Project	**IEEE 802.16 Broadband Wireless Access Working Group <http://ieee802.org/16>**
Title	**Metrics and Techniques for Evaluation of FEC Systems**
Date Submitted	**2000-04-26**
Source(s)	Eric Jacobsen Intel 5000 W. Chandler Blvd. CH7-410 Chandler, AZ 85226-3699 Voice: (480)554-6078 Fax: (480)552-0771 mailto:eric.a.jacobsen@intel.com
Re:	Call for Evaluations and Improvements, IEEE 802.16-00/11, Session #7.
Abstract	Performance metrics and evaluations techniques for assessing differing FEC systems are discussed. Parameters of most interest to the IEEE 802.16 working group are outlined.
Purpose	Assist the IEEE 802.16 working group in evaluating proposed FEC systems.
Notice	This document has been prepared to assist IEEE 802.16. It is offered as a basis for discussion and is not binding on the contributing individual(s) or organization(s). The material in this document is subject to change in form and content after further study. The contributor(s) reserve(s) the right to add, amend or withdraw material contained herein.
Release	The contributor grants a free, irrevocable license to the IEEE to incorporate text contained in this contribution, and any modifications thereof, in the creation of an IEEE Standards publication; to copyright in the IEEE's name any IEEE Standards publication even though it may include portions of this contribution; and at the IEEE's sole discretion to permit others to reproduce in whole or in part the resulting IEEE Standards publication. The contributor also acknowledges and accepts that this contribution may be made public by IEEE 802.16.
Patent Policy and Procedures	The contributor is familiar with the IEEE 802.16 Patent Policy and Procedures (Version 1.0) <http://ieee802.org/16/ipr/patents/policy.html>, including the statement "IEEE standards may include the known use of patent(s), including patent applications, if there is technical justification in the opinion of the standards-developing committee and provided the IEEE receives assurance from the patent holder that it will license applicants under reasonable terms and conditions for the purpose of implementing the standard." Early disclosure to the Working Group of patent information that might be relevant to the standard is essential to reduce the possibility for delays in the development process and increase the likelihood that the draft publication will be approved for publication. Please notify the Chair <mailto:r.b.marks@ieee.org> as early as possible, in written or electronic form, of any patents (granted or under application) that may cover technology that is under consideration by or has been approved by IEEE 802.16. The Chair will disclose this notification via the IEEE 802.16 web site <http://ieee802.org/16/ipr/patents/letters>.

Metrics and Techniques for Evaluation of FEC Systems

Eric Jacobsen
Intel

Introduction

Several disparate approaches for system Forward Error Correction solutions have been proposed for IEEE 802.16.1. Recent documents [1][2] have extended the discussion beyond the original proposals [3][4]. While it is generally beneficial for the working group to have the opportunity to select from such a rich range of options, it is crucial that candidate systems be evaluated using appropriate and uniform metrics in order to reach a fair and sound conclusion. Since FEC systems and nuances tend to be complex, it seems appropriate to provide a short survey of basic FEC performance metrics, their meanings, and general pitfalls and problems in comparing FEC systems.

System Performance

The fundamental goal is to select a solution that offers the best performance for the expected traffic and link conditions. It is anticipated that the first hurdle is to agree on what is meant by "performance", since, as is the case with many systems, performance may mean different things to different people looking from a different perspective. For FEC systems "performance" metrics tend to center around a few issues such as Bit Error Rate, complexity, latency, and output error distribution. In this case we will assume that output error distribution is not a driving concern since the data is most likely packetized in some way or other. Some systems utilize Packet Error Rate as a preferred metric in order to take this into account.

The primary performance concern is arguably Bit Error Rate, and this metric can be approached several ways. A common approach is to compare the relative power efficiency of particular codes using BER vs Eb/No curves. These performance curves ignore the differing spectral efficiencies of various code rates and reveal only power-related performance and coding gain. Coding gain is the difference in required transmit power to achieve the same BER as an uncoded (i.e., no FEC) system. This provides a metric revealing how efficiently the transmit power is being used with no regard for spectral efficiency. Another way to assess BER performance for an FEC scheme is Distance from Capacity, i.e., how close to Channel Capacity, the theoretical limit of performance, does the particular code allow practical operation. Unlike coding gain, Channel Capacity takes into account not only power efficiency but bandwidth efficiency (or FEC code rate) as well, and provides an overall metric of how effectively the channel resources are being exploited.

Complexity and Latency

Complexity of implementation may be important since it can affect equipment cost, power consumption, reliability and other factors which may influence selection of an FEC solution. Unlike Coding Gain or Distance from Capacity, complexity is difficult to objectively quantify since individual implementation of the same solution may differ in gate count, part count, power consumption, cost, etc. Reasonable estimates of gate counts for common components such as Viterbi or Reed-Solomon decoders are available, but complexity for more recent or less common techniques like Turbo Product Code decoders, APP decoders, BCH or Hamming code decoders, etc., are less refined. With gate costs and silicon geometries decreasing it is often not necessary for gate-count complexity estimates to be highly accurate in order to assess impacts on implementation. In any case "complexity" assessments, while roughly quantifiable, are subject to diversity in implementation and some subjectivity in interpretation of impact.

Some applications, the most prominent being two-way voice, are sensitive to channel latency that may be aggravated or dominated by the latency in the FEC solution. FEC latency is usually driven by interleaver depth or block size for the most pertinent solutions. Concatenated codes with inner codes that produce non-uniform error distributions and outer block codes generally benefit from interleaving across a number of outer code blocks (e.g., concatenated Viterbi-Reed-Solomon systems). This produces an unavoidable latency equal to the interleaver depth in both the modulator and demodulator. If the block codes are long, spreading across a large number of blocks can result in significant latency even at high bit rates. Turbo Codes using convolutional constituent codes require fairly large interleavers and BER performance is proportional to the size of the interleaver. Turbo Product Codes (which have also been referred to as Block Turbo Codes, although all Turbo Codes are block codes) do not require interleaving but do require buffering proportional to the block size in order to facilitate two-dimensional coding and decoding of the data. Like traditional Turbo Codes, TPCs in general benefit from large block sizes, and all Turbo Codes require iteration (i.e., multiple passes on the same data) in the decoder which can cause additional processing delays. In all of the above cases, including interleaving with concatenated codes, reducing the size of the interleaver or code block results in a degradation of BER performance, providing a natural tradeoff between BER performance and latency.

Coding Gain, BER, and Channel Capacity

The most generic method of displaying power efficiency performance is the BER vs Eb/No curve. This characterizes the behavior of an FEC solution in AWGN and reveals not only coding gain but sensitivity to varying levels of SNR (i.e., the steepness of the curve). This is useful for calculating link margins and assessing general system performance limits. It becomes less useful for systems limited by impairments other than thermal noise, such as CCI, ACI, or multipath reflections, although in these cases most FEC systems still provide significant performance improvement. The Eb/No parameter is useful since it focuses attention on performance relative to payload data and provides a natural normalization between modulation types and orders as well as code rates.

There is a direct relationship between SNR and Eb/No. Eb is merely the signal power divided by the bit rate, and No is merely the power spectral density in a unit Hertz bandwidth (e.g., the noise power divided by the measurement bandwidth for noise with constant spectral density). These quantities can be calculated or measured for a given signal without knowledge of the modulation type or order or the code rate of the FEC system. This provides a nicely normalized method of measurement that takes into account only the relevant power levels. Since this metric provides a measure of only power performance relative to payload data, it is not necessary or appropriate to take into account or adjust for the FEC code rate. For constant output power, FEC overhead will manifest itself in a spreading of the occupied spectrum and associated decrease in signal power spectral density proportional to the inverse of the code rate. Application of a rate _ code will double the spectral width of the signal and halve the power spectral density, but the total signal power, and therefore Eb, will remain the same. The difference in signal power between the uncoded signal and the coded signal required to achieve the same BER is the coding gain. Since the Eb parameter is derived only from total signal power and is independent of the code rate, and the noise power spectral density (No) does not change with the signal bandwidth, using BER vs Eb/No curves provides a fair means of comparison between FEC systems. Use of other SNR related parameters, such as SNR or CNR, requires that the signal bandwidth change due to the FEC code rate be taken into account due to the change in relevant noise bandwidth.

Channel Capacity, the asymptotic limit of which is known as the Shannon Limit, takes into account the channel (signal) bandwidth as well as the FEC code rate. This can be used to generate a performance metric that is somewhat different than coding gain, since it compares the performance of a particular FEC coded system at a specific code rate and modulation type to what is theoretically possible for that configuration. The use of this metric has become more significant in recent years since the introduction of Turbo Codes (and Turbo Product Codes) has resulted in practical FEC systems that run far closer to channel capacity than previously realized. An additional benefit of this metric is that it provides a means of determining how well the channel is being exploited in both power efficiency as well as bandwidth efficiency since the FEC code rate is taken into account. For systems concerned with efficient management of link margin as well as available spectrum, utilizing Channel Capacity metrics can provide additional insight into how efficiently the system is being architected.

Inspection of performance relative to Channel Capacity provides an interesting insight into the performance of typical Turbo Product Codes. Turbo Codes based on convolutional constituent codes have been demonstrated which operate within a few tenths of a dB of Channel Capacity. A Turbo Product Code has been demonstrated that provided performance within 0.25dB of Channel Capacity[5]. The TPC based on two-dimensional Hamming Codes implemented by AHA operates closest to Channel Capacity at code rates near ~0.8-0.9 with a distance from capacity of 0.5-1.1dB (depending on block size, number of iterations, etc.)[6]. Practical concatenated Viterbi-Reed-Solomon codes with interleaving generally perform no closer than 2-3dB from Channel Capacity.

Recommendations

In order to provide the most useful, sound, and fair comparisons of candidate FEC systems it is important to use a common set of metrics that provides the most insight into the relevant performances of the systems. Comparison of competing systems with dissimilar parameters (e.g., CNR and Eb/No) confuses the issue and may mask strengths or weaknesses which may otherwise be readily discerned. The use of comparable coding gain metrics is useful and comparison against Channel Capacity may provide additional valuable insight. Latency can be objectively bounded with reasonable ease and should be included for all candidate solutions. Complexity, while a softer metric, is also useful and reasonable gate-count estimates may prove useful.

Inclusion of the following parameters is recommended in order to provide a complete and fair assessment of candidate codes. These parameters should be included for all proposed code rates with all appropriate modulation types, or for representative code rates for variable-rate codes. For iterative codes the number of iterations should be included for each case. Recommended parameters include:

Required Eb/No – At $Pe = 10^{-9}$ (and possibly other representative BERs).

Coding gain – computed using BER vs Eb/No at $Pe = 10^{-9}$.

Distance from binary-input continuous-output Channel Capacity – computed using BER vs Eb/No at $Pe = 10^{-9}$.

Latency – in information bits. This should be indicated for both the encoder and decoder.

Block Size – in information bits. For block codes, particularly if different than latency.

Additionally, the estimated complexity in gates should be stated, with significant blocks of memory cell requirements indicated separately. Full BER vs Eb/No curves are helpful as well, particularly in assessing “error floor” or slope-change behavior for traditional Turbo Codes, but may not be required. It may not be necessary to include BER curves for each code rate if the code can be demonstrated to be well behaved using only representative curves.

For bursty transmission, the parameters should be indicated for representative burst sizes if the performance differs from the continuous transmission case. This should be done assuming perfect demodulation. Although practical systems will experience degradation due to imperfect synchronization during burst demodulation, it is desirable to decouple the effects of the demodulator and the FEC system in order to best evaluate the effects of the FEC scheme. This also decouples the analysis from implementation effects.

Inclusion of the indicated performance metrics, particularly in a tabular format, facilitates simplified comparison of candidate FEC systems. For some systems the pertinent metrics can be analytically calculated for the indicated conditions, and providing coding gain and distance from Channel Capacity at only $Pe = 10^{-9}$ reduces simulation time compared to generating complete BER curves for all cases. Additional data at higher bit error rates may be pertinent if system adaptation allowing degraded performance for voice or other Quality of Service considerations is deemed necessary.

References

[1] Ran, Moshe, “An Amendment to Mode B of 802.16.1pc-00/19”, Document #IEEE 802.16.1pc-00/22, submitted for Session #7.

[2] Klein, Jay, “FEC Alternatives for BWA Burst Communication”, Document #IEEE 802.16.1pc-00/23, submitted for Session #7.

[3] Foerster, Jeff, et al, “Physical Layer Proposal for the 802.16 Air Interface Specification”, Document #IEEE 802.16.1pc-00/19, submitted for Session #7.

[4] Klein, Jay et al, “PHY layer proposal for BWA”, Document #IEEE 802.16.1pc-00/20, submitted for Session #7.

[5] Burkert, Frank and Hagenauer, Joachim, “A Serial Concatenated Coding Scheme with Iterative ‘Turbo’ and Feedback Decoding”, International Symposium on Turbo-Codes, September, 1997.

[6] Advanced Hardware Architectures, Inc., “Primer: Turbo Codes”, white paper, www.aha.com.

[7] Couch, Leon W. II, “Digital and Analog Communication Systems”, MacMillan Publishing Company, 1993.

[8] Sklar, Bernard, “Digital Communications”, Prentice-Hall, 1988.

[9] Lindsey, William C. and Simon, Marvin K., “Telecommunication Systems Engineering”, Dover Publications, 1973.

Appendix

The following table provides example Channel Capacity figures for the indicated code rates. The indicated Capacity figures are for binary-input continuous-output channels with QPSK modulation.

FEC Code Rate	Channel Capacity, QPSK (dB)
_	0.18
_	1.62
7/8	2.85
9/10	3.2
13/14	3.67
19/20	4.22