HIGH DATA RATE VSB MODEM FOR CABLE APPLICATIONS INCLUDING HDTV: DESCRIPTION AND PERFORMANCE

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Abstract

The Digital HDTV Grand Alliance selected Vestigial Sideband Modulation over Quadrature Amplitude Modulation for their broadcast and cable modulation subsystem. This paper describes a 16-VSB modem which transmits 43 Mb/s over a 6-MHz channel. The VSB modem also has various modes of operation, trading robustness for data rate. The symbol rate, data rate, data frame, forward error correction (FEC), and synchronization pulses are all the same as those proposed and tested by the Grand-Alliance. Negligible additional hardware is required in future HDTV modems to receive and decode data transmitted by this modem.

INTRODUCTION

Based on comparative testing of digital modems for both broadcast and cable, the Digital HDTV Grand Alliance selected Vestigial Sideband Modulation (VSB) over Quadrature Amplitude Modulation (QAM) for their broadcast and cable modulation subsystem. Comparisons were made of an 8-VSB trellis coded modem to a 32-QAM trellis coded modem for broadcast applications and of a 16-VSB modem to a 256-QAM modem for cable applications. In those tests, the VSB modems out performed the QAM modems in both the broadcast mode and the cable mode. The VSB system was also subsequently accepted by the FCC Advisory Committee on Advanced Television Systems (ACATS).

This paper describes a 16-VSB cable modem, with various modes of operation, that is compatible with both the broadcast and cable modems proposed by the Grand-Alliance. Compatibility is increasing important especially in future applications where a common infrastructure is likely to exist for all digital services into the home. Digital televisions, computers, telephones, and other consumer equipment will accept data from this common infrastructure in order to support a variety of interoperable services into every home. Among these services are video-on-demand, video and audio telephony, home shopping and banking, computing, working at home, and information access.

There are two keys elements to the success of a common infrastructure for digital delivery into the home. The digital link into every home must be standardized, and the link must support a variety of flexible and reallocable services. The decision to use VSB for HDTV provides both of these essential elements. Not only will VSB be a prolific standard, existing in every high definition TV and able to receive digital signals from broadcast and cable, but it is also designed to accommodate flexible and reallocable services which will be necessary to share the data link between multiple applications. For maximum interoperability, it makes sense that all digital data delivery into the home also use VSB modems and thereby maintain compatibility with the HDTV's of the future. The high definition TV, with its display and VSB modem, will be the center for all kinds of home services and applications.

The 16-VSB modem transmits 43 Mb/s over a 6-MHz channel. The symbol rate, data rate, data frame, forward error correction (FEC), and synchronization pulses are all the same as those proposed and tested by the Grand-Alliance. Negligible additional hardware is required in future HDTV modems to receive and decode data transmitted by this modem. The data rate of the 16-VSB modem matches that required to transmit two HDTV programs over one 6 MHz cable channel.

HDTV BACKGROUND

In order to understand how this modem is compatible with the HDTV modem, a block diagram of the 8-VSB broadcast HDTV receiver tested by the Grand-Alliance is shown in Figure 1. For comparison purposes, a block diagram of the 16-VSB receiver is shown in Figure 2. By comparing the two diagrams, it is easy to see the similarities between the two; except for the Trellis decoder, the blocks are the same. Table I shows a detailed comparison between the functional differences of each block. In every case, the broadcast receiver is either identical, can be adapted with little or no change, or is a superset of the cable receiver.

16-VSB MODULATOR

A conceptual block diagram of the 16-VSB modulator is shown in Figure 3. A 16-level signal, representing 4-bits of information, is generated by applying the 4-bit input to a D/A converter. A new input appears at a 10.7 MHz rate and thus results in a transmission rate of:

$$10.7 \text{ MHz} \times 4 \text{ bits} = 43 \text{ Mb/sec.}$$

A small amount of DC is added to the output of the D/A to create a small amplitude pilot which is transmitted to aid the receiver's

BLOCK	**8-VSB Broadcast Receiver**	**16-VSB Cable Receiver (with 2, 4, & 8-VSB modes)**	**Comments**
Tuner	Tunes Broadcast and Cable Bands	Tunes Cable Bands	Cable ready broadcast tuner tunes to superset of channels
SAW Filter	5.38 MHz BW	5.38 MHz BW	Identical
IF Demodulator	Locks onto Pilot	Locks onto Pilot	Identical
A/D converter	8-Bits @ 10.7 MHz	8-Bits @ 10.7 MHz	Identical
Sync & Clock Recovery	Locks to Sync Signals	Locks to Sync Signals	Identical
Adaptive Equalizer	Feedforward + Feedback	Feedforward	Broadcast equalizer has more capability
Phase Tracker	Tracks 2 & 8 level signals	Tracks 2,4,8,&16 level signals	Broadcast receiver needs additional look-up table to receive cable modes
Trellis Decoder	Yes	None	Broadcast receiver can bypass to receive cable modes
De-interleaver	Yes	Yes	Broadcast receiver has more memory
R-S Decoder	(208,188) T=10	(208, 188) T=10	Identical

COMPARISON OF BROADCAST AND CABLE MODEM

TABLE I

carrier recovery. This signal is modulated to an IF band centered at 46.7 MHz and filtered to remove the upper sideband. The filter is a 11.5% roll-off root-Nyquist filter which leaves a small vestige of the upper sideband, hence the name Vestigial Sideband Modulation (VSB). The IF signal is subsequently modulated to a 6-MHz RF channel for transmission.

Because the transmitted data is random, the spectrum of the transmitted signal is flat throughout the band except at the band edge where the root-Nyquist filter rolls it off. A small pilot 310 kHz away from the lower band edge is also present. The pilot only contributes 0.3 dB to the signal's total power. A spectrum plot of the transmitted signal is shown in Figure 4. In this figure, the pilot is visible because the resolution bandwidth of the plot is only 100 kHz.

All data in the VSB system are sent in 188 byte blocks with 20 additional bytes of Reed-Solomon (T=10) parity for a total 208 byte block. Before transmission, the data blocks are placed into a fixed frame structure which aids in receiver synchronization. The fixed data frame is shown in Figure 5. A data frame consists of two data fields of 313 data segments each. Each data segment is made up of 836 symbols. Every data field begins with a one segment "Field Sync" signal which include several pseudo random sequences used by the receiver as a training reference for the adaptive equalizer. A 4 symbol segment sync is also transmitted at the beginning of every segment as part of the data frame.

The top of Figure 5 illustrates how blocks are packed into segments for the various VSB modes. For the 16-VSB mode, two blocks are sent per segment. In 8-VSB mode, 1½ blocks are sent per segment, in 4-VSB mode, one block is sent per segment and in 2-VSB mode, ½ block is sent per segment. Different VSB modes are simply transmitted by applying a different number of bits to the input of the D/A converter each symbol time. One bit for 2-VSB, two bits for 4-VSB, three bits for 8-VSB, and four bits for 16-VSB.

In order to protect against burst noise, data within the data frame are interleaved before transmission. The frame syncs and segment syncs are unaffected by interleaving.

VSB MODES

The different VSB modes supported by the modem enables the flexibility to trade-off data rate for robustness and may be exploited in various ways. The more robust modes may be used for poorer quality channels as might be found at the upper roll-off region of a cable system. Different VSB modes may also be used where low power transmission is desired. During equipment failures which cause a loss of carrier-to-noise ratio, the robust modes can be switched in to continue a level of service until the fault has been corrected. The VSB receiver automatically adjusts to the transmitted VSB mode.

Table 2 shows the trade-off for the various VSB modes between data rate and white noise performance.

VSB Mode	Xmitted Data (Mb/s)	Usable Data (Mb/s)	C/N Threshold
2-VSB	10.8	9.7	10 dB
4-VSB	21.5	19.3	16 dB
8-VSB	32.3	28.9	22 dB
16-VSB	43	38.6	28 dB

VSB Modes

TABLE 2

16-VSB RECEIVER

The following is a description of the blocks of the 16-VSB receiver shown in Figure 2 .

Tuner

The tuner for a cable modem will require better phase noise performance than standard NTSC tuners. The phase noise threshold of the 16-VSB modem has been measured by CableLabs at -82 dBc @20 kHz. For best performance, the tuner phase noise should be approximately 10 dB less than this.

SAW Filter

The IF filter is a SAW filter made of lithium niobate. Its response is a 11.5% roll-off root-Nyquist filter. In applications where the 16-VSB signal is run lower in power compared to adjacent NTSC signals, it is desirable to have at least 40-50 dB attenuation at the adjacent sound and picture carrier frequencies.

IF Demodulator

The IF demodulator recovers the carrier using the transmitted pilot. It consists of a frequency phase-locked loop (FPLL) which can pull-in at least 100 kHz. The PLL bandwidth is 2 kHz and can track out phase noise within this bandwidth.

The IF demodulator is one IC which includes IF and tuner AGC.

A/D Converter

The 16-VSB system uses an 8-bit A/D converter sampling at the symbol rate of 10.7 MHz.

Synchronization and Clock Recovery

Synchronization and clock recovery of the VSB system are very robust because they take advantage of the repeated segment sync signals. Synchronization and clock recovery are possible down to a 0 dB carrier-to-noise ratio, which is 10 dB beyond the 2-VSB threshold.

Adaptive Equalizer

In digital modems, the adaptive equalizer is one of the largest pieces of hardware in the receiver. The VSB adaptive equalizer is designed as a 63 tap feedforward equalizer using only real taps. In contrast to QAM systems which use two samples per symbol and require complex filters, this translates into a four to one reduction in complexity. In addition, the VSB equalizer adapts on a training sequence repeating at 24 Hz; this further simplifies the hardware complexity by only requiring relatively slow tap calculations. The VSB equalizer only uses one low speed multiplier for all the tap calculations.

Like the sync and clock recovery, the equalizer will operate down to a carrier-to-noise ratio of 0 dB.

Phase Tracker

The phase tracker is a first order decision feedback loop used to track out phase noise in the signal. The bandwidth of the phase tracker is approximately 60 kHz and tracks residual phase noise left by the IF PLL. The concatenated combination of IF PLL and phase tracker gives the VSB system excellent immunity to phase noise.

A fast gain and offset loop is also incorporated into the phase tracker to remove gain modulation and DC errors which might arise from various sources.

Deinterleaver

The VSB system uses interleaving at the transmitter and de-interleaving at the receiver to combat impulse noise. In order to minimize memory, a convolution structure is used. The 16-VSB system was measured at CableLabs to withstand 47 uS noise bursts repeating at a 10 Hz rate.

Reed-Solomon Decoder

The FEC used in the VSB system is a Reed-Solomon (R-S) T=10 code with a block size of (208,188). In comparison to trellis decoders whose complexity grow almost exponentially with the code length, the R-S decoder is very hardware efficient. The complexity of R-S decoders grow less than linearly with increasing T. With the R-S code, the 16-VSB modem achieves a white noise threshold of 28 dB.

Diagnostic Capability

A valuable feature of the VSB system is its ability to acquire even under extremely adverse conditions. The fact that the receiver can acquire and equalize the signal even under signal conditions where data is totally lost allows the receiver to supply diagnostic information to the cable operator or customer even after the system has failed. Information available from the VSB receiver include the received carrier-to-noise ratio and the condition of the equalizer taps.

This diagnostic information has proven useful in all the field tests of 16-VSB. All the proposed QAM cable modems cannot supply any information after data is lost.

PERFORMANCE

The performance of the 16-VSB system has been measured and publicly demonstrated on various occasions. Hardware measurements have shown that the 16-VSB system is able to achieve virtually theoretical performance. The use of a pilot and synchronization signals effectively eliminate implementation loss. Table 3 shows a performance summary of a 16-VSB system measured at CableLabs.

Besides laboratory measurements, the 16-VSB system has been field tested extensively. It has been tested on 3 cable systems including links with AML's, fiber, and up to 35 amplifiers. In all cases the 16-VSB system operated with margin and no plant modifications were necessary. The 16-VSB system has also been tested on hybrid fiber-coax links.

Parameter	Performance
Carrier-to-Noise	28 dB
CTB (CW)	43 dB
CSO (CW)	35 dB
Phase Noise Threshold	-82 dBc
Residual FM	4.9 kHz
Pull-in Range	+90 to -130 kHz
Burst Error @ 10 Hz Rep.	47 uS

16-VSB Performance Summary

TABLE 3

CONCLUSION

A 16-VSB modem which transmits 43 Mb/s has been demonstrated to operate over real cable systems. Laboratory measurements have shown that the modem achieves theoretical performance. The VSB modems have functional and complexity advantages over QAM systems and are compatible with the proposed Grand-Alliance VSB system. Future high definition TV's can demodulate the 16-VSB signal with minimal additional complexity.

The complexity of the receiver is low enough that the FPLL is being integrated into one analog IC while the sync and clock recovery, adaptive filter, phase tracker, de-interleaver including memory, and R-S decoder are being integrated into one digital IC. VSB technology offers a high performance, low cost solution which will be compatible with HDTV.

REFERENCES

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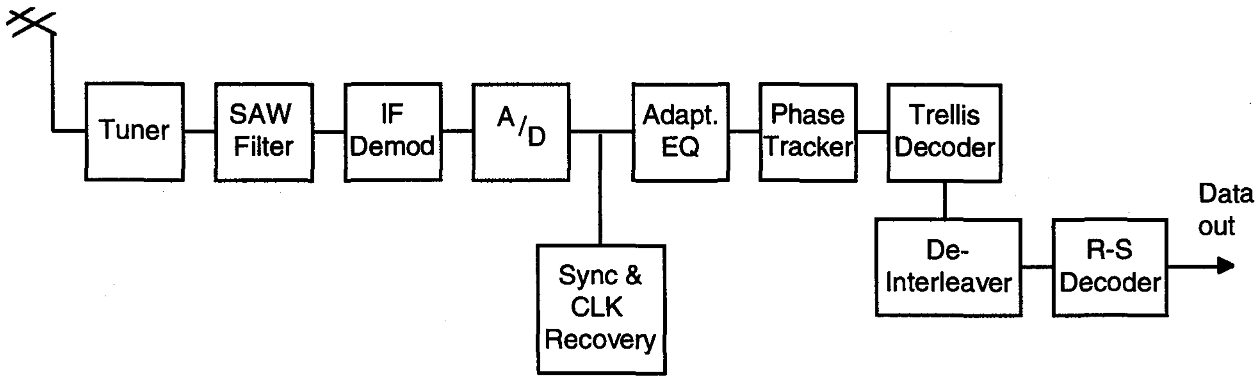
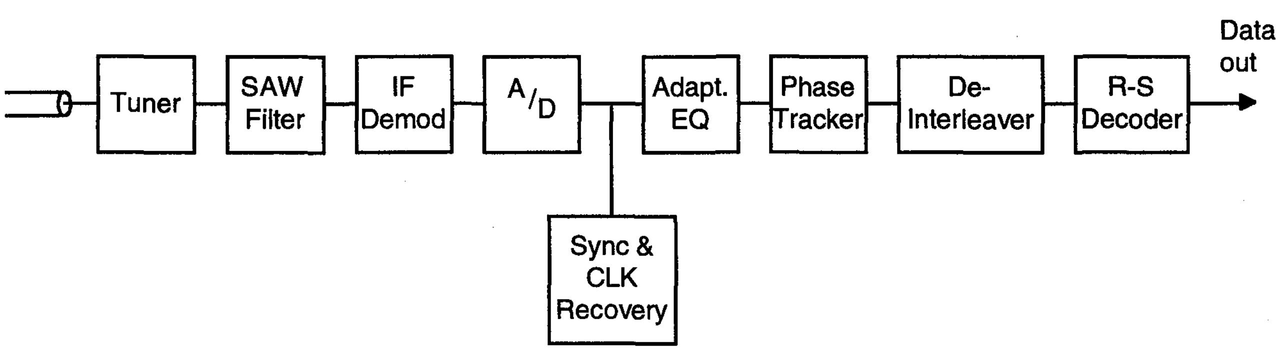
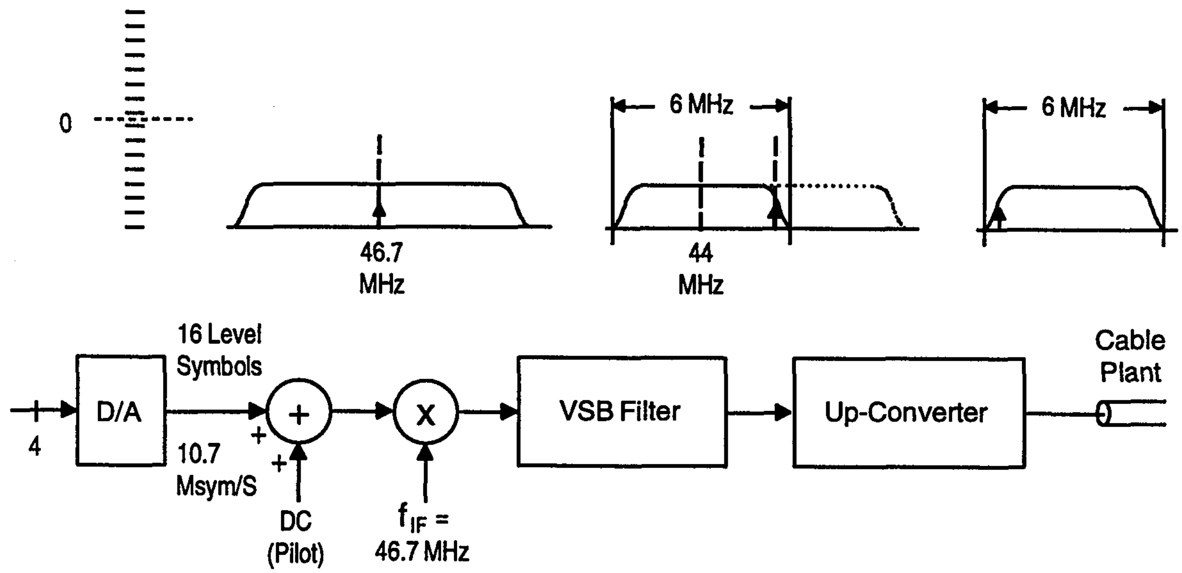
[3] "SUMMARY OF THE ZENITH 16-VSB MODEM FIELD TEST ON VIDEOTRON'S CABLE SYSTEM IN MONTREAL"; Technical Report by G. Sgrignoli, 6/21/93. Available from Zenith Electronics Corporation, Glenview, IL 60025.



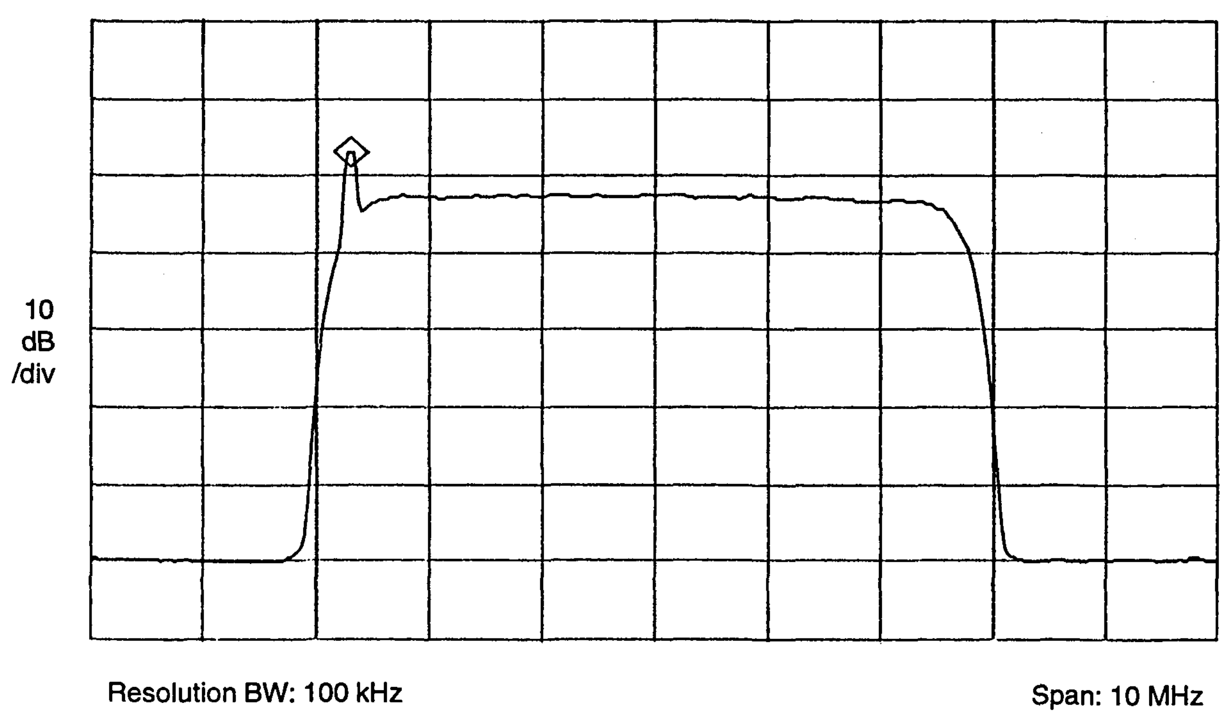
Grand Alliance 8-VSB Receiver
Figure 1



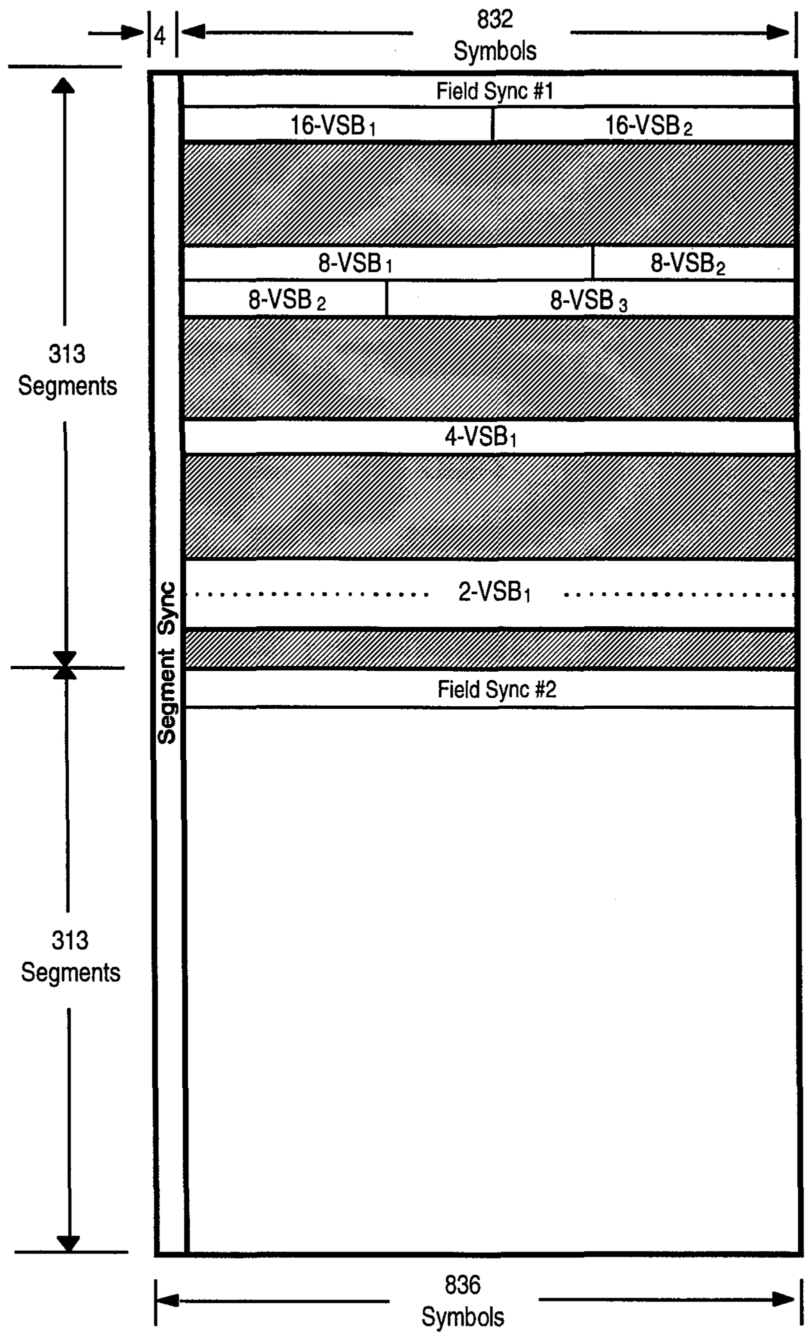
16-VSB Receiver
Figure 2



16-VSB Modulator
Figure 3



16-VSB Spectrum
Figure 4



1 Packet = 188 bytes + 20 bytes FEC

Variable Rate Data Frame
Figure 5