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TITLE: G.gen: Results of the requirements requested in the Coding Ad hoc report (BA-108R1) for the proposed Turbo Codes for ADSL modems by VOCAL Technologies Ltd in BA-020R1.

## ABSTRACT

In this paper we describe the results of the evaluation requested in the Coding Ad hoc report (BA-108R1) for the proposed Turbo Codes for ADSL modems by VoCAL Technologies Ltd in BA-020R1

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# 1. Introduction:

This paper provides the evaluation of VOCAL's proposed Turbo codes for G.dmt and G.lite as decribed in BA-020R1, according to the requirements requested in the Coding Ad Hoc report from the Antwerp meeting (BA-108R1).

This document introduces two differences with B-020R1. One is the inclusion of the 12 bit per tone patterns and the second is the modification of the interleaver proposed, that is the one defined by the 3GPP mobile group and proposed in part by document BA-088R1. Some parameters are included to allow the generation of the interleavers.

# 2. Description of the method for its implementation

## 2.1 Capacity Bounds

The minimum $E_b/N_0$ values to achieve the Shannon bound 64 QAM and 16384 QAM bounds for spectral efficiencies of 4 and 12 bits/s/Hz respectively are as in Table 1 for a BER=$10^{-5}$.

Table 1. Shannon bounds.

| **Spectral efficiency η [bit/s/Hz]** | **Shannon bound Eb/No [dB]** |
|---|---|
| 4 | 5.6 |
| 12 | 24.7 |

The conversion from SNR to $E_b / N_0$ is performed using the following relation

$$E_b / N_0[dB] = SNR\ [dB] - 10 \log_{10} (\eta)\ [dB] \qquad (1)$$

where η is the number of information bits per symbol.

For a D-dimension modulation the following formulae are used:

$$SNR = \frac{E\,[|\,a_k^2\,|]}{E\,[|\,w_k^2\,|]} = \frac{E\,[|\,a_k^2\,|]}{D\sigma_N^2} = \frac{E_{av}}{D\sigma_N^2} \qquad (2)$$

$$SNR = \frac{E_s}{D\frac{N_0}{2}} = \frac{\eta E_b}{D\frac{N_0}{2}} \qquad (3)$$

where $\sigma^2_N$ is the noise variance in each of the D dimension and η is the number of information bits per symbol. From the above relations:

$$\sigma_N^2 = E_{av}\left(\frac{2\eta E_b}{N_0}\right)^{-1} \qquad (4)$$

## 2.2 Coding

The proposed coding scheme is shown in Figure 1. The two systematic recursive codes (SRC) used are identical and are defined in Figure 2. The code is described by the generating polynomials 35o and 23o.

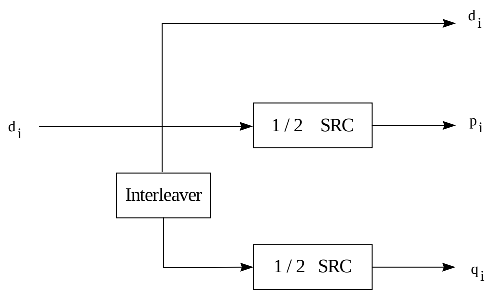


Figure 1

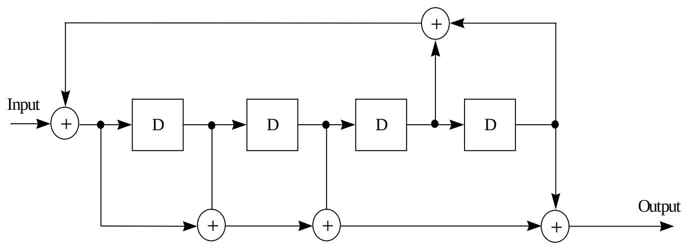


Figure 2

## 2.3 Turbo code internal interleaver.

### 2.3.1 Option 1: 3GPP interleaver design.

The Turbo code internal interleaver consists of bits-input to a rectangular matrix, intra-row and inter-row permutations of the rectangular matrix, and bits-output from the rectangular matrix with pruning. The bits input to the Turbo code internal interleaver are denoted by $x_1, x_2, x_3, \ldots, x_K$ , where $K$ is the integer number of the bits and takes one value of 40 $\leq$ $K$ $\leq$ 32000. The relation between the bits input to the Turbo code internal interleaver and the bits input to the channel coding is defined by $x_k = o_{irk}$ and $K = K_i$.

| | |
|---|---|
| K | Number of bits input to Turbo code internal interleaver |
| R | Number of rows of rectangular matrix |
| C | Number of columns of rectangular matrix |
| p | Prime number |
| v | Primitive root |
| s(i) | Base sequence for intra-row permutation |
| qj | Minimum prime integers |
| rj | Permuted prime integers |
| T(j) | Inter-row permutation pattern |
| Uj(i) | Intra-row permutation pattern |
| i | Index of matrix |
| j | Index of matrix |
| k | Index of bit sequence |

#### 2.3.1.2 Bits-input to rectangular matrix

The bit sequence input to the Turbo code internal interleaver $x_k$ is written into the rectangular matrix as follows.

(1) Determine the number of rows $R$ of the rectangular matrix such that:

$$R = \begin{cases} 5, \text{if } (40 \leq K \leq 159) \\ 10, \text{if } ((160 \leq K \leq 200) \text{ or } (481 \leq K \leq 530)) \\ 20, \text{if } (K = \text{any other value}) \end{cases}$$

where the rows of rectangular matrix are numbered 0, 1, 2, …, $R$ - 1 from top to bottom.

(2) Determine the number of columns $C$ of rectangular matrix such that:

if (481 $\leq$ $K$ $\leq$ 530) then

$p$ = *53* and $C = p$.

else

Find minimum prime $p$ such that

$(p + 1) - K/R \geq 0$,

and determine $C$ such that

if ($p - K/R \geq 0$) then

if ($p - 1 - K/R \geq 0$) then

$C = p - 1$.

else

$C = p$.

end if

else

$C = p + 1$

end if

end if

where the columns of rectangular matrix are numbered 0, 1, 2, …, $C - 1$ from left to right.

(3) Write the input bit sequence $x_k$ into the $R\times C$ rectangular matrix row by row starting with bit $x_1$ in column 0 of row 0:

$$\begin{bmatrix} x_1 & x_2 & x_3 & \cdots x_C \\ x_{(C+1)} & x_{(C+2)} & x_{(C+3)} & \cdots x_{2C} \\ \vdots & \vdots & \vdots & \cdots \vdots \\ x_{((R-1)C+1)} & x_{((R-1)C+2)} & x_{((R-1)C+3)} & \cdots x_{RC} \end{bmatrix}$$

2.3.2 Intra-row and inter-row permutations

After the bits-input to the $R\times C$ rectangular matrix, the intra-row and inter-row permutations for the $R\times C$ rectangular matrix are performed by using the following algorithm.

(1) Select a primitive root $v$ from table 2.

(2) Construct the base sequence $s(i)$ for intra-row permutation as:

$s(i) = [v \times s(i - 1)] \bmod p$, $i = 1, 2,\ldots, (p - 2)$., and $s(0) = 1$.

(3) Let $q_0 = 1$ be the first prime integer in $\{q_j\}$, and select the consecutive minimum prime integers $\{q_j\}$ ($j$ = 1, 2, …, $R$ - 1) such that:

g.c.d$\{q_j, p - 1\} = 1$, $q_j > 6$, and $q_j > q_{(j-1)}$,

where g.c.d. is greatest common divisor.

(4) Permute $\{q_j\}$ to make $\{r_j\}$ such that

$r_{T(j)} = q_j$, $j = 0, 1, \ldots, R - 1$,

where $T(j)$ ($j = 0, 1, 2, \ldots, R - 1$) is the inter-row permutation pattern defined as the one of the following four kind of patterns: $Pat_1$, $Pat_2$, $Pat_3$ and $Pat_4$ depending on the number of input bits $K$.

$$\{T(0), T(1), T(2), ..., T(R-1)\} = \begin{cases} Pat_4 & \text{if } (40 \le K \le 159) \\ Pat_3 & \text{if } (160 \le K \le 200) \\ Pat_1 & \text{if } (201 \le K \le 480) \\ Pat_3 & \text{if } (481 \le K \le 530) \\ Pat_1 & \text{if } (531 \le K \le 2280) \\ Pat_2 & \text{if } (2281 \le K \le 2480) \\ Pat_1 & \text{if } (2481 \le K \le 3160) \\ Pat_2 & \text{if } (3161 \le K \le 3210) \\ Pat_1 & \text{if } (3211 \le K) \end{cases},$$

where $Pat_1$, $Pat_2$, $Pat_3$ and $Pat_4$ have the following patterns respectively.

$Pat_1$: {19, 9, 14, 4, 0, 2, 5, 7, 12, 18, 10, 8, 13, 17, 3, 1, 16, 6, 15, 11}

$Pat_2$: {19, 9, 14, 4, 0, 2, 5, 7, 12, 18, 16, 13, 17, 15, 3, 1, 6, 11, 8, 10}

$Pat_3$: {9, 8, 7, 6, 5, 4, 3, 2, 1, 0}

$Pat_4$: {4, 3, 2, 1, 0}

(5) Perform the $j$-th ($j$ = 0, 1, 2, …, $R$ - 1) intra-row permutation as:

if ($C = p$) then

$U_j(i) = s([i \times r_j] \bmod (p - 1))$, $i$ = 0, 1, 2, …, ($p$ - 2)., and $U_j(p - 1) = 0$,

where $U_j(i)$ is the input bit position of $i$-th output after the permutation of $j$-th row.

end if

if ($C = p + 1$) then

$U_j(i) = s([i \times r_j] \bmod (p - 1))$, $i$ = 0, 1, 2, …, ($p$ - 2)., $U_j(p - 1) = 0$, and $U_j(p) = p$,

where $U_j(i)$ is the input bit position of $i$-th output after the permutation of $j$-th row, and

if ($K = C \times R$) then

Exchange $U_{R-1}(p)$ with $U_{R-1}(0)$.

end

if

end if

if ($C = p - 1$) then

$U_j(i) = s([i \times r_j] \bmod (p - 1)) - 1$, $i$ = 0, 1, 2, …, ($p$ - 2),

where $U_j(i)$ is the input bit position of $i$-th output after the permutation of $j$-th row.
end if

(6) Perform the inter-row permutation based on the pattern $T(j)$ ($j$ = 0, 1, 2, …, $R$ - 1),
where $T(j)$ is the original row position of the $j$-th permuted row.

**Table 2: Table of prime *p* and associated primitive root *v***

| p | v | p | v | p | v | p | v | p | v |
|---|---|---|---|---|---|---|---|---|---|
| 7 | 3 | 313 | 10 | 709 | 2 | 1129 | 11 | 1597 | 11 |
| 11 | 2 | 317 | 2 | 719 | 11 | 1151 | 17 | 1601 | 3 |
| 13 | 2 | 331 | 3 | 727 | 5 | 1153 | 5 | 1607 | 5 |
| 17 | 3 | 337 | 10 | 733 | 6 | 1163 | 5 | 1609 | 7 |
| 19 | 2 | 347 | 2 | 739 | 3 | 1171 | 2 | 1613 | 3 |
| 23 | 5 | 349 | 2 | 743 | 5 | 1181 | 7 | 1619 | 2 |
| 29 | 2 | 353 | 3 | 751 | 3 | 1187 | 2 | 1621 | 2 |
| 31 | 3 | 359 | 7 | 757 | 2 | 1193 | 3 | 1627 | 3 |
| 37 | 2 | 367 | 6 | 761 | 6 | 1201 | 11 | 1637 | 2 |
| 41 | 6 | 373 | 2 | 769 | 11 | 1213 | 2 | 1657 | 11 |
| 43 | 3 | 379 | 2 | 773 | 2 | 1217 | 3 | 1663 | 3 |
| 47 | 5 | 383 | 5 | 787 | 2 | 1223 | 5 | 1667 | 2 |
| 53 | 2 | 389 | 2 | 797 | 2 | 1229 | 2 | 1669 | 2 |
| 59 | 2 | 397 | 5 | 809 | 3 | 1231 | 3 | 1693 | 2 |
| 61 | 2 | 401 | 3 | 811 | 3 | 1237 | 2 | 1697 | 3 |
| 67 | 2 | 409 | 21 | 821 | 2 | 1249 | 7 | 1699 | 3 |
| 71 | 7 | 419 | 2 | 823 | 3 | 1259 | 2 | 1709 | 3 |
| 73 | 5 | 421 | 2 | 827 | 2 | 1277 | 2 | 1721 | 3 |
| 79 | 3 | 431 | 7 | 829 | 2 | 1279 | 3 | 1723 | 3 |
| 83 | 2 | 433 | 5 | 839 | 11 | 1283 | 2 | 1733 | 2 |
| 89 | 3 | 439 | 15 | 853 | 2 | 1289 | 6 | 1741 | 2 |
| 97 | 5 | 443 | 2 | 857 | 3 | 1291 | 2 | 1747 | 2 |
| 101 | 2 | 449 | 3 | 859 | 2 | 1297 | 10 | 1753 | 7 |
| 103 | 5 | 457 | 13 | 863 | 5 | 1301 | 2 | 1759 | 6 |
| 107 | 2 | 461 | 2 | 877 | 2 | 1303 | 6 | 1777 | 5 |
| 109 | 6 | 463 | 3 | 881 | 3 | 1307 | 2 | 1783 | 10 |
| 113 | 3 | 467 | 2 | 883 | 2 | 1319 | 13 | 1787 | 2 |
| 127 | 3 | 479 | 13 | 887 | 5 | 1321 | 13 | 1789 | 6 |
| 131 | 2 | 487 | 3 | 907 | 2 | 1327 | 3 | 1801 | 11 |
| 137 | 3 | 491 | 2 | 911 | 17 | 1361 | 3 | 1811 | 6 |
| 139 | 2 | 499 | 7 | 919 | 7 | 1367 | 5 | 1823 | 5 |
| 149 | 2 | 503 | 5 | 929 | 3 | 1373 | 2 | 1831 | 3 |
| 151 | 6 | 509 | 2 | 937 | 5 | 1381 | 2 | 1847 | 5 |
| 157 | 5 | 521 | 3 | 941 | 2 | 1399 | 13 | 1861 | 2 |
| 163 | 2 | 523 | 2 | 947 | 2 | 1409 | 3 | 1867 | 2 |
| 167 | 5 | 541 | 2 | 953 | 3 | 1423 | 3 | 1871 | 14 |
| 173 | 2 | 547 | 2 | 967 | 5 | 1427 | 2 | 1873 | 10 |
| 179 | 2 | 557 | 2 | 971 | 6 | 1429 | 6 | 1877 | 2 |
| 181 | 2 | 563 | 2 | 977 | 3 | 1433 | 3 | 1879 | 6 |
| 191 | 19 | 569 | 3 | 983 | 5 | 1439 | 7 | 1889 | 3 |
| 193 | 5 | 571 | 3 | 991 | 6 | 1447 | 3 | 1901 | 2 |
| 197 | 2 | 577 | 5 | 997 | 7 | 1451 | 2 | 1907 | 2 |
| 199 | 3 | 587 | 2 | 1009 | 11 | 1453 | 2 | 1913 | 3 |
| 211 | 2 | 593 | 3 | 1013 | 3 | 1459 | 3 | 1931 | 2 |
| 223 | 3 | 599 | 7 | 1019 | 2 | 1471 | 6 | 1933 | 5 |
| 227 | 2 | 601 | 7 | 1021 | 10 | 1481 | 3 | 1949 | 2 |
| 229 | 6 | 607 | 3 | 1031 | 14 | 1483 | 2 | 1951 | 3 |
| 233 | 3 | 613 | 2 | 1033 | 5 | 1487 | 5 | 1973 | 2 |
| 239 | 7 | 617 | 3 | 1039 | 3 | 1489 | 14 | 1979 | 2 |
| 241 | 7 | 619 | 2 | 1049 | 3 | 1493 | 2 | 1987 | 2 |
| 251 | 6 | 631 | 3 | 1051 | 7 | 1499 | 2 | 1993 | 5 |
| 257 | 3 | 641 | 3 | 1061 | 2 | 1511 | 11 | 1997 | 2 |
| 263 | 5 | 643 | 11 | 1063 | 3 | 1523 | 2 | 1999 | 3 |
| 269 | 2 | 647 | 5 | 1069 | 6 | 1531 | 2 | | |
| 271 | 6 | 653 | 2 | 1087 | 3 | 1543 | 5 | | |
| 277 | 5 | 659 | 2 | 1091 | 2 | 1549 | 2 | | |
| 281 | 3 | 661 | 2 | 1093 | 5 | 1553 | 3 | | |
| 283 | 3 | 673 | 5 | 1097 | 3 | 1559 | 19 | | |
| 293 | 2 | 677 | 2 | 1103 | 5 | 1567 | 3 | | |
| 307 | 5 | 683 | 5 | 1109 | 2 | 1571 | 2 | | |
| 311 | 17 | 691 | 3 | 1117 | 2 | 1579 | 3 | | |

2.3.3 Bits-output from rectangular matrix with pruning

After intra-row and inter-row permutations, the bits of the permuted rectangular matrix are denoted by $y'_k$:

$$\begin{bmatrix} y'_1 & y'_{(R+1)} & y'_{(2R+1)} & \cdots y'_{((C-1)R+1)} \\ y'_2 & y'_{(R+2)} & y'_{(2R+2)} & \cdots y'_{((C-1)R+2)} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ y'_R & y'_{2R} & y'_{3R} & \cdots & y'_{CR} \end{bmatrix}$$

The output of the Turbo code internal interleaver is the bit sequence read out column by column from the intra-row and inter-row permuted $R \times C$ matrix starting with bit $y'_1$ in row 0 of column 0 and ending with bit $y'_{CR}$ in row $R$ - 1 of column $C$ - 1. The output is pruned by deleting bits that were not present in the input bit sequence, i.e. bits $y'_k$ that corresponds to bits $x_k$ with $k > K$ are removed from the output. The bits output from Turbo code internal interleaver are denoted by $x'_1$, $x'_2$, …, $x'_K$, where $x'_1$ corresponds to the bit $y'_k$ with smallest index $k$ after pruning, $x'_2$ to the bit $y'_k$ with second smallest index $k$ after pruning, and so on. The number of bits output from Turbo code internal interleaver is $K$ and the total number of pruned bits is: $R \times C - K$.

2.3.2 Option 2: LRI interleaver design.

The interleaver proposed is the LRI interleaver. The interleaving sequence of LRI is as follows:

A. Determination of the interleaving buffer size.

M: Number of column in the interleaving buffer (M > 16).
N: Number of rows in the interleaving buffer (N > 16).
BL: Interleaving block size (BL= PxP >= MxN).
P: Minimum prime number that is larger than M.
v: Minimum primitive root of P.

B. Making basic random set whose length is M

$$C(0) = 1 \; ; \quad C(i+1) = v \times C(i) \bmod P, \qquad i = 0,1,\ldots P-3 \qquad (5)$$

C. Making j-th inter-row permutation pattern.

By shifting output of step 2 one by one per inter-row, a Latin square matrix is made. The last (M-1)th column is processed specially in order to avoid low hamming weight phenomenon caused by the forced termination.

$$CLj\,(i) = C\,(j + i \bmod M\text{-}1) \;\; ; \;\; CLj(M\text{-}1) = 0 \;\; ; \; i = 0,1,\ldots M\text{-}2 \; ; \quad j = 0\,,1,\ldots,N\text{-}1 \qquad (6)$$

D. Row by row 2D-mapping of di to MxN buffer.

$$d^*\,j\,(i) = i+Mxj \;\; , \; i = 0,1,\ldots,M\text{-}2 \;\; ; \;\; j=0,1,\ldots,N\text{-}1 \qquad (7)$$

E. Permutating of 2D-mapped input set di by the permutation pattern made in point 3.

$$d^{**}\,j(i) = d^*\,(N\text{-}j)\,(CL)N\text{-}j)\,(i)),\,,\; i = 0,1,\ldots,M\text{-}1;\; j = 0,1,\ldots,N\text{-}1 \qquad (8)$$

F. Reading a permuted input set column by column, and making output set.

$$d'(j+Nxi) = d^{**}j(i)\,,\; i = 0,1,\ldots,M\text{-}1;\; j = 0,1,\ldots,N\text{-}1 \qquad (9)$$

G. Pruning bits.

d' is pruned by deleting the l-bits in order to adjust the output d' to the input block length BL, where the deleted bits are non-existent bits in the input sequence. The pruning number L is defined as L = MxN - BL.

## 2.4. Coding And Modulation For 4 Bit/S/Hz Spectral Efficiency.

### 2.4.1 Puncturing

In order to obtain a rate 4/6 code, the puncturing pattern used is shown in Table 3.

Table 3. Puncturing and Mapping for Rate 4/6 64 QAM

| **Information bit (d)** | $d_1$ | $d_2$ | $d_3$ | $d_4$ |
|---|---|---|---|---|
| **parity bit (p)** | $p_1$ | - | - | - |
| **parity bit (q)** | - | - | $q_3$ | - |
| **8AM symbol (I)** | $(d_1, d_2, p_1)$ | | | |
| **8AM symbol (Q)** | $(d_3, d_4, q_3)$ | | | |
| **64 QAM symbol (I , Q)** | $(I, Q)=(d_1,d_2, p_1,d_3, d_4,q_3)$ | | | |

### 2.4.2 Modulation

Gray mapping was used in each dimension. Four information bits are required to be sent using a 64 QAM constellation. For a rate 4/6 code and 64 QAM, the noise variance in each dimension is

$$E_{av} = (8(49+25+9+1+25+49+49+9+49+1+25+9+25+1+9+1))\, A^2 / 64 = 42\, A^2 \qquad (10)$$

$$\sigma_N^2 = E_{av}\left(\frac{2\eta E_b}{N_0}\right)^{-1} = 42\, A^2\left(\frac{2 \times 4 \times E_b}{N_0}\right)^{-1} = 5.25\, A^2\left(\frac{E_b}{N_0}\right)^{-1} \qquad (11)$$

The puncturing and mapping scheme is shown in Table 6 for 4 consecutive information bits that are encoded into 6 coded bits, therefore one 64 QAM symbol. The turbo encoder with the puncturing presented in Table 6 is a rate 4/6 turbo code which in conjunction with 64 QAM gives a spectral efficiency of 4 bits/s/Hz. Considering two independent Gaussian noises with identical variance $\sigma^2_N$, the LLR can be determined independently for each I and Q. It is assumed that at time k $u_1^k$, $u_2^k$ and $u_3^k$ modulate the I component and $u_4^k$, $u_5^k$ and $u_6^k$ modulate the Q component of the 64 QAM scheme. At the receiver, the I and Q signals are treated independently in order to take advantage of the simpler formulae for the LLR values.

### 2.4.3 Bit Probabilities

The 8AM symbol is defined as $u^k= (u_1^k, u_2^k, u_3^k)$, where $u_1^k$ is the most significant bit and $u_3^k$ is the least significant bit . The following set can be defined.

1. bit-1-is-1 = $\{ A_4, A_5, A_6, A_7 \}$
2. bit-2-is-1 = $\{A_0, A_1, A_6, A_7 \}$
3. bit-3-is-1 = $\{A_1, A_2, A_5, A_6 \}$

From each received symbol, the bit probabilities are computed as follows:

$$LLR(u_n^k) = \log\left(\frac{\sum_{i=1}^{4}\exp[-\frac{1}{2\sigma_N^2}(I^k - a_{1,i,n}^k)^2]}{\sum_{i=1}^{4}\exp[-\frac{1}{2\sigma_N^2}(I^k - a_{0,i,n}^k)^2]}\right) \tag{12}$$

For I dimension. An identical computation effort is required for the Q dimension, the $I^k$ being replaced with the $Q^k$ demodulated value in order to evaluate LLR($u_4^k$), LLR($u_5^k$) and LLR($u_6^k$).

### 2.4.4 Simulation Results

Figure 3 shows the simulation results for 10,400 information bits with interleaver option 1. A BER of $10^{-7}$ can be achieved after 8 iterations at $E_b/N_0$ = 8.3 dB.

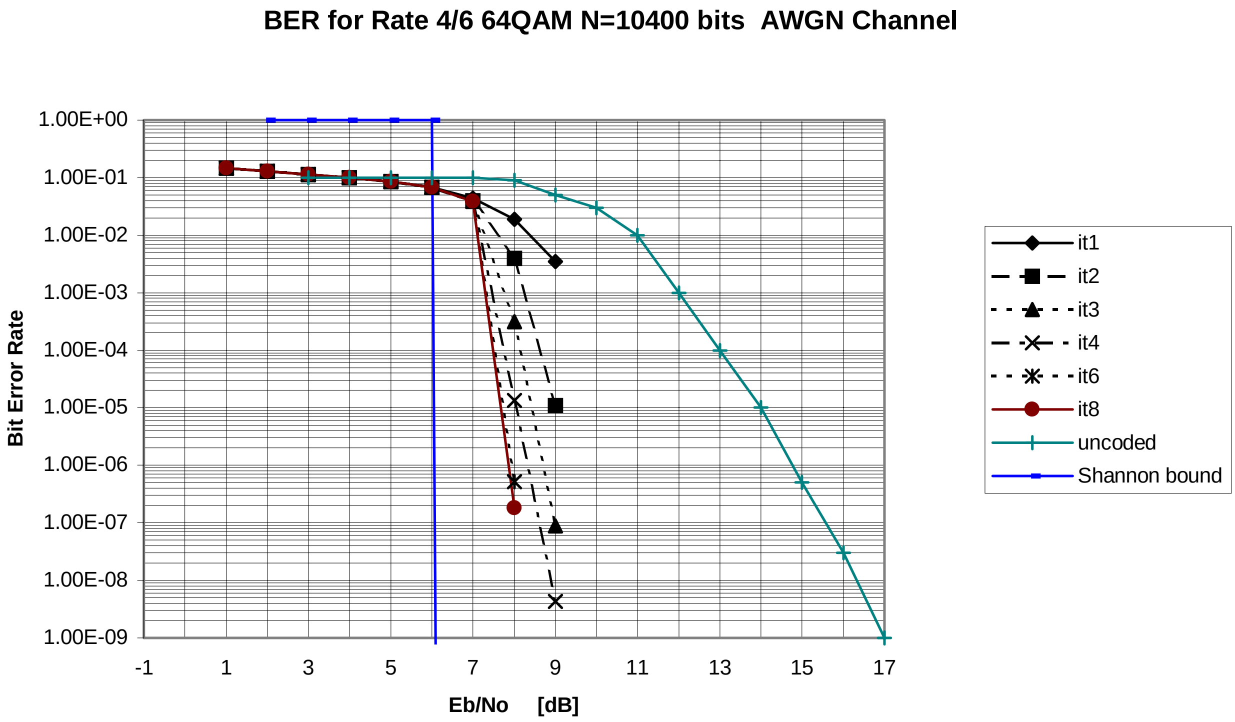


Figure 3.

## 2.5 Coding And Modulation For 12 Bit/S/Hz Spectral Efficiency.

This section investigated a rate 12/14 coding scheme with 16384 QAM.

### 2.5.1 Puncturing

In order to obtain a rate 12/14 code, the puncturing pattern used is shown in Table 4.

Table 4. Puncturing and Mapping for Rate 12/14 16384 QAM

| **Information bit (d)** | $d_1$ | $d_2$ | $d_3$ | $d_4$ | $d_5$ | $d_6$ | $d_7$ | $d_8$ | $d_9$ | $d_{10}$ | $d_{11}$ | $d_{12}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **parity bit (p)** | $p_1$ | - | - | - | - | - | - | - | - | - | - | - |
| **parity bit (q)** | - | - | - | - | - | - | $q_7$ | - | - | - | - | - |
| **128AM symbol (I)** | ($d_1$, $d_2$ , $d_3$, $d_4$ $d_5$, $d_6$ , $p_1$) | | | | | | | | | | | |
| **128AM symbol (Q)** | ($d_7$, $d_8$, $d_9$ ,$d_{10}$ , $d_{11}$, $d_{12}$, $q_7$ ) | | | | | | | | | | | |
| **16384 QAM symbol (I , Q)** | ($d_1$, $d_2$ , $d_3$, $d_4$ $d_5$, $d_6$ , $p_1$, $d_7$, $d_8$, $d_9$ ,$d_{10}$ , $d_{11}$, $d_{12}$, $q_7$ ) | | | | | | | | | | | |

## 2.5.2 Modulation

For a 16384 QAM constellation with points at –127A, -125A, -123A, -121A, -119A, -117A, -115A, -113A, -111A, -109A, -107A, -105A, -103A, -101A, -99A, -97A, -95A, -93A, -91A, -89A, -87A, -85A, -83A, -81A, -79A, -77A, -75A, -73A, -71A, -69A, -67A, -65A, -63A, -61A, -59A, -57A, -55A, -53A, -51A, -49A, -47A, -45A, -43A, -41A, -39A, -37A, -35A, -33A, -31A, -29A, -27A, -25A, -23A, -21A, -19A, -17A, –15A, -13A, -11A, -9A, -7A, -5A, -3A, -A, A, 3A, 5A, 7A, 9A, 11A, 13A, 15A, 17A, 19A, 21A, 23A, 25A, 27A, 29A, 31A, 33A, 35A, 37A, 39A, 41A, 43A, 45A, 47A, 49A, 51A, 53A, 55A, 57A, 59A, 61A, 63A, 65A, 67A, 69A, 71A, 73A, 75A, 77A, 79A, 81A, 83A, 95A, 87A, 89A, 91A, 93A, 95A, 97A, 99A, 101A, 103A, 105A, 107A, 109A, 111A, 113A, 115A, 117A, 119A, 121A, 123A, 125A, 127A. $E_{av}$ is:

$$E_{av} = 5461\ A^2 \tag{13}$$

It is assumed that at time k the symbol $u^k = (u_1^k, u_2^k, u_3^k, u_4^k, u_5^k, u_6^k, u_7^k, u_8^k, u_9^k, u_{10}^k, u_{11}^k, u_{12}^k, u_{13}^k, u_{14}^k)$ is sent though the channel. It is assumed that at time k the symbol $u_1^k$, $u_2^k$, $u_3^k$, $u_4^k$, $u_5^k$, $u_6^k$ and $u_7^k$ modulate the I component and $u_8^k$, $u_9^k$, $u_{10}^k$ $u_{11}^k$, $u_{12}^k$, $u_{13}^k$ and $u_{14}^k$ modulate the Q component of a 16384 QAM scheme.

For a rate 12/14 code and 16384 QAM, the noise variance is:

$$\sigma_N^2 = E_{av}\left(\frac{2\eta\, E_b}{N_0}\right)^{-1} = 5461\, A^2\left(\frac{2\ x\ 6\ x\ E_b}{N_0}\right)^{-1} = 455.08\, A^2\left(\frac{E_b}{N_0}\right)^{-1} \tag{14}$$

In order to study the performance of this scheme, a rate 6/7 turbo code and a 128AM is used. The 16384 QAM scheme will achieve a similar performance in terms of bit error rate (BER) at twice the spectral efficiency, assuming an ideal demodulator. The puncturing and mapping scheme shown in Table 8 is for 12 consecutive information bits that are coded into 14 encoded bits, therefore, one 16384 QAM symbol. The turbo encoder is a rate 12/14 turbo code, which in conjunction with 16384 QAM, gives a spectral efficiency of 12 bits/s/Hz.

## 2.5.3 Bit Probabilities

The 128AM symbol is defined as $u^k = (u_1^k, u_2^k, u_3^k, u_4^k, u_5^k, u_6^k, u_7^k)$, where $u_1^k$ is the most significant bit and $u_7^k$ is the least significant bit . The following set can be defined.

1. bit-1-is-1 = $\{A_{64},A_{65},A_{66}, A_{67}, A_{68}, A_{69}, A_{70}, A_{71}, A_{72}, A_{73}, A_{74}, A_{75}, A_{76}, A_{77}, A_{78}, A_{79}$ $A_{80}, A_{81}, A_{82}, A_{83}, A_{84}, A_{85}, A_{86}, A_{87}, A_{88}, A_{89}, A_{90}, A_{91}, A_{92}, A_{93}, A_{94}, A_{95}$ $A_{96}, A_{97}, A_{98}, A_{99}, A_{100},A_{101},A_{102},A_{103},A_{104}, A_{105},A_{106},A_{107},A_{108}, A_{109}, A_{110}, A_{111}$ $A_{112},A_{113},A_{114},A_{115},A_{116},A_{117},A_{118},A_{119},A_{120},A_{121},A_{122},A_{123},A_{124},A_{125}, A_{126}, A_{127}\}$
2. bit-2-is-1 = $\{A_{32}, A_{33}, A_{34}, A_{35}, A_{36}, A_{37}, A_{38}, A_{39}, A_{40}, A_{41}, A_{42}, A_{43}, A_{44}, A_{45}, A_{46}, A_{47}$ $A_{48},A_{49}, A_{50}, A_{51}, A_{52}, A_{53}, A_{54}, A_{55}, A_{56}, A_{57}, A_{58}, A_{59}, A_{60}, A_{61}, A_{62}, A_{63}$ $A_{64},A_{65},A_{66}, A_{67}, A_{68}, A_{69}, A_{70}, A_{71}, A_{72}, A_{73}, A_{74}, A_{75}, A_{76}, A_{77}, A_{78}, A_{79}$ $A_{80}, A_{81}, A_{82}, A_{83}, A_{84}, A_{85}, A_{86}, A_{87}, A_{88}, A_{89}, A_{90}, A_{91}, A_{92}, A_{93}, A_{94}, A_{95}\}$
3. bit-3-is-1 = $\{A_{16}, A_{17}, A_{18}, A_{19}, A_{20}, A_{21}, A_{22}, A_{23}, A_{24}, A_{25}, A_{26}, A_{27}, A_{28}, A_{29}, A_{30}, A_{31}$ $A_{32}, A_{33}, A_{34}, A_{35}, A_{36}, A_{37}, A_{38}, A_{39}, A_{40}, A_{41}, A_{42}, A_{43}, A_{44}, A_{45}, A_{46}, A_{47}$ $A_{80}, A_{81}, A_{82}, A_{83}, A_{84}, A_{85}, A_{86}, A_{87}, A_{88}, A_{89}, A_{90}, A_{91}, A_{92}, A_{93}, A_{94}, A_{95}$ $A_{96}, A_{97}, A_{98}, A_{99}, A_{100},A_{101},A_{102},A_{103},A_{104}, A_{105},A_{106},A_{107},A_{108}, A_{109}, A_{110}, A_{111}\}$
4. bit-4-is-1 = $\{A_8, A_9, A_{10}, A_{11}, A_{12}, A_{13}, A_{14}, A_{15}, A_{16}, A_{17}, A_{18}, A_{19}, A_{20}, A_{21}, A_{22}, A_{23},$ $A_{40}, A_{41}, A_{42}, A_{43}, A_{44}, A_{45}, A_{46}, A_{47}, A_{48},A_{49}, A_{50}, A_{51}, A_{52}, A_{53}, A_{54}, A_{55},$ $A_{72}, A_{73}, A_{74}, A_{75}, A_{76}, A_{77}, A_{78}, A_{79}, A_{80}, A_{81}, A_{82}, A_{83}, A_{84}, A_{85}, A_{86}, A_{87},$ $A_{104}, A_{105},A_{106},A_{107},A_{108}, A_{109}, A_{110}, A_{111}, A_{112},A_{113},A_{114},A_{115},A_{116},A_{117},A_{118},A_{119}, \}$
5. bit-5-is-1 = $\{A_4, A_5, A_6, A_7, A_8, A_9, A_{10}, A_{11},A_{20}, A_{21}, A_{22}, A_{23}, A_{24}, A_{25}, A_{26}, A_{27}$ $A_{36}, A_{37}, A_{38}, A_{39}, A_{40}, A_{41}, A_{42}, A_{43}, A_{52}, A_{53}, A_{54}, A_{55}, A_{56}, A_{57}, A_{58}, A_{59}$ $A_{68}, A_{69}, A_{70}, A_{71}, A_{72}, A_{73}, A_{74}, A_{75}, A_{84}, A_{85}, A_{86}, A_{87}, A_{88}, A_{89}, A_{90}, A_{91},$ $A_{100},A_{101},A_{102},A_{103},A_{104}, A_{105},A_{106},A_{107}A_{116},A_{117},A_{118},A_{119},A_{120},A_{121},A_{122},A_{123}, \}$

6. bit-6-is-1 = $\{A_0, A_1 A_6, A_7, A_8, A_9, A_{14}, A_{15}, A_{16}, A_{17} A_{22}, A_{23}, A_{24}, A_{25}, A_{30}, A_{31}$
$A_{32}, A_{33} A_{38}, A_{39}, A_{40}, A_{41} A_{46}, A_{47}, A_{48}, A_{49} A_{54}, A_{55}, A_{56}, A_{57} A_{62}, A_{63}$
$A_{64}, A_{65}, A_{70}, A_{71}, A_{72}, A_{73}, A_{78}, A_{79}, A_{80}, A_{81}, A_{86}, A_{87}, A_{88}, A_{89}, A_{94}, A_{95}$
$A_{96}, A_{97}, A_{102}, A_{103}, A_{104}, A_{105}, A_{110}, A_{111} A_{112}, A_{113}, , A_{118}, A_{119}, A_{120}, A_{121}, A_{126}, A_{127}\}$

7. bit-7-is-1 = $\{A_1, A_2, A_5, A_6, A_9, A_{10}, A_{13}, A_{14}, A_{17}, A_{18}, A_{21}, A_{22}, A_{25}, A_{26}, A_{29}, A_{30},$
$A_{33}, A_{34}, A_{37}, A_{38}, A_{41}, A_{42}, A_{45}, A_{46}, A_{49}, A_{50}, A_{53}, A_{54}, A_{57}, A_{58}, A_{61}, A_{62}$
$A_{65}, A_{66}, A_{69}, A_{70}, A_{73}, A_{74}, A_{77}, A_{78}, A_{81}, A_{82}, A_{85}, A_{86}, A_{89}, A_{90}, A_{93}, A_{94}, A_{97},$
$A_{98}, A_{101}, A_{102}, A_{105}, A_{106}, A_{109}, A_{110}, A_{113}, A_{114}, A_{117}, A_{118}, A_{121}, A_{122}, A_{125}, A_{126}\}$

From each received symbol, $R^k$, the bit probabilities are computed as follows:

$$LLR(u_n^k) = \log\left(\frac{\sum_{A_i \in bit\text{-}n\text{-}is\text{-}1} \exp\left(-\frac{1}{2\sigma_N^2}\left\| R^k - A_i \right\|\right)}{\sum_{A_j \in bit\text{-}n\text{-}is\text{-}0} \exp\left(-\frac{1}{2\sigma_N^2}\left\| R^k - A_j \right\|\right)}\right) \tag{17}$$

### 2.5.4 Simulation Results

Figure 4 shows the simulation results for 31200 information bits with interleaver option 1. A BER of $10^{-7}$ can be achieved after 8 iterations at $E_b/N_0$ = 28.25 dB.

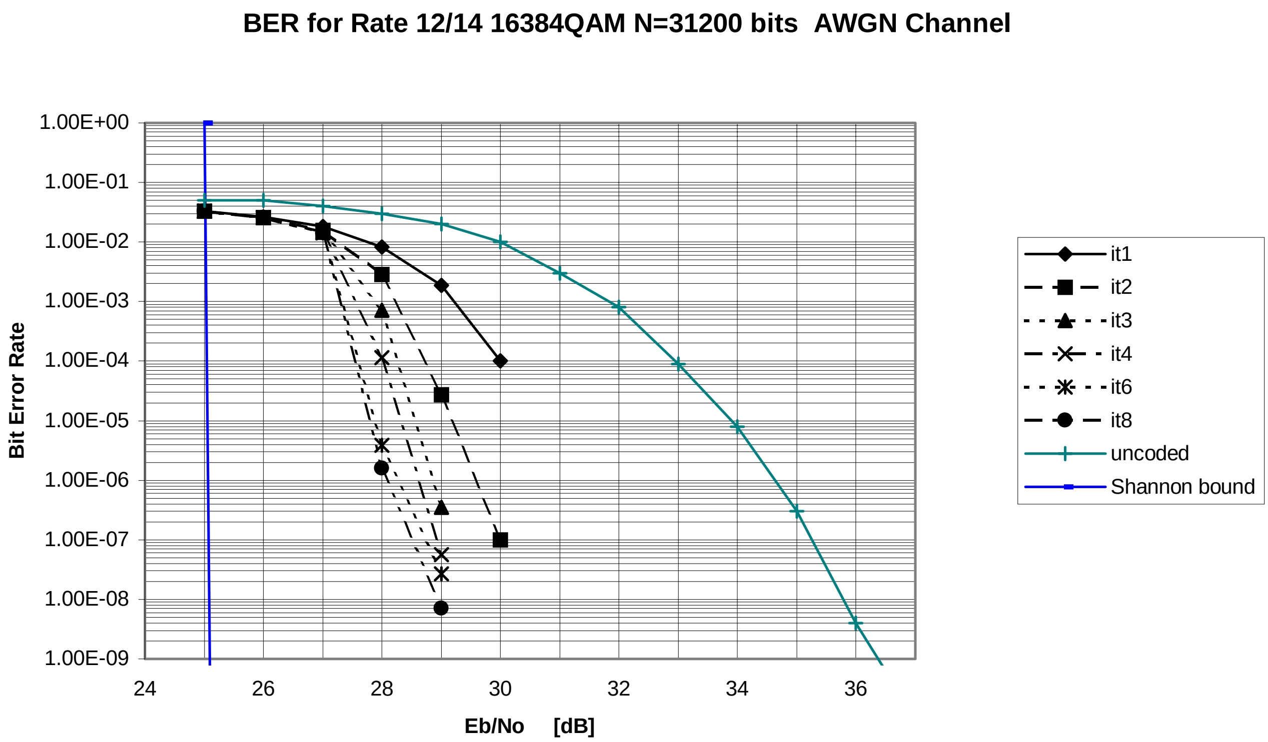


Figure 4

# 3. Results.

## 3.1 Without Reed-Solomon

### 3.1.1 Net Coding Gain.

Table 5. Net Coding Gain

| Bit/Tone | Tones | Interleaver Size | # of DMT symbols | Latency (Tx+Rx) ms < | $10^{-3}$ | $10^{-7}$ | $10^{-9}$ extrap. |
|---|---|---|---|---|---|---|---|
| 4 | 100 | 5,200 | 13 | 10.0 | 4.60 | 7.42 | 7.94 |
| | | 800 | 2 | 1.5 | 3.70 | 4.92 | 4.84 |
| | | 400 | 1 | 0.7 | 3.30 | 3.62 | 3.84 |
| | 200 | 10,400 | 13 | 10.0 | 4.60 | 7.52 | 8.14 |
| | | 1,600 | 2 | 1.5 | 4.10 | 6.42 | 6.64 |
| | | 800 | 1 | 0.7 | 3.70 | 4.92 | 4.84 |
| 12 | 100 | 15,600 | 13 | 10.0 | 4.10 | 5.91 | 6.03 |
| | | 2,400 | 2 | 1.5 | 3.60 | 5.51 | 5.63 |
| | | 1,200 | 1 | 0.7 | 3.00 | 3.91 | 4.03 |
| | 200 | 31,200 | 13 | 10.0 | 4.10 | 6.81 | 7.53 |
| | | 4,800 | 2 | 1.5 | 3.60 | 5.91 | 6.43 |
| | | 2,400 | 1 | 0.7 | 3.60 | 5.51 | 5.63 |

### 3.1.2 Errors due to Impulse noise.

The impulse noise is defined as 2 consecutive DMT symbols with an increase AWGN respect to the reference noise level of a carrier-to-noise ratio of 21.5 dB (for 4 bit/tone) and 45.5 dB (for 12 bit/tone).

Table 6. Error due to Impulse Noise

| Bit/ Tone | Tones | Interleaver Size | RL + 2.5 dB | RL + 5 dB | RL + 7.5 dB | RL + 10 dB | RL + 12.5 dB | RL + 15 dB | RL + 17.5 dB | RL + 20 dB |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 100 | 5,200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 |
| | | 800 | 0 | 0 | 39 | 65 | 104 | 140 | 188 | 243 |
| | | 400 | 0 | 0 | 10 | 50 | 89 | 127 | 161 | 214 |
| | 200 | 10,400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| | | 1,600 | 0 | 0 | 0 | 127 | 189 | 267 | 363 | 448 |
| | | 800 | 0 | 0 | 40 | 116 | 187 | 252 | 346 | 440 |
| 12 | 100 | 15,600 | 0 | 0 | 0 | 0 | 10 | 58 | 130 | 207 |
| | | 2,400 | 0 | 0 | 40 | 78 | 121 | 171 | 216 | 295 |
| | | 1,200 | 0 | 0 | 43 | 98 | 129 | 188 | 255 | 329 |
| | 200 | 31,200 | 0 | 0 | 0 | 0 | 90 | 175 | 313 | 482 |
| | | 4,800 | 0 | 0 | 75 | 177 | 254 | 341 | 462 | 608 |
| | | 2,400 | 0 | 0 | 80 | 166 | 244 | 345 | 457 | 598 |

### 3.1.3 Error Statistics.

### 3.1.3.1 For AWGN

Table 7. Error Statistics for AWGN

| Bit/Tone | Tones | Interleaver Size | 1 consec. error | 2 consec errors | 3 consec errors | 4 consec errors | 5 consec errors | 6 consec errors |
|---|---|---|---|---|---|---|---|---|
| 4 | 100 | 5,200 | 87.30% | 10.81% | 1.47% | 0.29% | 0.03% | 0.10% |
| | | 800 | 94.35% | 5.64% | 0.00% | 0.00% | 0.00% | 0.00% |
| | | 400 | 90.28% | 9.72% | 0.01% | 0.00% | 0.00% | 0.00% |
| | 200 | 10,400 | 89.90% | 8.63% | 1.21% | 0.20% | 0.06% | 0.00% |
| | | 1,600 | 97.94% | 2.06% | 0.00% | 0.00% | 0.00% | 0.00% |
| | | 800 | 90.28% | 9.72% | 0.01% | 0.00% | 0.00% | 0.00% |
| 12 | 100 | 15,600 | 99.79% | 0.21% | 0.00% | 0.00% | 0.00% | 0.00% |
| | | 2,400 | 98.72% | 1.28% | 0.00% | 0.00% | 0.00% | 0.00% |
| | | 1,200 | 97.94% | 2.06% | 0.00% | 0.00% | 0.00% | 0.00% |
| | 200 | 31,200 | 99.86% | 0.14% | 0.00% | 0.00% | 0.00% | 0.00% |
| | | 4,800 | 100.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| | | 2,400 | 98.72% | 1.28% | 0.00% | 0.00% | 0.00% | 0.00% |

### 3.1.3.2 Impulse Noise

Table 8. Error Statistics for Impulse noise

| Bit/Tone | Tones | Interleaver Size | 1 consec. error | 2 consec errors | 3 consec errors | 4 consec errors | 5 consec errors | 6 consec errors |
|---|---|---|---|---|---|---|---|---|
| 4 | 100 | 5,200 | 100.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| | | 800 | 75.97% | 18.99% | 18.99% | 3.36% | 0.84% | 0.84% |
| | | 400 | 79.89% | 17.24% | 1.72% | 1.15% | 0.00% | 0.00% |
| | 200 | 10,400 | 100.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| | | 1,600 | 80.24% | 13.05% | 4.47% | 1.68% | 0.47% | 0.00% |
| | | 800 | 79.03% | 17.50% | 2.46% | 0.46% | 0.46% | 0.00% |
| 12 | 100 | 15,600 | 95.19% | 4.81% | 0.00% | 0.00% | 0.00% | 0.00% |
| | | 2,400 | 94.61% | 5.28% | 0.11% | 0.00% | 0.00% | 0.00% |
| | | 1,200 | 93.63% | 5.95% | 93.63% | 0.00% | 0.00% | 0.00% |
| | 200 | 31,200 | 93.25% | 6.65% | 0.00% | 0.00% | 0.00% | 0.00% |
| | | 4,800 | 94.89% | 4.95% | 0.16% | 0.00% | 0.00% | 0.00% |
| | | 2,400 | 94.59% | 5.36% | 0.06% | 0.00% | 0.00% | 0.00% |

It is interesting that for the large turbo decoders the impulse errors still tends to stay within the 2 DMT symbols. This implies a moderately large turbo coder of 5 ms follow by a convolutional interleaver/Reed Solomon of 10 ms should create both robust performance and good impulse resistance.

## 3.2 With Reed-Solomon

### 3.2.1 Net Coding Gain.

Table 9. Coding Gain

| Bit/Tone | Tones | Interleaver Size | # of DMT symbols | Latency (Tx+Rx) ms < | $10^{-3}$ | $10^{-7}$ | $10^{-9}$ extrap. |
|---|---|---|---|---|---|---|---|
| 4 | 100 | 5,200 | 13 | 10.0 | 5.00 | 8.62 | 9.64 |
| | | 800 | 2 | 1.5 | 3.50 | 7.12 | 8.44 |
| | | 400 | 1 | 0.7 | 3.50 | 6.42 | 7.44 |
| | 200 | 10,400 | 13 | 10.0 | 5.30 | 8.82 | 9.84 |
| | | 1,600 | 2 | 1.5 | 4.60 | 7.72 | 8.74 |
| | | 800 | 1 | 0.7 | 3.50 | 7.12 | 8.44 |
| 12 | 100 | 15,600 | 13 | 10.0 | 4.40 | 7.71 | 8.53 |
| | | 2,400 | 2 | 1.5 | 4.60 | 7.41 | 8.33 |
| | | 1,200 | 1 | 0.7 | 4.10 | 6.81 | 7.63 |
| | 200 | 31,200 | 13 | 10.0 | 4.40 | 7.71 | 8.53 |
| | | 4,800 | 2 | 1.5 | 4.40 | 7.21 | 8.13 |
| | | 2,400 | 1 | 0.7 | 4.60 | 7.41 | 8.33 |

Table 10. Net Coding Gain

| Bit/Tone | Tones | Interleaver Size | # of DMT symbols | Latency (Tx+Rx) ms < | $10^{-3}$ | $10^{-7}$ | $10^{-9}$ extrap. |
|---|---|---|---|---|---|---|---|
| 4 | 100 | 5,200 | 13 | 10.0 | 3.42 | 7.04 | 8.06 |
| | | 800 | 2 | 1.5 | 1.78 | 5.40 | 6.72 |
| | | 400 | 1 | 0.7 | 1.94 | 4.86 | 5.88 |
| | 200 | 10,400 | 13 | 10.0 | 3.72 | 7.24 | 8.26 |
| | | 1,600 | 2 | 1.5 | 2.88 | 6.00 | 7.02 |
| | | 800 | 1 | 0.7 | 1.94 | 5.56 | 6.88 |
| 12 | 100 | 15,600 | 13 | 10.0 | 0.20 | 3.51 | 4.33 |
| | | 2,400 | 2 | 1.5 | 0.02 | 2.83 | 3.75 |
| | | 1,200 | 1 | 0.7 | -0.24 | 2.47 | 3.29 |
| | 200 | 31,200 | 13 | 10.0 | 1.06 | 4.37 | 5.19 |
| | | 4,800 | 2 | 1.5 | 0.76 | 3.57 | 4.49 |
| | | 2,400 | 1 | 0.7 | 0.26 | 3.07 | 3.99 |

### 3.2.2 Errors due to Impulse noise.

The impulse noise is defined as 2 consecutive DMT symbols with an increase AWGN respect to the reference noise level of a carrier-to-noise ratio of 21.5 dB (for 4 bit/tone) and 45.5 dB (for 12 bit/tone).

Table 11. Error due to Impulse Noise

| Bit/ Tone | Tones | Interleaver Size | RL + 2.5 dB | RL + 5 dB | RL + 7.5 dB | RL + 10 dB | RL + 12.5 dB | RL + 15 dB | RL + 17.5 dB | RL + 20 dB |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 100 | 5,200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 800 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 200 | 10,400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 1,600 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 800 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 100 | 15,600 | 0 | 0 | 0 | 0 | 10 | 58 | 130 | 207 |
| | | 2,400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 1,200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 200 | 31,200 | 0 | 0 | 0 | 0 | 90 | 175 | 313 | 482 |
| | | 4,800 | 0 | 0 | 0 | 0 | 0 | 10 | 11 | 65 |
| | | 2,400 | 0 | 0 | 0 | 0 | 9 | 10 | 24 | 115 |

### 3.2.3 Error Statistics.

The statistics results obtained are practically the same than for the non Reed-Solomon case

## 3.3 Complexity.

Table 12. Complexity of the Receiver and transmitter per Tone for a log-MAP decoder

| Bit/Tone | Tones | Interleaver Size | Estimates | Multiplies | Add/sub | RAM | lookups | # Compa. | Precision Fixed-Point |
|---|---|---|---|---|---|---|---|---|---|
| 4 | 100 | 5,200 | 6 | 6 | 7208 | 374,400 | 1536 | 2500 | 16 bits |
| | | 800 | 6 | 6 | 7208 | 57,600 | 1536 | 2500 | 16 bits |
| | | 400 | 6 | 6 | 7208 | 28,800 | 1536 | 2500 | 16 bits |
| | 200 | 10,400 | 6 | 6 | 7208 | 748,800 | 1536 | 2500 | 16 bits |
| | | 1,600 | 6 | 6 | 7208 | 115,200 | 1536 | 2500 | 16 bits |
| | | 800 | 6 | 6 | 7208 | 57,600 | 1536 | 2500 | 16 bits |
| 12 | 100 | 15,600 | 14 | 14 | 21624 | 1,123,200 | 4608 | 7500 | 16 bits |
| | | 2,400 | 14 | 14 | 21624 | 172,800 | 4608 | 7500 | 16 bits |
| | | 1,200 | 14 | 14 | 21624 | 86,400 | 4608 | 7500 | 16 bits |
| | 200 | 31,200 | 14 | 14 | 21624 | 2,246,400 | 4608 | 7500 | 16 bits |
| | | 4,800 | 14 | 14 | 21624 | 345,600 | 4608 | 7500 | 16 bits |
| | | 2,400 | 14 | 14 | 21624 | 172,800 | 4608 | 7500 | 16 bits |

Table 13. Complexity of the Receiver and transmitter per Tone for a MAX-log-MAP decoder

| Bit/Tone | Tones | Interleaver Size | Estimates | Multiplies | Add/sub | RAM | lookups | # Compa. | Precision Fixed-Point |
|---|---|---|---|---|---|---|---|---|---|
| 4 | 100 | 5,200 | 6 | 6 | 2088 | 374,400 | 0 | 1604 | 16 bits |
| | | 800 | 6 | 6 | 2088 | 57,600 | 0 | 1604 | 16 bits |
| | | 400 | 6 | 6 | 2088 | 28,800 | 0 | 1604 | 16 bits |
| | 200 | 10,400 | 6 | 6 | 2088 | 748,800 | 0 | 1604 | 16 bits |
| | | 1,600 | 6 | 6 | 2088 | 115,200 | 0 | 1604 | 16 bits |
| | | 800 | 6 | 6 | 2088 | 57,600 | 0 | 1604 | 16 bits |
| 12 | 100 | 15,600 | 14 | 14 | 6264 | 1,123,200 | 0 | 4812 | 16 bits |
| | | 2,400 | 14 | 14 | 6264 | 172,800 | 0 | 4812 | 16 bits |
| | | 1,200 | 14 | 14 | 6264 | 86,400 | 0 | 4812 | 16 bits |
| | 200 | 31,200 | 14 | 14 | 6264 | 2,246,400 | 0 | 4812 | 16 bits |
| | | 4,800 | 14 | 14 | 6264 | 345,600 | 0 | 4812 | 16 bits |
| | | 2,400 | 14 | 14 | 6264 | 172,800 | 0 | 4812 | 16 bits |