Understanding ATSC Mobile DTV Physical Layer

Whitepaper

The ATSC began work in 2007 on the development of an ATSC Mobile DTV Standard. This effort culminated in record time with the approval of the ATSC Mobile DTV Standard (A/153) in Oct. 2009. This paper will discuss the inherent challenges and the technology added to adapt the 8-VSB physical layer to mitigate the mobile fading channel and to enable ATSC Mobile DTV reception (A/153 standard).
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Introduction: ATSC Mobile DTV

The ATSC A/53 DTV standard was adopted in Dec. 1996 by the FCC as the DTV standard for the United States to transition from analog to digital television broadcasting. Figure 1 below shows a time line. The A/53 Digital Television broadcasting system was conceived and has been successfully operating as a fixed (reception) service bringing HDTV and SDTV programming to many terrestrial viewers. However, globally the interest in broadcasting audio and video content and data services to mobile and handheld devices increased (2004-2009) with the ensuing development of several mobile standards such as DVB-H, ISDB-T, T-DMB, CMMB and Media-FLO™.

Some European markets have DVB-H deployments, ISDB-T is used in Japan, T-DMB in Korea and CMMB is being used in China. In the United States, Qualcomm developed and standardized through TIA a mobile technology known as Media-FLO™. In 2007 encouraged by technical demonstrations¹ the ATSC believed it was technically possible to enable mobile broadcasting by adding enhancements to existing A/53 standard. The mobile system envisioned would allow a mixture of fixed and mobile services (dual stream system). This, while ensuring backward compatible in the sense that the new mobile services when present would have no negative effect on existing A/53 receivers. This in-band (6 MHz) dual stream system would require significant adaptation of physical layer to enable ATSC mobile receivers to successfully mitigate a mobile fading environment.

The ATSC began work in 2007 on the development of an ATSC Mobile DTV Standard. This effort culminated in record time² with the approval of the ATSC Mobile DTV Standard (A/153) in Oct. 2009. This paper will discuss the inherent challenges and the technology added to adapt the 8-VSB physical layer to mitigate the mobile fading channel and to enable ATSC Mobile DTV reception (A/153 standard).

ATSC (A/53) Fixed Services

The starting point and the foundational demonstrated a technology named Advanced-VSB to the ATSC, demonstrating that mobile reception was possible with ATSC 8-VSB while maintaining fixed services. This encouraged the ATSC BOD to issue a New Work Item Proposal (NWIP) in early 2007 to start development of the ATSC Mobile DTV Standard. 2 ATSC put the development process on a fast track since it was late in having a mobile solution and broadcasters feared delay would make market entry with mobile services more difficult.

¹ (2005-2007) Samsung and Rohde & Schwarz developed and
framework for ATSC Mobile DTV is ATSC A/53. We will first review A/53 to understand the assumptions made in the design of the A/53 physical layer. A/53 assumes a fixed service propagation model. Figure 2 ATSC Fixed Propagation Model shows this assumed propagation model. The receiver is assumed to have a dominant or direct line of sight (LOS) path to the transmitter and also other delayed paths reflected from stationary objects in the environment arrive at the receiving antenna. A receiver with an antenna gain of 10 dBi and a height of 30 ft above ground level is assumed. Though not explicitly shown in Fig 2 large-scale fading can often occur caused by (hills, forests, buildings, etc.) being located between the transmitter and receiver.

Diffraction occurs when the propagation path between the transmitter and receiver is obstructed by a dense body with large dimensions causing secondary waves to be formed behind the obstructing body. Diffraction is a phenomenon that accounts for the RF energy being able to travel from transmitter to receiver without a line-of-sight path between the two. The amplitude of the diffracted signal can be significantly attenuated. This is often termed *shadowing* because the diffracted signal can reach the receiver even when being shadowed by an impenetrable obstruction.

The 8-VSB physical layer will be analyzed in more detail later in this paper. However, it can be briefly stated now that the forward error correction (FEC) chosen for the 8-VSB physical layer consists of an (outer) Reed Solomon code (207, 187) t=10, capable of correcting 10 bytes errors per packet. An (inner) R=2/3 Trellis Code Modulation (TCM) with a receiver threshold of 15.2 dB (AWGN). These two codes are separated by a byte interleaver, this results in a good design for a fixed reception propagation model.

Since the 8-VSB physical layer is a single carrier system any inter-symbol interference (ISI) resulting from the received multipath signals must be mitigated by an adaptive equalizer in the A/53 receiver. The ATSC standard only specifies the emitted waveform not the receiver. To help an A/53 receiver mitigate a stationary multipath environment the 8-VSB physical layer frame includes a data field sync (DFS) region (see Figure 3) which contains a series of known PN sequences, one sequence is 511 symbols long and is called a PN 511. The equalizer can get an estimate of the channel by using the received PN 511 sequence located in the 8-VSB data field sync region. The data field sync is repeated approximately every 24.2 milliseconds or 313 data segments. The channel estimation...
is calculated at the receiver using a symbol-by-symbol cross-correlation of the recovered PN 511. The received PN511 sequence is correlated with ideal known PN 511 sequence stored at the receiver.

As the recovered PN511 sequence is incremented across the ideal sequence the channel impulse response is revealed showing all echo paths as a result of this correlation process. With this estimate the equalizer can begin by initializing its tap coefficients.

The length of a PN sequence determines the maximum time span between any two received paths (delay spread) over which an equalizer can initialize and begin to mitigate ISI. The ATSC A/74:2010\(^3\) (Receiver Performance Guideline) document suggests a guideline for a Single Static Echo of Varying Delay for which an A/53 receiver can successfully mitigate ISI. Figure 4 is from ATSC A/74:2010, a range of echo delays for a single delay path with respect to a main reference amplitude (0 dB) and zero time is shown.

\[
\begin{array}{|c|c|}
\hline
\text{Echo Delay (\mu s)} & \text{Amplitude (dB)} \\
\hline
-40.0 & -15 \\
-30.0 & -7 \\
-20.0 & -7 \\
-15.0 & -5 \\
-10.0 & -3 \\
-5.0 & -0.5 \\
5.0 & -0.5 \\
10.0 & -1 \\
15.0 & -1 \\
20.0 & -2 \\
30.0 & -3 \\
40.0 & -4 \\
50.0 & -15 \\
\hline
\end{array}
\]

Figure 4 ATSC A/74:2010 Single Echo Varying Delay

This is only a minimum recommendation and many known receiver designs now exceed this performance.

For the relatively benign channel model for fixed reception the length of the PN sequence and the repetition rate \(\sim 24.2\) milliseconds has proven to be successful in the field.

The PN sequence repetition rate remains a limiting factor on how fast the multipath can be changing such as from reflections of a moving object which will cause a frequency shift.
or Doppler Shift between paths. If the energy from this Doppler (Hz) component is significant the equalizer can have problems updating or tracking the channel since the PN sequences occur only at 24.2 ms intervals. For the majority of cases reliable stationary fixed services can be delivered.

One example of a corner case might be when a fixed roof antenna has tall trees with foliage in the vicinity and are shadowing the signal being received. If the wind speed then causes the trees to sway this may produces rapid changes in received signal which may be occurring faster than the equalizer can handle using the 24.2 ms update rate of PN 511. This may be a corner case but points out that enhancements to equalizer training sequences will be needed to mitigate a mobile fading channel to be discussed next.

**Mobile Fading Environment**

Figure 6 shows the propagation model of a mobile fading channel, this will be used to introduce the subject of the mobile fading environment.

**What is Fading**

The first observation is the mobile receiver antenna is small and may be mounted on a moving vehicle or in the case of a handheld receiver the antenna is even smaller and may be embedded inside the receiver itself and operated *only several feet above ground level* compared to the 30 ft height in the case of fixed reception. Hence, with mobile and handheld the receive antenna is expected to have very little clearance to the ground or to close by objects, so these reflecting surfaces in the vicinity of the receive antenna will have a *substantial* influence on the characteristics of the propagation path in the mobile environment.

The mobile channel is characterized by multipath reception. The composite signal offered to the receiver contains not only a possible direct line of sight (LOS) RF wave component, but also a large number of reflected RF waves. When the LOS component is present, it is termed Rician fading.

In urban environments, the line-of-sight is often blocked by obstacles, resulting in only a collection of delayed RF waves reaching the mobile antenna. When there is no LOS component present, it is termed Rayleigh fading.

These arriving coherent reflected RF waves setup an interference pattern at the receive antenna. The phasor diagram in figure 5 shows the reflected RF waves (blue) impinging on the receive antenna producing the vector sum of the arriving RF waves, this results in the fading envelope. (black vector) In a fading channel, every now and then the resulting fading envelope is very weak (fades) and bit
errors occur as the instantaneously signal level goes below the threshold for reception. This fading phenomenon remains present even if the (average) signal-to-noise ratio is large such as being closer to the transmitter in the urban environment. The signal strength doesn’t matter since this phenomena is caused by coherent RF waves constructively and destructively interfering at the receive antenna. If the antenna moves the channel varies with location and time, because the relative phases of the reflected RF waves change continuously. This leads to fading: time variations of the received amplitudes and phases sometimes resulting in a trough dipping below the receiver threshold for some period of time.

Several mutually independent, multiplicative propagation phenomena usually can be observed in a mobile environment and these are shown in Figure 6 and will be briefly commented on below.

**A: Free Space Loss** – free space loss model assumes a transmit antenna and a receive antenna is located in an otherwise empty space environment. Stated briefly when the propagation distance increases the radiated energy is spread so the power received decreases in proportion to the propagation distance squared ($d^2$).

**B: Reflection** - Reflection occurs when a propagating electromagnetic wave impinges on a smooth surface with very large dimensions compared to the RF signal wavelength ($\lambda$).

**C: Diffraction** - diffraction occurs when the propagating path between the transmitter and receiver is obstructed by a dense body with large dimensions compared to wavelength $\lambda$. This causing a secondary electromagnetic wave to be formed behind the obstructing body and the wave propagates around edges of the obstruction. Diffraction is a phenomenon that accounts for the RF

![Figure 6 Mobile Fading Environment](image)
energy traveling from transmitter to receiver without a line-of-sight path

**D: Scattering** - Scattering occurs when a radio wave impinges on a rough surface or any surface whose dimensions are on the order of $\lambda$ or less causing the reflected energy to be spread out or scattered in all directions. Many objects located close to the receive antenna in an urban environment can contribute to scattering.

**E: Shadowing** - shadowing causes the received signal power to fluctuate due to objects obstructing the propagation path between transmitter and receiver. In an urban environment tall buildings can cause a phenomenon called (birth, death). A mobile receiver may turn a corner in the urban concrete canyon and have a significant drop in signal strength (Death). Then move little further and the signal strength rapidly returns (Birth).

**F: Doppler** - Motion of a receive antenna or reflections from moving objects produces Doppler shifts of incoming received waves. Such motion leads to (time varying) phase shifts of individual reflected waves. Many waves each with different angle of arrivals will have their relative phases changing all the time, and this affects the amplitude of the resulting signal.

**Rayleigh Fading**

Rayleigh fading^4 is caused by multipath

4 See IEEE Communications Magazine, July 1997, Bernard Sklar,Rayleigh Fading Channels in Mobile Digital Communications Systems Part 1: Characterization

The mobile antenna receives a large number of coherent reflected and scattered waves from the broadcast antenna over various paths and because of the wave cancellation effects at the receive antenna, the instantaneous received signal power seen by a moving antenna becomes a random variable, dependent on the location of the antenna. Figure 7 shows a simulation of Rayleigh fading of un-modulated carrier (UHF) at a speed of 120 km/hr.

This simulation shows very well the signal amplitude (in dB) versus time for an antenna moving at this constant velocity. Notice the deep fades that occur occasionally. Note: A Doppler shift will also happen to the received signal components which must be mitigated, and although fading is a random process, deep fades still have a tendency to occur approximately every $\frac{1}{2}$ wavelength ($\lambda$) of antenna motion. One such trough is shown approximately at 200 ms that is -40 dB. To

![Figure 7 Rayleigh Fading](image)
make matters worse when the speed is reduced to pedestrian at 3 km/hr the width or duration of these deep fades will become longer.

Therefore, given these observations it was determined that to enable ATSC Mobile DTV additional known training sequences (which are both longer and have a faster repetition rate) are needed to enable fast synchronization and equalizer initialization and dynamic tracking in a mobile fading channel.

Also a new FEC at the physical layer with a lower C/N threshold and with inherent time diversity properties is needed to help mitigate the deep fades of a mobile channel.

Next a brief introduction of these specific enhancement technologies will be given. With an overview of the basic ATSC A/53 exciter and receiver block diagrams showing the blocks that will need to be enhanced to enable ATSC Mobile DTV.

**Introduction of Technology to enable ATSC Mobile DTV**

Figure 8 shows the basic block diagrams of an ATSC A/53 exciter on the top and an A/53 receiver on the bottom.

In the exciter a known PN 511 sequence is inserted in the DFS by the Mux shown ~ every 24.2 msec (grey). As a result the receiver equalizer only has known training symbols available at a rate that arguably can be sufficient for fixed reception but pose major limitations when synchronizing, initializing equalizer taps and tracking a mobile fading channel.

There is one segment (DFS) reserved for training out of every 313 segments in each VSB data field; the other 312 segments carry FEC coded data. As shown in Figure 9, to overcome this limitation for mobile additional long known training sequences are introduced at a faster repetition rate (virtual training sequences) using some of the 312 segments that normally carry FEC coded data. The term virtual means they will be hidden and not discoverable to A/53 receivers appearing within packets with an ATSC reserved PID and will be treated like...
Introduction of Technology to enable ATSC Mobile DTV

a null packet by A/53 receivers and discarded. However, to ATSC Mobile DTV receivers the virtual training sequences will be known sequences at known physical locations in VSB data field and are useable to help mitigate the mobile fading channel. Robustly encoded mobile signaling data also appears between two closely spaced long training sequences; this strategic placement of signaling data helps ensure discoverability by mobile receivers.

The A/53 standard uses a concatenated coding scheme for channel coding (FEC). Concatenation\(^5\) is a method of building long codes out of shorter ones; it attempts to keep decoding complexity low by breaking the required computation into manageable segments. In A/53 the exciter uses a 2/3 rate (inner) convolutional code which is concatenated with an (outer) Reed Solomon (RS) code (207, 187) t=10 separated by a Byte Interleaver. Note: Trellis Coded Modulation (TCM)\(^6\) is a jointly optimized coding and modulation technique. In short in TCM a signal alphabet is expanded and the transmitted symbols are assigned to signal points in the constellation to effectively enlarge the minimum Euclidean distance.

Figure 10 shows the 2/3 rate 4 state trellis encoder. One input bit is encoded into two output bits by using a 1/2 rate convolutional coder while the other input bit is pre-coded. A symbol mapping procedure follows, (1 of 8) levels is chosen to represent each (3 bit) codeword in the 8-VSB modulation that follows. In the receiver a single decoder using the Viterbi\(^7\) decoding algorithm is used for decoding the inner convolution code (TCM).

The Viterbi algorithm is a maximum likelyhood decoder. The Viterbi decoder examines the entire received sequence of symbols of a given length. The decoder computes a metric for each possible path through the trellis and

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Footnotes:
2. Invented by Gottfried Ungerboeck, IBM first described in a conference paper in 1976
makes decisions based on this metric. All possible paths are followed across the trellis shown in figure 8 until two paths converge on a node. Then the path with highest metric is kept (this is known as the survivor shown in blue) the other path is discarded. The Viterbi algorithm reduces decoding complexity by eliminating unlikely paths dynamically as the decoding progresses. Some of the assumptions of the Viterbi algorithm are worth noting: (1) an error occurs infrequently (2) the probability that two errors occur in a row is much smaller than a single error (3) errors are randomly distributed. Viterbi decoding works well on fixed propagation paths that are noise (AWGN) limited. However, Viterbi decoding doesn’t perform well on bursts of errors and is therefore concatenated with a byte interleaver to spread out error bursts from the Viterbi decoder so these errors can more easily be corrected by the Reed-Solomon decoder.

The Viterbi decoder can give good coding gain in an AWGN channel; with randomly distributed errors. It has been observed that good coding gain is achieved with TCM and Viterbi decoding in an AWGN channel. However, the TCM and Viterbi performance is mediocre and even worse than even un-coded modulation in the presence of mobile multipath fading.

An early attempt to bring enhancements to A/53 was proposed by Zenith and named Enhanced VSB (E-VSB). It used the enhanced inner TCM coding shown in figure 11. This is essentially an extension to existing (A/53) TCM. Its performance resulted in a 6dB gain (AWGN) over normal 8-VSB. The E-VSB system became an ATSC standard but was never commercially fielded. The E-VSB enhanced TCM and Viterbi decoding could perform only up to a certain depth of a fade, but then the E-VSB system degraded faster than un-coded modulation during events of deep selective-fading.

Research into mobile communications has shown to help mitigate mobile fading various forms of diversity should be utilized. A new FEC (inner) code constructed from two convolutional encoders separated by a long symbol interleaver and using two decoders in the receiver will be used for ATSC Mobile DTV. These two decoders in the mobile receiver work in an Iterative decoding scheme, and offer the coding gain and time diversity properties needed to help mitigate fading. The iterative decoding process has given this

Figure 11  E-VSB Enhanced TCM encoder
technology the name “Turbo Codes”. These powerful codes were invented in 1993\(^8\) and are now being used in many mobile standards today. Introducing Turbo Codes will be an important part of the overall strategy to enable ATSC Mobile DTV.

Introducing Turbo Codes will be an important part of the overall strategy to enable ATSC Mobile DTV. The ATSC single carrier system namely time diversity, antenna diversity, and transmitter diversity. It will be shown that using a serial Turbo code as the (inner) FEC offers the coding gain and time diversity needed.

**Closer Look at A/153 Mobile DTV Turbo Encoder and Iterative Decoding Process**

Diversity techniques are based on the notion that errors occur in reception when the channel is in a deep fade. If the receiver decoder can use several pieces of the same (information) signal transmitted randomly (at different time instants) over the fading channel, and use this information to decode the signal the error probability will we reduced considerably.

The top of Figure 13 shows two convolutional encoders separated by a symbol Interleaver. This forms the Turbo Encoder, or Serial

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\(8\) 1993, Claude Berrou, Alain Glavieux, Punya Thitimajshima

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**New FEC Scheme**
- Inner Turbo Encoder
- Outer RS-CRC block encoder
- Virtual Training Sequences
- Robust Mobile Signaling

**Inner Turbo Code (SCCC) FEC**

There are several different diversity techniques available to

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**Figure 12 Technologies to enable ATSC Mobile DTV**

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**Figure 13 Turbo Encoding and Iterative Decoding**
Concatenated Convolutional Coder (SCCC).

The encoder to the right of the interleaver is the existing A/53 inner 2/3 rate TCM encoder. The encoder to the left is a new (½ or ¼) rate convolutional encoder. (½ rate shown) First, each mobile data bit is encoded in the new convolutional encoder (left) and this produces the original data bit (D) plus a parity bit (P). A whole block of data is encoded and the output bit pairs are then sent to a new symbol interleaver. The new symbol interleaver receives this SCCC data block (up to 19,536 bits) and then performs a permutation on the block of data so that the bit pairs output are in a random order. The output permutated (bit pairs) are sent to the next convolutional encoder, the existing A/53 2/3 rate TCM encoder. The 2/3 rate encoder outputs a 3 bit codeword that is then mapped to (1 of 8) levels to create a symbol for the following normal 8-VSB modulation. To review the turbo encoding shown, we start with a single information bit (½ rate) convolutional encoded resulting in 2 bits (original data bit plus a parity bit), then a large block of this encoded data is collected and then permutated in the symbol interleaver and the output bit pairs are then 2/3 rate convolutional encoded with the resulting (3 bit) codeword being mapped to (1 of 8) levels and then normal 8-VSB modulation is performed.

The receiver decoder is shown in the bottom of figure 13. Two decoders are used, a 2/3 rate and 1/2 rate (this example) connected by a feedback loop (de-Interleaver and Interleaver) as shown. The process starts at the demodulator which outputs soft decision information in addition to a hard decision which indicates how much confidence should be placed on the hard decision. In addition to the (Data and Parity) both decoders shown also use and generate soft information. Both of the decoders are referred to as Soft in Soft out (SISO) decoder. The soft information usually takes the form of the log-likelihood ratio (LLR) for each data bit. The log likelihood ratio is the ratio of the probability that a given bit is a ‘1’ to the probability that it is a ‘0’. If the logarithm of this ratio is taken, then its sign (+/-) corresponds to the most probable decision on the bit (+) ‘1’ is most likely; if (-) ‘0’ is most likely). The LLR absolute magnitude is the measure of certainty about this decision. Thus the log-likelihood ratio is a measure of the total information we have about a particular bit. In fact this information comes from several separate sources. Some comes from the received data itself: this is known as the intrinsic information. The soft Information extracted from the two decoders is regarded as extrinsic information. This extrinsic information represented by (LLR) is updated by each decoder each time it processes the SCCC data block, this is passed to the other decoder as updated soft information. It is this feedback that has given rise to the term ‘turbo-code’, since the original inventors likened the process to a turbo-charged engine, in which part of the power at the output is fed back to the input to boost the performance of the whole system. This structure assumes that the two decoders operate much faster than the rate at which an incoming SCCC data block arrives. This means that as iterations continue with updating
(LLR) each symbol detection value influences symbol decisions in different time instants within an interleaved SCCC block. In this way, (LLR) information propagates in the decoding blocks of the outer and inner decoder taking advantage of the updated LLR soft information and the errors are corrected with iterations. These iterations continue until all the (LLR) indicate with high confidence (absolute magnitude) that the decoders are correct, this is called convergence. (Usually 6-10 iterations) At this point the combination of intrinsic and extrinsic information is used to decode the data, and then the corrected SCCC data block is output.

Since the updated LLR metrics represent the same information bit, but in different instants in time (permutation Interleaver), the convolutional decoders performing this type of decoding benefit from time diversity.

The turbo decoder time diversity (iteratively correcting bit errors), gives much better performance than a Viterbi (maximum likelihood sequence) decoder in a mobile fading channel. The A/153 prototype receiver hardware tested in the lab had a (½) rate C/N (7.1 dB) and (¼) rate C/N (3.2 dB) in AWGN. The Lab performance of the (¼) rate turbo code (with virtual training) in a dynamic multipath (TU 6) channel was 331 km/hr @ 17 dB C/N.
Equivalent Block A/153 Physical Layer

Figure 14 shows a simplified equivalent block diagram of the A/153 physical layer. On the top is (channel coding and modulation) on the bottom (demodulation and decoding). These will be used to introduce how the new FEC coding blocks are integrated into A/53 and what constraints are placed on A/53 operation.

A mixture of normal (A/53) TS Packets and mobile (A/153) IP packets are used as inputs into the A/153 dual stream system. The inner 2/3 rate TCM encoder is (time shared) by A/53 fixed and A/153 mobile. This existing 2/3 encoder is shown to right of the A/53 byte interleaver in figure 14, and is receiving time multiplexed normal and mobile packets. The (A/53) coded packets entering the 2/3 TCM are intended for normal A/53 receivers with a Viterbi decoder. The A/153 mobile coded packets entering the 2/3 TCM (part of turbo encoder) are intended only for a (A/153) mobile receiver with a turbo decoder. The reason the inner 2/3 TCM is time multiplexing normal/mobile is because this effectively allows the turbo code to be at the physical layer resulting in the best mobile performance, while maintaining A/53 backward compatibility. The mobile coded data is placed in deterministic (known) locations within virtual\(^9\) M/H Frame structure shown in figure 15. The M/H frame structure is 20 VSB frames (~ 968 milliseconds) and consists of (5) sub-frames each (4) VSB frames, each subframe consists of 16 Slots (80 Slots total M/H frame) which may carry mobile and normal data. The three Slots shown in yellow in figure 15 (are mapped identically in all five sub-frames a total of 15 Slots) and represent the data of one mobile channel. The M/H frame structure and mobile symbol mapping of Slots termed a (Parade),

\(^9\) A/53 receiver decodes all symbols, however mobile data will be erroneous and located in packets with a reserved ATSC PID and are treated like null packets and discarded by receiver

Mobile coded data is placed in deterministic (known) locations within virtual\(^9\) M/H Frame structure shown in figure 15. The M/H frame structure is 20 VSB frames (~ 968 milliseconds) and consists of (5) sub-frames each (4) VSB frames, each subframe consists of 16 Slots (80 Slots total M/H frame) which may carry mobile and normal data. The three Slots shown in yellow in figure 15 (are mapped identically in all five sub-frames a total of 15 Slots) and represent the data of one mobile channel. The M/H frame structure and mobile symbol mapping of Slots termed a (Parade),

\(^9\) M/H frame structure is made of exactly 20 VSB frames (12,480) packets, has possible 80 slots to transmit mobile data, this slot structure is signaled to the mobile receiver, the M/H frame structure is hidden from A/53 receivers, hence the term virtual.

\(^{11}\) To conserve battery power an M/H receiver only processes the Slots wanted that are turbo coded. Robust signaling and virtual training sequences permit rapid channel acquisition, the receiver only powers on fully when needed, this is called time slicing.

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deterministic placement of mobile symbols in the virtual M/H frame structure enables the mobile receiver’s to discriminate and process just turbo coded symbols and ignore symbols intended for normal A/53 receiver. Figure 16 shows the expanded view of the M/H Frame encoder comprised of an M/H Randomizer (yellow) and RS/CRC Encoder (blue) of figure 14. The mobile IP packets being input to the randomizer could represent the streaming A/V content from a H.264 / AAC encoder.

**Outer Reed-Solomon / CRC**

Recognizing that the Inner turbo encoding provides a low C/N and time diversity that is useful to mitigate fading there will still be many times when the mobile channel conditions result in some errors being output from the turbo decoder. The M/H frame encoder is an outer (packet layer) FEC for ATSC Mobile DTV that is designed to correct burst of errors that may occur at instants such as deep fading during the MH frame period of ~ 0.968 milliseconds. After the randomization, a CRC checksum and Reed Solomon (RS) Parity is used to enable detection and correction of errors. First the M/H frame table of IP packets is constructed. The IP packets enter into the table row by row (wrapping at ends) from top to bottom. A two byte header is placed at the beginning of each row and a 16 bit CRC checksum calculated over the row is appended to the end. There are always 187 rows of IP packets in an M/H frame. Each row is (N) bytes long, and N depends on the size (number of Slots), coding, etc used to construct M/H frame. Below the rows of IP packets are several rows of RS Parity bytes, consisting either of 24, 36 or 48 bytes (t) that are calculated (transversely) on the columns of 187 bytes.

**M/H Frame Time Diversity**

When M/H frame encoding is complete, the packets are output row by row and sent to next stage of the turbo (SCCC) encoder. Since, Slots...
(yellow in figure 17) are uniformly distributed across each sub-frame, the packets will benefit from time diversity as a result of this virtual interleaving over ~ 0.968 sec. The RS parity is calculated transversely on the columns of bytes and can be used by the receiver to either correct up to (t) byte errors or to both detect and correct up to (t/2) byte errors in each column. Given, (t = number RS parity bytes 24, 36, 48) in each column of the M/H frame. As will be shown in figure 18 the real advantage of adding the CRC checksum is to enable each row of packets after the receiver’s turbo decoder to be checked for any uncorrected errors. If there are no errors detected by CRC checksum on any rows the turbo decoder was successful in handling all errors (good channel conditions) and the RS decoding can be skipped. In erasure decoding the RS Parity bytes are only used to correct byte errors. The job of detecting and locating the byte errors is handled by CRC checksum and the known packet position in RS frame. By using the CRC checksum mechanism, an erasure can be set for an entire row of bytes. Then using RS erasure decoding (t) byte errors (t= 24, 36, 48) can be corrected since the detection and location of errors is handled by CRC checksum, etc. This erasure decoding capability is very useful when bursts of errors occur as shown in figure 18. There are multiple packet errors shown in sub-frames (2, 3, and 4) that occurred during the M/H frame period (~0.968 sec). Figure 18 shows that the CRC checksum has failed on some rows of packets in these sub-frames and these rows will be

Figure 18 Reed-Solomon Erasure Decoding
declared as erasures when the M/H frame \((187 + t)\) rows are totally reassembled in the M/H frame decoder. If the number of declared row erasures is less than or equal to \((t)\), then \((t)\) erased rows of packets can be corrected by RS erasure decoding. The following is an example for \((t=48)\), the number of total rows is \((187 + 48 = 235)\) and the 235 rows will be split equally over 5 sub-frames \((47\) rows of packets per sub-frame). With erasure decoding in this example 48 rows of erasures can be declared and corrected. Hence, a long burst error lasting one complete sub-frame can be corrected. The rows of packet errors and erasures could also be distributed randomly across whole M/H frame so long as the total number of erasures is less than or equal to \((t)\), RS erasure decoding will be successful. However, if erasure decoding fails \((number\ erasures > t)\) normal RS decoding can still be attempted \((detecting\ and\ correcting\ t/2\ byte\ errors\ per\ column)\) and depending on byte error distribution may be successful.

**Additional Training Sequences**

To increase the number and periodic rate of known training sequences appearing at known locations in physical layer \((VSB\ frame)\), additional virtual training sequence are created to help mitigate and track dynamic fading in the mobile reception environment.

**Tutorial on A/53 Byte Interleaver**

A brief tutorial of the \((mapping)\) of the ATSC A/53 Byte Interleaver is presented first to help reader gain general insight into the creation of virtual training sequences and the overall operational paradigm of A/153, which leverages \((cross\ layer\ mapping)\) the interleaver. In figure 14, it was observed that the ATSC byte A/53 Byte interleaver is a common for both A/53 and A/153. The mapping \((how\ segments/\ bytes\ change\ position\ when\ they\ transverse\ the\ A/53\ interleaver)\) needs to be...
understood to gain general insight into how the known training sequences are created at known locations of the physical layer (8-VSB frame).

Figure 19 is a graphical representation of the progression of mapping process in A/53 Byte Interleaver as data bytes enter and progress through and then exit interleaver.\(^{12}\) The A/53 Byte Interleaver mapping process can be stated mathematically, but a series of graphics may help increase understanding. Note: the M/H receiver locates the M/H training, M/H data and M/H signaling (TPC/FIC) symbols by their known positions in the physical layer of the broadcast M/H frame. Therefore, the permutation of the data in the interleaver (which benefits ATSC legacy receivers) must be mitigated for the M/H data by first placing these bytes into the exact position they will assume after the A/53 interleaver and then De-Interleaving (pre-processing) the M/H data before inserting it into transport stream in the M/H multiplexer. This inverse process (de-interleaving) will negate the permutation of the M/H data and allow a direct (cross layer) mapping of a packet (byte) into physical layer symbols.

At the input of the A/53 interleaver are shown 52 packets after the RS encoder (20 RS parity bytes orange) with total length 207 bytes. The 3 byte MPEG headers are shown (green). The

\(^{12}\) The byte Interleaver improves the burst error handling in A/53. We need to know mapping only for the special A/153 processing.
The first graphic after the interleaver shows the first step in the permutation process and is represented by a rotation by 90 degrees of the four (rectangle) data sections. Note: a series of down arrows show the progression path. The next step is a parallelogram is formed out of the whole data block. The next step is to slide only the upper triangle sections (parallelogram) down, forming the saw tooth pattern of data shown. Next, a dotted vertical line is drawn to limit the length of saw tooth pattern to 207 bytes. The final step is cutting and moving the section of saw tooth data to the right of dotted vertical line, by sliding all the way to the left as shown. This produces the final output of the A/53 Byte Interleaver. Note: the segments now appear horizontal and the bytes now appear diagonally along the saw tooth.

Given this insight, compare the Interleaver diagrams from the A/153 standard document shown in figure 20. Note: M/H training bytes before interleaver are aligned vertically (de-interleaved in pre-processor), after the A/53 interleaver (exciter) the M/H training bytes will become sequential in a segment shown horizontally. This sequential alignment in a segment is the pattern needed for the broadcast M/H training sequences.

Hence, one can design the byte positions desired after the A/53 interleaver with knowledge of A/53 mapping and by pre-processing the M/H data. Likewise, the M/H turbo encoded symbols and M/H signaling symbols are designed to appear at known positions in the physical VSB frame, etc.

**A/153 Virtual Training Sequences**

Figure 21 shows the VSB field with two MH Slots each having 6 long training sequences (white). At the beginning of each sequence...
(yellow) is used to indicate the trellis initialization bytes used to establish the starting states (to be discussed) of all 12 trellis encoders (TCM). By initializing all (12) trellis encoders to known zero states just before the known training (pre-calculated data assuming zero starting state) begins will create the known training symbol sequences that are very useful to M/H receiver equalizer in mobile fading.

Figure 22 shows one of the 12 TCM encoders in A/153, the X2 and X1 bit pair follow the normal (N) path at all times except during the trellis initialization procedure to be performed at the beginning of every training sequence. Just before the 2 init bits (yellow) enter X2, X1 the switch is moved down into the (I) Init position. The init bits (which are reserved for this purpose) never enter the encoder. Instead the combinatorial logic and memory (D) is put in a feedback loop by position of the switch (I). The novelty of this feedback is that independent of whatever states (represented by the memory elements) the trellis encoders are in, the feedback (logic) will drive them to all zero states after two symbol periods. The switch then returns up to the normal (N) position in time for beginning of first training sequence bit (white), the training bits were pre-calculated based on a zero start state of trellis encoders and therefore a known training symbol sequence results, the switch remains in (N) position until next trellis initialization cycle.

**A/153 Mobile Signaling Data**

Very Robust M/H signaling must be available to receiver, there are two types of M/H physical layer signaling data (1) TPC (Transmission Parameter Channel), used at M/H receiver to quickly locate the M/H virtual frame structure, discover the FEC encoding parameters used for the selected Parade (Slots carrying wanted content in MH frame) and (2) FIC (Fast Information Channel) to bind content selections made from upper layer to Parades carrying the selected content, etc.

Both the TPC and FIC are encoded using a \( \frac{1}{4} \) rate Parallel Turbo Code. Figure 23 shows the 6 training sequences (white) trellis init bytes (yellow) and the TPC/FIC (purple) located between the first and second training sequences of every mobile Slot. By locating the \( \frac{1}{4} \) rate Turbo Coded M/H signaling data in the area between these 2 training sequences provides for robust signaling reception (low error probability) in the fading channel. The signaling data must be very reliable since it is used to locate, start and continue decoding any selected A/153 mobile content.

**A/153 M/H Multiplexer (Studio)**

We have discussed the technologies used
to enable ATSC Mobile DTV and presented simple (equivalent) block diagrams of the system. We will now take a look at the two major pieces of A/153 broadcast equipment, the M/H Multiplexer (Studio) and the M/H Exciter (transmitter). The A/153 M/H Multiplexer (Studio) is shown in top half of figure 24. The dual stream output (Fixed, Mobile) is assembled by the Packet Mux and consists of normal A/53 TS packets from the output of ATSC multiplexer. The IP packets containing mobile data (H.264-video, AAC-audio, ESG, ...) are FEC processed by the (outer) RS/CRC and part of the (Inner) FEC blocks, M/H signaling and Training data is added then the mobile data is encapsulated into MHE (Mobile Handheld Enhancement) TS packets. The (cyan) blocks in figure 24 are used principally to maintain backward compatibility with A/53 receivers. The incoming normal A/53 TS packets must be moved in their original positions (stream) to make room for the 118 consecutive MHE TS packets. Therefore their timing and PCR values are
adjusted to maintain compatibility with A/53 buffer models. The IP packet streams are (FEC encoded) and then encapsulated into MHE TS packets. To review, the (outer) FEC encoding of IP packets begin with their randomization and RS/CRC encoding in the M/H frame encoder in the two (blue) blocks. Next, the two (green) blocks in the M/H Multiplexer and the third (green) block in the exciter (Inner 2/3 trellis encoder), collectively form the turbo (SCCC) encoder. The function of MH Group formatter is to assemble the M/H Group of mobile turbo (SCCC) data, pre-calculated training bytes, trellis initialization bytes, and M/H signaling data, etc. These bytes are assembled in the Group formatter into the desired mapping that will appear at the output of normal A/53 byte interleaver in the M/H exciter. Then an inverse process (A/53 byte De-Interveaver) returns the data to the correct position before the A/53 Interleaver. Several placeholder bytes used in group formatter process, such as RS Parity, etc. are removed and the packet formatter then forms the MHE TS packets by adding an MPEG sync byte and the three byte header with reserved PID containing as payload the processed IP Packet data. As previously mentioned the Packet Mux forms the Dual Stream output. The nominal ATSC TS rate is 19,392,658 bps. Note: to add mobile content say at a data rate of 5 Mbps, the normal A/53 TS would first be reduced by 5 Mbps. Whatever the mixture of Fixed and Mobile used the total data rate must be 19,392,658 Mbps. (including null packets, etc in the normal stream) Another constraint is that only 75 % (~ 14.7 Mbps) of the total data rate can be allocated to mobile, leaving a minimum of ~ 4.7 Mbps for normal A/53.

Constraining M/H Multiplexer average data rate to 19,392,658 bps

The A/53 standard specified TS data rate is 19,392,658 bps +/- 54 Hz. To ensure the byte mapping needed for A/153 and to enable symbols to appear at known locations in VSB frame, the M/H multiplexer output and M/H exciter must both be locked to an external time reference. This constraint enables buffer management to prevent buffer under- or overflow while maintaining the average data rate. Besides the data rate constraint the STL link must deliver the same packets output from the M/H Mux and in the same order to M/H exciter. Note: some existing STL terminal equipment including external interface equipment such as (SMPTE 310/ASI, ASI/SMPTE 310) format converters may allow adding or dropping of null packets to maintain data rate. Although fine for A/53, this action will be disastrous for A/153. When the M/H multiplexer builds an M/H frame it constructs data in exact packet locations and byte positions and if a packet would be dropped or added this would prevent A/153 system from operating normally. This puts a constraint on any STL terminal or external interface equipment that no reordering and or adding or dropping of packets is permitted when an ATSC Mobile DTV TS is being transported.

A/153 M/H Exciter (Transmitter)

The M/H exciter must first become synchronized to the M/H frame structure in
the incoming TS. The exciter must insert a DFS in cadence with the M/H frame structure as specified in standard. The M/H frame is aligned to ATSC Time (all M/H stations must emit start of M/H frame at the same instant in time using a temporal reference such as GPS). For these purposes additional signaling data is received from the M/H multiplexer over the STL, and used to aid M/H exciter in this process. Once synchronized the M/H exciter will process (channel code) the normal packets exactly as specified in A/53 standard, to ensure continued reception by existing A/53 receivers. The mobile or MHE TS packets are processed per the A/153 standard. The exciter parses the incoming TS for MHE TS packets to identify the mobile packets for A/153 processing. All other PID values will be processed as normal A/53 packets. Note: (cyan) blocks in figure 24 are used principally to maintain backward compatibility with A/53 receivers. The (white) blocks indicate no change from A/53.

The first block is the modified data randomizer; it bypasses all MHE TS packets and processes all other packets as normal A/53. Next, is the modified RS encoder that processes all normal packets with the normal systematic RS parity encoding. (20 RS Parity bytes appended to end of packet) The MHE packets, because of the special location of bytes needed before the interleaver to form training sequences are processed using a non-systematic RS encoding. (RS Parity bytes are located within the packet payload area to accommodate creation of M/H training sequences, etc.) Note: both systematic and non-systematic RS parity methods are processed normally by A/53 receivers.

Next, the A/53 Data Interleaver remains unchanged as described in A/53. Note: the knowledge of this mapping is leveraged in the pre-processing of A/153 data. The next two blocks are the parity replacer and the non-systematic RS re-encoder, these work together to ensure A/53 backward compatibility. As was discussed in figure 22 (Trellis State Initialization) all trellis encoder states were driven to a known zero states during two symbol clock cycles when the switch was in (I) initialization position, this put trellis encoder into a known state to start processing the pre-calculated training data bytes resulting in known training symbol sequences at physical layer. To maintain backward compatibility with A/53 it is necessary to repair any errors in RS parity created as a result of this initialization process. Note: the trellis encoder is downstream of RS encoder and the Initialization bytes appearing in MHE packets already had RS non-systematic parity calculated. The circuitry recalculates and dynamically replaces the non-systematic RS parity just in the MHE packets that contain initialization bytes. This ensures no RS parity errors on normal A/53 receivers. The modified trellis encoder contains circuitry to initialize the trellis states for training sequences. It also serves a dual purpose as the inner TCM for A/53 and part of the inner 2/3 trellis encoder of turbo encoder (SCCC). Finally, the Mux inserts enhanced signaling symbols into DFS to indicate to M/H receivers what mode is present A/53 or A/153.
Receiving the A/153 Signal (Fixed and Mobile)

Figure 25 shows the general block diagrams of both an A/53 and an A/153 M/H receiver. By walking through the reception process on both of these receivers should help give readers better insight into the Dual Stream system.

An A/153 RF waveform is being transmitted which has a mixture of both fixed and mobile services. The A/53 receiver will be discussed first.

Legacy A/53 Receiver

A legacy A/53 receiver will not be able to detect that any mobile services are being broadcast. The M/H frame structure and training signals are both virtual structures defined in A/153 and are not discoverable by A/53 legacy receivers.

All turbo coded M/H data, training sequences, signaling, etc are encapsulated into an MHE TS packet with an ATSC reserved PID.

The A/53 receiver proceeds to demodulate and equalize all transmitted symbols. The Viterbi decoder likewise will decode all symbols. Next, the A/53 De-Interleaver is used to improve the burst noise performance of the following Reed-Solomon systematic decoder in next block.

The output of the A/53 de-randomizer is the 19,392,658 bps TS. In the demultiplexing process that follows all MHE packets are ignored or discarded as if they were null packets. The discarding of all MHE TS packets ensures backward compatibility. The remaining

![Figure 25 A/53 and A/153 Block Diagrams](image-url)
packets are main service A/V and PSIP packets used by A/53 receiver, and these are decoded in normal fashion and the A/V is presented. No evidence of a dual stream signal, not even the enhanced signaling in the DFS is discoverable. Therefore fixed services (HDTV/SDTV) continue as normal except for some of total data rate has been allocated to mobile and handheld services.

**A/153 ATSC Mobile DTV Receiver**

The A/153 M/H receiver shown in figure 25 is quite different in how it processes the signal. Briefly stated it will only attempt to turbo decode and further process only select mobile symbols (Parade) in the virtual M/H frame that contains the wanted content. This can save battery on the mobile device since it only need power on and decode only the wanted M/H symbols containing the service of interest.

The tuner tunes to the wanted 6 MHz channel and down-converts the signal to an intermediate frequency (IF). The tuner outputs the signal to demodulator and to the Known Sequence Detector block. The demodulator performs self gain control, carrier recovery, and timing recovery on IF signal. The demodulator then outputs the baseband signal to the equalizer and to the known sequence detector.

The known sequence detector now has inputs before and after demodulator, searches for the known training sequences in mobile Slots in M/H frame. Once detected these mobile symbol location and timing information is sent to the equalizer which makes use of the long training sequences to acquire channel.

The timing information is also sent back to the demodulator and is useful during synchronization and carrier recovery.

This timing information is sent also to the turbo decoder to make it cognitive of mobile symbols of interest. It will iteratively decode all blocks of turbo (SCCC) coded mobile symbols of just the Parade (mobile content) selected. Moreover, the internal decisions being made by turbo decoder may be fed-back to equalizer thereby enhancing its performance.

The M/H signaling data (TPC/FIC) which is sandwiched between the first two training sequences in a mobile Slot are output from a stage in the turbo decoder and sent to the M/H signaling decoder. After decoding the TPC and FIC signaling data, this information is made available to stages of the receiver that can be enhanced. The upper layers instruct the known symbol detector what Parade of Slots needs to be decoded in the virtual M/H frame. The TPC signaling data is carried in each mobile Slot and has signaling information in form of the Sub-frame, Slot and Parade number, the FEC decoding parameters, etc. useful for turbo (SCCC) decoder.

The turbo decoder receives timing and control information on which Slots need to be decoded and the inner SCCC code rate used, etc. The iterative decoding continues with the loops now closed enabling the equalizer to track dynamically, etc. The turbo decoder converges after several iterations on the SCCC block data and this is then output to the data deformatter. This continues until all M/H data in
the Parade is decoded.

The data de-formatter, which knows the Slot structure outputs the IP packets that makes up the rows of M/H frame for parade.

The RS/CRC decoder receives signaling information on the size and mode of M/H frame including number of RS parity bytes, etc. All packets are then re-assembled into rows in the M/H frame format and the CRC checksum of each row of packet/s is used to detect an error. RS erasure decoding is performed if the number of row errors is less than or equal to the number of RS parity bytes used (24, 36, 48). The de-randomizer then outputs the IP packets of the selected M/H service.

The robust signaling, long training sequences and powerful FEC, used allows the receiver architecture shown reliable and fast service acquisition within several milliseconds. This supports the receiver powering down certain circuits to conserve battery power between Slots of interest.

**Conclusion**

This paper has presented some insight into the challenges any mobile receiver faces in the real world environment. The ATSC (single carrier) system used various technical options to enhance the performance in a mobile fading environment, while maintaining fixed services.

These technologies include a new inner FEC (Turbo Encoding) at physical layer, a robust packet layer FEC (RS/CRC), both offering powerful error correction and inherent time diversity properties. The training sequences used by M/H receiver’s equalizer both to acquire and track a dynamic fading channel, as well as a robust M/H signaling scheme.

In a period of only 2 years the ATSC developed and adopted the A/153 Mobile DTV standard. The Initial field test look encouraging and some broadcasters are now considering various business models to monetize these new mobile services.

Diversity in various forms will help mitigate fading and improve mobile reception. The time diversity introduced in the new A/153 channel coding (FEC) is but one example. Receiver antenna diversity in the case of vehicles or public transportation will improve reception. Transmitter diversity in the form of an on-channel repeater or a single frequency network (SFN) can deliver higher field strength within and different arrival angles to a mobile receiver. This helps reduce log-normal fading and shadowing experienced by the mobile, and to mitigate building penetration losses resulting in improved indoor service.

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The R&S®AEM100 multiplexer for ATSC Mobile DTV service combines the functions of IP encapsulation with multiplexing to enable broadcasters to offer new services inside their existing ATSC transport stream. The R&S®AVE264 mobile TV encoder can be teamed with the R&S®AEM100.

The R&S®Sx800 is a software configurable television exciter that features adaptive pre-correction for linear and non-linear distortions. The exciter can be adapted to different operating standards and modes, including ATSC Mobile DTV and Single Frequency Networks (SFN). Exciter retrofit packages are available to allow use of the R&S®Sx800 in transmitters produced by other manufacturers.

The R&S®Nx8000 family of transmitters is comprised of both liquid (R&S®NV8600) and air-cooled (R&S®NV8300/R&S®NW8200) transmitters for high and medium power applications. All R&S®Nx8000s feature the R&S®Sx800 television exciter for excellent signal performance and flexibility across both VHF and UHF. The R&S®Nx8000 transmitters are very energy efficient with redundant architecture for maximum reliability.

The R&S®ETL TV Analyzer performs 8VSB testing and optional MPEG monitoring in a single unit. It combines TV test receiver and spectrum analyzer functionality while providing high measurement accuracy. Both digital and analog TV standards can be integrated in a single instrument. The R&S®ETL TV Analyzer uses realtime demodulation throughout.

The R&S®SCx8000 is the ultimate in efficient design. It consists of the new exciter R&S®Sx801 and up to two amplifiers with integrated cooling, combiner and splitter. All major TV standards, including ATSC Mobile DTV are supported with the same hardware. Innovative redundancy concepts make the system highly reliable. Its modular design enables the system to be a stand-alone device, in existing racks and outdoor cabinets.
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