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Original Research Article

EVALUATION OF CONVOLUTIONAL ENCODERS WITH VITERBI DECODERS FOR NEXT GENERATION BROADBAND WIRELESS ACCESS SYSTEM

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Abstract:
The IEEE STD 802.16 – 2009 in their specification for the physical layer of the next generation Broadband Wireless Access (BWA) system approved a forward error correction, FEC with the concatenation of Reed-Solomon outer code and a rate compactible convolutional inner code.
This evaluation is based on modelling a configurable convolutional encoder and Viterbi decoder by making use of the stipulated rate-compactible punctured convolutional codes from the usual mother rate 1/2, constraint length K = 7 and generator polynomial , to obtain higher rates of 2/3, 3/4 and 5/6.

Key Words: Error Control Coding (ECC), Digital Subscriber Lines (DSL), Broadband Wireless Access (BWA), Inter-signal interference ISI.

Introduction:
Owing to the rapid growth of digital communication system in the recent years which majorly deals with the stepping down of power consumption while increasing the system reliability can both be achieved by using the Error Control Coding (ECC). The availability of bandwidth and transmitting power still remains the major constraint linked with the design of digital communications systems. Based on incessant demand for bandwidth by bandwidth-hungry application and digital communication equipment miniaturisation, these constraints are ever so increasingly stringent. Therefore the challenge encountered in designing good encoders and decoders for the next generation wireless communications system is not just based on designing a good coding technique which will require less transmitting power only, but also a technique which will inculcate an efficient use of the available bandwidth in its implementation.

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Broadband Wireless Access system is one technology that provides us with an option to wired access such as Digital Subscriber Lines (DSL), fibre optic link and coaxial cable system with regards to coverage, speed, and capacity [1]. Broadband Wireless Access (BWA) system is suggested to work efficiently in the 2 gigahertz – 11 gigahertz spectrum frequency aiming at 1000Mbit/s data rate for a fixed or slow dynamic user and 100Mbit/s for a high accelerating vehicle. Figure 1 below is a typical communication channel block diagram which can be used to represent the way in which every communication channel whether be it wireless or wired transmits its signal.

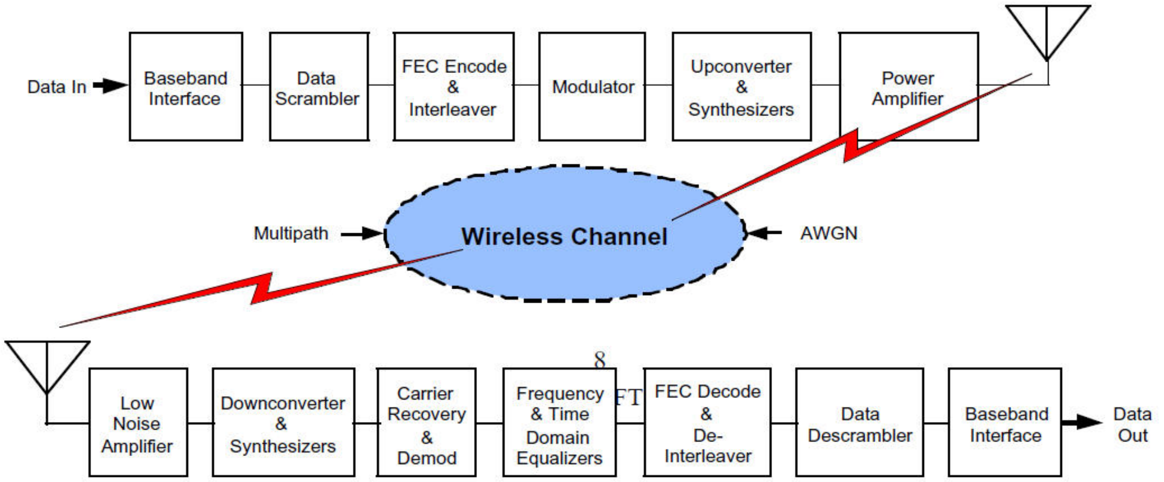

Fig. 1: Representation of a wireless communication system block diagram (Adapted from [2])

This communication channel shown in Figure 1 above can comfortably transmit limitless number of data without error given a time unit, if at all there actually existed a thing like a noise free analogue communication channel, but since nothing like this exists, and to worsen this case, if frequency or transmit power is increased, in other to increase the speed of transmitted signal or bandwidth, the noise on the other hand is also constantly being increased, giving room for more errors to be transmitted alongside the signal.

This now brings us to the goal meant to be achieved by channel coding in high speed communication system which is to tackle the resultant errors that occur when data is transmitted across an impaired channel. Such errors can occur in the form of fading, Inter-signal interference, ISI or noisy channel [3].

Therefore, for next generation BWA system to obtain an efficient and reliable data communication, it must employ the use of a method which can efficiently and effectively locate and correct errors; so as to help forward the standard established by IEEE for broadband wireless access systems. The operations involved in locating and correcting errors in a communication system is simply called Channel Coding (CC). Looking at the Figure above, CC is implemented at the information source (data input end) by cautiously putting some redundant data to the signal being transmitted in other to combat the outcomes of impairment in the channel. This makes it possible for the receiving end to correct and or detect the errors. Basically, what is actually implemented here or the main objective is that the Probability of bit error (P_b), or required Signal-to-Noise Ratio (SNR) is reduced at the expense of trading more bandwidth than would be required if an uncoded signal were to be transmitted [4].

The standards for the next generation BWA system according to IEEE 802.16 – 2009 PHY definition specified a Forward Error Correction (FEC) to be supportably by an assembling of a concatenation of Reed-Solomon outer code and a rate-compatible convolutional inner code [5].

This evaluation is focussed on the modelling of a rate-compatible convolutional encoder (in the absence of Reed-Solomon outer code) with a Viterbi Decoder for next generation BWA system and investigating its performance when exposed to an impaired channel like the Additive White Gaussian Noise (AWGN) channel.

Dimensions and Study Constraints

This work is centred on channel coding technique as stated by the IEEE 802.16 – 2009 standard for next generation BWA system.

Irrespective of the fact that concatenation of Reed-Solomon outer code and convolutional inner code has been specified, this work only considered the performance of convolutional codes. Again, this research work barely considered modulation technique which plays a very crucial part in studying the performance of wireless communication system over an impaired channel.

Design Tool/ Methodology

The encoders having code rates 2/3, 3/4 and 5/6, the rate 1/2 code which is otherwise referred to as the mother code are punctured for their modelling. Puncturing as the name goes is a technique that permits us to develop further encoders of varied rates from a common hardware, which also has a way of making the analysis of high code rates less complicated.

Background Study

The interconnection of systems without involving the use of wires as a medium for connectivity is called wireless network. This is generally linked with a telecommunication network where interconnectivity within nodes is performed in the absence of wires. Some typical examples of these wireless networks includes:-

- Wireless Local Area Network (WLAN)
- Wireless Wide Area Network (WWAN)
- Wireless Metropolitan Area Network (WMAN)
- Wireless Personal Area Network (WPAN)

This work however focuses mainly on the WPAN which can be indicated as WiMAX. This is fully treated in IEEE 802.16d and IEEE 802.16e standards. For a basic definition, we can say that a WMAN is a non-wired network that links many other WLANs.

In 2003, the development of WiFi signalled the ushering in of a new level in the movement towards non-wired services and as at 2005, the number of WiFi patronisers was One Hundred and Twenty million which increased to Two Hundred million in 2006 and was further suggested to go up to a billion come 2008 [12]. WiFi (which employs the use of IEEE 802.11 set of standard) due to the tremendous growth has been linked with WLAN.

WLAN links devices through a typically spread-spectrum (i.e. a wireless distribution method) providing a connection to a wider internet through an access point.

Merits and Demerits of Convolutional Codes Over Other Coding Techniques

The efficiency of convolutional codes anchors on their constraint length ‘K’. Codes possessing large constraint length are more powerful but have a set-back due to their high decoding complexity. This can be taken care of by using sequential decoding algorithm instead of Viterbi decoding algorithm.

One of the advantages of convolutional code is its speed and high affinity for error control. They are also quite less expensive when compared to block codes. For the same encoder/decoder level, convolutional codes generally out-perform block codes by providing higher coding gain.

One of its disadvantages could be seen on the instance of a user wishing to maintain the original uncoded information rate. Here, convolutional codes register a set-back due to the fact that they all require a bandwidth expansion to accommodate all the parity bits. Well, the good story here is that in 1976, Gottfried Ungerboeck discovered a class of codes called Underboeck codes or Trellis Coded Modulation (TCM) which has the ability to integrate both the coding and modulation functions without demanding a bandwidth expansion

Applications of Convolutional Codes

WiMAX: This is a new wireless technology which is based on the air interface standard IEEE 802.16 WMAN designed just like the normal cellular network which uses a point to multipoint base station of configuration to provide a service of high throughput broadband connection covering a radius of over many kilometres. Though it exhibits a slightly higher BER at low SNR, its range and non-line of sight makes the system attractive as it has been configured to complement both mobile and fixed broadband applications. Its applications can be seen in many areas like high-speed enterprise connectivity, cellular backhaul to mention but a few based on its possession of high spectrum efficiency and reliability in multipath propagation. Many researches have been carried out for different coding stages in WiMAX and the system has been proved to depend on OFDMA PHY layer as specified by the IEEE 802.16 STD.

One major physical application of WiMAX in convolutional encoder is seen in SAL50300E product. This is a WiMAX compatible high-speed convolutional encoder which has a high speed convolutional encoder as specified in IEEE 802.16 – 2004. It has a basic coding constraint length 7, rate 1/2 transparent code suitable with channels of predominantly Gaussian noise. The device also supports punctured rates 2/3, 3/4, 5/6 and 7/8 with a non-recursive/systematic encoder of [171, 133] polynomial.

Figure 2, below is a block diagram of WiMAX physical layer.

After generating the binary bit from the randomiser, they are sent into the encoder where it is matched with the appropriate code rate and after interleaving, it is sent into the modulator as a sequence of binary bit where they are mapped and modulated using QPSK modulator or either 16QAM or 64QAM which its symbol are attached to the designated data sub-carriers. The pilot symbol which creates a room for the receiver to estimate and trace the channel state information are also allocated unto the pilot sub-carriers. These procedures lead to the construction of OFDM symbols in the frequency domain and by employing the Inverse Fast Fourier Transform (IFFT) OFDM symbol are got into the time domain.

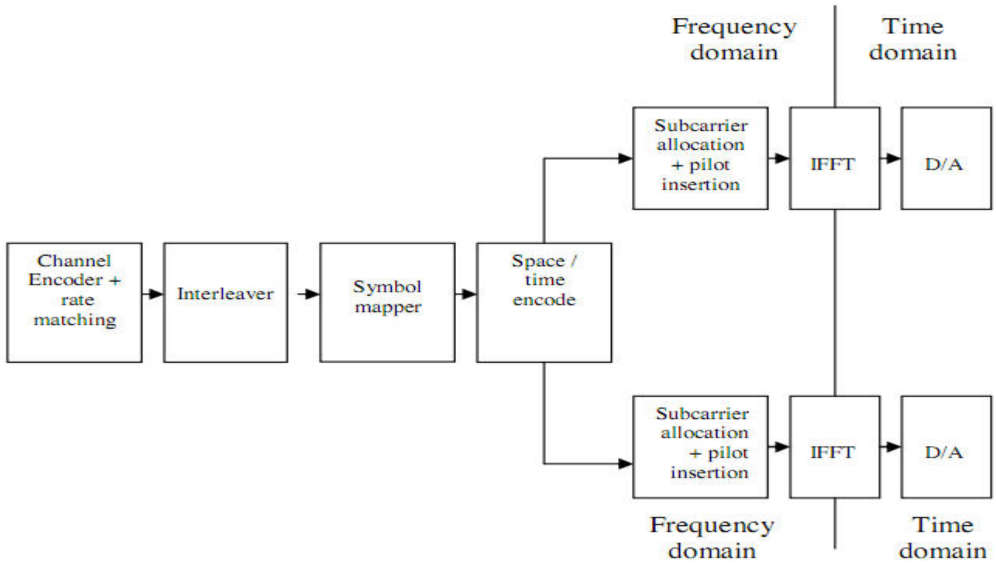

Figure 2: Physical layer of WiMAX system.

Useful in 4G NETWORKS

Long Term Evolution (LTE): This is the next generation network beyond 3G for mobile broadband standardization by 3GPP which is aimed at providing a capacity that will support demand for connecting from a new generation of consumers devices fashioned to a new mobile application.

Convolutional Codes and Its Coding Techniques

This is simply a technique used to bring the capacity of a channel into a more desirable or excellent condition by adding cautiously fashioned redundant signals to the data meant to be transmitted through the channel. The systematic series employed in the addition of these redundant signals is known as channel coding. Increasing both the code rate ‘k’ and constraint length 'K' automatically increases the complexity of the encoders. This can be taken care of by puncturing the mother code rate (e.g. rate ½ for this project work). Puncturing is a technique employed to generate higher code rates from a mother code rate which has an advantage of allowing us to make use of the same hardware in the implementation of several code rates thereby reducing the production cost of both encoders and decoders.

Convolutional encoders can be represented in a number of different but equivalent ways which can be any or in the form of State diagram, Trellis diagram and Tree diagram.

Convolutional Codes.

This being the first code that was utilised in the application of satellite and space communications could be traced back to have emerged as far back as 1955. Its usage is regularly seen in the correction of errors existing in a badly impaired channel due to their high affinity to error correction. These codes are recently majorly used in place of block codes when FEC is needed and have been registered to perform exceptionally well when run with Viterbi decoder which can be in the form of soft decision decoding or probabilistic decoding algorithm. The major difference between convolutional codes and block codes is that in block codes, the data sequence is first mapped out into individual blocks before it is encoded, whereas in convolutional codes, there is a direct mapping of that continuous information bit sequence to an encoder output bit. Figure 2.1a below represents a generalised block diagram of a convolutional encoder.

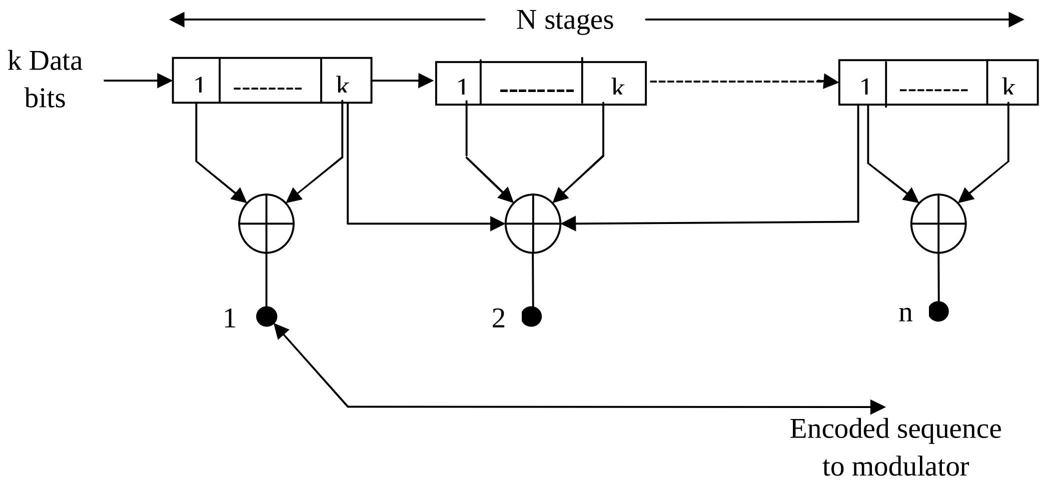

Figure 2.1a: A generalised block diagram of Convolution encoder.

With reference to Figure 2.1a, convolutional codes are generated by simply transmitting the data sequence across a finite shift register with 'N' k-bits stages and a linear algebraic function generator 'm'. A shift of data 'k' bits at any particular time in the shift register is recorded for every input of the data into the shift register and an output bit of 'n' bits is got for each 'k' bit user input.

The rate of an encoder is said to be ½ if the encoder outputs two bits for every one bit input. Therefore an encoder with 'k' input bits and 'n' output is said to possess a rate of 'k/n' which is simply defined as the code rate (Rc) of the system. Figure 2.1b below is a typical binary linear convolutional encoder.

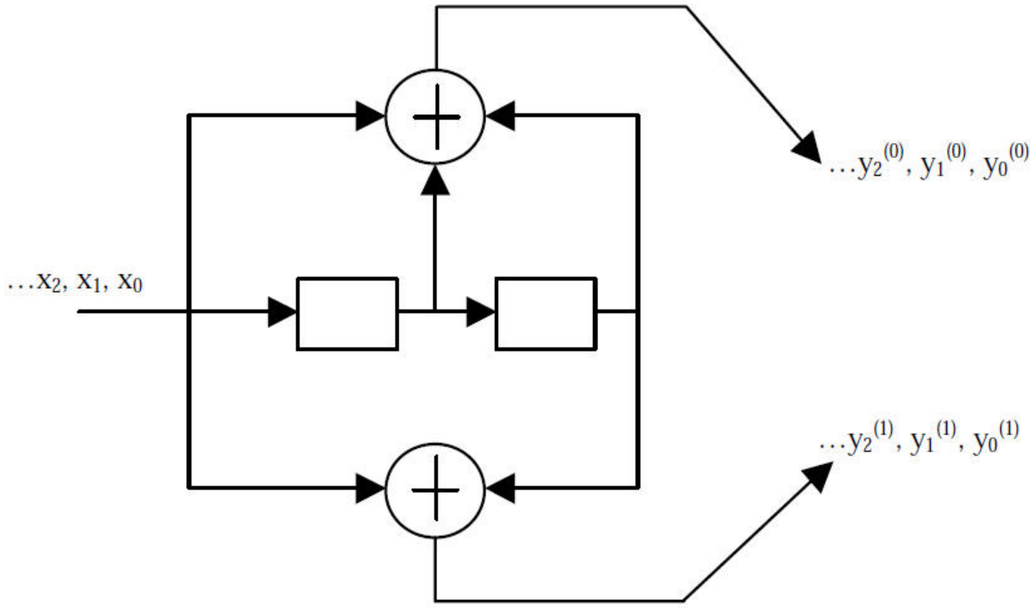

Figure 2.1b: A 1/2 rate Convolutional encoder

For the above figure, a binary data stream of $x = (x_0, x_1, x_2 \ldots)$ is added into a sequence of memory elements. The bits move across the shift register and the outcomes of the individual memory elements taken-off and summed up with respect to a fixed pattern using the modulo-2 addition. This generates a pair of output coded stream of data, $y^{(0)} = (y_0^{(0)}, y_1^{(0)}, y_2^{(0)} \ldots)$ and $y^{(0)} = (y_0^{(1)}, y_1^{(1)}, y_2^{(1)} \ldots)$. Multiplexing these output streams of data, a single encoded data stream is created as

$$y = (y_0^{(0)} y_0^{(1)}, y_1^{(0)} y_1^{(1)}, y_2^{(0)} y_2^{(1)}, \ldots)$$ [Equation 2.0]

This data stream of Equation 2.0 is known as the Convolutional code-word. In the interleaved output stream y, each element is a linear stream combination of the element in the input stream $x^{(0)}, x^{(1)}, \ldots. x^{(k-1)}$ provided that the shift register content prior to the encoding process was initialised to zeros.

The encoder structure of the Convolutional codes are characterised using the generator sequences which are derived by applying an impulse response $g_j^{(i)}$ where the i^{th} output of the encoder is got by simply applying a Dirac delta function $\delta = (1\ 0\ 0\ 0\ldots)$ data stream at the j^{th} input. For the encoder, the derived impulse responses can be stated as

$g^{(0)} = (1\ 1\ 1)$

$g^{(1)} = (1\ 0\ 1)$ [Equation 2.1]

This above Equation 2.1 is known as the generator polynomial which gives the code its unique error protection capability. For a convolutional code, the constraint length, $K = m + 1$ is said to be the maximum number of taps off the encoders shift register, with 'm' known as the number of the memory element contained in the encoder structure. The encoder memory exhibits a direct impact on the decoder complexity commonly for the VA that is used here. The VA in a practical implementation has its complexity an exponential of constraint length 'K' and the input bits number 'k'. The delay transform (D-transform) can be used to describe the Convolutional encoder. This is order wise known as a delay operator having an exponent which indicates the number of times delay is in relation to the $D^{(0)}$ term.

The state of a code and its diagrammatic representation

Figure 2.2 below shows a representation of a convolutional encoder state diagram.

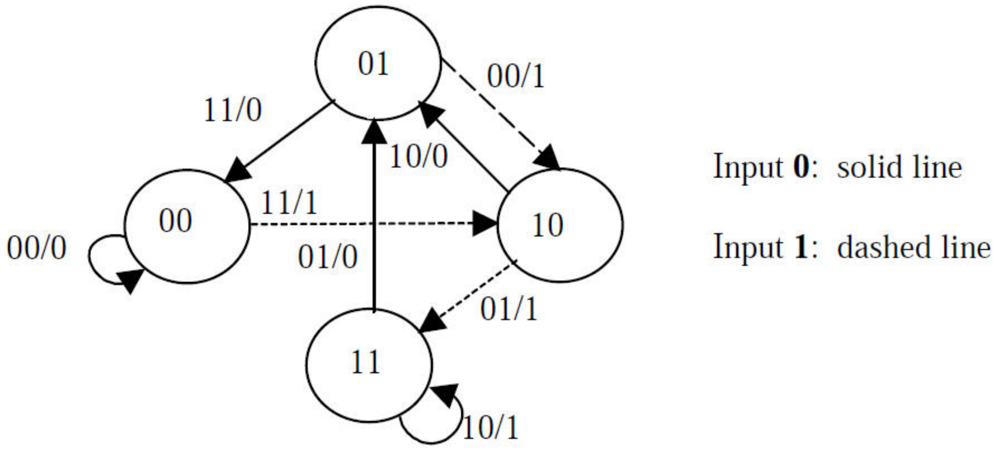

Figure 2.2: State diagram of a Convolutional Encoder.

The state diagrams display state information of a convolutional encoder which is stored in the shift register. Therefore we can say that the convolutional encoder is a state machine which contains memory elements whose contents decides the mapping between the next state of the input and output bits. If a convolutional encoder exhibits a memory length of 'm', then the number of states it possesses will be written as '2^m'.

The state encoder just like most finite-state machines has a limited manner of movement between the states, in which every branch in the state diagram possess a label of XX/Y. XX is said to be the output pair which corresponds to the input bit Y. Some of the benefits of the state diagram are that it gives the error rate performance and distance properties of a convolutional code. The performance measure which is considered as the main key when comparing convolutional code known as 'd_{free}' (minimum free distance) is represented thus:

$d_{free} \leq {}_{r \geq 1}{}^{Min}[2^{r-1}/2^{r-1}(K + r - 1)n]$ [Equation 2.2]

Where, r = number of input bits, n = number of encoded bits, [x] = largest integer contained in 'r', and K = constraint length.

A close observation of Equation 2.2 shows that an increase in 'K' or decrease in code rate increases the value of 'd_{free}'.

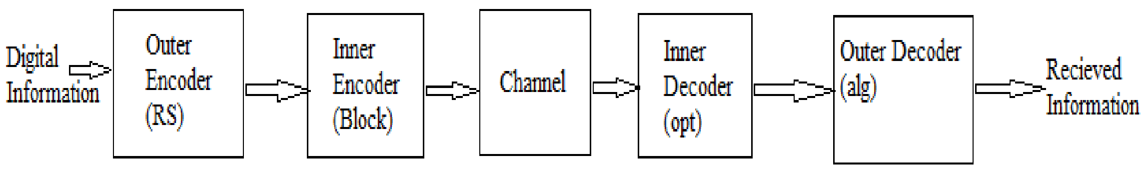

Figure 2.3: Original concatenated coding system.

Viterbi Decoder

This was first revealed in an IEEE transaction in 1967 [10] having been developed by Andrew J. Viterbi. It makes use of the Viterbi algorithm in decoding a bit stream which has been encoded with a convolutional code. Viterbi algorithm conforming to Fleming in 1999, are at present estimated to be utilised roughly in 1 billion cellular telephones and might be the greatest number in any application. Going by the recent application in Qualcomm which has it that not less than gigantic 10^15 bps are currently decoded using the Viterbi algorithm in digital television located all over the world per second of everyday. This breath-taking statistical use of VA goes a long way to emphasise on the great advantage of this decoder in the error correction technique. However, the complexity of VA grows exponentially with the number of constraint length of the encoder making this algorithm become less favourable or even impractical to implement for the very more resent modern communications system, where the constraint length of the encoder can easily reach up to nine. Research is presently going on to finding an alternative to VA so as to overcome this challenge.

Several methods are used to decode Convolutional codes of which are majorly categorised under two levels which are

a) Maximum Likelihood Decoding MLD, (Viterbi Decoding)
b) Sequential Decoding (Fano Algorithm)

Maximum Likelihood Decoding is faced with a major setback due to the fact that it requires numerous computations for all its existing code sequence but this is taken care of by Viterbi algorithm which in its computation does not take into consideration all possible sequences thereby reducing the MLD computational difficulty.

For sequential decoding, its advantage over Viterbi decoding is simply because its decoding complexity virtually does not depend on the constraint length 'K' of the code, unlike the Viterbi decoding whose complexity increases exponentially in line with the code length, making it unsuitable to be used for lengthy codes. Based on this advantage of sequential decoders over Viterbi decoding, they are employed mainly for very long codes. On the contrary, its major set-back is as a result of its erratic decoding latency.

Right from the time Viterbi decoding was developed, it has continually enjoyed so much popularity in this decoding aspect due to its ability to do maximum likelihood decoding and its frequent application in decoding convolutional codes with constraint length less than or equal to 9. It can be seen in Figure 3 below that our proposed block diagram of Viterbi decoder is made up of two major working blocks which are the Add and Compare Select (ACS) module and the Path Memory (PM) module with the former handling the Branch Metric calculations, Path Metric calculations and Add-Compare-Select, the latter keeps record and outputs the decoded information bits of the surviving path.

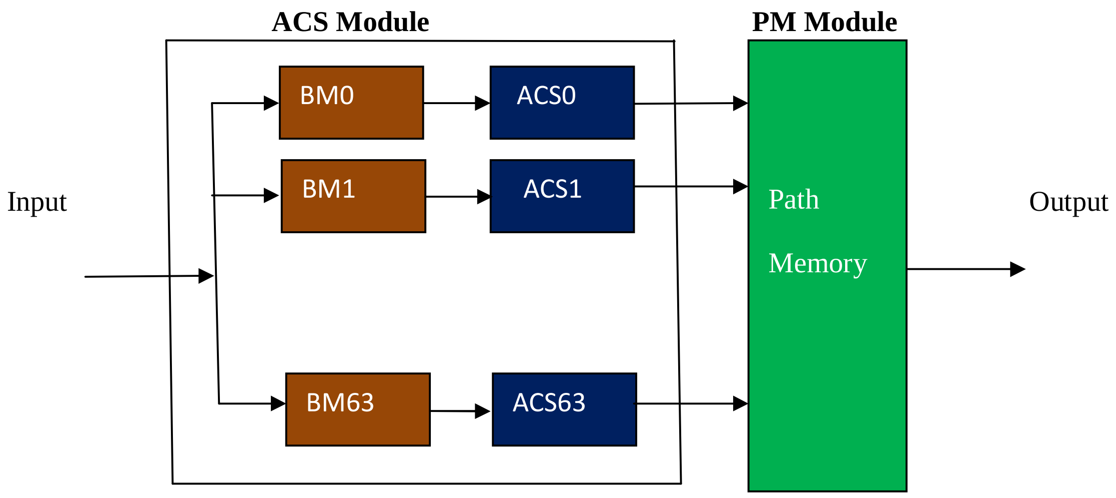

Figure 3: Viterbi decoder architecture for a convolutional code of rate ½ and constraint length 7

(Adapted from Kai He and Gert Cauwenberghs 'www.ieeexplore.ieee.org. **)**

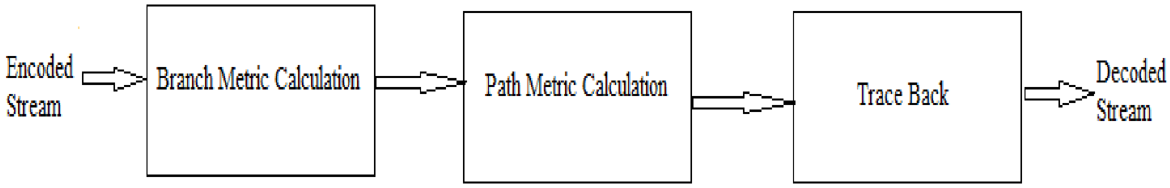

Figure 3.1: Viterbi Decoder Data Flow

The Viterbi decoder implementation can be represented for easy understanding using a flow chart diagram as shown below. This is self-explanatory.

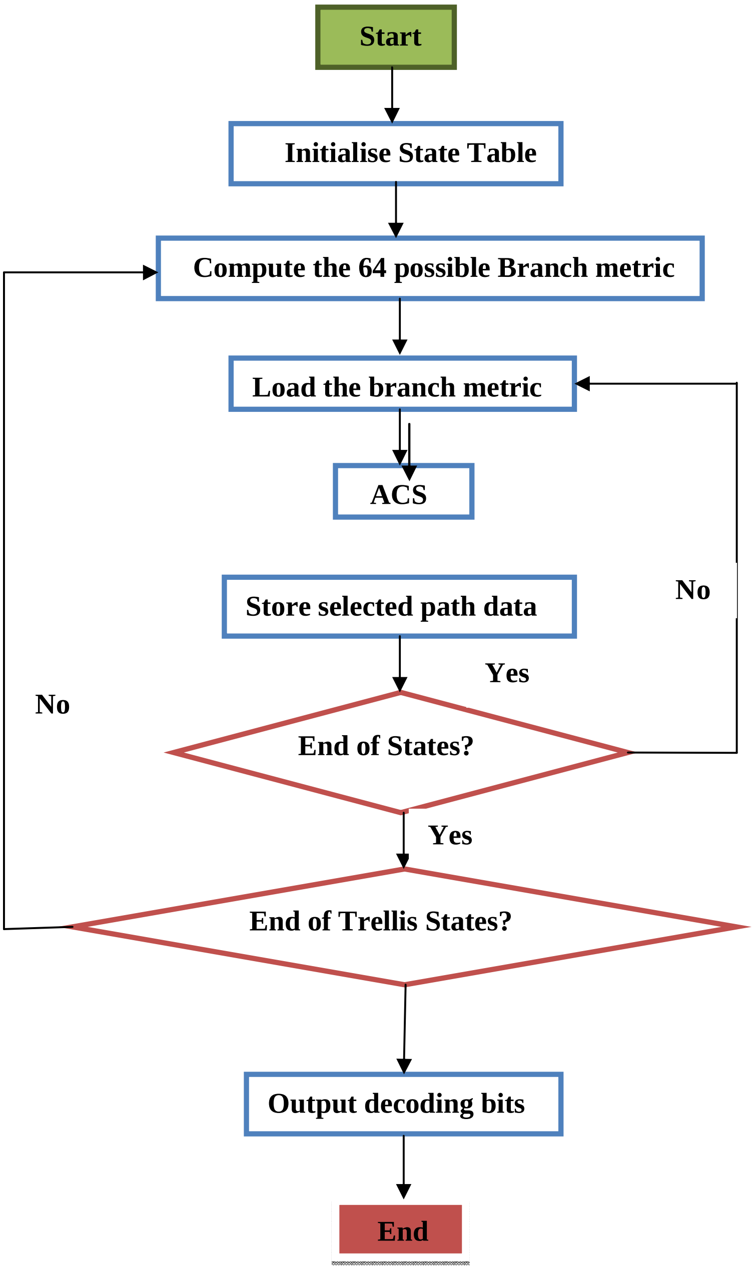

Figure 3.2: A flow chart showing the processes involved in Viterbi decoding

Calculating the Bit Error:

This calculation as handled by the responsible block compares the data sequence given out by the Viterbi decoder bit by bit with the sequence sent by the data generator such that if it discovers any bit from the decoded sequence to be different from the data sent in, it marks that particular bit as an error. Having done this for all the bit sequences, the whole cases of encountered errors are added up. The division of the total error summation by the total summation of the sent bits gives us our Bit Error Rate. Therefore,

BER = Total number of errors/ Total number of bits sent.

Conclusion

This work shows the benefits of making use of rate-compactible punctured codes as against the normal mother rate code in which the justification of using the punctured codes have been proved to perform more than their normal code counterparts when examined at the same rate and memory having compared their degree of computation and duration taken for each decoding to stimulate at a BER value of 10^{-5}. These established benefits were ascertained to increase with both the increase in SNR (E_b/N_o) and coding rates. Hence Viterbi decoding still stands out when it involves the decoding of convolutional encoder which is very powerful in random error correction.

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