Application and Standardization of Turbo Codes in Third-Generation High-Speed Wireless Data Services

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***Abstract*—This paper addresses the application of turbo codes for third-generation wireless services. It describes the specific characteristics of high-rate data applications in third-generation wide-band code-division multiple-access (CDMA) systems that make turbo codes superior to convolutional codes. In particular, it shows the positive effect of fast power control employed in these systems on the relative performance of turbo codes with respect to convolutional codes. It also shows how turbo and convolutional codes behave differently when the figure of merit is changed to frame error rate from bit error rate for high-speed data services. Furthermore, it describes in detail how and why the standardized turbo code has been selected in the presence of other candidates, which were also based on iterative decoding. Details of turbo interleaving and trellis termination as specified in the standards are explained. Performance of turbo codes under wide-band CDMA operating conditions are presented. The suitability of turbo codes for low-rate data applications is discussed. Finally, it is shown that the performance loss as a result of internal decoder parameter quantization is negligible.**

***Index Terms*—CDMA2000, third-generation wireless systems, turbo codes, wide-band code division multiple access (CDMA).**

I. Introduction

RESEARCH and development on wireless communications technology beyond the currently deployed digital cellular standards such as global system mobile (GSM) and code division multiple access (CDMA) have been pursued for some time. But the activities really went into full swing after a request for third-generation wireless system proposals was issued by the International Telecommunication Union (ITU). ITU has two major objectives for the third-generation wireless system: global roaming and multimedia services. Whereas the global roaming capability can be largely accomplished by common spectral allocation, a common air interface and roaming protocol design throughout the world, and the migration of wireless networks from voice-centric services to multimedia services poses many technological challenges. First, multimedia services require very high instantaneous throughput in comparison to a voice-only service. With the progress of voice coding technology, 8- or sub-8-kbps voice coders can provide satisfactory quality for most voice applications. But Internet applications typically require a much higher data rate. Secondly, some of the multimedia services require much better quality of service (QoS) than voice, which may in turn require much higher transmission power, thereby adversely affecting the capacity of a CDMA network.

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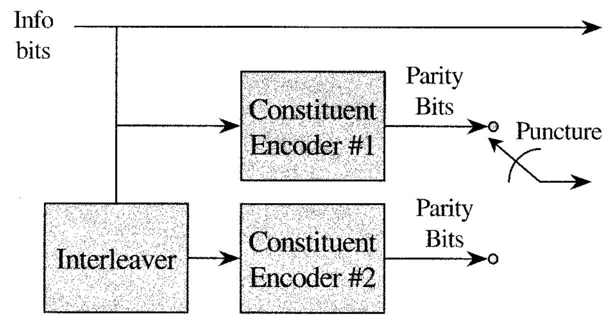


Fig. 1. General diagram of a turbo code encoder.

It is interesting to note that the spectral efficiency of current digital cellular technology is well below 0.2 bits per second per hertz per sector after factoring frequency reuse patterns into consideration. Although most third-generation wireless technology proposals are capable of supporting a wide range of bandwidths, current discussions typically assume a nominal bandwidth of 5 MHz. With 0.2 bits per second per hertz spectral efficiency, this nominal bandwidth will be able to support an aggregated 1 Mbits/s throughput in each sector. Thus, two active users operating at the 384-kbps speed mandated by the ITU requirement will take up most of the sector capacity. This situation is obviously unacceptable. Therefore, one of the major challenges for the third-generation wireless system is to improve spectral efficiency to the extent possible. Fortunately for CDMA, the lower power requirement leads to lower interference from each user imposed on the system, which translates directly into capacity gain. Turbo codes, capable of near Shannon limit power efficiency, have recently been adopted to improve the system capacity effectively for the third-generation high-speed wireless data services by the standards-setting organizations in the United States, Europe, and Asia.

In this paper, we show the performance of turbo codes under high-speed data transmission conditions and compare it with other coding alternatives. After a brief introduction of turbo codes in Section II, the standardized turbo codes for the cdma2000 standard, as proposed by the Telephone Industry Association (TIA) in the United States[10], and for the UTRA/W-CDMA standard, as proposed by the European Telecommunications Standards Institute (ETSI) and the Association of Radio Industry and Business (ARIB) in Europe and Japan, respectively, are described in Section III. This section also discusses how a high-performance, formula-based turbo interleaver (that requires storing only a small number

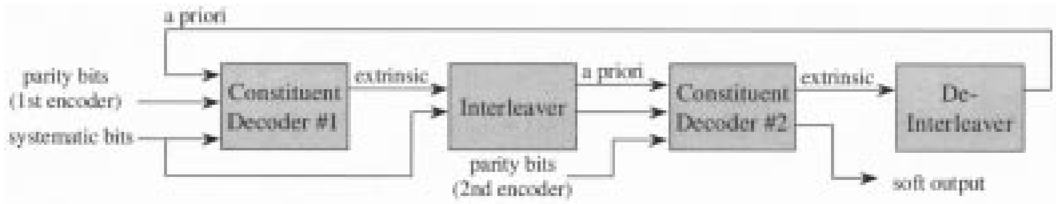


Fig. 2. General diagram of a turbo code decoder.

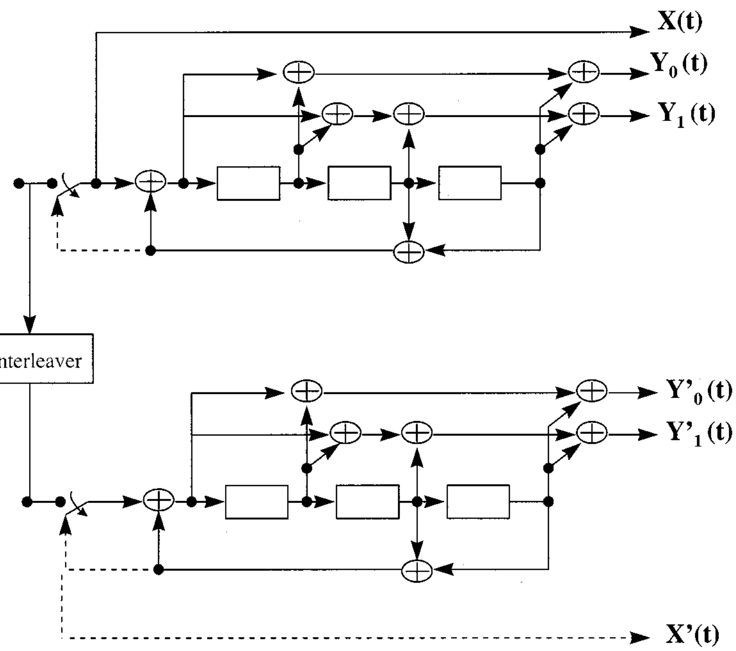


Fig. 3. Standardized turbo code for third-generation wireless systems (dotted lines effective for trellis termination only).

of parameters) for any frame size has been designed [8]. Section IV explains why the characteristics of the third-generation high-speed wireless data systems work in favor of turbo codes over convolutional codes. It also shows the performance of turbo codes under realistic cdma2000 and UTRA/W-CDMA channel and receiver models. Section V describes the performance of turbo codes for short frame sizes as required by low-data-rate applications. In this section, we also show that turbo decoding can be made very robust against internal decoder variables.

ITU's goal is to achieve a harmonized third-generation wireless standard that would allow users to roam anywhere in the world without resorting to multimode terminals. Although a small part of the overall system, the turbo code specifications in the cdma2000 and UTRA/W-CDMA systems, as described in Section III, are designed to have as much commonality as possible toward achieving this goal.

TABLE I
PUNCTURING PATTERNS FOR THE TURBO CODE OF Fig. 3

RATE	1/2	1/3	1/4
$X(t)$	11	11	11
$Y_0(t)$	10	11	11
$Y_1(t)$	00	00	10
$X'(t)$	00	00	00
$Y'_0(t)$	01	11	01
$Y'_1(t)$	00	00	11

II. GENERAL DESCRIPTION OF TURBO CODES

The turbo encoder [1] employs two systematic recursive convolutional codes connected in parallel, with an interleaver (the "turbo interleaver") preceding the second recursive convolutional encoder (Fig. 1). The two recursive convolutional codes are called the constituent codes of the turbo code. The information bits are encoded by both encoders. The first encoder operates on the input bits in their original order, while the second encoder operates on the input bits as permuted by the turbo interleaver. The information bits are always transmitted across the channel. Depending on the code rate desired, the parity bits from the two constituent encoders are punctured before transmission. For example, with constituent codes of rate 1/2 and for a turbo code of rate 1/3, all parity bits are transmitted, whereas, for a rate 1/2 turbo code, the parity bits from the constituent codes are punctured alternately. For transmission over a fading channel, the coded bits should be further interleaved by a channel interleaver before transmission.

Fig. 2 gives a general block diagram for a turbo code decoder [5], [6]. Soft information out of the demodulator regarding the systematic bits and parity bits from the first constituent code is

TABLE II
VALUES FOR c FOR CDMA2000 TURBO INTERLEAVERS [10]

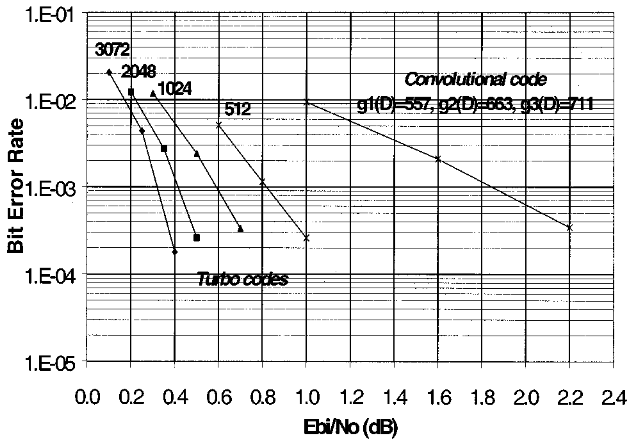
Table Index	n = 4 Entries	n = 5 Entries	n = 6 Entries	n = 7 Entries	n = 8 Entries	n = 9 Entries	n = 10 Entries
0	5	27	3	15	3	13	1
1	15	3	27	127	1	335	349
2	5	1	15	89	5	87	303
3	15	15	13	1	83	15	721
4	1	13	29	31	19	15	973
5	9	17	5	15	179	1	703
6	9	23	1	61	19	333	761
7	15	13	31	47	99	11	327
8	13	9	3	127	23	13	453
9	15	3	9	17	1	1	95
10	7	15	15	119	3	121	241
11	11	3	31	15	13	155	187
12	15	13	17	57	13	1	497
13	3	1	5	123	3	175	909
14	15	13	39	95	17	421	769
15	5	29	1	5	1	5	349
16	13	21	19	85	63	509	71
17	15	19	27	17	131	215	557
18	9	1	15	55	17	47	197
19	3	3	13	57	131	425	499
20	1	29	45	15	211	295	409
21	3	17	5	41	173	229	259
22	15	25	33	93	231	427	335
23	1	29	15	87	171	83	253
24	13	9	13	63	23	409	677
25	1	13	9	15	147	387	717
26	9	23	15	13	243	193	313
27	15	13	31	15	213	57	757
28	11	13	17	81	189	501	189
29	3	1	5	57	51	313	15
30	15	13	15	31	15	489	75
31	5	13	33	69	67	391	163

sent to the first decoder. The first decoder generates soft-decision likelihood values for the information bits that are passed to the second decoder as *a priori* information after reordering in accordance with the turbo interleaver. In addition, the second decoder accepts the demodulator output regarding the systematic bits and the parity bits from the second constituent encoder. The second decoder improves on the soft-decision likelihood values for the information bits, which are then fed back to the first decoder to repeat the process. The process can be iterated as many times as desired. However, only a relatively small number of iterations are usually needed, since additional iterations generally produce diminishing returns. Hard decisions on the systematic information bits are made after the last decoder iteration is completed.

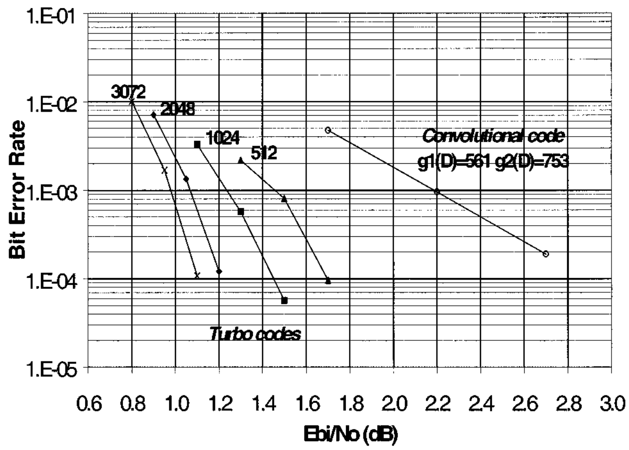
III. THE STANDARDIZED TURBO CODES

The turbo code shown in Fig. 3 is used in the cdma2000 standard [10] for high-speed (above 14.4 kbps) data services. Rate 1/2, 1/3, and 1/4 turbo codes are realized with appropriate puncturing patterns, given in Table I. For the UTRA/W-CDMA proposed by ETSI and ARIB [11], the same constituent code is used for the rate 1/3 turbo code. Other code rates are obtained by a "rate matching" process, where coded bits are punctured or repeated accordingly [11]. The turbo code shown in Fig. 3 was adopted after extensive simulation study, a small subset of which will be given in Section IV.

For both cdma2000 and UTRA/W-CDMA systems, turbo codes are terminated in a similar way. Since the constituent



(a)



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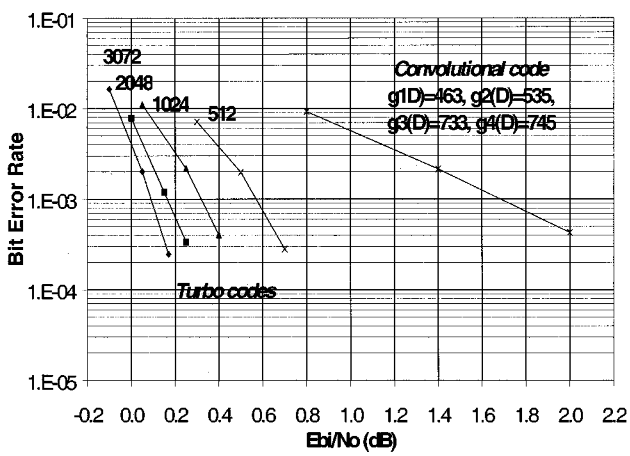
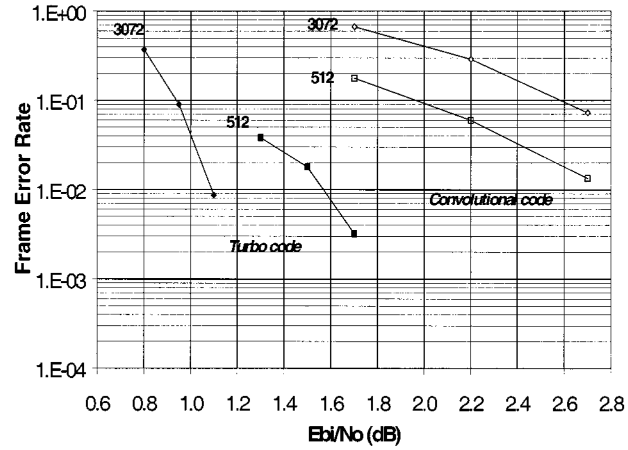


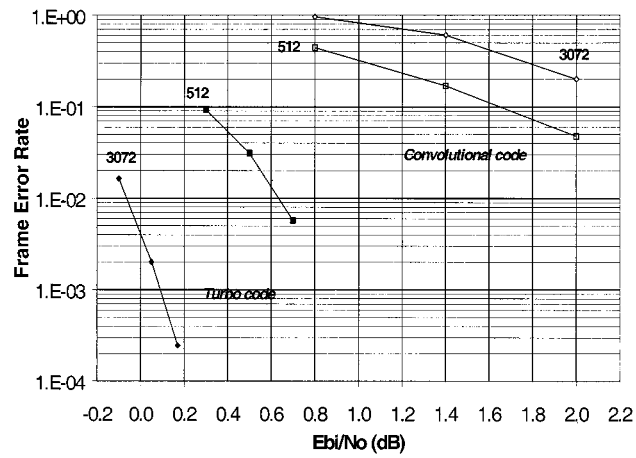
(c)

Fig. 4. BER comparison of turbo codes with eight iterations and convolutional codes, AWGN channel. (a) Rate 1/3, (b) rate 1/2, and (c) rate 1/4.

encoders are recursive, appending simply zero tail bits does not bring the trellises back to the all zero state. Instead, tail bits come from the current contents of the shift registers, as shown by the dotted lines in Fig. 3. Moreover, because of the turbo interleaver, the contents of the shift registers at the beginning of trellis termination are different for both constituent encoders. Therefore, for the standardized turbo code with eight-state constituent codes, a total of $3 \times 2 = 6$ tail bits are required to terminate both encoders.



(a)



(b)

Fig. 5. FER comparison of turbo codes with eight decoder iterations and convolutional codes, AWGN channel. (a) Rate 1/2 and (b) rate 1/4.

For the sake of description, we assume that the first three tail bits are used to terminate the upper constituent encoder, while the last three tail bits are used to terminate the lower constituent encoder. In the cdma2000 system, for rate 1/2 turbo codes, the tail output symbols for each of the first three tail bit periods are XY_0, and the tail output symbols for each of the last three tail bit periods are $X'Y_0'$. For rate 1/3 turbo codes, the tail output symbols are XXY_0 and $X'X'Y_0'$, respectively. Finally, for rate 1/4 turbo codes, they are XXY_0Y_1 and $X'X'Y_0'Y_1'$. In the UTRA/W-CDMA system, the tail output symbols for each of the first three tail bit periods are XY_0, and the tail output symbols for each of the last three tail bit periods are $X'Y_0'$.

The standardized turbo interleavers for the two systems belong to the same general class of interleavers in that they share the following properties.

1) A small number of "mother interleavers" are specified from which interleavers for intermediate sizes are derived by pruning [8] unnecessary indexes. By pruning, we mean ignoring an index that results in an invalid address because it exceeds the range of interest. For instance, if a mother interleaver of size eight is specified by the permutation (3, 6, 2, 0, 4, 5, 7, 1), then an interleaver of length

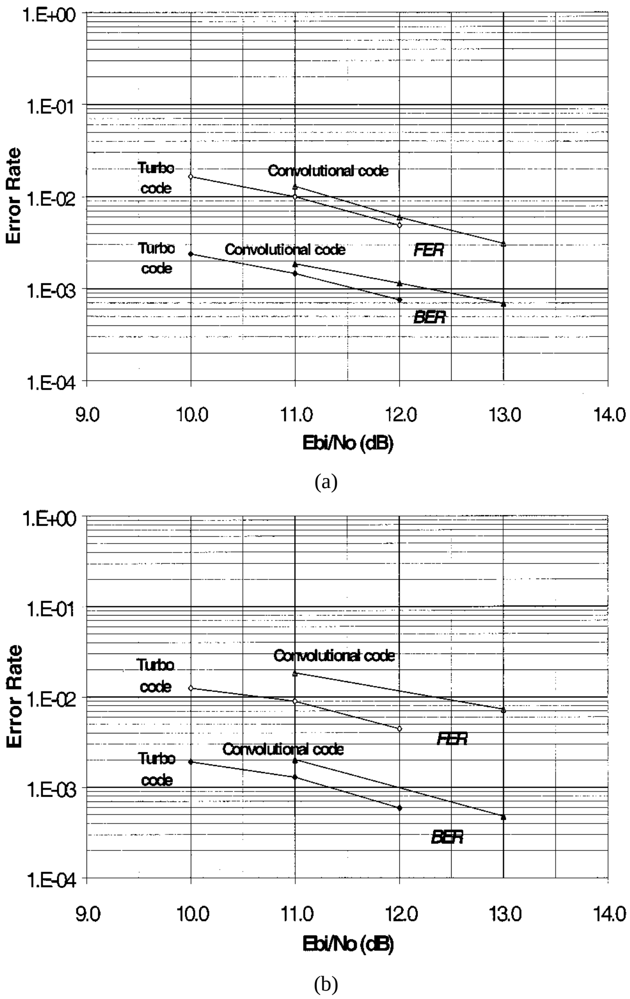


Fig. 6. Comparison of rate 1/2 turbo codes and convolutional codes over rayleigh fading channel, no power control, $v = 30$ kmph. Interleaver length (a) 512 bits and (b) 3072 bits.

five can be derived from the mother interleaver as the permutation (3, 2, 0, 4, 1) by pruning the indexes 6, 5, and 7. (See [8] for further details.)

2) The mother interleavers can be viewed as two-dimensional matrices, where the entries are read in the matrix row by row and read out column by column.
3) Before reading out the entries, intra- and interrow permutations are performed.

Pruning as described in item 1) is convenient to derive any turbo interleaver with a granularity of one bit from a small set of mother interleavers. The parameters that govern the intra- and interrow permutations can be designed so that some minimum weight distribution characteristics of the final turbo code are guaranteed for any turbo interleaver size [8].

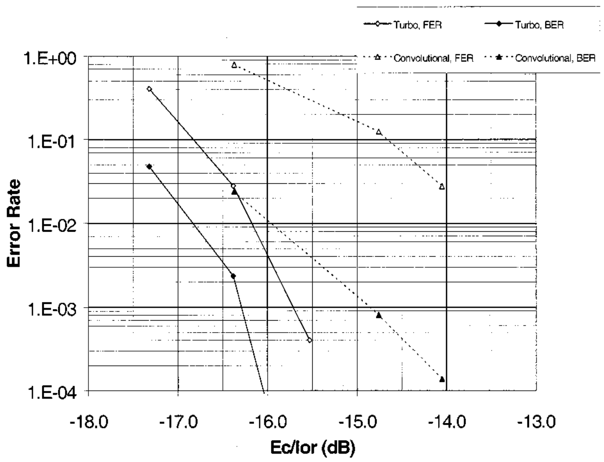
In the following, we describe the cdma2000 turbo interleavers [10]. UTRA/W-CDMA turbo interleavers [11] differ from cdma2000 interleavers in the exact specification of intra- and interrow permutations and the matrix dimensions of the mother interleavers.

For cdma2000, the mother interleavers have dimension 32 $\times$ 2^n, where n is an integer between four and ten. Conceptually, the entries are read into the interleaver matrix row by row. The elements within each row are permuted according to a row-specific linear congruence sequence given by $x(i+1) = (x(i)+c) \bmod 2^n$, where $x(0) = c$ and c is a row-specific value from a table lookup. The values of c for several values of n are shown in Table II. The rows are then shuffled according to a bit-reversal rule. In other words, they are reordered according to the following row indexes: 0, 16, 8, 24, 4, 20, 12, 28, 2, 18, 10, 26, 6, 22, 14, 30, 1, 17, 9, 25, 5, 21, 13, 29, 3, 19, 11, 27, 7, 23, 15, 31. Finally, the output addresses are read out column by column. To determine an interleaver with arbitrary size N, the smallest mother interleaver of size greater than or equal to N is chosen. The mother interleaver is then pruned down to the desired size N as specified in item 1) above.

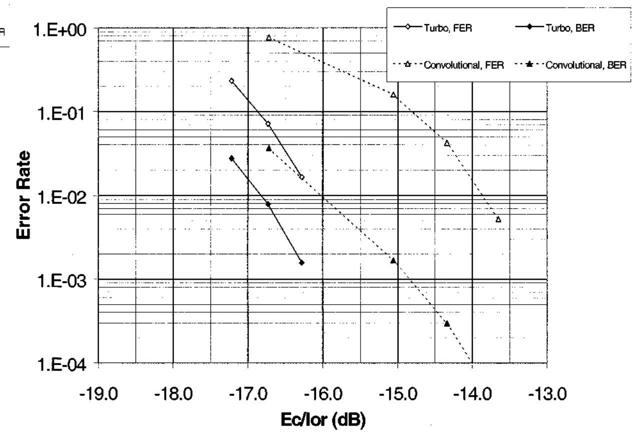
IV. Comparison of Turbo and Convolutional Codes for Third-Generation Wireless Systems and Their Performance in CDMA2000 and UTRA/W-CDMA Systems

There are several reasons why turbo codes are especially suited for high-speed data services of third-generation wireless systems. First, at high speeds, sufficiently long blocks of data can be accumulated (e.g., within a frame of 10 or 20 ms) without causing substantial delay in the system. Turbo codes become more and more effective as the block (turbo interleaver) size increases because of spectral thinning (i.e., the multiplicity of "neighbor" codewords becomes smaller as the interleaver size gets larger) [2]–[4]. As an example, Fig. 4 shows the performance of rate 1/2, 1/3, and 1/4 turbo codes with increasing frame sizes in comparison with convolutional codes. In each case, eight iterations are used in the decoder. Around a bit error rate (BER) of 10^{-4}, for the most practical interleaver lengths that have been simulated, there is about 0.2 dB to be gained when the interleaver length is doubled each time. Of course, this gain eventually diminishes as the interleaver length is increased outside this range.

The second reason why turbo codes are particularly suitable for third-generation high-speed data services is that error-free data transmission is typically accomplished by an automatic repeat request (ARQ) protocol implemented in higher layers. As such, the more appropriate figure of merit is frame error rate (FER), rather than bit error rate (BER). The performance difference between turbo and convolutional codes becomes even larger when compared in terms of FER as opposed to BER [7]. Furthermore, in Fig. 5, one notes that as the information frame size increases from 512 to 3072, the frame error rate for turbo codes decreases sharply, at least in the waterfall region, while that of the convolutional code increases significantly. Ignoring edge effects, the bit error rate for convolutional codes is essentially uniform across the frame and is a constant independent of frame size. Thus, for a given Eb/No, the expected number of bit errors increases with frame size, and the frame error rate worsens. For turbo codes, however, the power of the code increases significantly as the frame size increases due to spectral thinning. This increase in power is more than sufficient to overcome the burden of protecting a larger frame of data. It should be pointed out that this result applies in the waterfall region It is well known [2] that there is no interleaver gain for turbo codes in terms of FER in the error asymptote region. For an analytic



(a)



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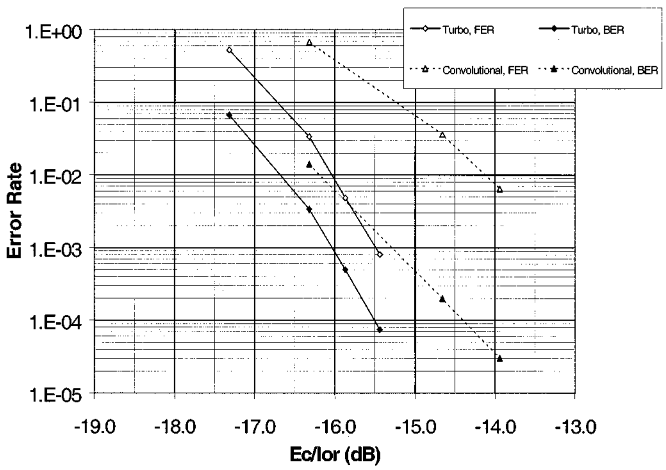

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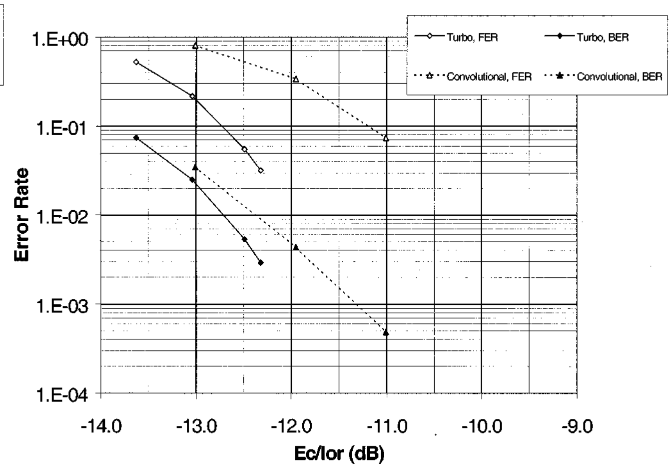

(d)

Fig. 7. Performance of rate 1/3 turbo and convolutional codes with power control, 76.8 kbps, 20 ms frame duration, CDMA2000 receiver model. (a) $Ior/Ioc = 8$ dB, vehicle speed $= 120$ kph. (b) $Ior/Ioc = 8$ dB, vehicle speed $= 30$ kph. (c) $Ior/Ioc = 8$ dB, vehicle speed $= 3$ kph. (d) $Ior/Ioc = 0$ dB, vehicle speed $= 120$ kph.

investigation of the waterfall region performance of turbo codes, see [12].

The third reason for turbo codes to become an effective forward error-control technique for third-generation wireless systems is the fast power control employed in these systems. Indeed, without any power control, the performance advantage of turbo codes over convolutional codes decreases considerably. As an example, Fig. 6 shows the performance of rate 1/2 turbo and convolutional codes over a Rayleigh fading channel withoutpower control at a 30-kmph vehicle speed. As usual, eight iterations are used in the turbo decoder. In fact, especially for the 512-bit frame size, one might argue that the BER and FER performance of the turbo and convolutional codes are so similar that the extra complexity of the turbo decoder is not worthwhile. Fig. 7, on the other hand, shows that the use of fast power control can restore the performance advantage of turbo codes to gains close to that achieved on the additive white Gaussian noise (AWGN) channel. For this comparison, the Vehicular Test Environment Channel A specified by ITU is used as the fading channel model. In this model, there are six Rayleigh fading paths of varying delay and strength, as shown in Table III. The chip rate is 3.6864 Mchips/s, there are six samples per

TABLE III
VEHICULAR TEST ENVIRONMENT CHANNEL A TAPPED-DELAY-LINE PARAMETERS

Taps	Delay (samples)	Average Power (dB)
1	0	0
2	7	-1
3	16	-9
4	24	-10
5	38	-15
6	56	-20

chip, the data rate is 76.8 kbps, and the frame duration is 20 ms. A fixed low-pass infinite impulse response filter given by $y(n) = x(n)/768 + 767y(n-1)/768$ is used for phase estimation at all vehicle speeds. The signal-to-noise ratio (SNR) estimation required for turbo decoding is readily obtained from the power-control algorithm. Each power-control bit is sent every 1.25 ms with a delay of 0.715 ms and an error rate of 4%. To simulate real systems accurately, interference from 20 other users is obtained by actually encoding their bits and sending them over the channel. A pulse shaping filter at the transmitter and a matched filter at the receiver is also implemented. Eight

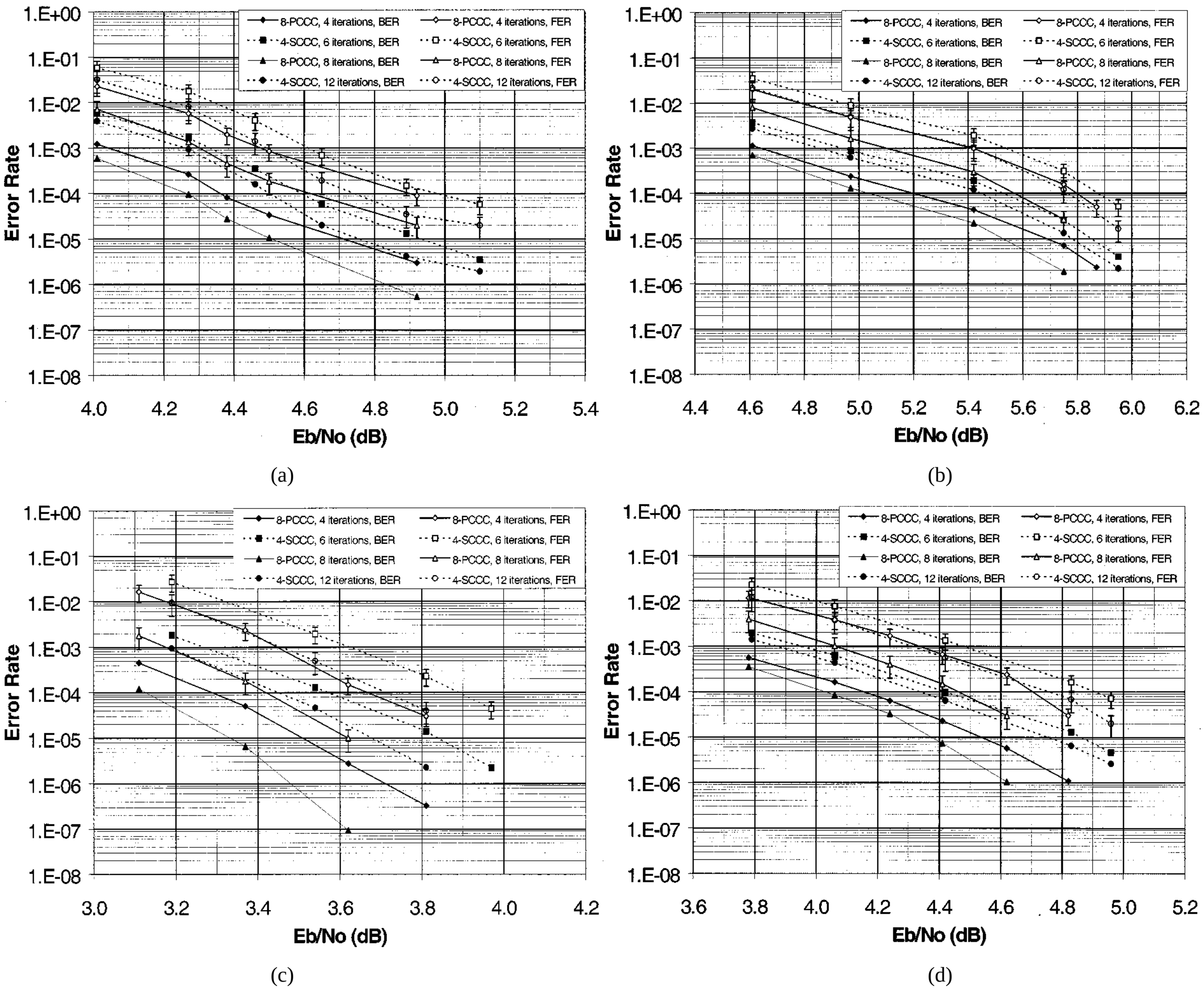

Fig. 8. Comparison of serially and parallel concatenated codes, rate$= 1/3$, UTRA/W-CDMA receiver model, 10-ms frame duration. (a) 32 kbps, $v = 3$ kmph. (b) 32 kbps, $v = 30$ kmph. (c) 64 kbps, $v = 3$ kmph. (d) 64 kbps, $v = 30$ kmph.

turbo decoder iterations are performed. In the first three plots of Fig. 7, other-cell interference is kept at 8 dB below the intended base station; in the last plot, other-cell interference has the same level as the intended base station. Turbo codes provide substantial gain in all cases, although the cases with higher vehicle speeds and lower other-cell interference seem to favor turbo codes more than convolutional codes.

For a UTRA/W-CDMA third-generation wireless system, serial and parallel concatenated convolutional codes were investigated as candidates for high-speed, high-quality data transmission ($\text{BER} = 10^{-6}$). A sample of the simulation results is given in Fig. 8. These simulations are done under the frame and pilot structures of a representative UTRA/W-CDMA system. In particular, each turbo code frame spans 10 ms, which consists of 16 slots. The modulation scheme is quaternary phase-shift keying, and there are four pilot symbols per slot multiplexed with information bearing symbols. Channel estimation is performed by averaging the pilot symbols over six slots around the decoded slot with the weighting coefficients 0.3 0.8 1.0 1.0 0.8 0.3. In the context of these simulation studies, tradeoffs regarding pilot symbol power versus nonpilot symbol power were made to minimize the absolute operating SNR. As a result of this optimization, a factor of four has been chosen as the ratio of pilot power over nonpilot power symbols. Four rake fingers are used for the purpose of maximum ratio combining. The power-control step size is 1 dB, the power-control command error rate is assumed to be zero, and power control is applied immediately on the next slot following the slot of measurement. A block channel interleaver is used.

The parallel concatenated convolutional code (PCCC) used in the simulations of Fig. 8 has already been described in the previous section. The serially concatenated convolutional code (SCCC) has four-state rate 1/2 systematic, recursive constituent codes [denominator polynomial $d(D) = 1 + D + D^2$ and numerator polynomial $n(D) = 1 + D^2$] where the outer constituent code is punctured to obtain a rate 2/3 code. Fig. 8 shows that the PCCC outperforms the SCCC by 0.2–0.4 dB under all conditions at the region of $\text{BER} = 10^{-6}$ for the UTRA/W-CDMA high-quality data service option. Error bars on frame error rates are also included. They represent 99% confidence intervals based on the Poisson approximation under the assumption that each consecutive frame is faded independently. The number of decoder iterations for the four-state SCCC is kept 1.5 times the number of decoder iterations for the eight-state PCCC so that the comparisons are made on equal complexity basis. (This factor is 1.5 and not two since the computational complexity of the inner constituent decoder of the SCCC is $1/R$ times the computational complexity of the outer

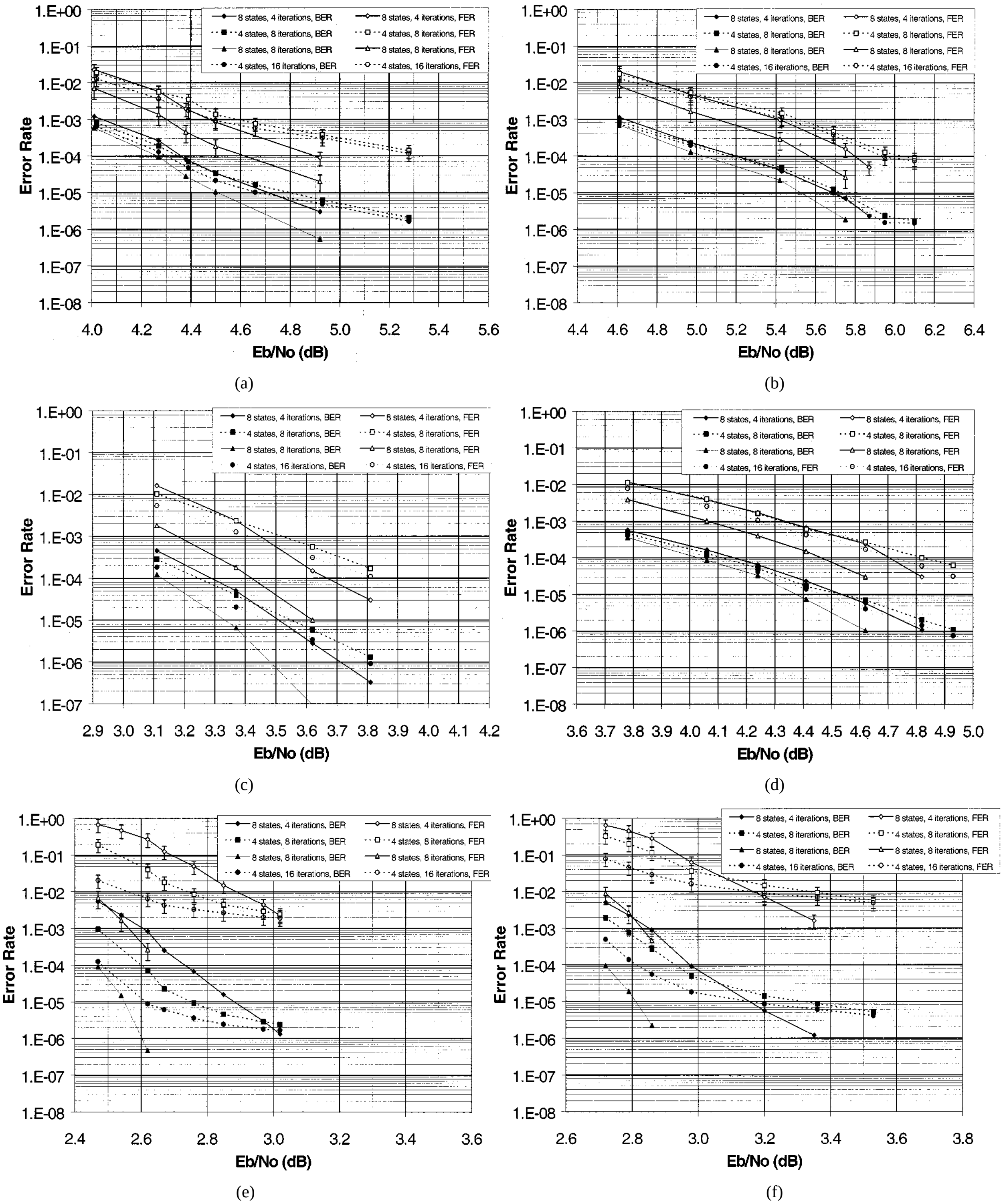

Fig. 9. Comparison of eight-state and four-state parallel concatenated codes, rate $= 1/3$, UTRA/W-CDMA receiver model, 10-ms frame duration. (a) 32 kbps, $v = 3$ kmph. (b) 32 kbps, $v = 30$ kmph. (c) 64 kbps, $v = 3$ kmph. (d) 64 kbps, $v = 30$ kmph. (e) 64 kbps, $v = 3$ kmph, 80-ms channel interleaver. (f) 64 kbps, $v = 30$ kmph, 80-ms channel interleaver.

constituent decoder, where R is the rate of the outer constituent code. In this situation $R = 2/3$.) Storage requirements for these coding schemes are dominated by the buffering of the channel inputs. Therefore, the number of VLSI gates required to store the internal decoder parameters is negligible with respect to the gate count for channel input storage [9]. Hence, in terms of gate count, both schemes are similar.

Similar comparisons were performed between eight-state and four-state PCCC using the same UTRA/W-CDMA system receiver simulation package as described above. Representative results are shown in Fig. 9.

In order to make a comparison based on similar computational cost, the number of decoding iterations for the four-state turbo codes is twice the number of iterations for the eight-state

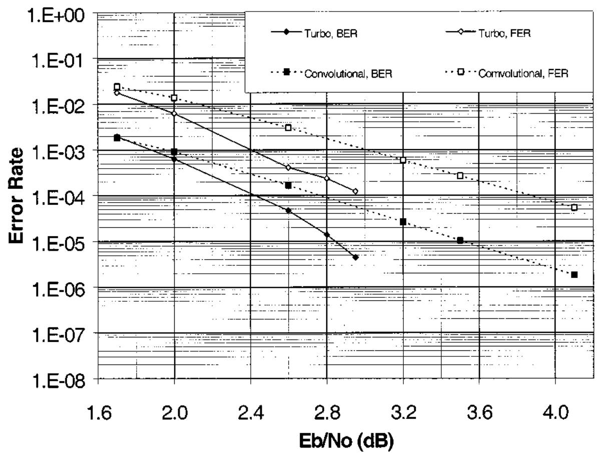

Fig. 10. Standardized turbo code with eight iterations versus 256-state convolutional code, 9.6 kbps, 10-ms frame size, AWGN.

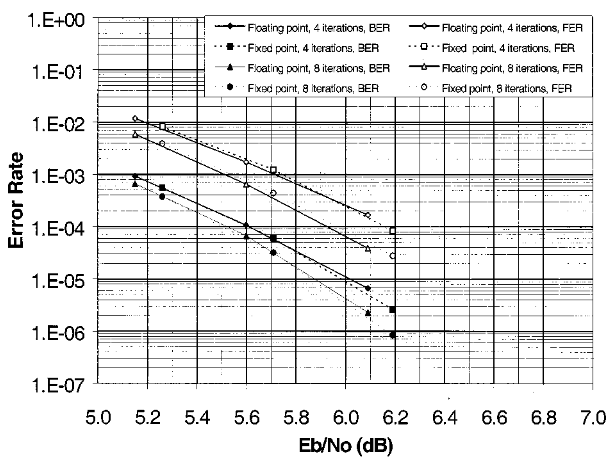

Fig. 11. Performance of 8-bit fixed-point versus floating-point simulations, eight-state turbo codes, UTRA/W-CDMA receiver model.

codes. Furthermore, similar to the previous case, the gate count for hardware implementation is governed by channel input buffering and hence is about the same for both codes. Results in Fig. 9 show that the four-state turbo code usually suffers from an early error floor and hence is not suitable for this system.

Based on the above and similar results, the eight-state turbo code [with denominator polynomial $d(D) = 1 + D^2 + D^3$ and numerator polynomial $n(D) = 1 + D + D^3$] has been adopted for high-data-rate (above 32 kbps) and high-quality services for UTRA/W-CDMA systems following its adoption for the cdma2000 US standard.

V. Other Issues: Performance of Turbo Codes for Low-Data-Rate Services and Turbo Decoder Internal Quantization Losses

Turbo codes are mainly attractive for high-data-rate services due to the relatively long interleaver. Initially, the standard bodies limited turbo code only to high-data-rate services. Results show that turbo codes still offer some modest gains with respect to convolutional codes with a frame size as low as 100 bits, as shown in Fig. 10. For extremely short interleavers, convolutional codes outperform turbo codes. Theoretically, it is best to switch to convolutional codes when the amount of data to be transmitted is small. On the other hand, this switching typically requires signaling; it incurs extra delay and overhead. For a network primarily servicing high-speed data, it may occasionally need to send a short burst. In this case, it may be more advantageous to simply send the burst with the turbo encoder rather than incur the additional overhead for switching the encoder. For this reason, third-generation systems allow turbo codes to be used across almost all data rates.

All of the previous results in this paper were obtained with floating-point simulators. Fig. 11 shows the impact of quantization on the performance of turbo codes over fading channels with UTRA/W-CDMA channel receiver models as described in Section IV. As shown in the figure, with 8-bit quantization, there is almost no performance degradation with respect to floating-point simulations.

VI. Summary

In this paper, we have shown that turbo codes are a natural forward error-correction scheme for third-generation high-speed wireless data services. The performance of standardized turbo codes as well as other candidate schemes is given under realistic third-generation high-speed data-transmission conditions. Turbo interleaving and trellis termination techniques as given in the standards are explained. It is shown that turbo decoders can be made quite robust against internal parameter quantization. Finally, turbo and convolutional codes are compared for short frame sizes, another possible application for turbo codes in third-generation wireless systems.

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