ENHANCED 8-VSB TRANSMISSION FOR NORTH-AMERICAN HDTV TERRESTRIAL BROADCAST

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ABSTRACT

We present a new robust backward compatible 8-VSB transmission system for HDTV terrestrial broadcast. The new transmission system allows better reception of signals for portable, mobile and indoor receivers. In the proposed system a scalable fraction of the main service is used to transmit robustly encoded data. The robust service has at least a 6 dB fade margin advantage over the main service. In addition, the data allocated to the robust stream can also be used at the receiver to improve the reception of the normal stream. The robust data is utilized by the normal stream receiver as randomly distributed training symbols which can be used in the equalizer to improve the receiver performance for dynamic mutli-path channels.

1. INTRODUCTION

The high definition television (HDTV) terrestrial standard, known as 8 vestigial side-band (8-VSB), was adopted in 1995 by the Advanced Television System Committee (ATSC) as the standard for North-America. The 8-VSB standard specifies a single carrier modulation system designed for terrestrial broadcast of high quality video, audio and ancillary data over a single 6MHz bandwidth channel [1]. The basic block diagram representation of the system is shown in Figure 1 below.

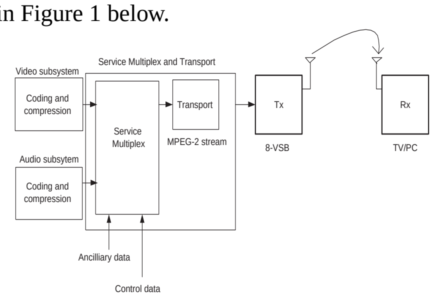

Fig. 1. Digital terrestrial television broacasting

Encoded compressed video and AC-3 audio sub-streams are multiplexed with data and service information in a MPEG2 packet stream [3]. The packets multiplexed by the encoder transport system are broadcast in the UHF/VHF band with the 8-VSB modulator. In this range of the spectrum, difficulties in signal reception are due, for the most part, to frequency selective fades in the signal power, giving rise to both static and dynamic multi-path distortion which must be cancelled by the receiver. To mitigate static multipath the receiver may use training information embedded in the signal to adjust the equalizer coefficients. More effective solutions based on blind equalization techniques can also be used in this context, to cope with slow dynamic multi-path, see [5].

To enhance the performance of indoor reception the ATSC has recently requested proposals for potential revisions to the transmission specification of the 8-VSB standard. A specialists group on radio frequency (RF) transmission within the ATSC, (T3/S9), has been overseeing this effort. In this contribution, we describe an ATSC compatible submission to that group which significantly improves the reception of the normal 8-VSB packets in severe dynamic and static multipath conditions and allows reception of the robust 8-VSB packets in low signal level conditions where normal 8-VSB reception is not theoretically possible.

The proposed solution is a new backward compatible multi-rate data transmission system that addresses broadcaster requests for portable, pedestrian and mobile applications by means of an enhanced 8-VSB (E8-VSB) robust and scalable data stream. In the proposed E8-VSB system the robust stream can co-exist with the normal stream. New receivers will be able to receive the robust mode, but existing receivers will simply discard the robust data as NULL packets. Backward compatibility with the 8-VSB modulation format is crucial since it guarantees that the performance of current available receivers (in set top box, PC, etc.) will not be affected.

The E8-VSB system offers several modes of operation which include a main service mode, referred to as normal mode, and two scalable robust modes. The main service data is protected by the normal 8-VSB FEC (described in Section II). The robust modes apply various levels of increased redundancy in a robust FEC layer allowing the user to trade off data rate for increased robustness. The robust streams have significant signal to noise ratio (SNR) advantages over the normal stream (which offers at least a 6dB over the main stream SNR). In addition to the offered robust service the new enhanced VSB system provides improved reception of the normal 8-VSB data stream by taking advantage of the robust symbols scattered in the normal/robust VSB transmitted frame. This is probably the most original aspect of the design. Typically, the normal service can utilize the robust data as pseudo ”training” symbols to mitigate impaired channels with strong or dynamic multi-path. Efficient semi-blind equalization techniques can take advantage of these new symbols.

The remainder of the paper is organized as follows. Section II gives a brief overview of the current 8-VSB transmission system. Section III describes the new E8-VSB transmitter. The issues of backward compatibility are also discussed in this section. Section IV gives a generic description of receiver for the E8-VSB transmitter followed by a performance evaluation of the new system. Finally, complementary remarks and a conclusion are furnished in Section V.

2. 8-VSB TRANSMITTER OVERVIEW

The current HDTV terrestrial broadcast format offers two modes of transmission; an 8-VSB low data rate mode and a 16-VSB high data rate mode. For sake of simplicity, we consider hereafter only the low data rate mode which supports a payload up to 19.39 Mbps. The 8-VSB transmitter is divided into two functional blocks, a channel coding block which also includes the 8-VSB modulation, and the RF up converter. The input to the coding subsystem from the transport sub-system is a serial data stream comprised of 188-byte MPEG2 compatible data packets which include a sync byte and 187 bytes of data.

The 8-VSB coding sub-system uses several levels of data protection. The protection against noise is ensured by a concatenated Reed Solomon (RS) and trellis encoding. Embedded pilot and synchronization symbols are used for the synchronization of the received signal in time and frequency. Finally, a known pseudo-random sequence and pre-coder filter are introduced to enable channel equalization and co-channel rejection of the analog NTSC video and audio signal if needed.

The incoming data comprises a MPEG2 transport stream that is first randomized with a 16-bit shift register randomizer with the generator polynomial function $g_{16}(x) = x^{16} + x^{13} + x^{12} + x^{11} + x^7 + x^6 + x^3 + x + 1$ where eight of the shift register outputs are selected for randomizing the payload bytes through an exclusive-or operation. The randomized data is then processed into two layers of forward error correction (FEC) in the form of a systematic (207, 187) $t = 10$, RS encoder for which the 20 RS parity bytes are added to the end of each packet, and a 2/3 rate 4-state Ungerboeck trellis encoder. The RS encoder operates on $GF(2^8)$ and has the generator polynomial function $g_{rs}(x) = \Pi_0^{2t-1}(x + \alpha^i)$, and $G(x) = x^8 + x^4 + x^3 + x^2 + 1$ for the field generator polynomial, which offers a 10 byte error correction ($t = 10$).

A detailed description of the trellis encoder is given in Figure 2. Each byte of data is segmented into 4 four groups of 2-bit nibbles (x_1, x_2). Each byte produces four symbols per trellis *via* the mapping $2(4Z_2 + 2Z_1 + Z_0) - 7$. Each symbol at the output of the trellis encoder is therefore an 8-level signal ($-7, -5, -3, -1, +1, +3, +5, +7$) which carries 2 bits of information per symbol. In order to allow the rejection of the NTSC co-channel at the receiver the input bit x_2 of the trellis encoder is pre-coded with the IIR filter $[\frac{1}{1-z^{-D}}]$, and a total of 12 parallel trellis encoders are used in such a way that each trellis operates on every 12th byte ($D = 12$), see [2] for operational details.

Between the RS and the trellis encoder 1/6 data field interleaving is performed with a convolutional interleaver of parameters $N = 208$ bytes, $B = 52$ data packets, and an increment of $M = 4$ bytes. This furnishes a 4ms deep interleaver. Following randomization and forward error correction processing, the data is formatted into data frames for transmission. Each data frame consists of two data fields, each containing 313 data packets of 832 symbols. The framing used can be seen, roughly speaking, as a transposition of the NTSC data format/synchronization into the digital world.

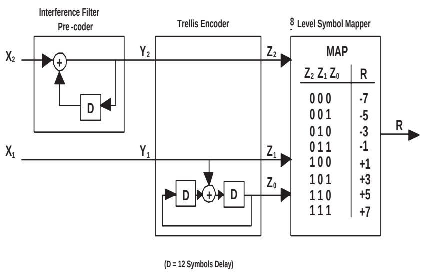

Fig. 2. Interference pre-coder and trellis encoder

A single data field synchronization packet is added at the beginning of each field. This packet includes training symbols (intended to be used in equalization) and control information used at the receiver. Each of the remaining 312 data packets per field carry the data from a 188-byte transport packet plus its associated FEC. For each of the 313 packets per field a synchronization segment is additionally added at the beginning of the packet in a form of 4 binary symbols $(+5, -5, -5, +5)$. After organization of the VSB frame, a DC offset is added to each of the 8-level symbols. This offset adds a pilot tone in the frequency domain inserted at the -3 dB point of the lower band edge of the signal spectrum. This pilot is intended to be used by the receiver to perform accurate frequency synchronization. The 10.76 Mhz symbol stream is finally filtered with a VSB/square root cosine filter (SQRC) of 11.5% roll-off factor and sent to the RF up converter for broadcasting.

3. ENHANCED MULTI-RATE ATSC TRANSMITTER

3.1. Principle

From the description of the HDTV encoder sub-system above it is clear that it is always theoretically possible to enhance the channel coding gain performance of the transmission system. For example, the 2/3 trellis encoder could in theory be replaced with a 1/3 encoder without changing the mapping function (which would reduce the rate by 2 for potentially a better coding gain performance). This is in essence what it is proposed in the new enhanced HDTV transmitter. The difficulty lies in the issue of backward compatibility. In particular the modification of the trellis code must be done without any alteration of the current HDTV encoder. In the proposed solution the enhanced transmitter requires neither the replacement nor the modification of existing HDTV transmitter units. This point is described in detail in the rest of the section.

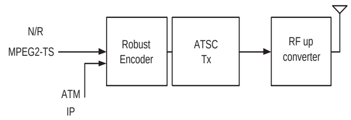

Fig. 3. Enhanced HDTV transmitter

A simplified functional block diagram of the new enhanced transmitter is given in Figure 3. A robust encoder sub-system is inserted prior to the HDTV coding sub-system unit of the 8-VSB transmitter. The input of the robust encoder sub-system has two types of data, referred to as normal MPEG2 packets and so-called robust data which could be either MPEG2 packets or other MPEG2 compatible transport packets such as IP or ATM. The distinction between the two streams occurs in the program identification (PID) headers of the MPEG2 packet. This information can be used by the broadcaster to introduce different levels of prioritization of the transmitted data. Practically speaking, the robust stream furnishes another service which can be used in applications for which an enhanced robustness to channel impairments and reception at lower received signal power is needed. In the proposed scheme two robust data modes of the E8-VSB transmitter (referred as $1/2$ and $1/4$ rate mode) allow the broadcaster to allocate a portion of the 19.39 Mbps stream to a robust data rate transmission. Transmission of multiple robust streams of data with different channel coding in addition to the main service data provides different trade-off between robust transmission and data rate reduction.

The robust encoder sub-system is, more precisely, divided in three functional blocks: a pre-processor which is used to format the robust data into RS encoded MPEG2 equivalent packets, a convolutional encoder introduced to improve the coding gain performance of the ATSC trellis encoder, and a ”map” encoder which is used to indicate to the receiver the presence and position of robust data in each transmitted frame (this function which uses another specific coding will not be described for sake of simplicity). The two main units are described in the next two subsections. To simplify the presentation we consider only the case of a single robust stream (which will be referred as the 1/2 robust rate).

3.2. Pre-processor

The incoming normal and robust data streams, provided to the transmission sub-system from the transport sub-system, are treated separately in two different paths. The normal MPEG2 data payload is up to a 19.39 Mbps serial data stream comprised of 188-byte packets. The robust data payload rate is selected at the option of the user and may be zero.

The first step consists in slicing the robust stream into units of 164 bytes which are RS $(184, 164)$ encoded with the same RS generator polynomial function as the normal 8-VSB RS encoder. The robust RS encoder is followed by a convolutional interleaver with parameters B=46, M=4, N=184. Its principal of operation is the same as the interleaver that occurs in the 8-VSB processor which occurs later in the processing chain (the parameters are different). This interleaver provides additional protection against bursty errors produced by channel degradation.

The 184-byte RS encoded blocks are then mapped into 2 184-byte packets which leads to the so-called 1/2 robust data mode. Each byte $b_0b_1b_2b_3b_4b_5b_6b_7$ of the 184-byte block is split into two bytes as follows $b_00b_10b_20b_30$ and $b_40b_50b_60b_70$. Thus, each 184 bytes output from the interleaver creates 2 184-byte MPEG2 data packets. The zeros inserted between the bits are used as place holders. They are replaced by trellis encoded bits further down in the robust trellis encoder. To create fully compliant MPEG2 packets an MPEG2 sync byte and a 3 byte NULL PID header are pre-appended to each 184-byte packet, creating a 188 byte MPEG2 packet with full backward compatibility. The NULL PID header is a key element for backward compatibility. The NULL PID enables the robust data to be discarded by the MPEG decoder in cases where a legacy receiver is used.

The robust pre-processor and a VSB field synchronized MPEG2 multiplexer then perform the functions of multiplexing robust data packets with the normal MPEG2 transport stream. During this process a normal/robust (N/R) flag is added and carried through the intervening blocks to mark the robust data for special processing in the robust trellis encoder. The robust flag of the expanded MPEG2 packets is applied only to the robust data payload and not to the 4-byte MPEG2 packet header or the parity bytes generated by the normal RS encoder.

An important point concerns the location of the robust MPEG2 packets in the VSB frame. The position of the robust data becomes a key element when the data is used by the normal stream to improve the tracking performance of channel equalization. The robust data, with its greater immunity to noise and channel distortions, can be viewed compared to the normal data, as known information. Optimization of the position of the robust data in the frame is an important problem which will not be addressed in this presentation because of lack of space.

To complete the process of robust FEC encoding, the multiplexed normal/robust MPEG2 packets are then sent to the robust convolutional encoder sub-system.

3.3. Convolutional encoder

The second part of the robust encoding sub-system consists of the robust convolutional encoder. The idea is to concatenate the robust convolutional encoder with the normal 8-VSB trellis encoder to get a more powerful coding system that is treated as a single convolutionally encoded system in the enhanced receiver. The intended resulting overall trellis encoder is shown in Figure 4.

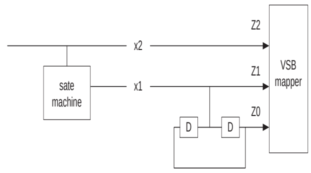

Fig. 4. Combined convolutional and VSB-8 trellis encoder

The convolutional encoder applies the encoding only to data marked with the robust flag. The place holders in the robust packets, which were introduced in the robust pre-processor sub-system, are replaced with a convolutionally encoded bit. Each robust byte of the robust MPEG2 packet is split into groups of 2-nibble bits, in such a way that $b_00b_10b_20b_30$ and $b_40b_50b_60b_70$ become b_00, b_10, b_20, b_30 and b_40, b_50, b_60, b_70. Each first bit of the 2-nibble bits is processed in a 1/2 rate systematic convolutional encoder in such a way that $b_x, 0$ is transformed into b_x, b'_x where b'_x is an encoded bit of b_x. These 2 bits are equivalent to the (x_2, x_1) bits in the normal trellis encoder. Notice that at the receiver the information bit b_x can be decoded from the output bits z_0 and z_1. Different options for the 1/2 convolutional code are possible.

To achieve the result described in Figure 4, the states of the robust convolutional encoder and the normal 8-VSB trellis encoder must be synchronized. The data coming from the robust pre-processor and the N/R flags are passed through a randomizer, a RS encoder and an interleaver. The randomizer and interleaver are identical to those used in the normal 8-VSB transmitter. The RS encoder function here is to simply introduce 20 RS place holder parity bytes. The convolutional 1/2 rate code is then applied to the robust data. For the normal data each 2-nibble bits is unchanged. To re-create the MPEG2 equivalent packet de-interleaver, RS removal and de-randomizer blocks are added after the convolutional encoder. Moreover, since the normal trellis encoder uses 12 parallel encoders which operate on every 12 bytes, similar function needs to be introduced to the robust convolutional encoder.

Furthermore, as shown in Figure 4, the overall trellis encoder for the robust symbol does not contain a pre-coder filter as is the case for normal data as described in Figure 2. The function of precode overide is realized by differentiating the b_x bit. The input x_1 is therefore given by $x_1 = [1 - z^{-D}]b'_x$ (where $D = 12$). To avoid interruption of the precoding during transmission of normal data, the diffrentiation is inhibited for normal data (the data is pseudo-randomly dispersed within the robust stream via the interleaver). Notice that this strategy is not effective for the "normal" data which belong to the RS parity bytes associated with robust packets (at this point the parity cannot be computed since half of the bits of the robust packets are not defined yet). This creates an ambiguity in the polarity of the symbol which can be resolved at the receiver.

4. PERFORMANCE EVALUATION OF E8-VSB RECEIVER

The basic functions of an E8-VSB receiver are described below. The IF data generated by the tuner are processed by the receiver front end (FE) to sample and synchronize the transmitted signal in time and frequency. The baseband channel is then sent to the equalizer to remove the interference intersymbol (ISI) introduced by the multi-path channel. The robust data map is simultaneously extracted from the field sync segment of the VSB frame and decoded. The positions of the robust symbols in the frame are then pre-computed. This information is used to create a table associated with each transmitted normal/robust E8-VSB frame, which flags the robust symbols in the received symbol stream. The robust symbols are simultaneously used in the equalizer module to perform a semi-blind equalization technique, for example. This function is fundamental since it allows a performance improvement in dynamic channels. The improvement of the equalizer function increases the BER performance and coverage area for the normal stream. The symbols at the output of the equalizer are then decoded with an enhanced trellis decoder which will decode simultaneously the normal and the robust encoded symbols. The normal and robust symbols (associated with the rate 1/2 and 1/4) decoded by the trellis are then processed by the backend normal 8-VSB FEC which consists of the de-interleaver, the RS decoder and the de-randomizer. The robust MPEG2 packets are then extracted with the packet de-multiplexer module. At this point the normal packet can be sent to the MPEG decoder. The robust packets still need to be de-multiplexed and processed with the backend robust decoder, which consists of another RS decoder, a de-interleaver and a MPEG sync decoder.

Next we highlight the performance gain of the E8-VSB system for AWGN and an example of dynamic channel. We first focus on the post trellis BER curves for AWGN. In Figure 5 we compare the BER curves for a 16-state (solid line) and a 32-state (dashed line) trellis encoder. At the threshold of (picture) visibility (TOV) of 2×10^{-3} BER the 32-state code furnishes only a small gain of 0.2 dB vis a vis the 16-state code.

Fig. 5. Advantages of robust trellis coding

Notice that for the 16-state code the TOV is reached for 8.2 SNR. For comparison the TOV for the current 8-VSB system is close to 15 dB. The 4-state coding gain also gives an advantage of 3 dB over an uncoded system (where known data replaces the x_1 bit, leaving only the x_2 bit for robust data carriage). In this case the z_0 and z_1 bits are known. The z_2 bit can be recovered with a binary slicer whose slice point varies depending upon the state of z_0 and z_1. In Figure 6, we illustrate the performance improvement on the normal stream when the equalizer is using the information provided by the 1/2 rate robust data. This channel, given in Table I, one of the synthetic channels defined by the ATSC to evaluate the performance on dynamic multi-path of 8-VSB system in laboratory. The channel is known for being an example of realistic sever dynamic multi-path.

Table I.

Ensemble	#1	#2	#3	#4	#5	#6
CRC3:Atten (dB)	0	14	14	4	TOV	12
Delay (μs)	0	-1.80	0.15	1.80	5.70	35.0
Phase/doppler	0	125	80	45	5Hz	90

In the curve it is shown that a 0dB/5Hz doppler echo can be canceled by the equalizer. A 3dB gain is furnished in this case over the normal transmission (0% robust data). Notice also that performance improvement is shown with as low as 5% robust data. The performance measurement used is a zero post-RS error detection for 1 s of data. As expected, the performance varies with the position of the robust packets in the normal/robust VSB frame for low robust ratio ($< 25\%$). A uniform distribution of the pre-interleaver robust packets shows better performance over the distribution of 1 robust packet every 4 packets (which is more adapted to AWGN channels). When the doppler frequency decreases, the difference in performance between the two curves is reduced.

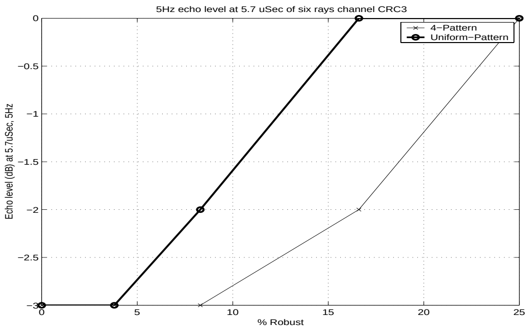

Fig. 6. CRC3 5Hz

5. CONCLUSION AND FINAL REMARKS

A new backward compatible robust transmission system for HDTV terrestrial broadcast is proposed to enhanced the performance of the ATSC 8-VSB US standard. In addition to improved reception in multi-path channels, the proposed solution furnishes a new multi-rate robust scalable service which can be used by broadcasters in a wide range of applications. A prototype receiver, built in a collaborative effort between Nxtwave Communications/ATI and Zenith Electronics, has been released and is currently being tested by the VSB Enhancements Testing Consortium (VETC) under the request of the ATSC group T3/S9, to evaluate extensively the performance of the new system. Laboratory testing has been completed and field tests of outdoor and indoor performance are underway. Preliminary results show an average improvement in reception success of 10 to 20% with a 1.5 Mbps and 4.5 Mbps robust 1/2 rate mode (which is the less robust option of the two robust modes), for more than 2000 tests conducted in the Washington DC area. Among these results, it has been shown that E8-VSB reception reached the remarkable number of 100% service availability with a 30 foot outdoor antenna.

6. REFERENCES

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