Enhanced Array-Receiver Operation with Turbo Codes for Increasing the Capacity of Wideband CDMA Networks

Hong XU[1,2], Sofiène AFFES[1], and Paul MERMELSTEIN[1]
[1] INRS-Télécommunications, Université du Québec,
Place Bonaventure, 900, de la Gauchetière Ouest, Niveau C
Case Postale 644, Montréal, Québec, H5A 1C6, Canada
[2] Nortel Networks
100 Constellation Cresc., Nepean, Ontario, K2G 6J8, Canada

Abstract

STAR, the spatio-temporal array-receiver, was recently shown to outperform RAKE-type array-receivers and to increase the capacity of wideband CDMA networks. Turbo codecs were also identified as offering significant performance improvements. In this contribution we demonstrate the gain achieved by turbo codecs over conventional convolutional codecs in a STAR-based CDMA system. For high data-rates of 153.6 Kbps with low mobility, link-level simulations on the uplink indicate that turbo codecs gain 2 to 3 dB in required SNR at a $BER < 10^{-6}$. System-level simulations confirm that SNR gains almost double capacity, from 7 to 13 mobiles/cell for blind STAR (i.e., without pilot) and from 10 to 22 mobiles/cell for pilot-aided STAR.

1 Introduction

The spatio-temporal array receiver (STAR) [1] efficiently exploits both the spatial and temporal diversities resulting from use of antenna arrays. Antenna arrays effectively reduce the interference which limits CDMA systems' performance and hence significantly increase their capacity. STAR was recently shown to outperform RAKE-type array-receivers and to increase the capacity of wideband CDMA networks [2].

Turbo codecs [3] have also been found to boost capacity by achieving performance superior to conventional convolutional codecs. The fact that they appear in 3G standard proposals [4],[5] shows that their application has matured. We investigate the benefits of integrating turbo codecs in a STAR-based CDMA system. By exploiting both advanced channel-coding and smart antennas technologies performance can be potentially enhanced more than by using just one factor alone.

This contribution demonstrates the gain achieved by turbo codecs over convolutional codecs in a STAR-based CDMA system. For high data-rate transmissions of 153.6 Kbps with low mobility, link-level simulations on the uplink indicate that turbo codecs gain 2 to 3 dB in required SNR at a $BER < 10^{-6}$ (data QoS). System-level simulations confirm that SNR gains almost double capacity, from 7 to 13 mobiles/cell for blind STAR (*i.e.*, without pilot) and from 10 to 22 mobiles/cell for pilot-aided STAR.

2 Data Model and Assumptions

We denote by M the number of the uplink receiving antennas at the base-station and consider a multipath Rayleigh fading environment with number of paths P. After channel coding and interleaving of the information data at the transmitter (see Fig. 1), the interleaved coded bits are BPSK-modulated at the rate $1/T$ where T is the symbol duration. The BPSK symbols denoted as $\underline{b}_n$, where n is the symbol index, are possibly encoded differentially as $b_n = \underline{b}_n b_{n-1}$. Otherwise, we simply assign $b_n = \underline{b}_n$ (see Fig. 1). In either case we spread b_n by a channel code and mark the corresponding data channel with superscript δ. When differential encoding is not used, we code-multiplex the spread data with a pilot and mark the pilot channel with superscript π.

After we despread the data channel at the receiver, we form from the $M \times P$ diversity branches the $MP \times 1$ data observation vector as [6]:

$$\underline{Z}_n^\delta = \underline{H}_n s_n^\delta + \underline{N}_n^\delta = \underline{H}_n \psi_n b_n + \underline{N}_n^\delta , \qquad (1)$$

where $s_n^\delta = \psi_n b_n$ is the data signal component and ψ_n^2 is the total received power. $\underline{H}_n$ is the $MP \times 1$ spatio-temporal Rayleigh fading channel vector normalized to $\sqrt{M}$. $\underline{N}_n^\delta$ is a spatially-uncorrelated Gaussian interference vector with mean zero and variance σ_N^2 after despreading of the data channel. The resulting input SNR after despreading is $SNR_{\text{in}} = \psi^2/\sigma_N^2$ per antenna element.

Similarly when a pilot is used, we form the $MP \times 1$ pilot observation vector as [6]:

$$\underline{Z}_n^\pi = \underline{H}_n s_n^\pi + \underline{N}_n^\pi = \underline{H}_n \xi \psi_n + \underline{N}_n^\pi , \qquad (2)$$

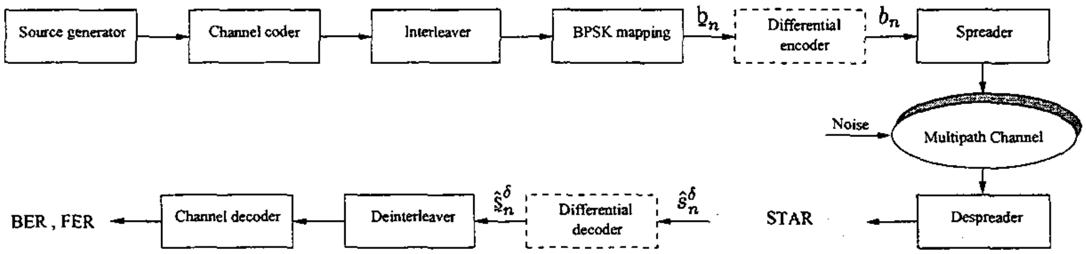

Figure 1. Block diagram of the uplink transceiver using STAR with a convolutional or turbo codec.

where ξ^2 denotes the allocated pilot-to-data power ratio and $\mathbf{N}_n^\pi$ is a zero-mean spatially-uncorrelated Gaussian interference vector with the same variance as $\mathbf{N}_n^\delta$ (*i.e.*, σ_N^2).

3 Use of Turbo Codecs in STAR

We investigate integration of a turbo codec in two STAR-based versions of an uplink transceiver (see Fig. 1). The first is blind (*i.e.*, without a pilot) and requires differential encoding of the BPSK symbols. The second is pilot-channel assisted and does not require differential encoding. Below we provide a brief reminder of these two versions of STAR, then explain how we combine them with a turbo codec.

3.1 Blind STAR

Using the channel estimate $\hat{\mathbf{H}}_n$ at iteration n, blind STAR first extracts the data signal component by spatio-temporal MRC [1],[6]:

$$\hat{s}_n^\delta = \mathrm{Re}\left\{\frac{\hat{\mathbf{H}}_n^H \mathbf{Z}_n^\delta}{M}\right\} . \qquad (3)$$

The data sequence b_n is then estimated as:

$$\hat{b}_n = \mathrm{Sign}\left\{\hat{s}_n^\delta\right\} . \qquad (4)$$

In a second step, blind STAR feeds back the estimate of the data signal component $\hat{s}_n^\delta$ (or $\hat{\psi}_n \hat{b}_n$) in a decision feedback identification (DFI) scheme to update the channel estimate as follows (for details see [1],[6]):

$$\hat{\mathbf{H}}_{n+1} = \hat{\mathbf{H}}_n + \mu\left(\mathbf{Z}_n^\delta - \hat{\mathbf{H}}_n \hat{s}_n^\delta\right)\hat{s}_n^\delta , \qquad (5)$$

where $\hat{\mathbf{H}}_n$ is the adaptive channel estimate and μ the adaptation step-size.

The simple decision feedback identification (DFI) scheme [1] of Eqs. (3) and (5) identifies the channel within a sign ambiguity, say $a = \pm 1$, thereby giving $\hat{\mathbf{H}}_n \simeq a\,\mathbf{H}_n$, $\hat{s}_n^\delta \simeq a\,\psi_n\,b_n$, and $\hat{b}_n = \mathrm{Sign}\left\{\hat{s}_n^\delta\right\} \simeq a\,b_n$. However, differential decoding of the hard decisions $\hat{b}_n$ resolves the sign ambiguity in the BPSK symbol estimates $\hat{\underline{b}}_n = \hat{b}_n \hat{b}_{n-1} = \mathrm{Sign}\left\{\hat{s}_n^\delta \hat{s}_{n-1}^\delta\right\}$. These values can be passed on to the channel decoder after deinterleaving. For better performance, we transmit instead the differential soft output $\hat{\underline{s}}_n^\delta = \hat{s}_n^\delta \hat{s}_{n-1}^\delta$ (see Fig. 1).

3.2 Pilot-Channel-Assisted STAR

Pilot-aided STAR also extracts the signal component estimate $\hat{s}_n^\delta$ using Eq. (3). However, it exploits the fact that the pilot signal is a known reference signal (*a priori* constant 1) and modifies the DFI scheme of blind STAR in Eqs. (3) and (5) as follows [6]. Pilot-aided STAR extracts the pilot signal component estimate:

$$\hat{s}_n^\pi = \mathrm{Re}\left\{\frac{\hat{\mathbf{H}}_n^H \mathbf{Z}_n^\pi}{M}\right\} , \qquad (6)$$

then feeds it back[1] to the following channel identification procedure:

$$\hat{\mathbf{H}}_{n+1} = \hat{\mathbf{H}}_n + \mu\left(\mathbf{Z}_n^\pi - \hat{\mathbf{H}}_n \hat{s}_n^\pi\right)\hat{s}_n^\pi . \qquad (7)$$

As a result, the DFI scheme identifies the channel without ambiguity (*i.e.*, $a = 1$). Hence, we estimate the BPSK symbol estimates as $\hat{\underline{b}}_n = \hat{b}_n = \mathrm{Sign}\left\{\hat{s}_n^\delta\right\}$. These values can be passed on to the channel decoder after deinterleaving. For better performance, we transmit instead the differential soft output $\hat{\underline{s}}_n^\delta = \hat{s}_n^\delta$ (see Fig. 1).

Note that both receiver versions of STAR require estimates of the received power ψ_n^2 for power control and possibly for decision feedback. The turbo codec (see next subsection) needs these estimates as well, along with estimates of the variance of the residual noise $\sigma_{\mathrm{res}}^2 = \sigma_N^2/2M$ in the soft output $\hat{s}_n^\delta$. Pilot-aided STAR estimates $\hat{\psi}_n^2$ and $\hat{\sigma}_{\mathrm{res}}^2$ as follows [6]:

$$\hat{\psi}_n^2 = (1-\alpha)\hat{\psi}_{n-1}^2 + \frac{\alpha}{1+\xi^2}\max\left\{|\hat{s}_n^\delta|^2 + |\hat{s}_n^\pi|^2 - 2\hat{\sigma}_{\mathrm{res}}^2, 0\right\}, \qquad (8)$$

$$\hat{\sigma}_{\mathrm{res}}^2 = (1-\alpha)\hat{\sigma}_{\mathrm{res}}^2 + \frac{\alpha}{2}\left(\mathrm{Im}\left\{\frac{\hat{\mathbf{H}}_n^H \mathbf{Z}_n^\delta}{M}\right\}^2 + \mathrm{Im}\left\{\frac{\hat{\mathbf{H}}_n^H \mathbf{Z}_n^\pi}{M}\right\}^2\right), \qquad (9)$$

[1] We actually feed back $\xi\hat{\psi}_n$ (or $|\hat{s}_n^\pi|$) which always has the *a priori* known positive sign of the pilot instead of $\hat{s}_n^\pi$ where sign errors could occur due to the residual interference.

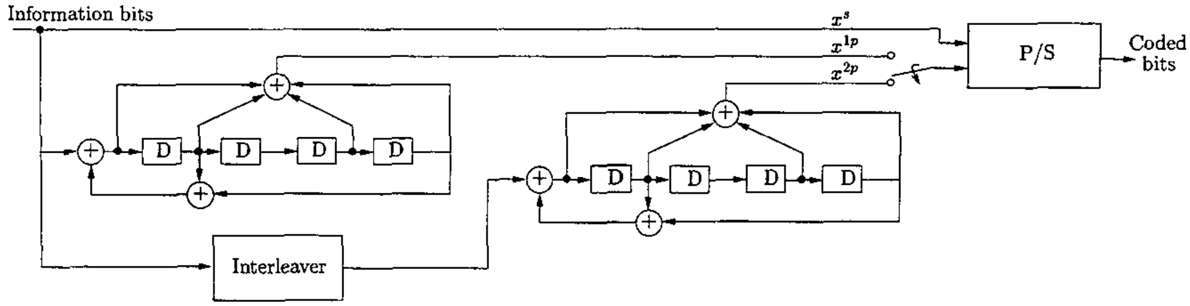

Figure 2. Block diagram of the turbo encoder.

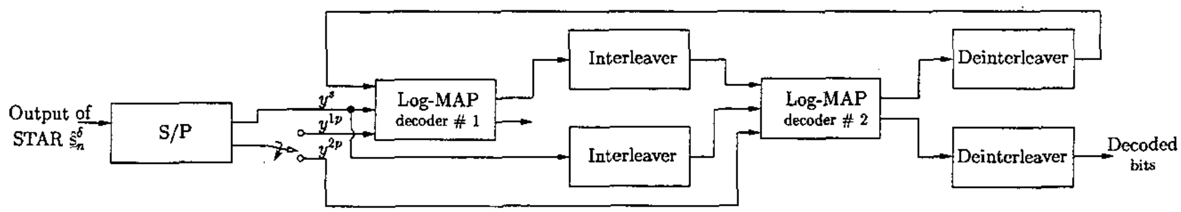

Figure 3. Block diagram of the turbo decoder.

where $\alpha \ll 1$ is a smoothing factor. In blind STAR, Z_n^{π}, $\hat{s}_n^{\pi}$ and ξ are simply set to zero in Eqs. (8) and (9) and the factors 2 and 1/2 there are both replaced by 1.

3.3 The Turbo Codec

In the uplink transceiver of Fig. 1, a rate-1/2 turbo encoder/decoder pair is incorporated. The corresponding reference system uses a rate-1/2 conventional convolutional code $(753, 561)_{oct}$ with constraint length of 9 and the Viterbi algorithm for decoding. The mother code of the turbo code is a rate-1/3 turbo code specified by the polynomial $(31, 33)_{oct}$ with constraint length of 5.

The structure of the turbo encoder is illustrated in Fig. 2. It contains two identical binary rate-1/2 memory-4 recursive systematic convolutional (RSC) encoders concatenated in parallel through an S-Random interleaver. The overall code-rate 1/2 is achieved by alternatively puncturing the parity bits (x^{1p}, x^{2p}) from the two RSC encoders. After P/S transformation, the coded bit sequence $\{\cdots, x^s(n), x^{1p}(n+1), x^s(n+2), x^{2p}(n+3), x^s(n+4), x^{1p}(n+5), \cdots\}$ is referred to as $\mathfrak{b}_n$ after interleaving (see Figs. 1 and 2).

The structure of the turbo decoder is illustrated in Fig. 3. It uses the exact log-MAP algorithm [7] known for its optimal performance. There exist a few sub-optimal algorithms (*cf.* [8] and the reference therein) which can achieve close to optimal performance while keeping the complexity sufficiently low. These versions can be considered for possible hardware implementation. Our prime objective here is to assess the best performance achievable with turbo codes. We introduce the so-called hard-decision-aided (HDA) early stopping criterion proposed in [9] into the decoder to reduce iterations and thereby reduce complexity.

As shown in Fig. 3, the decoder processes the soft output $\hat{s}_n^{\delta}$ from either STAR version (see previous subsections) after deinterleaving. Actually the turbo decoder also receives estimates $\hat{\psi}_n^2$ and $\hat{\sigma}_{res}^2$ from STAR (not shown in the figure) for use by the log-MAP algorithm. When differential coding is used, note that the additive noise which corrupts the received signal prior to the channel decoder is no longer Gaussian. However, the study made in [10] indicates that the turbo decoder performs nearly as well as a modified version with the log-MAP algorithm adjusted to the exact distribution of noise.

4 Performance Evaluation

We assess the performance of both versions of STAR (*i.e.*, blind and pilot-channel-assisted) with turbo codecs versus convolutional codecs for a data rate of 153.6 Kbps. By link-level simulations [11], we find in each case the SNR value SNR_{req} required to achieve a BER below 10^{-6}. By system-level simulations [11], we translate each SNR value into a maximum capacity in users per cell achievable with an outage probability below 1%.

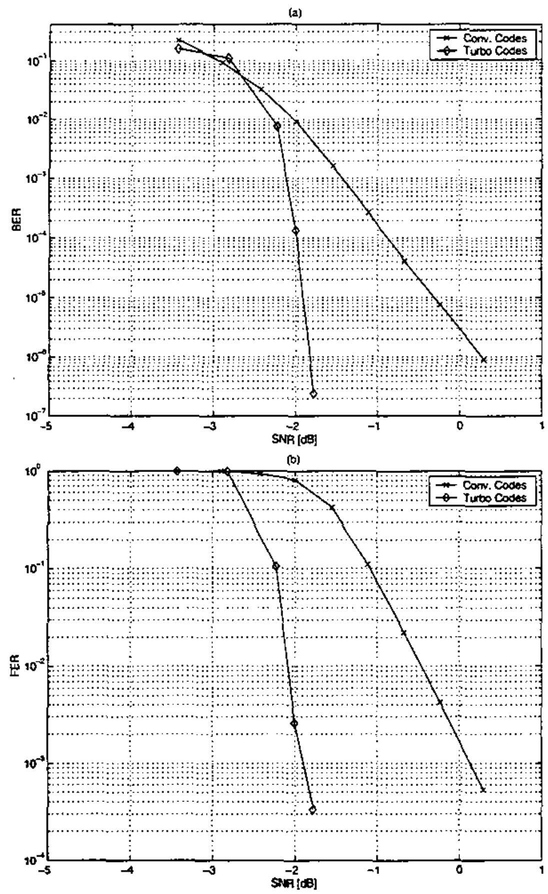

Figure 4. Link-level performance of blind (*i.e.*, without pilot) STAR with two receive-antennas and convolutional/turbo coding at 153.6 Kbps in 5 MHz bandwidth. (a): BER vs. SNR. (b): FER vs. SNR

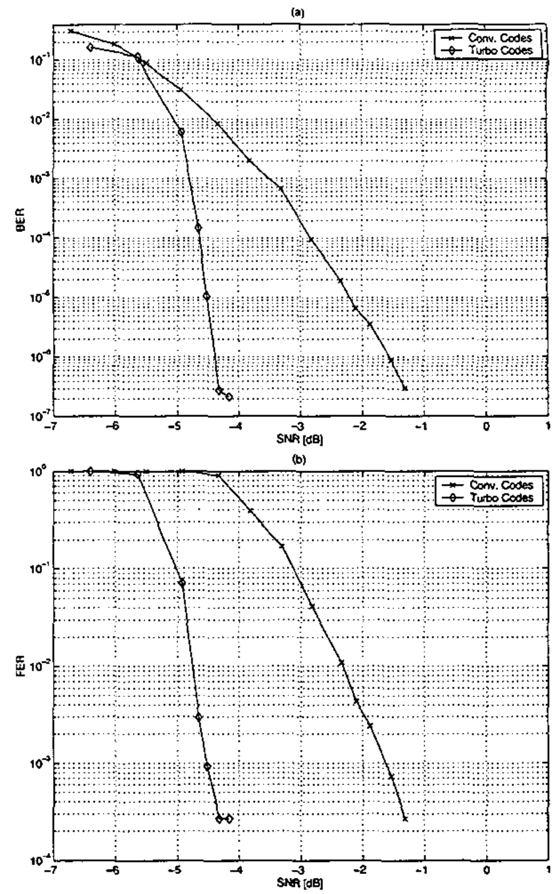

Figure 5. Link-level performance of pilot-channel-assisted STAR with two receive-antennas and convolutional/turbo coding at 153.6 Kbps in 5 MHz bandwidth. (a): BER vs. SNR. (b): FER vs. SNR.

4.1 Simulation Setup

We consider a wideband CDMA system with 5 MHz bandwidth operating at a carrier frequency of 1.9 GHz. The propagation environment is characterized by three equal-power paths. The base station is equipped with two receiving antennas. Mobiles have a pedestrian speed of 1 Kmph. Power control update is enabled at 800 Hz with a step-size of 0.25 dB. Its command bit suffers from a transmission delay of 1.25 ms and 10% BER.

Channel coding (convolutional or turbo) with rate 1/2 is applied to frames of 20 ms to produce 6144 coded bits per frame. To ensure that the BER results are statistically reliable after channel decoding, we have simulated more than 10,000 frames (*i.e.*, more than 30 million information bits) per simulation point.

4.2 Simulation Results

In Figs. 4 and 5, we plot both BER and FER versus the input SNR after despreading SNR_{in} for blind and pilot-aided STAR, respectively. The curves confirm that the pilot-chancel-assisted version of STAR outperforms the blind one. They also indicate that even more significant gains can be achieved by STAR with a turbo codec as compared to STAR with a convolutional one. In Tab. 1, we report from Figs. 4 and 5 significant SNR gains at the required QoS (*i.e.*, BER less than 10^{-6}), between 2 and 3 dB. Note that similar gains can be observed based on a more practical QoS that sets the FER below 1%.

The system-level simulation results in Tab. 1 confirm that on account of this link level performance advantage, the use of a turbo codec against a convolutional one can

	SNR_{req} @ 10^{-6} [dB]			capacity [users/cell] – efficiency [bps/Hz]		
	blind	pilot	gain	blind	pilot	gain
CC	+0.27	-1.57	+1.84	7 – 0.22	10 – 0.32	43%
TC	-1.83	-4.39	+2.56	13 – 0.40	22 – 0.68	69%
gain	+2.10	+2.82		86%	120%	

Table 1. Performance results of STAR with channel coding (CC: convolutional, TC: turbo) for data links of 153.6 Kbps in 5 MHz with two receive antennas.

almost double the user's capacity or spectrum efficiency. Pilot-aided STAR with a turbo codec can achieve a spectrum efficiency of 0.34 bps/Hz/antenna, three times higher than the 0.11 bps/Hz/antenna figure of blind STAR with a conventional convolutional codec.

The large performance gain achieved by turbo codecs can be attributed to the fact that we use a large internal interleaver[2] in the turbo code. In a more exhaustive study [10], we found that the coding gain of a turbo codec is less significant at the low data rates due to a smaller size of the interleaver. We also observed that high mobility is another factor that significantly reduces the performance advantage of a turbo codec over a convolutional one. The loss in performance is due to the fact that increasing channel estimation errors have a more severe impact on turbo codecs than on convolutional ones. Taking the computational cost of the uplink transceiver into account, combination of a turbo codec with STAR is most practical for high data-rates at low mobility.

5 Conclusions

STAR was recently shown to outperform RAKE-type array-receivers and to provide a strong leverage for increasing capacity of wideband CDMA networks [2]. Turbo codecs were also identified to offer significant performance improvements. In this contribution, we investigated the benefits of integrating turbo codecs in CDMA uplink transceivers using both blind and pilot-aided STAR. By link- and system-level simulations, we demonstrated the gains achieved by turbo codecs over conventional convolutional ones in such STAR-based transceivers. By exploiting both advanced channel-coding and smart antenna technologies, we gain 2 to 3 dB in SNR and almost double the system's capacity or spectrum efficiency at a high data-rate of 153.6 Kbps.

[2]Note that even better performance gains could be achieved with an optimized internal interleaver.

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