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Advanced Hybrid-ARQ Receivers for Broadband MIMO Communications

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1. Introduction

Multiple input multiple output (MIMO) and hybrid-automatic repeat request (ARQ) mechanisms play a key role in the evolution of current wireless communications systems towards high data rate wireless packet access. In MIMO techniques, the spatial dimension of the MIMO channel is exploited through the use of multiple antennas at both the transmitter and receiver sides. This translates into an improvement in the spectrum efficiency and/or the link quality Wolniansky et al. (1998). Hybrid-ARQ protocols provide an important source of time diversity through the combination of channel coding and ARQ. This is performed with the aid of *packet combining* techniques where erroneous data packets are kept in the receiver to help detect/decode retransmitted frames.

In broadband MIMO communications, the MIMO wireless link suffers from intersymbol interference (ISI) caused by multipath propagation. This effect can be mitigated using channel equalization and/or Hybrid-ARQ. In this chapter, we focus on the joint design of the packet combiner and the channel equalizer for MIMO ARQ transmission over the broadband wireless channel. We start the chapter by reviewing the various approaches for joint packet combining and equalization. We introduce the considered broadband MIMO ARQ transmission scheme. Then, we derive the structure of the optimal maximum *a posteriori* (MAP) turbo packet combiner and study its outage performance. Finally, we introduce a new class of low-complexity minimum mean square error (MMSE)-based turbo packet combiners and analyze their implementation requirements and block error rate (BLER) performance.

2. Advanced Receivers for MIMO ARQ

In the last few years, a special interest has been paid to the design of advanced MIMO ARQ receivers where packet combining and signal processing, i.e., detection/equalization, are jointly performed. The concept of integrated equalization (IEQ) has been proposed in the framework

of MIMO systems with flat fading for joint multiple antenna interference (MAI) suppression and packet combining (see for instance Onggosanusi et al. (2003) and Samra & Ding (2006)). Turbo coded ARQ schemes with iterative MMSE frequency domain equalization (FDE) for MIMO code division multiple access (CDMA) has been proposed in Garg & Adachi (2006). Recently, we have introduced a new family of packet combining techniques for broadband MIMO ARQ systems, where the decoding of a data packet is performed with the aid of an iterative (turbo) processing between the soft combiner, i.e., joint packet combining and equalization unit, and the soft input soft output (SISO) decoder (see Ait-Idir & Saoudi (2009)). The following sections of this chapter focus on this new class of broadband MIMO ARQ techniques. Our notation is introduced in the next section followed by the communication model of the considered MIMO ARQ system.

3. Notation

In this chapter, scalars are denoted by small-case letters, vectors by small-case boldface letters, and matrices by upper-case boldface letters. Superscripts T and H denote the transpose and transpose conjugate, respectively. $\mathbf{I}_N$ is the $N \times N$ identity matrix, and $\mathbf{0}_{N \times M}$ is the $N \times M$ zeros matrix. $\otimes$ is the Kronecker product, and $\Pr \{.\}$ denotes the probability of a given event.

4. Broadband MIMO ARQ Transceiver Scheme

4.1 MIMO ARQ Transmission

Let us consider a broadband multi-antenna, i.e., multiple input multiple output (MIMO), system operating over a frequency selective fading channel and using an ARQ protocol at the upper layer. The transmitter and the receiver are equipped with N_T transmit (index $t = 1, \dots, N_T$) and N_R receive (index $r = 1, \dots, N_R$) antennas, respectively. The MIMO channel suffers from intersymbol interference (ISI) and is composed of L symbol-spaced taps (index $l = 0, \dots, L - 1$). Each data stream is first encoded with the aid of a ρ -rate channel encoder, interleaved using a semi-random interleaver Π , then modulated and space-time multiplexed over the N_T transmit antennas. This transmission scheme corresponds to the so-called space-time bit interleaved coded modulation (STBICM). Let $\mathcal{S}$ denote the constellation set, and $M = \log_2 \{|\mathcal{S}|\}$ its cardinality. A sequence of M coded and interleaved bits $b_{1,t,i}, \dots, b_{M,t,i}$ available on antenna t is transmitted at discrete-time instant $i = 0, \dots, T - 1$ over symbol $s_{t,i} \in \mathcal{S}$ according to the mapping function $\Psi : \{0, 1\}^M \rightarrow \mathcal{S}$. The symbol vector to be transmitted at time i is denoted

$$\mathbf{s}_i \triangleq [s_{1,i}, \dots, s_{N_T,i}]^T \in \mathcal{S}^{N_T}. \quad (1)$$

The rate of this transmission scheme is therefore $R = \rho M N_T$. The transmit symbol energy is normalized to one. Assuming infinitely deep space-time interleaving we get, $\mathbb{E} [\mathbf{s}_i \mathbf{s}_i^H] = \mathbf{I}_{N_T}$. At the receiver side, a positive/negative acknowledgment ACK/NACK message is sent back to the transmitter upon the decoding of the information block. When the transmitter receives a NACK message due to an erroneously decoded packet, subsequent transmission rounds occur until the packet is correctly received or a preset maximum number of rounds K (index $k = 1, \dots, K$) is reached. Parameter K is called the ARQ delay. Reception of a ACK message indicates a successful decoding and the transmitter moves on to the next packet. We assume an error-free feedback channel (the signaling channel carrying the ACK/NACK message), and perfect packet error detection (using a cyclic redundancy check –CRC code). We focus on Chase-type ARQ, i.e., the entire information block is retransmitted using the same STBICM

Fig. 1. STBICM ARQ Transmission over a short-term quasi-static MIMO channel

code. To prevent inter-block interference (IBI), we use either zero padding (ZP) or cyclic prefix (CP)-aided transmission.

The MIMO-ISI channel is assumed to be short-term quasi-static block fading, i.e., constant during one ARQ round and independently changes from round to round. The long-term dynamic corresponds to the case when the channel is constant during all ARQ rounds corresponding to the transmission of the same information packet (see El Gamal et al. (2006)). The short-term assumption is justified by the fact ARQ protocols are mainly used to improve the link quality in the case of delay-tolerant applications where the processing delay is not a major constraint. Let $\mathbf{H}_l^{(k)}$ denote the $N_R \times N_T$ complex matrix of the l th tap connecting the transmitter and the receiver at ARQ round k . The elements of $\mathbf{H}_l^{(k)}$ are zero-mean circularly symmetric Gaussian random variables, i.e., $h_{r,t,l}^{(k)} \sim \mathcal{CN}(0, \sigma_l^2)$, where $h_{r,t,l}^{(k)}$ denotes the (r, t) th element of matrix $\mathbf{H}_l^{(k)}$ and σ_l^2 is the energy of tap l . The total channel energy is normalized as $\sum_{l=0}^{L-1} \sigma_l^2 = 1$. The discrete baseband signal received by antenna r at ARQ round k and time instant i is given by

$$y_{r,i}^{(k)} = \sum_{l=0}^{L-1} \sum_{t=1}^{N_T} h_{r,t,l}^{(k)} s_{t,i-l} + n_{r,i}^{(k)}, \quad (2)$$

where $\mathbf{n}_i^{(k)} \triangleq [n_{1,i}^{(k)}, \dots, n_{N_R,i}^{(k)}]^\top \sim \mathcal{CN}(\mathbf{0}_{N_R \times 1}, \sigma^2 \mathbf{I}_{N_R})$ is the thermal noise at the N_R receive antennas. The STBICM ARQ transmission scheme over a short-term MIMO channel, i.e., k distinct MIMO channels, is depicted in Fig. 1.

4.2 MIMO ARQ Turbo Receiver

In Ait-Idir & Saoudi (2009), *turbo packet combining* has been introduced as an efficient technique for combining multiple transmissions in the case of broadband MIMO ARQ systems. In turbo packet combining, the decoding of a data packet is performed in an iterative (turbo) fashion through the exchange of soft (extrinsic) information between the SISO packet combiner and the SISO decoder. The soft combiner exploits signals received at multiple ARQ rounds to compute extrinsic log-likelihood ratios (LLRs). Note that in conventional LLR-level

Fig. 2. Block diagram of the turbo packet combining-aided MIMO ARQ receiver

combining techniques, the soft outputs obtained at different transmissions are simply added together before channel decoding.

The general block diagram of the turbo packet combining-aided MIMO ARQ receiver is depicted in Fig. 2. Let

$$\boldsymbol{\phi}_{t,i}^a \triangleq [\phi_{1,t,i}^a, \dots, \phi_{M,t,i}^a]^\top \quad (3)$$

denote the $M \times 1$ real vector of *a priori* LLRs corresponding to coded and interleaved bits $b_{1,t,i}, \dots, b_{M,t,i}$, and available at the input of the soft combiner at a certain iteration of ARQ round k . Using *a priori* information $\boldsymbol{\phi}_{1,0}^a, \dots, \boldsymbol{\phi}_{N_T,T-1}^a$ and signals received at rounds $1, \dots, k$, the soft packet combiner computes extrinsic LLR vectors

$$\boldsymbol{\phi}_{t,i}^e \triangleq [\phi_{1,t,i}^e, \dots, \phi_{M,t,i}^e]^\top, \quad (4)$$

which are de-interleaved and sent to the SISO decoder to obtain *a posteriori* LLRs about useful bits and extrinsic information about coded bits. The generated extrinsic LLR values are then interleaved and fed back to the soft combiner to help compute soft information during the next turbo iteration of the same ARQ round. After a preset number of iterations, the decision about the data packet is performed, and the ACK/NACK message is sent back to the transmitter accordingly. Note that during the first iteration, *a priori* information corresponds to the soft information available from the last iteration of previous ARQ round $k - 1$.

5. Information-Theoretic Issues

In this section, we derive the optimal maximum *a posteriori* (MAP) turbo packet combining receiver for broadband MIMO ARQ transmission, and investigate its outage performance. We first show that optimal turbo packet combining can be formulated as a MIMO-ISI turbo equalization problem. We then obtain the outage probability of the broadband MIMO ARQ channel, and analyze the impact of the ARQ delay, i.e., maximum number of ARQ rounds K , on the outage performance.

5.1 Optimal Turbo Packet Combining

To derive the optimal maximum *a posteriori* (MAP) turbo packet combiner at ARQ round k , let us consider the following signal vector that groups signals corresponding to all ARQ rounds $1, \dots, k$,

$$\mathbf{y}^{(k)} \triangleq \left[\mathbf{y}_{T-1}^{(1)\top}, \dots, \mathbf{y}_{T-1}^{(k)\top}, \dots, \mathbf{y}_0^{(1)\top}, \dots, \mathbf{y}_0^{(k)\top} \right]^\top \in \mathbb{C}^{kN_R T}, \quad (5)$$

where

$$\mathbf{y}_i^{(u)} \triangleq \left[y_{1,i}^{(u)}, \dots, y_{N_R,i}^{(u)} \right]^\top \in \mathbb{C}^{N_R} \quad (6)$$

is the vector of received signals at ARQ round $u = 1, \dots, k$ and time instant i .

The formulation in (5) is of a great importance because it allows us to view each ARQ round as a set of virtual N_R receive antennas. Note that in this section we assume that all signals and channel matrices corresponding to previous ARQ rounds are available at the receiver side at round k . In Section 6, we will present an optimized turbo packet combining technique that makes use of all signals and channel matrices without being required to be explicitly stored in the receiver. With respect to (2) and (5) and assuming a ZP-aided transmission strategy, the signal vector $\mathbf{y}^{(k)}$ corresponding to the transmission of the entire symbol frame over k MIMO-ISI channels can be expressed as,

$$\mathbf{y}^{(k)} = \mathbf{H}^{(k)} \mathbf{s} + \mathbf{n}^{(k)}, \quad (7)$$

where $\mathbf{H}^{(k)}$ is a block Toeplitz matrix given as

$$\mathbf{H}^{(k)} \triangleq \begin{bmatrix} \boxed{\begin{matrix} \mathbf{H}_0^{(1)} \\ \vdots \\ \mathbf{H}_0^{(k)} \end{matrix}} & \cdots & \boxed{\begin{matrix} \mathbf{H}_{L-1}^{(1)} \\ \vdots \\ \mathbf{H}_{L-1}^{(k)} \end{matrix}} & & \\ & \ddots & & \ddots & \\ & & \boxed{\begin{matrix} \mathbf{H}_0^{(1)} \\ \vdots \\ \mathbf{H}_0^{(k)} \end{matrix}} & \cdots & \boxed{\begin{matrix} \mathbf{H}_{L-1}^{(1)} \\ \vdots \\ \mathbf{H}_{L-1}^{(k)} \end{matrix}} \end{bmatrix}_{kN_R T \times N_T T}, \quad (8)$$

and vectors $\mathbf{s}$ and $\mathbf{n}^{(k)}$ are defined as,

$$\mathbf{s} \triangleq \left[\mathbf{s}_{T-1}^\top, \dots, \mathbf{s}_0^\top \right]^\top \in \mathcal{S}^{N_T T}, \quad (9)$$

$$\mathbf{n}^{(k)} \triangleq \left[\mathbf{n}_{T-1}^{(1)\top}, \dots, \mathbf{n}_{T-1}^{(k)\top}, \dots, \mathbf{n}_0^{(1)\top}, \dots, \mathbf{n}_0^{(k)\top} \right]^\top \in \mathbb{C}^{kN_R T}. \quad (10)$$

The communication model (7) corresponds to a MIMO-ISI equalization problem with N_T transmit and kN_R virtual receive antennas. It allows for jointly (over all ARQ rounds) canceling both multiple antenna interference (MAI) and ISI, while exploiting all the diversities available in the MIMO-ISI ARQ channel. Using the MAP criterion and given *a priori* LLRs, the extrinsic information about coded and interleaved bit $b_{m,t,i}$ can be expressed as,

$$\phi_{m,t,i}^e = \log \frac{\Pr \left\{ \mathbf{y}^{(k)} \mid b_{m,t,i} = 1; \mathbf{H}_0^{(1)}, \dots, \mathbf{H}_{L-1}^{(k)}, \text{a priori LLRs} \right\}}{\Pr \left\{ \mathbf{y}^{(k)} \mid b_{m,t,i} = 0; \mathbf{H}_0^{(1)}, \dots, \mathbf{H}_{L-1}^{(k)}, \text{a priori LLRs} \right\}}. \quad (11)$$

Then, by invoking the multi-round communication model (7), $\phi_{m,t,i}^e$ can be obtained as,

$$\phi_{m,t,i}^e = \log \frac{\sum_{\mathbf{s} \in \mathcal{S}_{m,t,i}^1} \exp \left\{ -\frac{1}{2\sigma^2} \left\| \mathbf{y}^{(k)} - \mathbf{H}^{(k)} \mathbf{s} \right\|^2 + \sum_{(m',t',i') \neq (m,t,i)} \Psi_{m'}^{-1}(s_{t',i'}) \phi_{m',t',i'}^a \right\}}{\sum_{\mathbf{s} \in \mathcal{S}_{m,t,i}^0} \exp \left\{ -\frac{1}{2\sigma^2} \left\| \mathbf{y}^{(k)} - \mathbf{H}^{(k)} \mathbf{s} \right\|^2 + \sum_{(m',t',i') \neq (m,t,i)} \Psi_{m'}^{-1}(s_{t',i'}) \phi_{m',t',i'}^a \right\}}, \quad (12)$$

where the subset $\mathcal{S}_{m,t,i}^b$ is defined as $\mathcal{S}_{m,t,i}^b \triangleq \{ \mathbf{s} \in \mathcal{S}^{N_T T} \mid \Psi_m^{-1}(s_{t,i}) = b \}, b = 0, 1$.

5.2 Outage Performance Analysis

Outage probability is a useful tool that allows to analyze the performance of non-ergodic channels, i.e., quasi-static channels. It provides a lower bound on the BLER, and is generally defined as the probability that the mutual information, as a function of the channel realization and the average signal to noise ratio (SNR) γ per receive antenna, is below the transmission rate R Tse & Viswanath (2005).

The outage probability of an ARQ protocol can be derived using the *renewal theory* (see Wolff (1989)) as in Caire & Tuninetti (2001) and El Gamal et al. (2006). In the case of a broadband MIMO system with Chase-type ARQ, perfect packet error detection, and error-free ACK/NACK feedback, the outage probability can be derived using the multi-round communication model (7) and the renewal theory (see Ait-Idir & Saoudi (2009)) as

$$P_{out}^R(\gamma) = \Pr \left\{ \frac{1}{K} I(\mathbf{s}; \mathbf{y}^{(K)} \mid \mathbf{H}^{(K)}, \gamma) < R, \bar{\mathcal{A}}_1, \dots, \bar{\mathcal{A}}_{K-1} \right\}, \quad (13)$$

where K is the ARQ delay, and $\bar{\mathcal{A}}_k$ denotes the event that an ACK message is fed back at round k , i.e., the data packet is positively acknowledged at ARQ round k . The quantity $\frac{1}{K} I(\mathbf{s}; \mathbf{y}^{(K)} \mid \mathbf{H}^{(K)}, \gamma)$ denotes the mutual information rate at the last ARQ round K , and is expressed in the case of a MIMO broadband channel with Gaussian inputs as

$$\frac{1}{K} I(\mathbf{s}; \mathbf{y}^{(K)} \mid \mathbf{H}^{(K)}, \gamma) = \frac{1}{KT} \sum_{i=0}^{T-1} \log_2 \left(\det \left(\mathbf{I}_{KN_R} + \frac{\gamma}{N_T} \mathbf{\Lambda}_i^{(K)} \mathbf{\Lambda}_i^{(K)H} \right) \right), \quad (14)$$

where $\mathbf{\Lambda}_i^{(K)}$ is the discrete Fourier transform (DFT) of the $KN_R \times N_T$ virtual MIMO-ISI channel at round K and frequency bin i , i.e.,

$$\mathbf{\Lambda}_i^{(K)} \triangleq \sum_{l=0}^{L-1} \begin{bmatrix} \mathbf{H}_l^{(1)} \\ \vdots \\ \mathbf{H}_l^{(K)} \end{bmatrix} \exp \left\{ -j \frac{2\pi}{T} il \right\}. \quad (15)$$

Note that the factor $\frac{1}{K}$ appearing in the outage probability (13) is due to the fact that a transmission scheme with Chase-type ARQ, and an ARQ delay K is equivalent to a repetition coding scheme where K parallel sub-channels are used to transmit the same symbol frame.

In the following, we investigate the impact of the ARQ delay K on the outage performance. We consider a MIMO-ISI channel with $L = 2$ taps having equal powers, i.e., $\sigma_0^2 = \sigma_1^2 = \frac{1}{2}$. At each ARQ round k , the mutual information rate $\frac{1}{k} I(\mathbf{s}; \mathbf{y}^{(k)} | \mathbf{H}_0^{(k)}, \mathbf{H}_1^{(k)}, \gamma)$ of the MIMO ARQ system after k rounds is evaluated similarly to (14). If the target rate R is not reached and $k < K$, the system moves on to the next round $k + 1$. An ARQ process is stopped and another is started, either because of system outage, i.e., the mutual rate after K rounds is below R , or the rate R is achieved at a certain round $k \leq K$. In all scenarios, we take $T = 256$ discrete time instants.

Fig. 3. Outage probability performance for two transmit and two receive antennas

In Fig. 3, we plot the outage probability performance for the $N_T = N_R = 2$ antenna configuration, with a target rate $R = 2$. We observe that the ARQ diversity gain, due to the short-term static channel dynamic, clearly appears when the ARQ delay is set to $K = 2$. It offers a significant SNR gain compared with the non-ARQ case ($K = 1$). When, the ARQ delay is increased to $K = 3$, the outage performance is similar to that of $K = 2$. This means that if the system is in outage in the second ARQ round, then it will almost be in outage in the third round. In Fig. 4, we investigate the outage performance when the number of transmit antennas is increased to $N_T = 4$, while $N_R = 2$. The target rate is set to $R = 4$. As in the previous configuration, both ARQ delays $K = 2$ and $K = 3$ provide almost the same outage performance, while the overall diversity gain is more important than that corresponding to $N_T = N_R = 2$. This can be seen from the steeper slopes of outage curves. Note that the ARQ diversity due to multiple transmissions does not completely translate into a receive diversity gain (related to the N_R virtual receive antennas at each ARQ round). This is due to the fact that the target rate R has to be maintained, as it can be seen from the expression of the outage probability (13). This means

that the diversity gain does not linearly increase with increase of the ARQ delay K . This issue has been addressed by El Gamal et al. (2006) in the case of flat fading MIMO ARQ systems.

Fig. 4. Outage probability performance for four transmit and two receive antennas

6. MMSE-Based Turbo Packet Combining

The optimal MAP turbo packet combining algorithm we have presented so far in Subsection 5.1 has a computational complexity that exponentially increases with the increase in the number of ARQ rounds. In addition, all signals and channel matrices have to be stored in the receiver to perform combining at each ARQ round. In this section, we present alternative MMSE-based sub-optimal techniques (see Ait-Idir & Saoudi (2009)) that allow for performing turbo packet combining with reduced computational complexity and memory requirements. We first introduce the so-called *signal-level turbo combining* technique where packet combining is performed at the signal level similarly to MAP combining but based on MMSE processing. Then, we present the *symbol-level turbo combining* algorithm where packets are combined at the input of the soft demapper after performing MMSE channel equalization separately for each transmission. We also provide a brief presentation of the conventional LLR-level combining technique. For all combining schemes, we assume a ZP-aided block transmission. The multi-round block communication model is therefore described by a block Toeplitz channel matrix as in (7).

6.1 Signal-Level Turbo Combining

The signal-level turbo packet technique is a low-complexity MMSE-based combining algorithm that performs packet combining jointly with MAI and ISI cancellation using a block length equal to $\varepsilon = \varepsilon_1 + \varepsilon_2 + 1 \ll T$, where ε_1 and ε_2 are the lengths of the forward and backward filters, respectively. Packet combining at ARQ round k is therefore performed with

respect to the following ε -length block communication model

$$\underline{\mathbf{y}}_i^{(k)} = \underline{\mathbf{H}}^{(k)} \underline{\mathbf{s}}_i + \underline{\mathbf{n}}_i^{(k)}, \quad (16)$$

where

$$\underline{\mathbf{y}}_i^{(k)} \triangleq \left[\mathbf{y}_{i+\varepsilon_1}^{(1)\top}, \dots, \mathbf{y}_{i+\varepsilon_1}^{(k)\top}, \dots, \mathbf{y}_{i-\varepsilon_2}^{(1)\top}, \dots, \mathbf{y}_{i-\varepsilon_2}^{(k)\top} \right]^\top \in \mathbb{C}^{kN_R\varepsilon}, \quad (17)$$

$$\underline{\mathbf{n}}_i^{(k)} \triangleq \left[\mathbf{n}_{i+\varepsilon_1}^{(1)\top}, \dots, \mathbf{n}_{i+\varepsilon_1}^{(k)\top}, \dots, \mathbf{n}_{i-\varepsilon_2}^{(1)\top}, \dots, \mathbf{n}_{i-\varepsilon_2}^{(k)\top} \right]^\top \in \mathbb{C}^{kN_R\varepsilon}, \quad (18)$$

$$\underline{\mathbf{s}}_i \triangleq \left[\mathbf{s}_{i+\varepsilon_1}^\top, \dots, \mathbf{s}_{i-\varepsilon_2-L+1}^\top \right]^\top \in \mathcal{S}^{N_T(\varepsilon+L-1)}, \quad (19)$$

and $\underline{\mathbf{H}}^{(k)}$ is a block Toeplitz matrix which is defined similarly to (8) but using ε block rows and $(\varepsilon + L - 1)$ block columns.

First of all, the soft packet combiner computes conditional means and variances of transmitted symbols using *a priori* information vectors $\boldsymbol{\phi}_{t,i}^a$, where $t \in \{1, \dots, N_T\}$, and $i \in \{0, \dots, T - 1\}$, available from the previous iteration. Note that, as it has been mentioned before, the soft information generated by the SISO decoder during the last iteration of ARQ round $k - 1$ serves as *a priori* information at the first iteration of round k . Conditional symbol expectations, also called *soft symbols*, serve for regenerating soft interference caused by multiple antenna transmission and multipath propagation, i.e., MAI plus ISI. Conditional symbol variances and channel matrices corresponding to ARQ rounds $1, \dots, k$ are used for computing the multi-round MMSE filter that serves for performing signal combining. At each iteration of ARQ round k , the signal-level turbo packet combiner exploits the communication model (16) to cancel soft MAI plus ISI (estimated at the current iteration of round k) from all signals received at rounds $1, \dots, k$. Then, it combines the resulting soft interference-free signals to generate soft decisions about transmitted symbols.

Let $\tilde{s}_{t,i} \triangleq \mathbb{E} [s_{t,i} | \boldsymbol{\phi}_{t,i}^a]$ and $\tilde{\sigma}_{t,i}^2 \triangleq \mathbb{E} [|s_{t,i} - \tilde{s}_{t,i}|^2 | \boldsymbol{\phi}_{t,i}^a]$ denote the conditional mean and variance of symbol $s_{t,i}$. By invoking the special block Toeplitz structure of matrix $\underline{\mathbf{H}}^{(k)}$, and the structure of the multi-round signal vector (17), the signal-level turbo packet combiner computes, at a particular iteration of ARQ round k , soft decision $\tilde{\varsigma}_{t,i}^{(k)}$ about symbol $s_{t,i}$ using the following forward-backward filtering structure,

$$\tilde{\varsigma}_{t,i}^{(k)} = \mathbf{F}_t^{(k)} \underline{\mathbf{z}}_i^{(k)} | \mathbf{B}_t^{(k)} \tilde{\mathbf{s}}_{i|t}, \quad (20)$$

where $\tilde{\mathbf{s}}_{i|t}$ is the $N_T(\varepsilon + L - 1)$ -length soft symbol vector corresponding to (19) with zero at the $(\varepsilon_1 N_T + t)$ th position corresponding to soft symbol $\tilde{s}_{t,i}$. $\mathbf{F}_t^{(k)}$ and $\mathbf{B}_t^{(k)}$ are the forward and backward filters related to antenna t . $\underline{\mathbf{z}}_i^{(k)}$ is a vector that contains properly weighed and combined copies of signals received at rounds $1, \dots, k$. It does not change in the course of turbo iterations corresponding to the same ARQ round, and is produced at round k according to the following recursion

$$\begin{cases} \underline{\mathbf{z}}_i^{(k)} &= \underline{\mathbf{z}}_i^{(k-1)} + \underline{\mathbf{H}}^{(k)H} \underline{\mathbf{y}}_i^{(k)}, \\ \underline{\mathbf{z}}_i^{(0)} &= \mathbf{0}_{N_T(\varepsilon+L-1) \times 1}. \end{cases} \quad (21)$$

The signal vector $\mathbf{y}_i^{(k)}$ and the channel matrix $\mathbf{H}^{(k)}$ correspond to the ε -length block communication model of ARQ round k , and are given as,

$$\mathbf{H}^{(k)} \triangleq \begin{bmatrix} \mathbf{H}_0^{(k)} & \cdots & \mathbf{H}_{L-1}^{(k)} \\ & \ddots & \\ & & \mathbf{H}_0^{(k)} & \cdots & \mathbf{H}_{L-1}^{(k)} \end{bmatrix}_{N_R \varepsilon \times N_T(\varepsilon+L-1)}, \quad (22)$$

$$\mathbf{y}_i^{(k)} \triangleq [\mathbf{y}_{i+\varepsilon_1}^{(k)\top}, \dots, \mathbf{y}_{i-\varepsilon_2}^{(k)\top}]^\top \in \mathbb{C}^{N_R \varepsilon}. \quad (23)$$

Filters $\mathbf{F}_t^{(k)}$ and $\mathbf{B}_t^{(k)}$ are iteration-dependent, and are computed as

$$\mathbf{F}_t^{(k)} = \left(\sigma^2 + \left(1 - \tilde{\sigma}_t^2 \right) \mathbf{e}_t^\top \mathbf{\Lambda}^{(k)} \mathbf{Y}^{(k)} \mathbf{e}_t \right)^{-1} \mathbf{e}_t^\top \mathbf{\Lambda}^{(k)}, \quad (24)$$

$$\mathbf{B}_t^{(k)} = \mathbf{F}_t^{(k)} \mathbf{Y}^{(k)}. \quad (25)$$

where $\mathbf{e}_t$ is a $N_T(\varepsilon + L - 1)$ -length vector of zeros with one at the $(\varepsilon_1 N_T + t)$ th position, i.e.,

$$\mathbf{e}_t \triangleq [\underbrace{0, \dots, 0}_{\varepsilon_1 N_T + t - 1}, 1, \underbrace{0, \dots, 0}_{(\varepsilon_2 + L) N_T - t}]^\top. \quad (26)$$

$\tilde{\sigma}_t^2$ is the unconditional variance of symbols transmitted over antenna t , and is computed as the time average of conditional variances $\tilde{\sigma}_{t,0}^2, \dots, \tilde{\sigma}_{t,T-1}^2$, i.e., $\tilde{\sigma}_t^2 = \frac{1}{T} \sum_{i=0}^{T-1} \tilde{\sigma}_{t,i}^2$. The square matrix $\mathbf{\Lambda}^{(k)}$ is updated at each turbo iteration according to,

$$\mathbf{\Lambda}^{(k)} = \mathbf{I}_{N_T(\varepsilon+L-1)} - \mathbf{Y}^{(k)} \left(\mathbf{Y}^{(k)} + \sigma^2 \mathbf{\Xi}^{-1} \right)^{-1}, \quad (27)$$

where

$$\mathbf{\Xi} = \mathbf{I}_{\varepsilon+L-1} \otimes \begin{bmatrix} \tilde{\sigma}_1^2 & & \\ & \ddots & \\ & & \tilde{\sigma}_{N_T}^2 \end{bmatrix} \in \mathbb{C}^{N_T(\varepsilon+L-1) \times N_T(\varepsilon+L-1)}, \quad (28)$$

and $\mathbf{Y}^{(k)}$ is recursively computed as,

$$\begin{cases} \mathbf{Y}^{(k)} &= \mathbf{Y}^{(k-1)} + \mathbf{H}^{(k)H} \mathbf{H}^{(k)}, \\ \mathbf{Y}^{(0)} &= \mathbf{0}_{N_T(\varepsilon+L-1) \times N_T(\varepsilon+L-1)}. \end{cases} \quad (29)$$

Details regarding the derivation of the forward-backward filtering structure (20) can be found in Ait-Idir & Saoudi (2009)

Extrinsic information $\phi_{m,t,i}^e$ about coded and interleaved bit $b_{m,t,i}$, $m = 1, \dots, M$, can be obtained using the decision statistic $\tilde{\zeta}_{t,i}^{(k)}$ of (20) as,

$$\phi_{m,t,i}^e = \log \frac{\sum_{s \in \mathcal{S}_m^1} \exp \left\{ -\frac{1}{2\delta_t^{(k)^2}} \left| \tilde{\zeta}_{t,i}^{(k)} - \alpha_t^{(k)} s \right|^2 + \sum_{m' \neq m} \Psi_{m'}^{-1}(s) \phi_{m',t,i}^a \right\}}{\sum_{s \in \mathcal{S}_m^0} \exp \left\{ -\frac{1}{2\delta_t^{(k)^2}} \left| \tilde{\zeta}_{t,i}^{(k)} - \alpha_t^{(k)} s \right|^2 + \sum_{m' \neq m} \Psi_{m'}^{-1}(s) \phi_{m',t,i}^a \right\}}, \quad (30)$$

where it is assumed that conditional soft demapper input $\tilde{\xi}_{t,i}^{(k)} \mid s_{t,i}$ is Gaussian with mean $\alpha_t^{(k)}$ and variance $\delta_t^{(k)^2}$, and are given by,

$$\begin{cases} \alpha_t^{(k)} &= \mathbf{B}_t^{(k)} \mathbf{e}_t \\ \delta_t^{(k)^2} &= \left(1 - \alpha_t^{(k)}\right) \alpha_t^{(k)}, \end{cases} \quad (31)$$

and the set $\mathcal{S}_m^b$ is defined as $\mathcal{S}_m^b \triangleq \{s \in \mathcal{S} \mid \Psi_m^{-1}(s) = b\}$ for $b = 0, 1$.

6.2 Symbol-Level Turbo Combining

In symbol-level turbo packet combining, MMSE turbo equalization is separately performed for each ARQ round k based on the ε -length block communication model of round k ,

$$\mathbf{y}_i^{(k)} = \mathbf{H}^{(k)} \mathbf{s}_i + \mathbf{n}_i^{(k)}, \quad (32)$$

where $\mathbf{s}_i$, $\mathbf{H}^{(k)}$, and $\mathbf{y}_i^{(k)}$ are given by (19), (22), and (33), respectively, and

$$\mathbf{n}_i^{(k)} \triangleq \left[\mathbf{n}_{i+\varepsilon_1}^{(k)\top}, \dots, \mathbf{n}_{i-\varepsilon_2}^{(k)\top} \right]^\top \in \mathbb{C}^{N_R \varepsilon} \quad (33)$$

is the spatially and temporally white Gaussian noise at the input of the equalizer at ARQ round k , i.e., $\mathbf{n}_i^{(k)} \sim \mathcal{CN}(\mathbf{0}_{N_R \varepsilon \times 1}, \sigma^2 \mathbf{I}_{N_R \varepsilon})$. Soft combining is iteratively performed at the level of unconditional MMSE filter outputs by combining the output at each iteration of ARQ round k with those obtained at the last iteration of previous rounds $1, \dots, k-1$.

The forward and backward filters $\mathbf{F}_t^{(k)}$ and $\mathbf{B}_t^{(k)}$ in the case of symbol-level turbo packet combining can easily be derived using the equations provided in the previous subsection with $k = 1$. Now, let $\check{\xi}_{t,i}^{(k)}$ denote the MMSE filter output corresponding to symbol $s_{t,i}$ at a specific turbo iteration of round k . The conditional decision statistic $\check{\xi}_{t,i}^{(k)} \mid s_{t,i}$ is Gaussian, with mean $\check{\alpha}_t^{(k)}$ and variance $\check{\delta}_t^{(k)^2}$ given similarly to (31). For ARQ rounds $u = 1, \dots, k-1$, $\check{\xi}_{t,i}^{(u)}$ denotes the decision statistic obtained at the last iteration of round u . Therefore, the soft combiner provides extrinsic information $\phi_{m,t,i}^e$ about coded and interleaved bit $b_{m,t,i}$ as

$$\phi_{m,t,i}^e = \log \frac{\sum_{s \in \mathcal{S}_m^1} \exp \left\{ -\frac{1}{2} \left(\check{\xi}_{t,i}^{(k)} - s \check{\alpha}_t^{(k)} \right)^H \Delta_t^{(k)-1} \left(\check{\xi}_{t,i}^{(k)} - s \check{\alpha}_t^{(k)} \right) + \sum_{m' \neq m} \Psi_{m'}^{-1}(s) \phi_{m',t,i}^a \right\}}{\sum_{s \in \mathcal{S}_m^0} \exp \left\{ -\frac{1}{2} \left(\check{\xi}_{t,i}^{(k)} - s \check{\alpha}_t^{(k)} \right)^H \Delta_t^{(k)-1} \left(\check{\xi}_{t,i}^{(k)} - s \check{\alpha}_t^{(k)} \right) + \sum_{m' \neq m} \Psi_{m'}^{-1}(s) \phi_{m',t,i}^a \right\}}, \quad (34)$$

where vector

$$\check{\xi}_{t,i}^{(k)} \triangleq \left[\check{\xi}_{t,i}^{(1)}, \dots, \check{\xi}_{t,i}^{(k)} \right]^\top \in \mathbb{C}^k \quad (35)$$

gathers MMSE filter soft outputs corresponding to all rounds $1, \dots, k$. $\check{\alpha}_t^{(k)}$ and $\Delta_t^{(k)}$ are the mean and covariance of the conditional Gaussian vector $\check{\xi}_{t,i}^{(k)} \mid s_{t,i}$, and are given by,

$$\check{\alpha}_t^{(k)} \triangleq \left[\check{\alpha}_t^{(1)}, \dots, \check{\alpha}_t^{(k)} \right]^\top \in \mathbb{C}^k, \quad (36)$$

$$\Delta_t^{(k)} = \begin{bmatrix} \delta_t^{(1)^2} & & \\ & \ddots & \\ & & \delta_t^{(k)^2} \end{bmatrix}_{k \times k}. \quad (37)$$

6.3 LLR-Level Turbo Combining

In conventional LLR-level combining, LLR values of transmitted bits obtained at multiple ARQ rounds are stored in the receiver and simply added together to update the LLRs at each ARQ round. In our framework, LLR-level turbo combining is carried out by separately performing MMSE turbo equalization for multiple transmissions using the ε -length block communication model (32). Extrinsic LLRs $\phi_{m,t,i}^e$ corresponding to coded and interleaved bits $b_{m,t,i} \forall m, t, i$ are then computed at each iteration of ARQ round k using only decision statistics $\tilde{\zeta}_{t,i}^{(k)}$ introduced in the previous subsection. LLR values obtained at multiple ARQ rounds are then added together to produce the soft LLR outputs

$$\text{LLR}_{m,t,i}^{(k)} = \sum_{u=1}^k \phi_{m,t,i}^{e(u)}, \quad \forall m, t, i, \quad (38)$$

which are de-interleaved and fed back to the SISO decoder. Note that in (38), $\phi_{m,t,i}^{e(u)}$ denotes the extrinsic LLR at the last iteration of ARQ round $u = 1, \dots, k$.

6.4 Implementation Issues

In signal-level turbo combining, the computation of the forward and backward filters $\mathbf{F}_t^{(k)}$ and $\mathbf{B}_t^{(k)}$ involves, at each turbo iteration of ARQ round k , one inversion of the $N_T(\varepsilon + L - 1) \times N_T(\varepsilon + L - 1)$ matrix $\mathbf{Y}^{(k)} + \sigma^2 \mathbf{\Xi}^{-1}$. The cost of computing $\mathbf{F}_t^{(k)}$ and $\mathbf{B}_t^{(k)}$ is therefore in the order of $\mathcal{O}(N_T^3 \varepsilon^3)$ complex operations. This indicates that the computational complexity of the signal-level combining scheme is less sensitive to k . The number of ARQ rounds only influences the number of additions required for performing recursions (21) and (29), which is in the order of $N_T^2(\varepsilon + L - 1)^2 + N_R \varepsilon T$ complex additions. Note that the operations of computing $\mathbf{H}^{(k)H} \mathbf{H}^{(k)}$ and $\mathbf{H}^{(k)H} \mathbf{y}_i^{(k)}$ are also required in the case of symbol-level combining. Therefore, the computational cost of forward and backward filters is almost the same for both signal and symbol-level turbo combining schemes. The LLR-level turbo combining algorithm approximately involves the same amount of operations as symbol-level combining.

In the case of signal-level combining, memory requirements are determined by (21) and (29), where two $N_T(\varepsilon + L - 1) \times N_T(\varepsilon + L - 1)$ and $N_T(\varepsilon + L - 1) \times T$ complex matrices are required to accumulate channel matrices $\mathbf{H}^{(k)H} \mathbf{H}^{(k)}$, and signal vectors $\mathbf{z}_0^{(k)}, \dots, \mathbf{z}_{T-1}^{(k)}$, respectively. Note that the two recursions (21) and (29) play a key role in signal-level turbo combining since they avoid the storage of all signals and channel matrices as in MAP turbo combining. In symbol-level combining, only N_T complex matrices of size $K \times T$ and two $K \times N_T$ complex matrices are required to store filter outputs and their corresponding parameters given by (35), (36), and (37). Therefore, signal-level combining requires slightly more memory than its symbol-level counterpart. Finally, in LLR-level turbo combining, a real vector of size $N_T M T$ is required to combine extrinsic values. Therefore, the three combining strategies have similar implementation requirements. They slightly differ in the number of additions and storage memory.

Fig. 5. BLER performance comparison for $N_T = N_R = 2$ and QPSK.

6.5 BLER Performance

In this subsection, we provide simulated BLER performance for the packet combining strategies studied in the previous subsections. The main focus of the analysis we provide is to show that signal-level turbo combining has better ISI cancellation capability and diversity gain compared with the other combining schemes.

We consider an STBICM transmitter with a 64-state $\frac{1}{2}$ -rate convolutional code whose polynomial generators are $(133_8, 171_8)$. The length of the code frame is 1800 bits. The modulation scheme is quadrature phase shift keying (QPSK). The MIMO-ISI channel has the same profile as in Subsection 5.2, i.e., two equal power taps. The ARQ delay is chosen $K = 2$ according to the theoretic analysis in Subsection 5.2. In all figures, the BLER is per ARQ round, and the SNR is per symbol per receive antenna.

We compare the resulting BLER performance with the outage probability and the matched filter bound (MFB). Note that for the purpose of fair comparison, the computation of the outage probability does not take into account the rate distortion as in (14). The MFB curves are obtained for each transmission assuming perfect ISI cancellation and maximum ratio combining (MRC) of all time, space, multipath, and delay diversity branches.

In Fig. 5, we consider an STBICM code with $N_T = N_R = 2$ transmit and receive antennas. This corresponds to a rate $R = 2$. The filter length is chosen equal to $\varepsilon = 9$ ($\varepsilon_1 = \varepsilon_2 = 4$) for all combining schemes. A quick inspection of Fig. 5, shows that both signal and symbol-level turbo combining offer a significant performance improvement after the second ARQ round compared with LLR-level combining. The signal-level scheme has better ISI cancellation capability compared with symbol-level combining. It almost achieves the MFB, while the symbol-level scheme presents a gap of approximately 1dB compared with the MFB. Also, note that both signal and symbol-level combining achieve the asymptotic slope of the outage probability.

In Fig. 6, we evaluate the BLER performance of a ST-BICM code with $N_T = 4$. This corresponds to a rate $R = 4$. The number of receive antennas is $N_R = 2$. Note that this

Fig. 6. BLER performance comparison for $N_T = 4$, $N_R = 2$ and QPSK.

type of unbalanced MIMO configurations where the transmitter is equipped with more antennas than the receiver is suitable for the forward link. The filter length is increased to $\varepsilon = 13$ ($\varepsilon_1 = \varepsilon_2 = 6$) for all combining schemes. The signal-level combining technique is shown to achieve BLER performance close to the MFB with a gap less than 0.5dB, while both the LLR-level and the symbol-level techniques have degraded BLER performance. The signal-level combining manifests itself in almost achieving the diversity gain of the MIMO-ISI ARQ channel, while it is shown that symbol-level combining fails to do so. This is because in the second ARQ round, the signal-level scheme constructs a 4×4 virtual MIMO-ISI channel for ISI cancellation and symbol detection, while the MIMO configuration remains unbalanced in the case of symbol and LLR-level combining.

7. Conclusion

In this chapter, we considered the design of efficient iterative turbo packet combining algorithms for broadband MIMO systems with Chase-type ARQ. We derived the structure of the optimal MAP turbo packet combining technique that exploits all the diversities available in the MIMO-ISI ARQ channel to perform packet combining, and analyzed its outage probability. As optimal MAP turbo packet combining has a huge computational cost and memory requirements, we introduced a new class of low-complexity MMSE-based turbo packet combining schemes. In MMSE-based signal-level combining, each ARQ round is viewed as a set of virtual receive antennas, and packet combining is jointly performed with ISI cancellation at the signal level. In MMSE-based symbol-level combining, multiple transmissions are separately turbo equalized, and combining is performed at the level of filter outputs. The simulation results provided in this chapter indicate that signal-level combining provides better BLER performance than that of symbol-level and conventional LLR-level combining.

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Radio Communications

Edited by Alessandro Bazzi

ISBN 978-953-307-091-9

Hard cover, 712 pages

Publisher InTech

Published online 01, April, 2010

Published in print edition April, 2010

In the last decades the restless evolution of information and communication technologies (ICT) brought to a deep transformation of our habits. The growth of the Internet and the advances in hardware and software implementations modified our way to communicate and to share information. In this book, an overview of the major issues faced today by researchers in the field of radio communications is given through 35 high quality chapters written by specialists working in universities and research centers all over the world. Various aspects will be deeply discussed: channel modeling, beamforming, multiple antennas, cooperative networks, opportunistic scheduling, advanced admission control, handover management, systems performance assessment, routing issues in mobility conditions, localization, web security. Advanced techniques for the radio resource management will be discussed both in single and multiple radio technologies; either in infrastructure, mesh or ad hoc networks.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Tarik Ait-Idir, Houda Chafnaji, Samir Saoudi and Athanasios Vasilakos (2010). Advanced Hybrid-ARQ Receivers for Broadband MIMO Communications, Radio Communications, Alessandro Bazzi (Ed.), ISBN: 978-953-307-091-9, InTech, Available from: <http://www.intechopen.com/books/radio-communications/advanced-hybrid-arq-receivers-for-broadband-mimo-communications>

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