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Adaptive Coding and Modulation (ACM) in the CDM-625 Advanced Satellite Modem

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Overview

Adaptive Coding and Modulation (ACM) is a very significant new feature in the CDM-625 Advanced Satellite Modem. This feature requires Firmware Version 1.4.0, or later, with a VersaFEC™ plug-in module, and the appropriate FAST codes. VersaFEC ACM is a patents-pending technology, wholly owned and developed by Comtech EF Data and Comtech AHA.

- **ACM turns fade margin into increased link capacity – gains of 100% or more are possible, compared to traditional Constant Coding and Modulation (CCM). This is accomplished by automatically adapting the modulation type and FEC code rate to give highest possible throughput.**

- **ACM maximizes throughput regardless of link conditions (noise or other impairments, clear sky, rain fade, etc). Initial set-up is easy, and then requires no further user intervention.**

- **With a CCM system, severe rain fading can cause the total loss of the link, and zero throughput. ACM keeps the link up (with lower throughput) – and can yield much higher system availability.**

- **ACM in the CDM-625 is used in conjunction with VersaFEC and is currently for *IP traffic only.***

Background

ACM is not a new concept. It has been used for some time in wireless communications, including terrestrial microwave applications, and more recently over satellite links. Its primary function is to optimize throughput in a wireless data link, by adapting the modulation order used and the Forward Error Correction code rate (which both directly affect spectral efficiency, expressed in bits per second per Hertz), according to the noise conditions (or other impairments) on the link.

Implicit in this concept is that the symbol rate (and power) of the wireless communication system *must remain constant.* This ensures that the bandwidth allocated for a particular link is never exceeded. Given that the symbol rate does not change, if modulation and coding are changed, the data rate must therefore be modified.

This is expressed in the simple equation

*Symbol rate = bit rate / (modulation order * code rate)*

For example, for Rate 3/4 QPSK (where modulation order = 2)

*Symbol rate = bit rate * 0.666*

Re-arranging:

*Bit rate = symbol rate * modulation order * code rate*

So, in changing to a higher modulation order or code rate, the bit rate is increased, and in changing to a lower modulation order or code rate, the bit rate is reduced.

However, there are several important factors to be considered, namely:

- The digital communications system must be able to tolerate a change in bit rate. Synchronous serial interfaces (such as G.703 E1, which operated at a fixed data rate of 2.048 Mbps) are totally unsuitable in a scheme where data rate is changing. The only practical application for this scheme is a packet-based scheme that will tolerate a change in data rate, and which has mechanisms within its protocols to recognize when increased or reduced bandwidth is available. The best example of this is Ethernet, and this discussion is limited to schemes that employ it.

- The bit rate cannot be changed arbitrarily - the link noise conditions - described in terms of Eb/No or SNR, must be able to support reliable communications for the given modulation order and code rate. This is a key point, as in fact, *the link SNR is the input that drives the adaptation.*

Requirements for ACM

There are a number of essential requirements to enable this scheme:

a) A modulator and FEC encoder that can instantaneously, when commanded, change either modulation type (order) or FEC encoder rate, or both. This needs to be accomplished without the corruption of data anywhere in the path. Block FEC codes are considered to be the most practical in achieving the required synchronization. Recently, a specific nomenclature has emerged to describe a combination of a modulation type and code rate – namely, ***ModCod*** (also referred to as ***Mod/Code***). The modulator is required to send the value of ModCod at the start of each code block to signal the demodulator/decoder how to configure for the correct modulation type and FEC code rate.

b) A receiver that is capable of demodulating and decoding the signal transmitted by a) without any *a priori* knowledge of when a change has taken place, but based purely on the value of ModCod seen at the start of each FEC block. Again, this needs to be accomplished without the corruption of data anywhere in the path.

c) The receiver in b) needs to derive an estimate of the link quality (in terms of Eb/No, SNR, etc.) and then communicate this estimate, via a return channel, to the modulator in a).

d) The modulator in a) needs to able to process the link quality metric from the demodulator in b), and then, based upon a pre-determined algorithm, adapt the data rate and change the ModCod sent to the receiver at the distant end. Thus, the data rate on the link can be maximized, given the current link noise conditions.

A generic example of ACM over satellite is shown in the Figure 1.

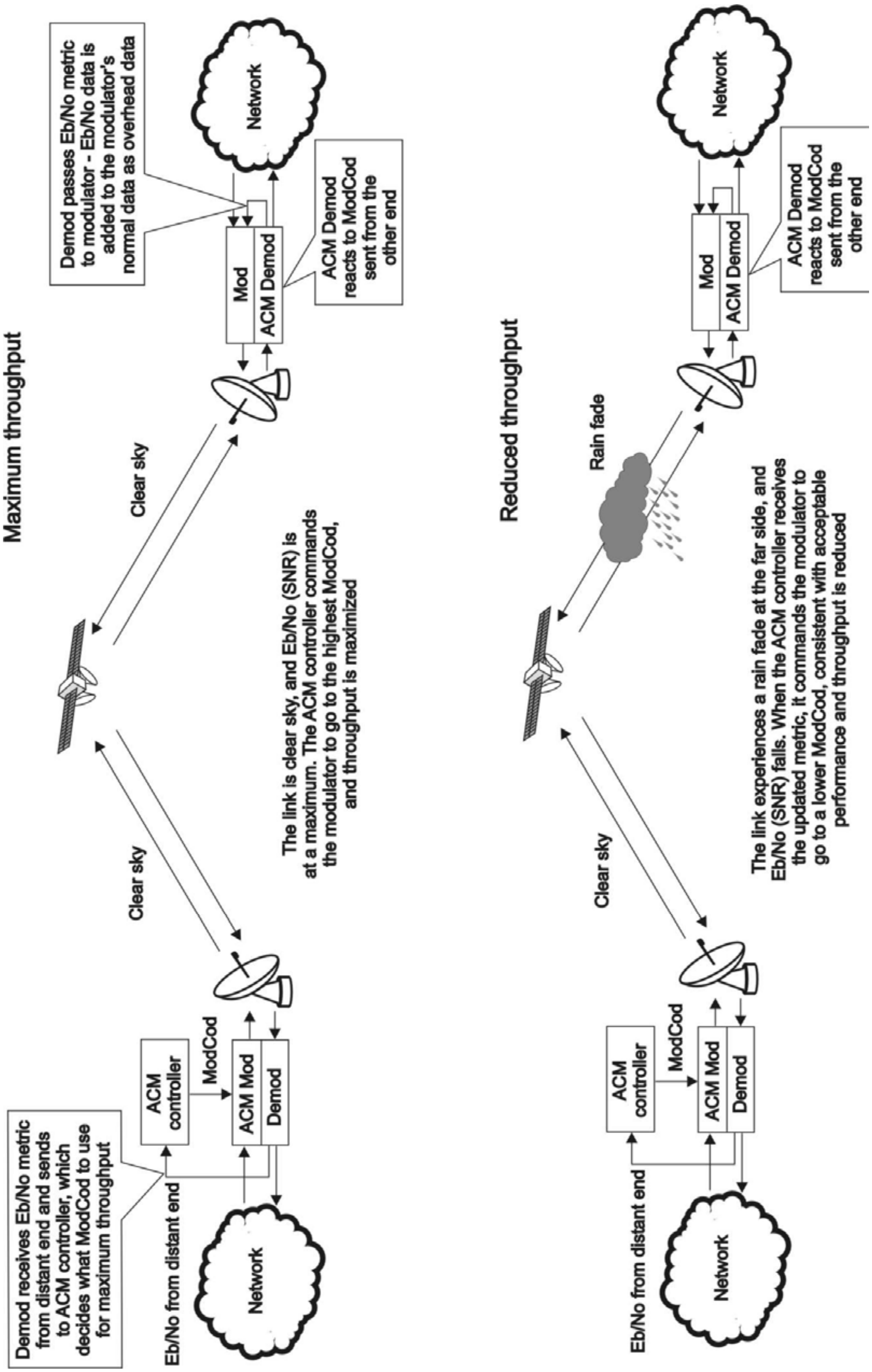

Figure 1 – Point-to-Point ACM

Disadvantages of DVB-S2

While the scheme defined by DVB-S2 is undoubtedly very effective for many broadcast and higher data rate applications, it is definitely not a 'one size fits all' solution. Here are some of the disadvantages:

- Excessive latency – the so-called short blocks are too long for low latency IP applications at low data rates. This is exacerbated by the addition of interleaving.

- It is overly complex in its implementation - the design of DVB-S2 dictated that all FEC blocks should be constant in ***bits.*** This means that for each ModCod, there are a varying number of ***symbols.*** This then makes the task of synchronization a much more demanding task. Also, because of the limitations of tracking the higher-order modulations in a very low SNR environment, so-called pilot symbols were added in order to aid tracking.

- Since the introduction of the original LDPC/BCH scheme an enormous amount of research has been done on the design of LDPC codes. The concatenated BCH code was added to mitigate the problem of error rate 'flaring' and 'flooring'. This is no longer necessary. Most importantly, however, LDPC codes can now be designed that yield almost equivalent coding gain, but with considerably shorter block lengths.

- In an ACM mode, no overhead channel was defined by DVB-S2 for the purpose of reporting SNR metrics to the originating end. It has been left to individual equipment manufacturers to decide their own methods. This illustrates that all ACM systems, DVB-S2 or not, are proprietary. In addition, it implies that additional bandwidth needs to be consumed for the SNR reporting, and this is not accounted for in the code rate.

VersaFEC ACM

VersaFEC™ (a trademark of Comtech AHA), in concert with a novel ACM approach, addresses ***all*** of the shortcomings of DVB-S2 outlined above. There are patents pending for both VersaFEC and the ACM scheme.

VersaFEC covers a family of 12 short-block LDPC ModCods, specifically designed for low latency and ACM applications. However, the VersaFEC codes are equally well suited to Constant Coding and Modulation (CCM) applications.

The requirements for an ACM system that approaches the minimum possible latency are:

- The shortest possible LDPC codes that give performance at or very close to DVB-S2, in order to minimize latency, and which do no use interleaving.

- Design of the encoder to further reduce latency to the minimum possible.

- A constant number of ***symbols*** per block, to reduce the demodulator and decoder complexity, and significantly also reduces latency in the ACM case.

- The elimination of the need for pilot symbols for carrier tracking at low SNR by substitution of other modulation techniques. This further reduces the complexity of the demodulator.

- A reduction in the number of ModCods to further reduce complexity.

- The inclusion, at the physical layer, of an overhead channel to permit the reporting of SNR metrics back to the originating end. Note that this does not have to be enabled or disabled – it is part of the fundamental frame structure of VersaFEC ACM, and has been take into account in the code rate.

The family of VersaFEC short-block LDPC codes is presented below in Table 1. The modulation types include BPSK, QPSK, 8-QAM and 16-QAM. It will be seen from the table that in order to maintain a constant number of symbols per block, the block size in bits (data + parity) must necessarily change, depending on both the modulation type (which affects the number of bits per symbol) and the code rate. For VersaFEC, the block size varies between 2k and 8.2k bits. At worst, therefore, the VersaFEC codes are 50% shorter than the 'short' DVB-S2 codes.

Modulation	Code Rate	Spectral efficiency, bps/Hz	Block size, bits	Typical Eb/No, for BER = 5 x 10^{-8}	Latency at 64 kbps, in milliseconds	Min. Data Rate, CCM mode	Max. Data Rate, CCM mode
BPSK	0.488	0.49	2k	2.4 dB	26	18 kbps	5.7 Mbps
QPSK	0.533	1.07	4.1k	2.2 dB	53	20 kbps	10 Mbps
QPSK	0.631	1.26	4.1k	2.7 dB	59	23 kbps	10 Mbps
QPSK	0.706	1.41	4.1k	3.4 dB	62	26 kbps	10 Mbps
QPSK	0.803	1.61	4.1k	3.8 dB	66	28 kbps	12 Mbps
8-QAM	0.642	1.93	6.1k	4.6 dB	89	35 kbps	12 Mbps
8-QAM	0.711	2.13	6.1k	5.2 dB	93	39 kbps	12 Mbps
8-QAM	0.780	2.34	6.1k	5.6 dB	97	43 kbps	12 Mbps
16-QAM	0.731	2.93	8.2k	6.3 dB	125	53 kbps	12 Mbps
16-QAM	0.780	3.12	8.2k	7.0 dB	129	57 kbps	14 Mbps
16-QAM	0.829	3.32	8.2k	7.5 dB	131	60 kbps	14 Mbps
16-QAM	0.853	3.41	8.2k	8.0 dB	132	62 kbps	16 Mbps

Table 1. The VersaFEC ModCod set

The VersaFEC codes compared with the Shannon bound are shown in the Figure below. It can be seen that the performance of VersaFEC at or near the DVB-S2 performance with 16 kbit blocks.

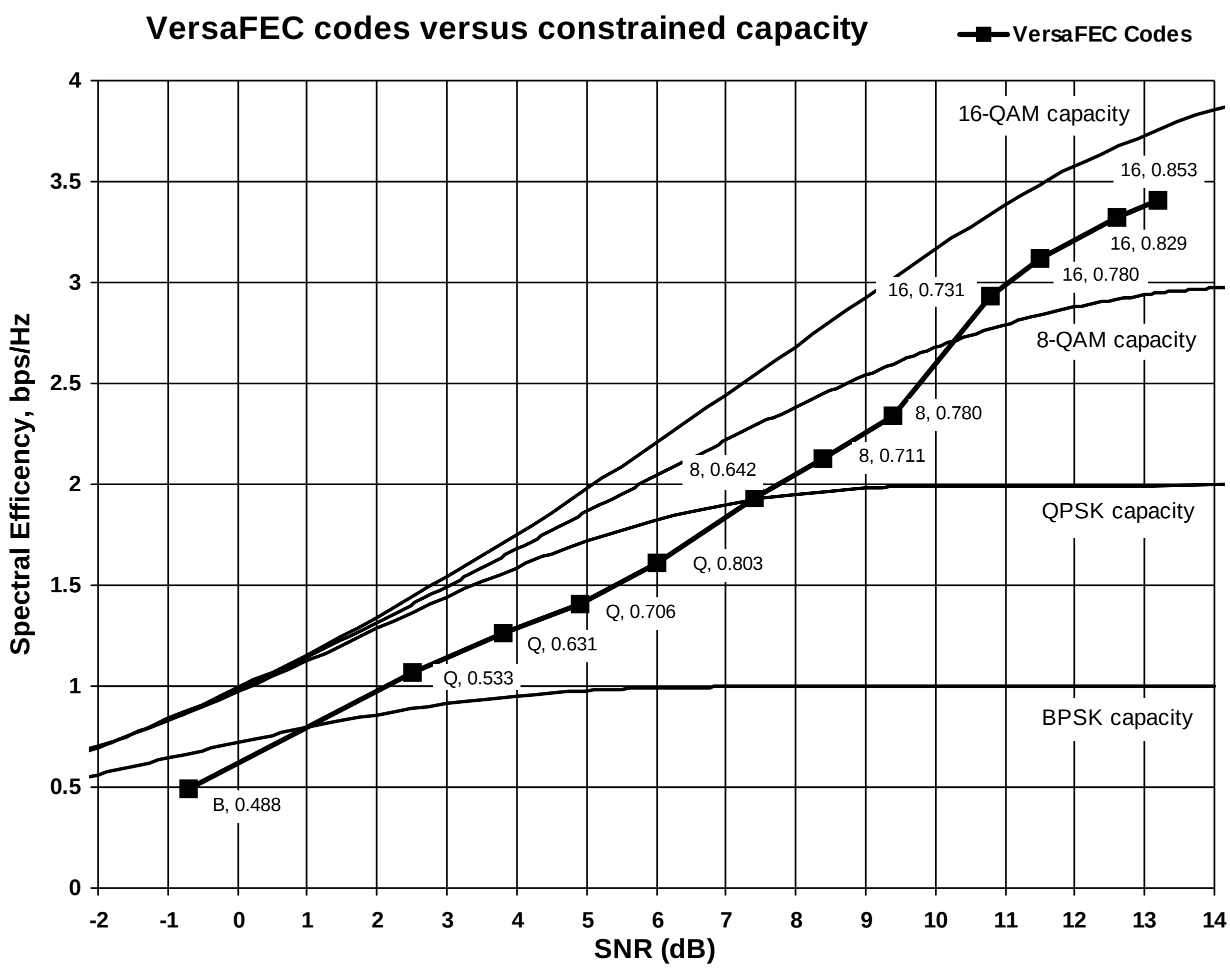

Figure 2. VersaFEC versus constrained capacity

Note that SNR is used in place of Eb/No - a convention for comparing ACM ModCods. SNR is defined as Eb/No + 10log(Spectral Efficiency).

VersaFEC ACM Latency

In an ACM system that has a number of ModCods, each having a different latency, what defines the overall system latency? The answer is simple – the latency of the worst-case ModCod. This, to some, may not seem obvious, and it is beyond the scope of this document to provide a rigorous proof of this statement. However, it is a correct statement, in spite of certain believers in non-causal systems and encoders that possess the magical quality of negative latency….

Examining the data in Table 2, below, latency for each ModCod is shown for the example of VersaFEC ACM at a fixed 100 ksymbols/second rate. Of particular note is that even though the ModCods span a 7:1 variation in throughput, the latency is only varying between 25 and 34 milliseconds. A careful analysis will show that this is a consequence of using a ***constant number of symbols per block.*** In the example shown, the worst-case latency for this ACM scheme is 34 milliseconds, + WAN Buffer delay (which is configurable, with a minimum value of 20 milliseconds).

VersaFEC implementation of ACM – example case of 100 ksymbols/sec					
ModCod	**Modulation**	**Code Rate**	**Spectral efficiency, bps/Hz**	**Bit rate (throughput)**	**Minimum Latency, milliseconds, for each ModCod**
0	BPSK	0.488	0.49	49 kbps	34 + WAN BUFFER
1	QPSK	0.533	1.07	107 kbps	32 + WAN BUFFER
2	QPSK	0.631	1.26	126 kbps	30 + WAN BUFFER
3	QPSK	0.706	1.41	141 kbps	28 + WAN BUFFER
4	QPSK	0.803	1.61	161 kbps	26 + WAN BUFFER
5	8-QAM	0.642	1.93	193 kbps	30 + WAN BUFFER
6	8-QAM	0.711	2.13	213 kbps	28 + WAN BUFFER
7	8-QAM	0.780	2.34	234 kbps	27 + WAN BUFFER
8	16-QAM	0.731	2.93	293 kbps	27 + WAN BUFFER
9	16-QAM	0.780	3.12	312 kbps	26 + WAN BUFFER
10	16-QAM	0.829	3.32	332 kbps	25 + WAN BUFFER
11	16-QAM	0.853	3.41	341 kbps	25 + WAN BUFFER
OVERALL SYSTEM LATENCY = Worst-case ModCod (ModCod0) Latency = 34 milliseconds + WAN Buffer delay					

Table 2. A worked example of VersaFEC ACM Latency at 100 ksymbols/sec

By way of comparison, consider the same 100 ksymbols/second rate, but this time using DVB-S2. It becomes clear that there is an unintended penalty to having a ***constant number of bits per block*** (besides demodulator complexity). Each time the ModCod is lowered, and the throughput is reduced, the latency grows accordingly, due to the block size being related to data rate, not symbol rate. Remembering that, for the ACM case, the system latency is equal to the latency of the worst-case ModCod, DVB-S2 shows a severe penalty. For 16k short blocks, this calculates to be 329 milliseconds (+ WAN Buffer delay) versus 34 milliseconds (+ WAN Buffer delay) for VersaFEC ACM. For 64k block DVB-S2, the core latency is 4 times higher. Assuming a WAN Buffer of 20 milliseconds:

Latency for 64k block DVB-S2 ACM at 100 ksps = **1336 milliseconds**
Latency for 16k block DVB-S2 ACM at 100 ksps = **349 milliseconds**
Latency for VersaFEC ACM at 100 ksps = **54 milliseconds**

Summary:

For the example shown, the latency for a 16k block DVB-S2 ACM scheme is approximately 7 times higher than VersaFEC ACM.

The latency for a 64k block DVB-S2 ACM scheme is approximately 25 times higher than VersaFEC ACM.

Configuring VersaFEC ACM in the CDM-625

IMPORTANT

VersaFEC ACM requires the correct hardware module (PL-0000264) to be installed in the CDM-625, Version 1.4.0 (or higher) firmware, and the appropriate FAST code for the maximum operating symbol rate.

Configuration is very straightforward. From the front panel, proceed as follows:

1) Under **CONFIG, MODE**, select IP-ACM.

2) Under **CONFIG, TX, SYMB,** enter the desired transmit symbol rate. Note that is a fundamental departure from the way in which the modem is configured traditionally.

IMPORTANT

The Transmit symbol rate is limited by the FAST code installed. There are three options:
37 ksps to 300 ksps
37 ksps to 1200 ksps
37 ksps to 4100 ksps

3) Under **CONFIG, TX, POWER,** enter the desired transmit output level.

4) Under **CONFIG, RX, SYMB,** enter the desired receive symbol rate. Note that asymmetric operation is supported - transmit and receive symbol rates do not have to be equal.

5) Under **CONFIG, ACM,** configure the desired ACM operating parameters:

a) Min/Max ModCod Here the user defines the range of ModCods that the system will operate over. ModCod0 is BPSK Rate 0.488 (0.49 bps/Hz), while ModCod11 is 16-QAM Rate 0.853 (3.41 bps/Hz).

IMPORTANT

If the user wishes to constrain the system to run at a fixed ModCod, set the Min and Max ModCod values to be equal.

WARNING

The value of Max ModCod may be limited by other FAST codes installed.

For example, suppose the 4100 ksps FAST option is installed, and the symbol rate set to 4100 ksps, the theoretical maximum data rate would be 14 Mbps at ModCod 11. However, if CnC is being used, with a 10 Mbps FAST limit, the Max ModCod will be limited to ModCod 7, or 9.6 Mbps.

b) Unlock Action Here the user decides the desired action when the remote demod loses lock. This is important, as the ACM system depends on the feedback of the SNR metric from the remote demod to determine the optimum ModCod.

The choices are:
Maintain the current ModCod
Go to minimum ModCod (recommended)

c) Target Eb/No margin This is a VERY important parameter. The ACM system is designed to switch based on thresholds that correspond to a BER of 5×10^{-8} for each ModCod. However, in order to prevent oscillation around two ModCods at this exact value, 0.3 dB of hysteresis has been added. The switch points and the hysteresis are shown below:

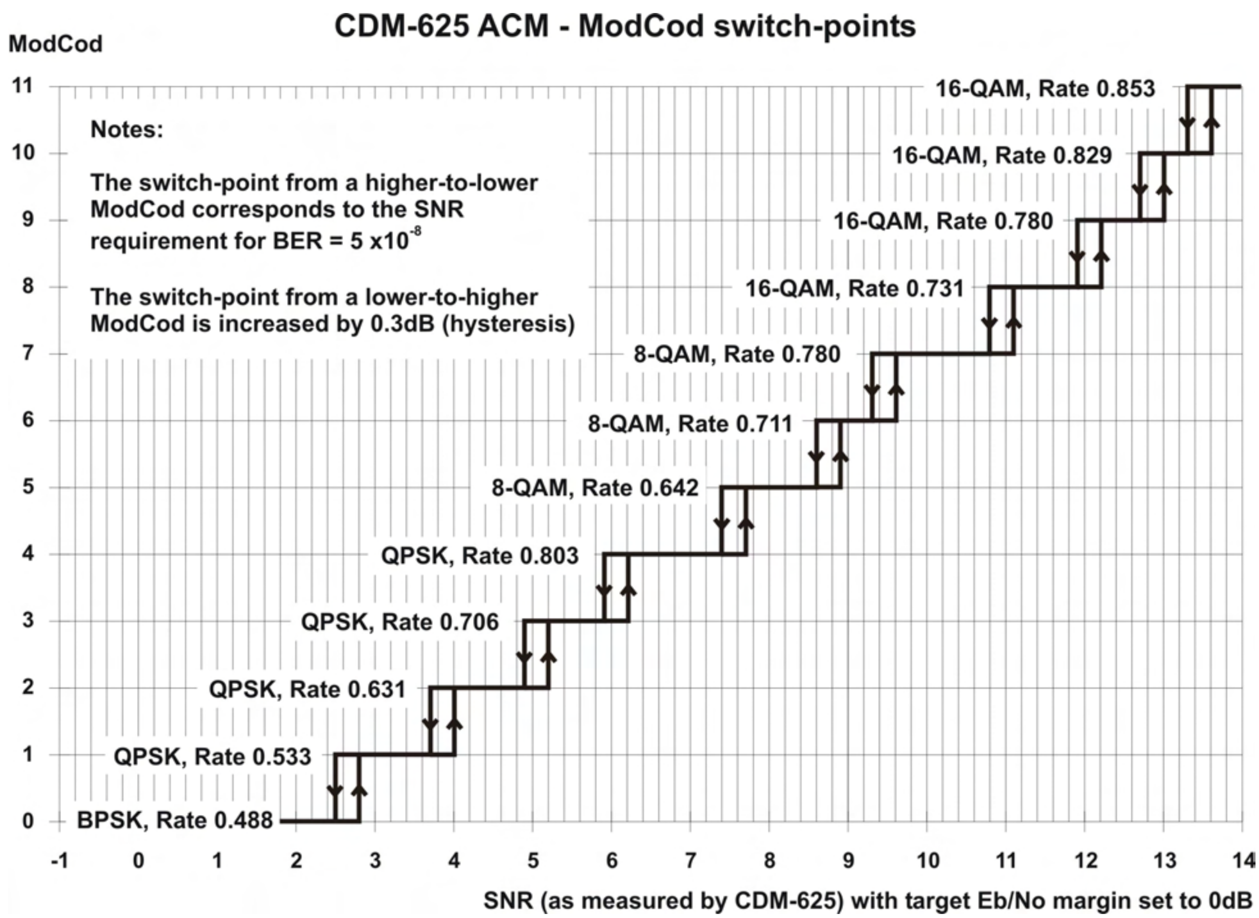

Figure 3.

The graph shows the switch points with the Target Eb/No margin set to 0dB. However, the switch points can be moved (increased) by configuring the Target Eb/No margin parameter, which can vary from 0 to 4.5 dB, in 0.5dB steps. In a fading environment it is highly recommended to add sufficient margin to maintain an adequate link quality (and to maintain demod lock) during the interval between the Eb/No degrading and the ACM controller responding by lowering the ModCod. See the Notes and Recommendations section.

6) Under **CONFIG, IP, Switch Set Up, WAN BUFFER**, enter the desired size of the WAN Buffer. The minimum size is 20 milliseconds, and is referred to the data rate corresponding to ModCod0. In order to achieve minimum system latency, do not make this value unnecessarily large.

Monitoring ACM performance

The CDM-625 provides a number of ways in which the current state of the ACM system can be determined.

Using the front panel menus, the user may select **MONITOR, ACM,** where the current Tx and Rx ModCod are displayed, along with the Local and Remote SNR. The SNR displays values between –3.0 dB and +22.0 dB, with a resolution of 0.1 dB. If either the local or remote demod is unlocked, the SNR will show 'No Sync'. Of course, under **MONITOR, Rx PARAMETERS,** the Eb/No continues to be displayed corrected for modulation type and code rate, in case the user does not wish to deal with SNR values.

If the user wishes to see the exact detail of the ModCod (data rate, modulation, code rate) then these parameters can be seen under **INFO, Tx** or **Rx.** Furthermore, if the user is in a **CONFIG**, **Tx** or **Rx** screen, both the symbol rate and data rate are displayed. All of these screens update dynamically, so if a ModCod changes, the parameters are refreshed.

This information is also available through the Remote Control (serial interface), as well as the Web Server, SNMP and Telnet interfaces.

If the user wishes to use the 'Constellation over Ethernet' application that comes with the current version of the firmware, it is also informative to see the demodulator changing type 'on the fly'. With no noise, and a modem in a loop on itself, the user may wish to experiment with Min and Max ModCod values to drive the adaptation.

Alternatively, if the user has access to an Oscilloscope in X-Y mode, the Alarms connector provides analog voltages to monitor the constellation. This has the advantage that it will show a change in modulation type instantaneously, unlike the 'Constellation over Ethernet' application, which only updates once per second.

If a user wishes to verify that link performance is meeting the required level, the internal BERT tester is an excellent tool. When using the IP interface, it is not an easy matter to verify BER performance. The internal BERT will not only do this, but is also tolerant of the change in bit rate that accompanies a change in ModCod. The BERT can be used to confirm that there are no sync losses or bursts of bit errors when a ModCod changes.

ACM Congestion Control

When the ACM controller switches from a lower to a higher ModCod the bandwidth of the Ethernet link is instantaneously increased. This is not a problem, and the link will adapt to push more packets/second through the link.

Conversely, when the ACM controller switches from a higher to a lower ModCod the bandwidth of the Ethernet link is instantaneously reduced. Unless the FIFO in the WAN encapsulator is configured to be very large, the FIFO will tend to overflow, and packets will be lost before the network recognizes that there is congestion, and reduces the rate at which packets are sent.

In order to mitigate packet loss when bandwidth is reduced, the CDM-625 ACM system incorporates a method for congestion control. This is illustrated in the Figure 4.

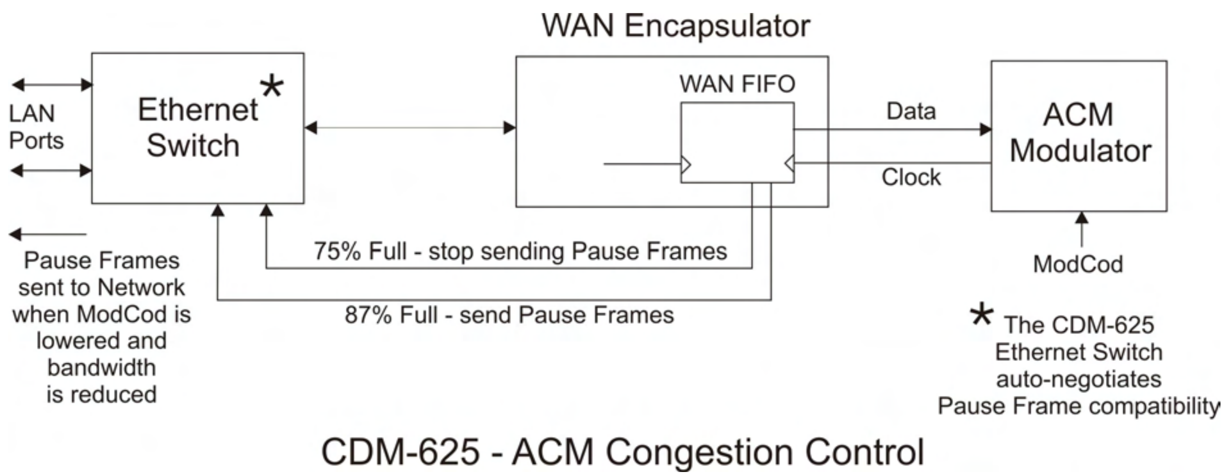

Figure 4.

The WAN FIFO (the size of which is configurable in the IP Switch setup) produces two control signals that enable and disable the sending of Ethernet ***Pause Frames***. A Pause Frame is an Ethernet frame designed to implement flow control at the MAC layer. A switch supporting 802.3x can send a Pause Frame (with Pause time set to 0xFFFF) to force the link partner to stop sending data. Devices use the Auto-Negotiation protocol to discover the Pause Frame capabilities of the device at the other end of the link.

In the diagram it can be seen that when the WAN FIFO reaches a fill state of 87%, it signals the Ethernet Switch to send Pause frames back to the LAN to inhibit the sending of further data. The Pause Frames continue to be sent until the FIFO fill state has reduced to 75%. At this point, normal operation in resumed by sending a Pause Frame with Pause time set to 0x0000.

This mechanism has been shown to be very effective at mitigating packet loss when the ACM controller reduces bandwidth.

Notes and Recommendations

- VersaFEC ACM is for point-to-point applications. It is required that both directions on the link run in IP-ACM mode, although the symbol rates do not need to be equal. If the user wishes to constrain one direction to run in CCM, simply set the Min and Max ModCod to be equal.

- ACM constitutes a closed-loop control system (similar in concept to AUPC) and it should be remembered that like all control systems, the speed at which the system can react is governed by a number of factors, including the time taken to estimate SNR to the required accuracy, and the transport delay over the satellite. Realistically, it can cope with fading and other link impairments that do not exceed 1dB/second (more if Target Eb/No margin is increased).

- The ACM controller algorithm that resides in the CDM-625 modem does not have to switch through ModCods sequentially – it can change, if needed, directly from ModCod0 to ModCod11 (or vice versa). When the demod first locks at ModCod0 the ACM controller will examine the SNR from the remote end and switch directly to the ModCod that maximizes throughput.

- While ACM can do remarkable things, the fundamentals still apply. Don't expect the demod to run at a 16-QAM ModCod if the SNR instantaneously drops to 0dB – the demod will lose lock and the system will recover by switching to ModCod0 (if so configured). ***We highly recommend setting the Minimum ModCod to 0 (the ModCod of last resort) and set the Unlock Action to 'Go to minimum ModCod'. This will give the most robust link performance.***

- When running in ACM mode the demodulator is performing *blind acquisition* – meaning that it has no *a priori* knowledge of the modulation type or code rate. For this reason the demodulator acquisition time will be slower than in CCM mode. However, the acquisition time is typically under 1 second for all symbol rates and noise conditions.

- Running the ACM link with the Target Eb/No Margin set to 0dB will give the best utilization of link power, but in conditions of fast fading may cause demod unlock events, or highly degraded BER just prior to the switch to a lower ModCod. In order to mitigate this, we recommend a Target Eb/No Margin of at least 1dB – more if the fading events are particularly severe and/or frequent.

- The value of Max ModCod may be limited by other FAST codes installed in the CDM-625. For example, suppose the 4100 ksps FAST option is installed, and the symbol rate set to 4100 ksps, the theoretical maximum data rate would be 14 Mps at ModCod 11. However, if CnC is being used, with a 10Mbps FAST limit, the ACM Max ModCod will be limited to ModCod 7, or 9.6 Mbps. Therefore, if for a given symbol rate, it is not possible to set the Maximum ModCod to the desired value, the user should check to determine what other FAST codes may be limiting it.

- The BER versus Eb/No performance of the ModCods is identical to the VersaFEC CCM modes described in the Operations Manual (FEC Options Chapter).

- SNR is the preferred metric for driving the adaptation – this is the value displayed on the monitor screens. If the user wants to convert this to Eb/No then remember that the relationship is simply Eb/No = SNR - 10log(Spectral Efficiency).

- To achieve minimum latency, set the WAN buffer to the smallest practical value. The default setting is 20ms, and we recommend keeping it at this level.

- At this time Comtech EF Data has chosen to disable AUPC while ACM is active. This may change in the future, but for now, ACM should be considered to be a constant power, constant symbol rate scheme.

- All IP features that are available in the CDM-625 (VLAN, QoS, etc) are available when in IP-ACM mode. The sub-mux feature, however, is not available.

- VersaFEC ACM is 100% compatible with Carrier-in-Carrier.

- If required, VersaFEC ACM may be used in conjunction with any of the EDMAC modes, either for serial remote control of the remote modem, or for SNMP proxy. It should be emphasized, however, that unlike AUPC, a framing mode is ***not*** required for SNR reporting.

- ACM maximizes throughput not only when Eb/No varies due to atmospheric conditions, but will also mitigate the effects of other impairments, such as antenna pointing error (due, for example, to operation with an inclined-orbit satellite), excessive phase noise and certain types of interference. However, rapidly fluctuating impairments (~ less than 1 second) such as scintillation at low antenna look-angles at C-band will generally not be improved by ACM.

- VersaFEC ACM modes are ***not*** compatible with VersaFEC CCM modes, due to differences in frame preambles.

- The CDM-625 was purposely architected to provide the platform for VersaFEC ACM, and has required new approaches to the signal processing employed in both modulator and demodulator. It is the intention of Comtech EF Data to include VersaFEC ACM in future modem platforms.

VersaFEC ACM – Summary of Specifications

System type	Adaptive Coding and Modulation, using BPSK, QPSK, 8-QAM, 16-QAM and VersaFEC short-block LDPC coding. Total of 12 ModCods
Interface	10/100 BaseT Ethernet, with auto-negotiated Congestion Control
Remote SNR reporting	Automatically reported from remote modem – built in function at the physical layer – requires no additional overhead
Max span of data rate	7:1 over range of adaptation
Switch point (decreasing SNR)	Corresponds to SNR (Eb/No) that gives BER = 5×10^{-8}
Switch point hysteresis	0.3 dB
Max fading rate	Approximately 1 dB/second (higher if Target Eb/No margin > 1 dB)
Max ModCod update rate	1 update every 2 seconds (no restriction on distance between ModCods)
Configurable parameters	Minimum and Maximum ModCod (ModCod0 through ModCod11) Remote Demod Unlock Action: Maintain current ModCod or Go to Min ModCod Target Eb/No margin (0 to 4.5 dB, 0.5 dB steps)
System latency	54 milliseconds max (for a system operating at 100 ksps, and assuming a WAN buffer of 20 milliseconds, not including satellite path)
Monitored parameters	Tx and Rx ModCods Local and Remote SNR (-3.0 dB to +22.0dB, 0.1dB resolution, +/- 0.5 dB accuracy) Config and monitor menus displaying data rate, modulation and code rate update dynamically with ModCod

Modulation	Code Rate	Spectral efficiency, bps/Hz	Typical Eb/No, for BER = 5×10^{-8}	Min. Data Rate, ACM mode	Max. Data Rate, ACM mode
BPSK	0.488	0.49	2.4 dB	18.1 kbps	2.00 Mbps
QPSK	0.533	1.07	2.2 dB	39.6 kbps	4.38 Mbps
QPSK	0.631	1.26	2.7 dB	46.7 kbps	5.16 Mbps
QPSK	0.706	1.41	3.4 dB	52.2 kbps	5.78 Mbps
QPSK	0.803	1.61	3.8 dB	59.6 kbps	6.60 Mbps
8-QAM	0.642	1.93	4.6 dB	71.5 kbps	7.91 Mbps
8-QAM	0.711	2.13	5.2 dB	78.8 kbps	8.73 Mbps
8-QAM	0.780	2.34	5.6 dB	86.6 kbps	9.59 Mbps
16-QAM	0.731	2.93	6.3 dB	108.5 kbps	12.01 Mbps
16-QAM	0.780	3.12	7.0 dB	115.5 kbps	12.79 Mbps
16-QAM	0.829	3.32	7.5 dB	122.8 kbps	13.61 Mbps
16-QAM	0.853	3.41	8.0 dB	126.2 kbps	14.00 Mbps