MULTI-RATE DETECTION FOR THE IS-95 CDMA FORWARD TRAFFIC CHANNELS

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ABSTRACT

The IS-95 Direct Sequence Code Division Multiple Access (DS-CDMA) system has become a U.S. digital cellular standard. In the forward traffic channels (from the base station to the mobiles), the speech encoder rate can vary, depending on the speech activity in the transmitter. At the receiver, the decoder does not know which one of the speech encoder rate the transmitter used. This paper focuses on the IS-95 system that uses the 8kbps speech encoder and describes an algorithm to determine the encoder rate used for the transmitted sequence, with high confidence, so that the appropriate Viterbi decoder can be applied only once and not four times. This can reduce the overall decoder complexity and increase the throughput by a factor of two. It can also reduce the power consumption in the decoder.

1. INTRODUCTION

The IS-95 Direct Sequence Code Division Multiple Access (DS-CDMS) system has become a U.S. digital cellular standard. The system uses a powerful rate 1/2, 256 states convolutional code [1, 3, 4, 5] for error control in the forward channel (from base station to the mobile station) [6, 7]. It also allows the speech encoder rate to be reduced when the speech activity in the transmitter is low. This paper presents an algorithm to detect the speech encoder rate used in the transmitter efficiently so that the Viterbi decoder that decodes the convolutional code [1, 2, 3, 4, 5] can be used once and not four times. This will reduce the complexity in the decoder and result in a speed up of about a factor of two in the decoder. It can also reduce the amount of power consumption in the decoder for packets with low data rates since the decoder can be turned off ones the decoding of the given frame of data is done.

In the IS-95 forward traffic channel where the speech information is transmitted, two sets of data rates can be encoded, depending on the speech encoder used. This paper focuses on the 8kbps speech coder. If the 8kbps speech coder is used, each frame of data can consist of 192, 96, 48 or 24 information bits that corresponds to a information bit rate of 9.6kbps (sub-rate R_1), 4.8kbps (sub-rate R_2), 2.4kbps (sub-rate R_3) or 1.2kbps (sub-rate R_4) as shown in Figure 5 and 6 [6]. The information bit rate used in each frame can vary from frame to frame depending on the speech activity and thus the speech encode rate used. The data packets are then encoded by a rate-$1/2$ convolutional (channel) encoder and the encoded data are repeated twice, four times and eight times for the frames with 4.8kbps, 2.4kbps and 1.2kbps respectively (Figure 5) so that a constant transmission symbol rate of 19.2ksps is maintained.

At the receiver, the Viterbi decoder [6] that decodes the data packets does not know which one of the four sub-rates that is used in the transmitter for the current received frame of data. One way to determine the correct data rate at the receiver is to use the Viterbi decoder to decode the packet according to each of the four possible encoding methods, and then select the decoded data packet that has the least number of errors. We propose an algorithm to pre-determine, with high confidence, the sub-rate used in the transmitter before applying the Viterbi decoder so that the appropriate Viterbi decoder can be used only once.

The multi-rate detection algorithm uses bit repetition properties in the data packets to determine the transmitted bit pattern in Gaussian and Rayleigh Fading channels using statistical methods. The detection algorithm is tested in Rayleigh Fading channels. The algorithm introduces Frame Error Rates (FER) that are at least an order of magnitude smaller than the allowed 1% FER.

The following section first describes the general transmission system for the forward traffic channels and gives the background for our algorithm. Section 3. presents the multi-rate detection algorithm. The results of our simulations in Rayleigh Fading channels are presented in Section 4. Finally, we compared the implementational complexity of our algorithm to that of the conventional method in Section 5.

2. GENERAL SYSTEM DESCRIPTION

The transmitter system with the 8kbps speech encoder is given in Figure 5. Prior to transmission, the packets are interleaved using the IS-95 standard interleaver [6]. After interleaving, 32 bits in each frame are replaced by power control bits in the following manner: In each of the 16 sets of 24 consecutive bits, one of the first 16 bit positions is selected according to the content of four bit positions in the Long code. In effect, the position is selected randomly. After that, a pair of power control bits is inserted in the selected position and the next position, replacing the original content. The power control bit positions can be reconstructed from the Long code at the receiver. At the receiver, data bits in each frame are also de-interleaved.

In each frame of data, 384 bits are transmitted (Figure 5). Our multi-rate detection algorithm utilizes bit repetition properties to identify the transmitted bit pattern. Prior to the power control bit insertion, each frame of data consists of 8-tuples of identical bits for sub-rate R_4, 4-tuples for sub-rateR_3, and pairs for sub-rate R_2 Our multi-rate detection algorithms evaluates tuples of bits according to the tuple structure. The encoded packets are "random looking" in the following sense. The probability that the encoder outputs each pair among 00,01,10,11 is about the same. In particular, the pairs $\{01, 10\}$ are about as likely as the pairs $\{00, 11\}$. Hence, it is very unlikely that a packet of sub-rate R_1 (respectively, R_2, R_3) will consist of a sequence of pairs (resp., 4-tuples, 8-tuples) of identical bits and be mistaken for a lower-rate packet. Power bit insertions and the presence of noise make the rate detection a much more challenging problem. If the bits in the tuple are not identical it is either a higher rate packet or a low rate packet that was subject to noise. We use statistical methods to determine which is the case.

We considered both hard-decision detection and soft-decision detection methods. For hard-decision detection, our algorithm introduces Frame Error Rates (FER) that are less than 10^{-5} when the Bit-Error-Rates (BER) at the input to the multi-rate detector is less than 15%. This corresponds to a SNR (E_b/N_o) of about $2dB$ for AWGN channels with power control bit erasure. At high BER and using hard-decision detection, the transmitted n-tuple sequences will look no longer like n-tuples due to the high BER. For example, for sub-rate R_2, an even pair of sequence will be transmitted, assuming that there is no puncturing and no power control bit erasure. If there is 15% BER introduced in the AWGN channel, 25.5% odd pairs are expected at the receiver (input to the multi-rate detector). This noisy sequence is hard to be differentiated from a sequence in R_1.

For soft-decision detection, we can handle a much wider range of SNR. Since space is limited here, the paper only presents the soft-decision detection algorithm in the following section.

3. MULTI-RATE DETECTION ALGORITHM

The input to the soft-decision detector is a sequence of 384 symbols where each symbol is an integer in the range $[-7,\ldots,7]$. The detector outputs a rate in $\{R_1, R_2, R_3, R_4\}$, where R_1 (corresponds to 9.6kbps of information bits) is the highest rate and R_4 (corresponds to 1.2kbps of information bits) is the lowest.

The algorithm inputs packets as arrays of size 384

$$(b_0, b_1, \ldots, b_{383}) ,$$

where $b_i \in [-7,\ldots,7]$ correspond to the averaged, rounded, and truncated received values. We assume that the power bit locations are set to the value 0. We note that a more complex algorithm that takes into account the powr bit locations can be devised, but the success of our current approach indicates that it is not necessary. The advantages of substituting 0 in power bit locations is simplicity of the algorithm and also the Viterbi decoder uses the same scheme at the input of the decoder. By subsituting zeros for the power control bits, the Viterbi decoder does not use these symbols to compute the branch metrics. Thus, the power control bits will not errorneously affect the decision of the Viterbi decoder.

The soft-decision multi-rate detection algorithm is as follows:

MULTI-RATE DETECTION ALGORITHM:
The algorithm first computes the quantities LE_i, E_i, UE_i, and r_i (for $i = 1, 2, 3$). These values are used later in the classification rule.

1. **Computing LE_1, UE_1, E_1:**
   $E_1 \leftarrow 0, LE_1 \leftarrow 0, UE_1 \leftarrow 0$.
   For $i = 0,\ldots,191$:
   (a) $E_1 \leftarrow E_1 + |b_{2i} + b_{2i+1}|$
   (b) $LE_1 \leftarrow LE_1 + ||b_{2i}| - |b_{2i+1}||$
   (c) $UE_1 \leftarrow UE_1 + |b_{2i}| + |b_{2i+1}|$
2. **Computing LE_2, UE_2, E_2:**
   $E_2 \leftarrow 0, LE_2 \leftarrow 0, UE_2 \leftarrow 0$.
   For $i = 0,\ldots,95$:
   (a) $E_2 \leftarrow E_2 + |b_{4i} + b_{4i+1} + b_{4i+2} + b_{4i+3}|$
   (b) $LE_2 \leftarrow LE_2 + ||b_{4i} + b_{4i+1}| - |b_{4i+2} + b_{4i+3}||$
   (c) $UE_2 \leftarrow UE_2 + |b_{4i} + b_{4i+1}| + |b_{4i+2} + b_{4i+3}|$
3. **Computing LE_3, UE_3, E_3:**
   $E_3 \leftarrow 0, LE_3 \leftarrow 0, UE_3 \leftarrow 0$.
   For $i = 0,\ldots,47$:
   (a) $E_3 \leftarrow E_3 + \left|\sum_{j=8i}^{8i+7} b_j\right|$
   (b) $LE_3 \leftarrow LE_3 + \left||\sum_{j=8i}^{j=8i+3} b_j| - |\sum_{j=8i+4}^{j=8i+7} b_j|\right|$
   (c) $UE_3 \leftarrow UE_3 + |\sum_{j=8i}^{j=8i+3} b_j| + |\sum_{j=8i+4}^{j=8i+7} b_j|$
4. **Computing the ratios r_1, r_2, r_3 :**

$$r_1 \leftarrow \frac{E_1 - LE_1}{UE_1 - LE1}, r_2 \leftarrow \frac{E_2 - LE_2}{UE_2 - LE2}, r_3 \leftarrow \frac{E_3 - LE_3}{UE_3 - LE3}$$

The following claims are easy to establish. They help motivate our classification algorithm.

1. For $i = 1, 2, 3$, we have $LE_i \le E_i \le UE_1$, that is, LE_i is a lower bound and UE_i an upper bound on the quantity E_i. Hence, $r_i \in [0, 1]$.
2. If the signs of the received bits $(b_0,\ldots,b_{383})$ are selected randomly (as is approximately the case for sub-rate R_1), the expected values of the ratios are
$$< r_1 >=< r_2 >=< r_3 >= 0.5 .$$
3. For R_2 packets (where the signs of every pair of bits are independent and random) the expected values are $< r_2 >= 0.5$ and $< r_3 >= 0.5$. If the channel is clean (that is, the signs of the received bits is the same as the transmitted bits) then $r_1 = 1$. In the presence of noise the value of r_1 decreases.
4. For R_3 packets we have $< r_3 >= 0.5$ but r_1 and r_2 are high ($r_1 = r_2 = 1$ when the channel is clean.)
5. For R_4 packets we expect r_1, r_2 and r_3 to be high.

Based on that we propose a simple classification algorithm that uses 3 preset threshold values $\{T_1, T_2, T_3\} \in [0.5, 1]$.

Simple Classification Rule:

1. **if** $r_3 > T_3$, **return** R_4. Otherwise,
2. **if** $r_2 > T_2$, **return** R_3. Otherwise,
3. **if** $r_1 > T_1$, **return** R_2. Otherwise,
4. **return** R_1.

Values for the thresholds T_1, T_2, T_3 are determined using the histograms of values of r_1, r_2 and r_3 for each sub-rate. From the histograms, the thresholds can be set according to the tradeoffs between the noise level we wish to handle and the misclassification rate we can tolerate. Optimally, we would like the misclassifiaction algorithm to have a small absolute error rate (less than 0.5%) on the range of noise levels and sub-rates where the Viterbi decoder performs well. We also would like the frame error rate due to misclassifiaction to be small relative to the frame error rate that occurs due to the Viterbi Decoder.

We tested the performance of the simple misclassification algorithm with carefull setting of the thresholds. The misclassification rate can be significantly reduced if we use more complex conditions, involving more than one of the r_i's at a time. To understand why it pays off to employ more complex conditions consider (for example) the following behavior. If the sub-rate is R_1, R_2 or R_3, then the expected value of r_3 is 0.5. However, when the sub-rate is R_1, the quantities LE_3, E_3, and UE_3 have smaller values and hence r_3 has a larger standard deviation. Therefore, in the simple algorithm, there is a wider range where R_1 packets can be confused with R_3 or even noisy R_4 packets. To correct this, when the value of r_3 is in the ambigous range, we consider the values of r_1 and R_2 for the classification. The same behavior and correction happen for the parameter R_2 when the sub-rates are R_1 and R_2. We present one variant of a finer tuned classification algorithm below. This is the one we used to obtain the results given in Section 4.. Obviously, many variants are possible and some yield better results. The classification algorithm also considers the parameter LE_1. The magnitude of LE_1 is correlated with the noise level (smaller when the noise level is low).

Example of finer-tuned Classification Rule:

- **if** $(LE_1 < 400) \wedge (r_1 < 0.6)$, **return** R_1.
- **if** $r_3 \geq 0.8$, **return** R_4.
- **if** $r_3 \geq 0.7$
  1. **if** $r_2 \geq r_3 + 0.07$ **return** R_3
  2. **if** $r_1 + r_2 < 1.05$ **return** R_1
  3. **if** $(r_1 > r_3) \wedge (r_2 < 0.62)$ **return** R_2
  4. **return** R_4.
- **if** $r_2 \geq 0.73$ **return** R_3
- **if** $r_2 \geq 0.67$
  1. **if** $(r_1 > r_2 + 0.05)$ **return** R_2
  2. **if** $(r_2 \leq 0.69) \wedge (r_1 < 0.55)$ **return** R_1
  3. **return** R_3
- **if** $r_2 \geq 0.62$
  1. **if** $r_1 < 0.6$ **return** R_1
  2. **if** $(r_1 > r_2 + 0.07)$ **return** R_2
  3. **return** R_3
- **if** $r_1 \geq 0.64$ **return** R_2
- **return** R_1

An alternate way of improving the classification algorithm is using the fact that if sub-rate R_4 is transmitted, only $\frac{1}{8}$ of the power is transmitted, compared to the power transmitted for sub-rate R_1 [6]. Thus, if the received power is very low, it is either because the signal has gone through a deep fade or sub-rate R_4 is transmitted. In this case, we can bias the detector to classify as R_4 since even if another sub-rate was transmitted, the signal that has gone through a deep fade will be so noisy that the Viterbi decoder will not be able to decode the sequence correctly anyway.

4. PERFORMANCE EVALUATION

We simulated the performance of our algorithm in Gaussian and Rayleigh fading environments. The threshold settings and the classification rules are heavily dependent on the range of the Signal-to-Noise (SNR) ratios used in the channel. In our simulations, we assumed that the information bits (Figure 6) are random and we appended eight zero tail bits before sending the information packet into the convolutional encoder (Figure 7). The interleaver and de-interleaver are used according to the IS-95 Standard. We also erased 16 pairs of bits per frame for power bits before sending the packets into the channel (Section 2.).

We generated 10^4 to 10^6 frames of random information bits for our simulations. We studied the misclassification rates with different SNR using our algorithm for each sub-rate. We assumed that if the multi-rate detector misclassifies the frame to a wrong sub-rate, we lose the frame and thus increase the Frame Error Rate (FER). After rate detection, the received frame of data is sent into the Viterbi decoder. If one single bit is in error at the output of the Viterbi decoder, the frame is considered to be in error and thus also constitutes to the FER. This FER using the multi-rate detector algorithm is then compared to that of the best possible FER at the Viterbi decoder output, where the Viterbi decoder has knowledge of the sub-rate used in the transmitter. Notice that this best possible Viterbi decoder FER will always be lower or equal to that of the traditional method where the Viterbi decoder is used four times to detect the sub-rate. This is because there are sequences that can be a valid coded sequence of more than one sub-rate. For example, the all zero coded bit sequence can be a valid coded sequence for all four sub-rates. The FER simulation results, given that sub-rates R_1, R_2, R_3 and R_4 are transmitted in Rayleigh fading environment, are shown in Figures 1, 2, 3 and 4 respectively. For the Rayleigh fading channel simulations, we used the Rayleigh fading model given in [8]. We used three multi-paths and a three-branch rake diversity receiver. We also used the finer-tuned classification rule described in Section 3.

The IS-95 system allows a FER of less than 0.01 at the output of the Viterbi decoder. To achieve this, the system has to operate at around 7 dB if rate R_1 is transmitted (Figure 1). If sub-rate R_2 is transmitted, the system will reduce the transmitted power by half [6]. If sub-rate R_3 is transmitted, the system will reduce the transmitted power by $\frac{1}{4}$, compared to that of rate R_1. Similarly, if sub-rate R_4 is transmitted, the system will reduce the transmitted power by $\frac{1}{8}$. Thus, if sub-rates R_2, R_3 and R_4 are transmitted, the system will operate at SNR around 4 dB, 1 dB and -2 dB respectively. We can see from Figures 1- 4 that the FER for each sub-rate using the multi-rate detector is well below the allowed 0.01 around its respective operating SNR.

For sub-rate R_4, the Viterbi decoder can decode sequences even at very low SNR because an average value of the 8-tuples is computed and sent into the Viterbi decoder as one input value. Thus, the effective SNR of the averaged values at the Viterbi decoder input is much higher. To make sure that the multi-rate detector will have similar performance to the Viterbi decoder for sub-rate R_4, we have to set the thresholds and classification rules in a way that even if the sequence is quite random looking, we will still consider that as an 8-tuples sequence. That is, we will detect R_4 even if the ratio r_3 is relatively low. This increases the chance of confusing R_4 with R_3, R_2 and R_1. Thus, trading off the performance of detecting sub-rates R_3, R_2 and R_1. With our current threshold settings and classification rules, the FER performances for detecting sub-rates R_1 and R_2 will level off at around 10^{-3}. This is still an order of magnitude lower than the allowed 1% FER.

5. IMPLEMENTATIONAL COMPLEXITY

This section considers the complexity of implementing the multi-rate detector and compared it to that of the traditional

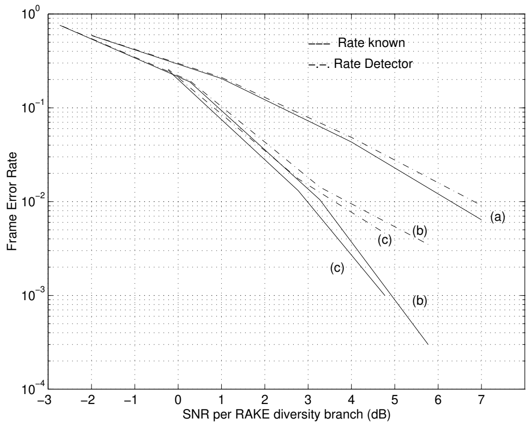

Figure 1. Performance comparison at output of Viterbi decoder (VD) if sub-rate R_1 is transmitted: multi-rate detector vs VD performance if R_1 is known at receiver. In Rayleigh Fading channels with vehicle speeds: (a) 5km/hr, (b) 50km/hr and (c) 100km/hr

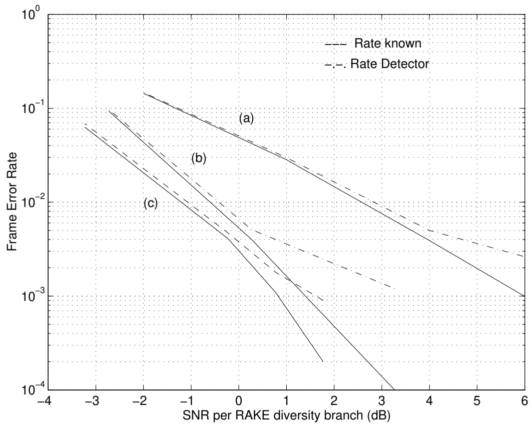

Figure 2. Performance comparison at output of Viterbi decoder (VD) if sub-rate R_2 is transmitted: multi-rate detector vs VD performance if R_2 is known at receiver. In Rayleigh Fading channels with vehicle speeds: (a) 5km/hr, (b) 50km/hr and (c) 100km/hr

method where the Viterbi decoder is used to decode the sequence four times to determine the transmitted sub-rate.

Referring to the multi-rate detection algorithm described in Section 3., 1149 add and 768 absolute value operations are required to compute E_1, LE_1 and UE_1. Similarly, 1149 add and 384 absolute value operations are required to compute E_2, LE_2 and UE_2, and 1149 add and 192 absolute value operations are required to compute E_3, LE_3 and UE_3. To compute r_1, r_2 and r_3, 6 add and 3 division operations are required. Thus, a total of 3453 add, 1344 absolute value and 3 division operations are required for the most straightforward implementation of the algorithm. This count includes adding zeros (the power control bits) that may be avoided depending on the hardware implementation. Depending on the classification rules (Section 3.), a few comparison operations are also required.

The conventional method decodes the received sequence four times, using the Viterbi decoder, and then compares each bit in the decoded sequence for each sub-rate to the sign of the corresponding symbol in the received sequence. The sub-rate corresponds to the decoded sequence that has the least number of bit errors compared to the received sequence is selected. To decode one frame of R_1, the Viterbi

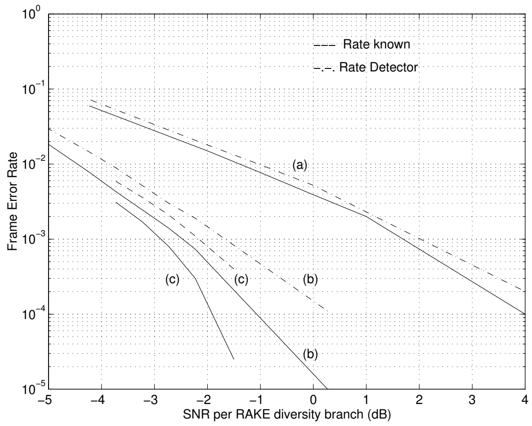

Figure 3. Performance comparison at output of Viterbi decoder (VD) if sub-rate R_3 is transmitted: multi-rate detector vs VD performance if R_3 is known at receiver. In Rayleigh Fading channels with vehicle speeds: (a) 5km/hr, (b) 50km/hr and (c) 100km/hr

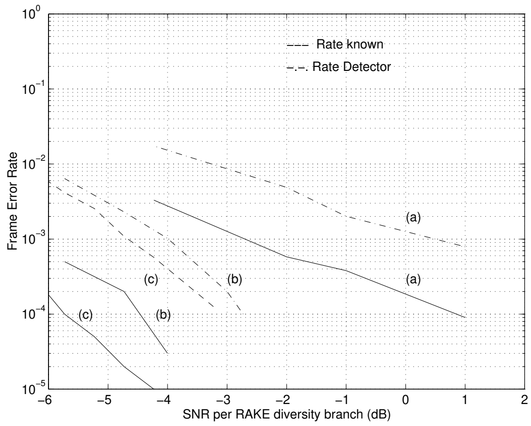

Figure 4. Performance comparison at output of Viterbi decoder (VD) if sub-rate R_4 is transmitted: multi-rate detector vs VD performance if R_4 is known at receiver. In Rayleigh Fading channels with vehicle speeds: (a) 5km/hr, (b) 50km/hr and (c) 100km/hr

decoder has to go through 192 iterations since there are 192 information bits in the frame. Similarly, the Viterbi decoder has to go through 96, 48 and 24 iterations to decode sequences of sub-rates R_2, R_3 and R_4 respectively. For each iteration, just to update the survivor path alone, the Viterbi decoder requires 512 add and 256 comparison operations [9]. This does not include branch metric computations, updating the optimum paths, path trace back and the comparison between the decoded bit sequence to the received sequence of symbols [9]. Thus, we can see that the number of computations required by the multi-rate detector is very small compared to that of decoding one frame of data using the Viterbi algorithm. If sub-rate R_1 is selected by the multi-rate detector, the Viterbi algorithm is used once to decode the R_1 sequence. Thus, 192 iterations are required to decode the sequence. If sub-rate R_4 is selected, only 24 iterations are required to decode the 24 bit sequence. Thus, we can see that the multi-rate detector can increase the throughput by at least a factor of two. Furthermore, for the shorter sequences (R_2, R_3 and R_4), the decoder can be turned off once the decoding is done. This reduces the power consumed by the decoder.

6. CONCLUSION

The IS-95 DS-CDMA system uses four different sub-rates for the speech encoder. If the speech activity is low, the speech encoder rate can be reduced to $\frac{1}{2}$, $\frac{1}{4}$ or $\frac{1}{8}$ of the full-rate (8kbps). The frame of information bits at the output of the speech coder will go through a rate 1/2 256 state convolutional channel encoder. To ensure a constant transmission rate of 19.2 ksps, this coded bit sequence at the output of the convolutional encoder will be repeated twice, four times and eight times to form a 2-tuples sequence, 4-tuples sequence and 8-tuples sequence for the $\frac{1}{2}$ rate, $\frac{1}{4}$ rate and $\frac{1}{8}$ rate speech coders respectively.

At the receiver, the Viterbi decoder that decodes the sequences coded by the convolutional coder does not know which speech encoder sub-rate is used. The conventional method uses the Viterbi decoder to decode the received sequence four times, based on the four possible coding schemes, in order to determine the most likely sub-rate used in the transmitter.

This paper takes advantage of the 2-tuples, 4-tuples and 8-tuples bit patterns to determine the most likely speech encoder sub-rate used before the Viterbi decoder for the appropriate sub-rate is applied at the receiver. Thus, the Viterbi decoder is used once and not four times. This can reduce the overall decoder complexity and increase the throughput by at least a factor of two. It can also reduce the power consumption in the decoder.

The algorithm is tested in Gaussian and Rayleigh fading environments. We verified that the FER due to the multi-rate detector using the proposed algorithm is at least an order of magnitude smaller than the allowed FER of about 1%, even at very low SNRs.

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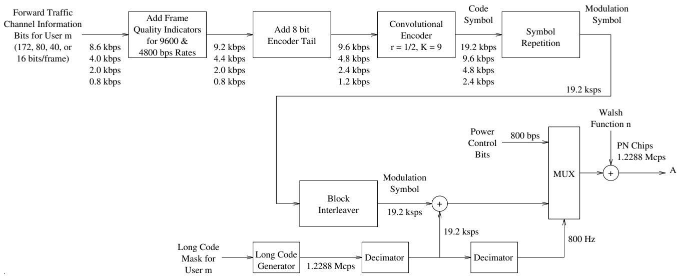

Figure 5. Forward Traffic Channel Structure

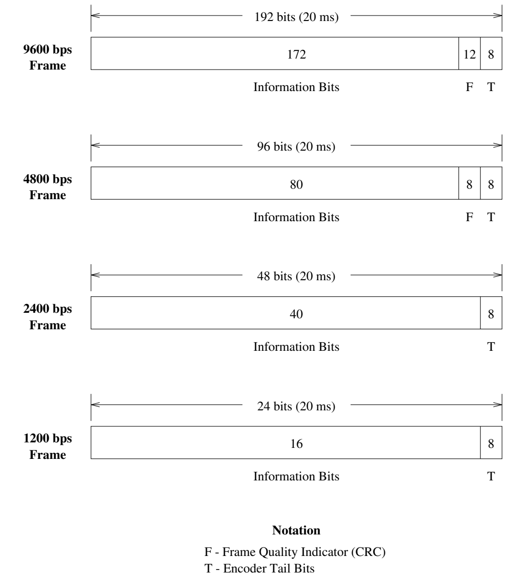

Figure 6. Forward Traffic Channel Frame Structure

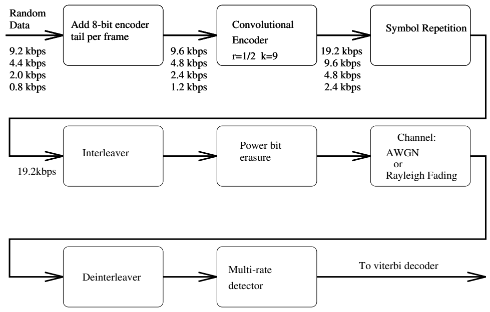

Figure 7. Model used for performance simulations