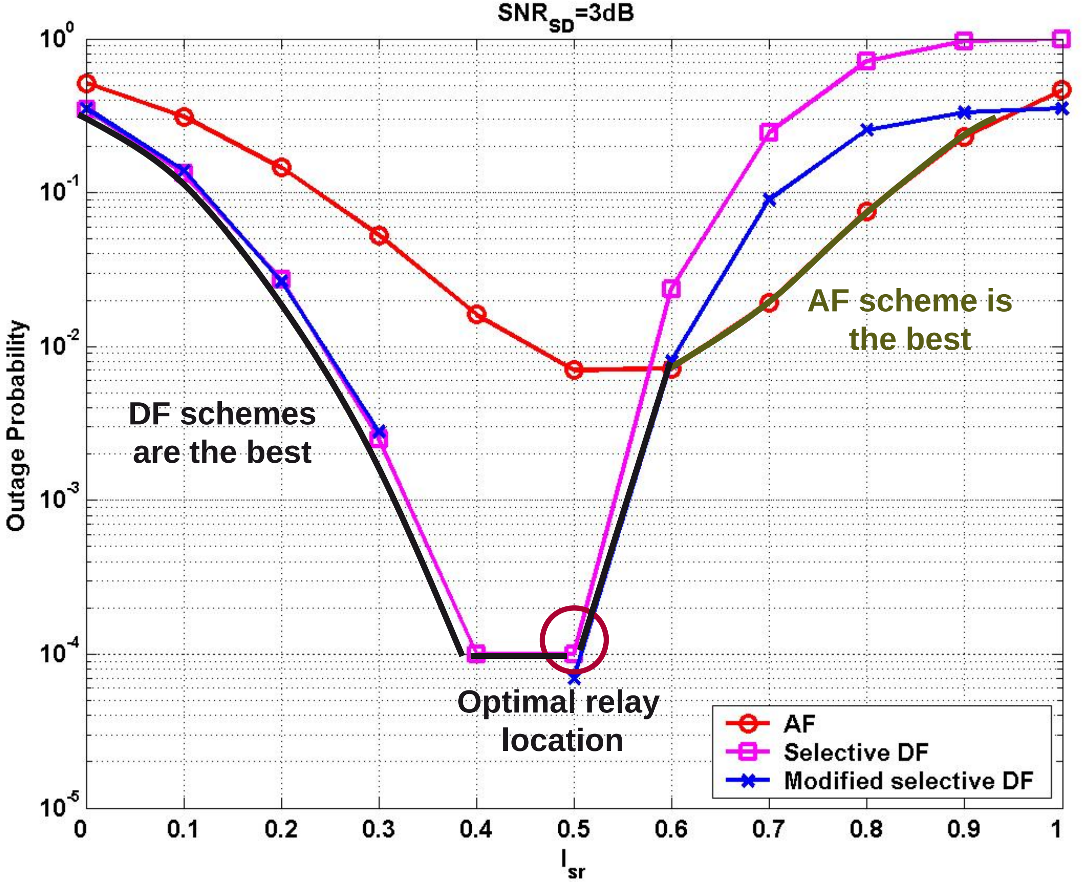
Performance Evaluation (1/5)

Simulation Settings

- The distances are normalized: $l_{SR} + l_{RD} = l_{SD} = 1$.
- All digital nodes use the same BICM scheme.
- Coded block length: 2048 (including tails).
- SISO decoding: Max-Log-MAP.
- All links have the same channel profile with L=3.
- Number of iterations: $N_{iter} = 3$.
- Performance evaluation: Outage Probability vs l_{SR} and BLER vs SNR_{SD} (S $\rightarrow$ D link signal-to-noise ratio per useful bit per receive antenna).
- References: Conventional hybrid-ARQ and conventional LLR-level packet combining.

Performance Evaluation (2/5)

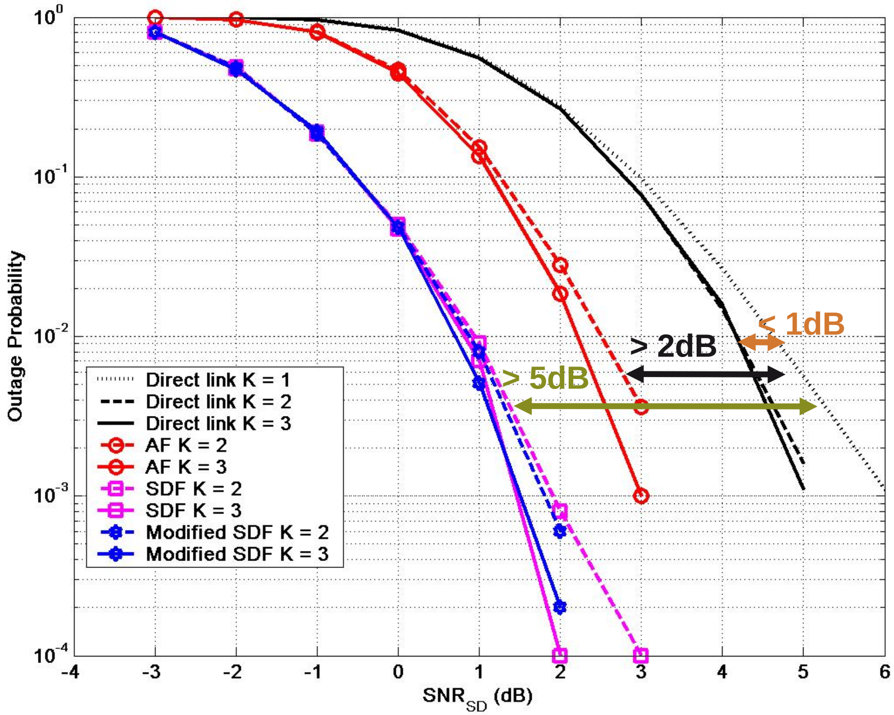
Outage Probability: $M_S = M_R = M_D = 2$ and $K = 2$



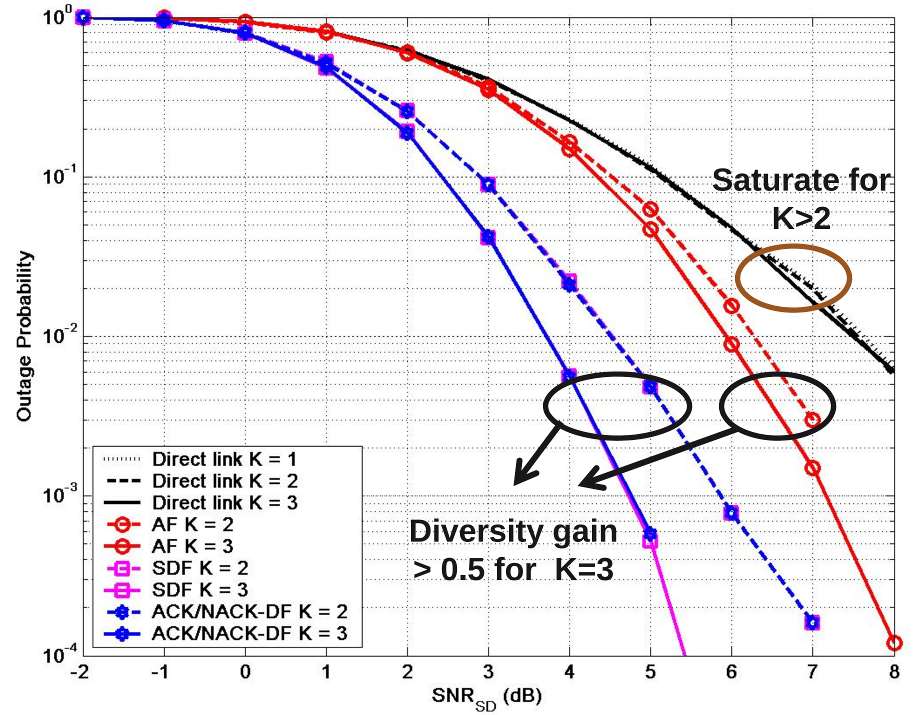
Generalized ARQ for Broadband Cooperative Communications

Performance Evaluation (3/5)

Outage Probability: I_{SR} = 0.5



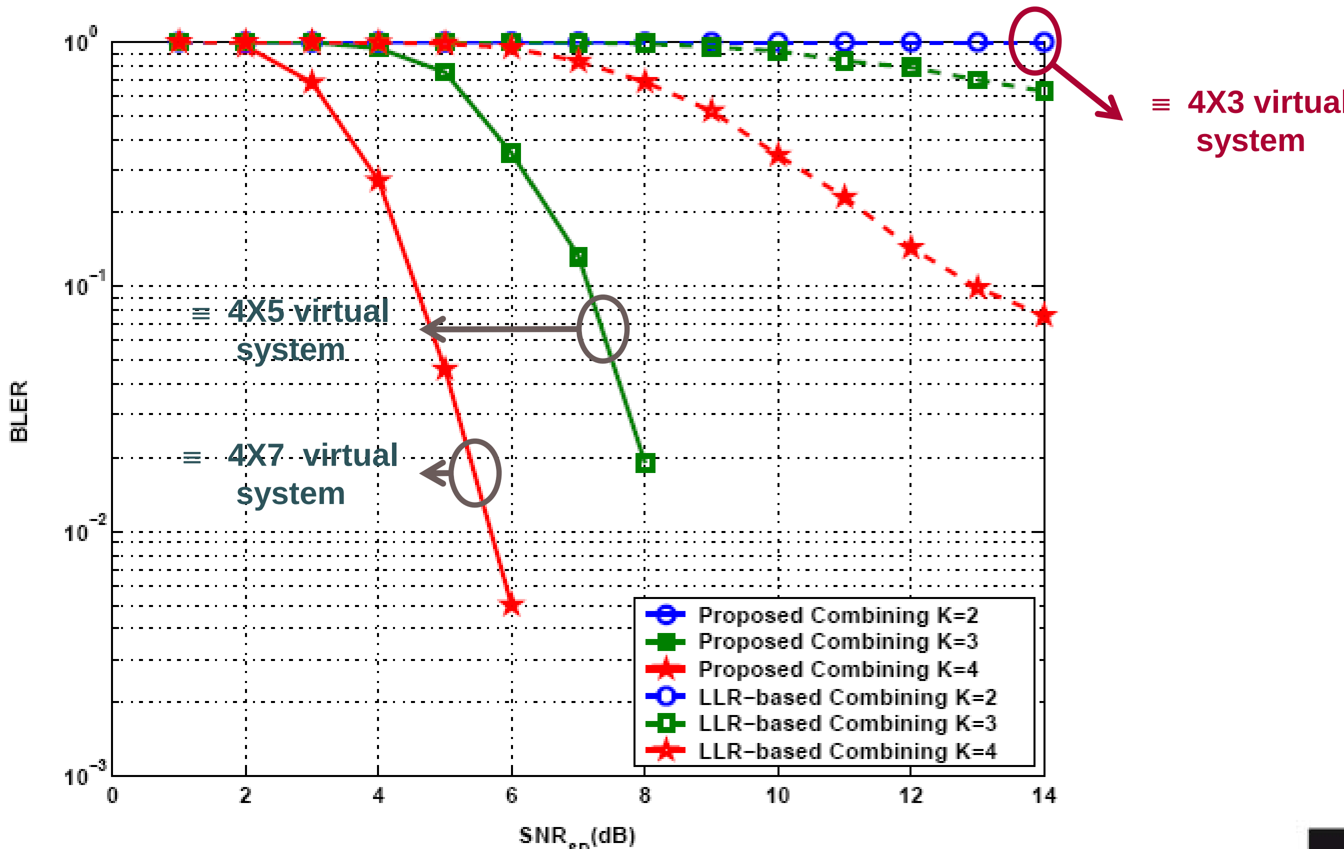
$M_S = M_R = M_D = 2$



$M_S = M_R = 2, M_D = 1$

Performance Evaluation (5/5)

Modified Selective DF: $M_S = 4$, $M_R = 2$, $M_D = 1$ and $l_{SR} = 0.3$



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Conclusions and Future Work

Conclusions

- **New class of turbo packet combiners for broadband MIMO communications.**
- **Asymptotic Analysis of the CCI effect.**
- **Two efficient turbo receiver schemes for multi-antenna multi-code CDMA transmission with ARQ.**
- **An appropriate communication model to mask the cooperation in broadband multi-antenna cooperative systems.**

Conclusions and Future Work

Future research directions:

- Extension to uplink multi-user space division multiple access (SDMA) framework.
- Investigate the influence of imprecise CSI on the proposed turbo receiver.
- Hybrid AF/DF scheme under the framework of broadband multi-user.

Related Publications (1/3)

Book Chapter

- T. Ait-Idir, **H. Chafnaji**, S.Saoudi, and A. V. Vasilakos, “Advanced Hybrid-ARQ Receivers for Broadband MIMO Communications,” Chapter in “Radio Communications", Alessandro Bazzi (Ed.), ISBN: 978-953-307-091-9, INTECH.

Journal Articles

- T. Ait-Idir, **H. Chafnaji**, and S.Saoudi, “Turbo Packet Combining for Broadband Space-Time BICM Hybrid-ARQ Systems with Co-Channel Interference,” *IEEE Transactions on Wireless Communications,* vol. 9, no. 5, pp. 1686-1697, May 2010.

- **H. Chafnaji**, T. Ait-Idir, S.Saoudi, and A. V. Vasilakos, “Frequency Domain Hybrid-ARQ Chase Combining for Broadband MIMO CDMA Systems,” To be submitted to *EURASIP Journal on Wireless Communications and Networking*.

- **H. Chafnaji**, T.Ait-Idir, H. Yanikomeroglu, and S. Saoudi, “Relaying Schemes and Joint Turbo Processing for Spatial Multiplexing over Broadband MIMO Channels,” To be submitted to *IEEE Transactions on Wireless Communications*.

Related Publications (2/3)

Conference papers (12 accepted)

- **H. Chafnaji**, T.Ait-Idir, H. Yanikomeroglu, and S. Saoudi, "Signal-level turbo packet combining for multi-rate relay-assisted systems over multi-antenna broadband channels," Accepted to *IEEE GLOBECOM 2010*, Miami, Florida, USA , 6-10 December 2010.
- **H. Chafnaji**, T.Ait-Idir, and S. Saoudi, "A comparative study of frequency domain HARQ Chase combining schemes for broadband single carrier MIMO CDMA systems," Accepted to *IEEE GLOBECOM 2010*, Miami, Florida, USA , 6 December 2010.
- **H. Chafnaji**, T.Ait-Idir, H. Yanikomeroglu, and S. Saoudi, "Analysis of Packet Combining for Single Carrier Multi-Relay Broadband Systems," *IEEE SPAWC 2010*, Marrakech, Morocco, Jun. 2010.
- **H. Chafnaji**, T.Ait-Idir, H. Yanikomeroglu, and S. Saoudi, "Turbo Packet Combining Techniques for Multi-Relay-Assisted Systems over Multi-Antenna Broadband Channels," *ACM IWCMC 2010*, Caen, France, Jun. 2010.
- **H. Chafnaji,** T.Ait-Idir, H. Yanikomeroglu, and S. Saoudi, "On the Design of Turbo Packet Combining Schemes for Relay-Assisted Systems over Multi-Antenna Broadband Channels," *IEEE 71st Semi-Annual VTC10Spring, Taipei, Taiwan*, May 2010.
- T. Ait-Idir, **H. Chafnaji**, and S. Saoudi, "Frequency Domain Hybrid-ARQ Chase Combining for Broadband MIMO Communication with Co-Channel Interference," *IEEE GLOBECOM 2009*, Honolulu, Hawaii, Nov-Dec. 2009.

Related Publications (3/3)

Conference papers

- T. Ait-Idir, **H. Chafnaji**, H. Yanikomeroglu, and S. Saoudi, “Turbo Packet Combining for Broadband MIMO Relay Communication,” *9th IEEE Mediterranean Microwave Symposium, MMS 2009*, Tangiers, Morocco, Nov. 2009. (Invited Paper).
- **H. Chafnaji**, T.Ait-Idir, H. Yanikomeroglu, and S. Saoudi, “Joint Turbo Equalization for Relaying Schemes over Frequency-Selective Fading Channels,” *ACM IWCMC 2009*, Leipzig, Germany, Jun. 2009.
- **H. Chafnaji**, T.Ait-Idir, and S. Saoudi, “Packet Combining and Chip Level Frequency Domain Turbo Equalization for Multi-Code Transmission over Multi-Antenna Broadband Channel,” *19th Annual IEEE Symposium PIMRC 2008*, Cannes, France, Sep. 2008.
- **H. Chafnaji**, T.Ait-Idir, and S. Saoudi, “Implementation and Complexity evaluation of Packet Combining for Multi-Code Transmission over Multi-Antenna Broadband Channel,” *IEEE IWCMC 2008*, Crete Island, Greece, Aug. 2008.
- T. Ait-Idir, **H. Chafnaji**, and S. Saoudi, “Frequency Domain Packet Combining with Integrated MMSE Block Turbo Equalization for Broadband MIMO Communications,” *ISIVC 2008*, Bilbao, Spain, Jul. 2008 (Invited Paper).
- T. Ait-Idir, **H. Chafnaji**, and S. Saoudi, “Joint Hybrid ARQ and Iterative Space-Time Equalization for Coded Transmission over MIMO-ISI Channel,” *IEEE WCNC 2008*, Las Vegas, NV, Mar-Apr. 2008.

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pour Obtenir le grade de

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