Low Complexity Viterbi Decoder for RSCC Concatenated Codes

To cite this article: Ramy Samy and Ashraf Mahran 2020 J. Phys.: Conf. Ser. 1447 012040

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Low Complexity Viterbi Decoder for RSCC Concatenated Codes

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Abstract. One of the primary obstacles to achieving reliable communication transmission for aerospace applications is the power constraints. Therefore, it is appealing to use powerful channel coding techniques with small complexity of decoding. The robust forward error correction scheme using Reed-Solomon as outer code concatenated with convolutional as inner code is an appealing scheme whose apps are commonly used in wireless and space transmissions. In this work we aim to reduce the complexity of the convolutional code decoding process as the number of computations and memory need increases exponentially with the code’s constraint length. We use the Adaptive Viterbi Algorithm to bring Viterbi decoder with small complexity. The proposed work yields approximately the same error performance as the conventional concatenated Reed-Solomon convolutional, while requiring a substantially smaller average number of computations for the convolutional code decoding process.

1. Introduction

Due to several reasons (interference, rain fade, free space loss, etc.), the transmitted signal can be diminished. In the existence of such harmful conditions, many techniques are used at the receiver to accomplish reliable and efficient data transmission [1]. The use of robust channel coding techniques is the vital route to achieve reliable decoding with a small Signal-to-Noise Ratio (SNR). Using such techniques offers higher coding gain that allows us to achieve the necessary Bit Error Rate (BER) at small SNR but with greater decoding complexity.

Concatenated Reed Solomon and convolutional codes, RSCC, are efficient channel codes to reduce the impacts of channel impairments. Thus, they have been employed in many wireless communication standards such as DVB-S [2], IEEE 802.16e WiMAX [3] and most importantly in CCSDS space communication standard [4].

The RSCC decoding scheme uses the Viterbi algorithm (VA) [5] to decode the inner Convolutional Code (CC) and the Berlekamp-Massey algorithm (BMA) [6] for the algebraic decoding of the outer Reed-Solomon (RS) code. Although this scheme has enormous asymptotic coding gain, the complexity of the hardware has been a barrier to this gain. This decoding complexity can be described as extra time and power consumption for baseband processing, which contradicts the essence of a power-limited system.

Most research focused on enhancing the decoding efficiency of RS codes with sensible soft decision decoding complexity [7][8]. Yet, the CC used, particularly those with large constraints, still have problems with increased decoding delays and large memory demands.

The decrease of VA complexity has been the goal of many researchers for several years. The several multiple-paths breadth-first CC decoding algorithms, such as the M-algorithm [9] and Simmons’
algorithm [10], are an example of these effective attempts. With the use of these algorithms we could miss the right path; accordingly the retrieval process is difficult and leads to very large error events. The principle of varying the decoding complexity as a function of the SNR has been proven to be an efficient way to reduce complexity for block codes [11][12], and convolutional codes as well [13]. The Adaptive Viterbi Algorithm (AVA) as a decoding algorithm for the CC is one of the most effective VA decoding complexity reduction works [13]. This AVA demonstrates quasi-optimum performance when the value of the discard threshold is equal to the error correction capability of the CC, together with a lower computing load relative to the original VA. Nonetheless, the aforementioned benefits are the same for both hard and soft decision decoding. In addition, the use of AVA was effectively implemented to decrease the complexity of Reed-Muller decoding as revealed in [14].

The paper is organized as follows. Section 2 summarizes the concatenated coding scheme. The low complexity AVA will be introduced for hard and soft decision decoding in sections 3 and 4, respectively. Simulation results for Additive White Gaussian Noise (AWGN) and Rayleigh Flat Fading (RFF) channels will be presented at section 5. Finally, conclusions will be figured out in section 6.

2. RSCC Concatenated Coding Scheme

The proposed RSCC coding scheme that uses RS code as an outer code and the CC as an inner one, with an interleaver between them, is illustrated at Figure 1. RS codes are nonbinary cyclic codes with symbols belonging to $GF(q=2^m)$. Each $q$-ary symbol of the Galois field can be mapped to $m$ binary elements. The RS codes can be defined by $(n_{RS}, k_{RS}, t_{RS})$, where $n_{RS}$ is the codeword length, $k_{RS}$ is the information symbols number, and $t_{RS}$ is the symbol error correcting capability of the code.

Usually, the interleaver between the inner and outer codes is needed to spread the error bursts that may appear at the output of the inner coding operation. As a result of interleaving the coded message before transmission and deinterleaving after receipt, the error bursts to spread in time. Consequently, the decoder will treat them as random errors.

CC can be implemented by knowing three primary parameters $(n_c, k_c, K)$, where $k_c/n_c$ ratio is the code rate (information per coded bit) that it has for block codes; however, $n_c$ does not describe a block or codeword length as it does for block codes. The parameter $K$ is the constraint length; it represents the number of $K$-tuple stages in the encoding shift register.

For decoding of CC, VA is allocated to the receiver for optimal decoding [6]. The VA mainly performs maximum likelihood decoding (MLD) to correct the errors in the received data caused by the channel noise. Instead of using the VA, it is recommended that the AVA be used to decode the CC as it achieves approximately the BER as the original VA with minimal effort as shown at Figure 1.

![Figure 1. RSCC Coding Scheme.](image-url)
3. Adaptive Viterbi Algorithm

The significance of using AVA [13] is that a small amount of surviving paths should have been maintained at each trellis stage. Therefore, the decoding complexity and memory need can be minimized. The two primary parameters described by the AVA are:

- A path with a metric smaller than or equal to \((d_{\min} + T)\) is preserved and is called the surviving path where \(T\), known as the discarding threshold value and \(d_{\min}\), is the minimum Hamming path metric of all survivor paths in the prior trellis decoding stage.
- The complete amount of remaining paths at each trellis stage is limited to a predefined value, \(N_{\text{max}}\), which is acquired before the communication service starts.

At each trellis stage, the first parameter is admitted to remove paths with metrics higher than the discard threshold among all the most probable paths, thus eliminating their decoding processes. The second parameter is used to limit the complete amount of survivor paths to a predefined value. In this work, the complete amount of surviving paths at each trellis stage is limited to \(2^{K-1}\).

The optimum discarding threshold value, \(T_{\text{opt}}\), at which the AVA has approximately the same error performance as the initial VA is given in [13] to be equal to the error correction capability of the CC, \(t_c\):

\[
T_{\text{opt}} = \left\lfloor \frac{d_f - 1}{2} \right\rfloor
\]

Where \(d_f\) is the minimum free distance of the CC.

4. Adaptive Viterbi Algorithm For Soft Decision Decoding

The significant distinction between Viterbi soft-decision and hard-decision decoding is that the soft-decision algorithm utilizes the Euclidean distance metric rather than the Hamming distance metric as it offers superior resolution.

In soft decision decoding the discarding threshold which is called \(T_{\text{soft}}\) is given by computer simulation. We replicate the impact of using different values of the \(T_{\text{soft}}\) discarding threshold on the performance of the BER; once the BER reaches saturation, which implies no further enhancement as \(T_{\text{soft}}\) increases; this \(T_{\text{soft}}\) value will be the suitable value to be regarded. We made the same procedure in [13] to obtain the appropriate \(T_{\text{soft}}\) value.

Figure 2 demonstrates the BER performance versus the discarding threshold \(T_{\text{soft}}\) for the RS(255,239,8), CC (2,1,7) and interleaver depth (I=8) using Binary Phase Shift Keying (BPSK) over AWGN channel and M-bit quantizer, where \(M=3\).
In this simulation, the impact of various $T_{\text{soft}}$ values on the BER at $E_b/N_0=2.25$ dB indicates that the error performance reaches its saturated level, i.e., no more better performance can be obtained, for $T_{\text{soft}} \geq 18$. We can realize that the greater the $T_{\text{soft}}$ value, the reduced the AVA complexity reduction. The authors at [13] therefore tend to select the $T_{\text{soft}}$ minimum value once the BER reaches its minimum.

5. Simulation Results
Simulations for decoding of RSCC code based on VA and AVA are carried out considering BPSK modulation over an AWGN and RFF channels. In terms of BER performance and complexity reduction, we will compare the RSCC decoded using the AVA with the conventional VA. The measure of complexity reduction will be regarded as the average ratio of the removed paths to the total number of traditional VA paths throughout the entire trellis. The simulation results are carried out using RS (255, 223, 16), RS (255, 239, 8) as outer codes and CC (2,1,7) as inner code CCSDS-recommended [4]. An interleaver with depth 8 symbols is used between the two steps of the code. Our suggested modification to the classical RSCC will be tested for both Binary Symmetric Channel (BSC) and soft quantized channel using 8-level quantization. In case of BSC; the CC (2,1,7) has $(d_f=10)$ and $(t_c=4)$, so that the elimination rule is $(d_{\text{min}}+4)$. For the soft case $T_{\text{soft}}$ can be acquired by computer simulation as shown at Figure 2. Figure 3 introduces the BER performance for the RSCC using VA, AVA over AWGN. Either for Hard-In-Hard-Out (HIHO) or Soft-In-Hard-Out (SIHO) decoding, they have the same BER performance which comply with the results of [13]. In other words, concatenation with RS codes has no effect on the BER performance of the adaptive decoding.

![Figure 3. BER performance of RSCC using VA and AVA over AWGN channel](image)

![Figure 4. Complexity reduction over AWGN using hard and soft decision decoding.](image)
Figure 4 shows the complexity reduction for the AVA. In spite of inferior BER results, the decrease in complexity in the case of hard decision decoding is greater than in the case of soft decision because the discarding threshold value is very low relative to the soft decision, until the SNR ratio is large; the soft decision receives much more complexity reduction than the hard decision situation. Furthermore, we can see in Figure 4 that the AVA has a greater decrease in complexity as the code rate increases. Our simulations will be extended to include the RFF channel. The received samples can be outlined as follows for a fading channel:

\[ Y = A e^{i\theta} X + N \]  

(2)

Where \( A e^{i\theta} \) is a Gaussian random variable with \( A \) having a Rayleigh probability density function (pdf) and \( N \) is the Gaussian added noise.

If we can further suppose that the fading is so slow, we can assess the phase shift \( \theta \) with adequate precision and thus account for it. The \( A e^{i\theta} \) term can therefore be embraced as a random variable whose value impacts the amplitude of the received signal. We also suppose that at the receiver the value of \( A \) is specified (this is recognized as perfect channel state information).

Choosing the soft decision demodulator step size in case of RFF channel is an essential aspect to maximize the channel capacity. We have adopted the outcomes mentioned in [15] to calculate the respective step size at each SNR for a 3-bit quantizer.

Figure 5 introduces the BER for the conventional and the proposed RSCC based on the AVA over RFF channel.

**Figure 5.** BER performance of RSCC using VA and AVA over RFF channel

**Figure 6.** Complexity reduction over RFF using hard and soft decision decoding.
As a result of soft decision decoding, the coding gain acquired is slightly smaller than for the AWGN channel. This is true for VA and AVA. In addition, these findings are achieved using the optimized RFF channel quantizer described in [15]. These results can be inferred from the reality that the VA is significantly affected by the Rayleigh noise and this was expressed in the soft decision outcomes of the above mentioned decoding algorithms. Figure 6 demonstrates a significant reduction in complexity for the AVA using hard and soft decision decoding over the RFF channel.

6. Conclusion
In this work, we introduced low-complex Viterbi decoder based on the adaptive Viterbi algorithm to replace the classic Viterbi algorithm used in the RSCC codes. The suggested modification achieves approximately the same error performance as the standard RSCC but with a significant reduction in complexity.

In the case of AWGN channel; we can achieve around 45% decrease in complexity for hard decision and 15% for soft decision decoding using 8-level quantization for the demodulator output at $10^{-5}$ BER performance.

In the case of RFF channel; we can gain around 55% reduction in complexity for hard decision and 50% for soft decision decoding using 8-level quantization for the demodulator output at $10^{-5}$ BER performance.

The results acquired render it optimistic to use the AVA in an iterative fashion for the inner convolutional code decoding [8].

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