Adaptive Algorithms for Choosing Transmission Parameters in Dynamic Channel Conditions

Itay Lusky, Senior Modem Designer/MGTS
Noam Geri, Strategic Marketing Manager
Zvi Reznic, DSP Engineer
Cable Broadband Communications Group, Texas Instruments

Abstract

Modern communication systems are designed to be robust while maximizing achieved capacity. To achieve this goal many standards allow the use a variety of coding schemes, constellations, error coding capabilities and other transmission parameters. The actual transmission parameters in use should be tailored to the actual channel conditions. Hence, there is a need for algorithms that analyze channel impairments using digital signal processing methods and determine the optimal transmission parameters accordingly. Furthermore, as channel conditions vary over time, these algorithms should be adaptive. The capabilities of the receiver in use should be taken into consideration as well.

In this paper we present the benefits of developing such adaptive algorithms and demonstrate them in several contemporary standards. In the case of cable modem communication we present a solution that employs Digital Signal Processor (DSP) based Upstream Channel Analysis (DUCA) adaptive algorithms. Simulation results of such adaptive algorithms conclude this paper.

Introduction

Modern communication systems are designed to provide their operator the best of all worlds. In severe channel conditions they are designed to provide sophisticated coding schemes and robust transmission at the expense of achieved capacity. In moderate channels conditions they are designed to provide maximal throughput at the expense of robustness to channel impairments. As a result, the need to provide operators the option to address such a diverse set of channels led many contemporary common standards to include a wide variety of transmission parameters.

The allowed transmission parameters may include different modulation types, constellation sizes and baud rates. Transmission power may be an important parameter, as well as the carrier frequency used. Different error correction schemes can be used such as Reed Solomon (RS) codes, Convolutional codes, Trellis Coded Modulation (TCM) codes, Turbo codes and concatenated codes [1],[2],[3],[4],[5]. Different coding rate can be used. Interleaving can be used in order to introduce time diversity. In such a case a tradeoff between required interleaver effect and the added processing delay should be taken into consideration. A training sequence may be used. In that case the spectral characterization of the training sequence, its length, power, and constellation should be chosen properly. All the possibilities described above may be allowed in a single communication system. Various examples of common communication systems that allow a subset of the above possibilities are described in section 2.

Many communication systems today lack the ability to dynamically analyze channel conditions and to automatically choose transmission parameters accordingly. This is particularly true for broadband communication systems that are relatively less mature. As a result, operators tend to choose overly robust transmission parameters just to be on the safe side. This results in an inefficient use of bandwidth, and a substantial decrease in capacity. The algorithms described here help in improving the efficiency of these communication systems.

Transmission Parameters in Common Communication Systems

Cable DOCSIS2.0:
The new DOCSIS2.0 standard for the upstream channel is an excellent example of a standard providing the user substantial tools to accommodate various channel impairments. As such, it will be explored in details as a special test case in section 3.

Wireless LAN, 802.11:
802.11 standard, with its various flavors, offers the use of several transmission parameters, such as center frequency, modulation scheme (Barker/CCK/PBCC/OFDM), transmission rate, transmission power, and preamble properties. Due to the typical wireless channel parameters it is extremely important to identify the channel conditions and make a decision accordingly about transmission parameters to use.

Home phone line networking alliances (HPNA):
The HPNA 2.0 standard allows using a variety of constellations (QPSK-256QAM) and different baud- rates (2Mbaud or 4Mbaud). This results with achievable throughput of 4 Mbit/sec up to 32Mbit/sec, as a function of the channel conditions. Efficient use of those tools requires an adaptive mechanism to analyze and track varying channel conditions. Adding RS coding to the standard extends even further the possibilities.

Telephony, V.34 modem:
Another interesting example of a communication system that provides numerous transmission parameters is the telephony V.34 modem. This modem provides the ability to use various constellations (from QPSK to over 1500 constellation points), six baud rates, center frequencies (two options for each baud rate), constellation shaping, control

of the transmission power, the use of training sequence (TRN), and also provides tools to mitigate non-linear distortions. Dedicated signals are provided for channel characteristic analysis. These signals include training sequence (TRN), frequency comb (L1, L2), MSE measurements and more.

A Test-Case: DOCSIS 2.0 Upstream Physical Layer Specification

The newly published DOCSIS 2.0 upstream standard may be one of the best examples available in the industry today for the need for an adaptive mechanism that will monitor channel condition and choose transmission parameters accordingly.

The Cable Upstream Channel

The cable network upstream channel has always been the weakest link in the cable network infrastructure. Given the tree-and-branch topology of the cable network, noise and interferences from the entire network are accumulated at the headend. Common upstream impairments include the following noise sources:

1) White noise generated by active components in the network.
2) Narrow band ingress noise that may result from Common Path Distortion.
3) High rate impulse noise originating from electric current.
4) Low rate wideband burst noise originating from several sources including electrical appliances in homes and laser clipping. In addition to the noise sources described above the upstream signal is also subject to multi-path reflections due to impedance mismatch of the plant's components and non-terminated cables. For a more detailed description of cable upstream impairments see [1][6].

DOCSIS 2.0 Specification

At the end of 2001 cable operators finalized the new DOCSIS 2.0 upstream physical layer specification. The specification includes both Advanced Time Division Multiple Access (A-TDMA), based on a proposal by Texas Instruments and Broadcom [1][3], and Synchronous Code Division Multiple Access (S-CDMA) using spread-spectrum techniques based on a proposal by Terayon. Both of these technologies were also included in the IEEE 802.14a specification, which was never finalized [4].

DOCSIS 2.0 transmission parameters include the choice of modulation scheme (A-TDMA or S-CDMA), baud rate (160Kbaud-5.12Mbaud), constellation (QPSK-128QAM), carrier frequency (anywhere in the range of 5-42Mhz in DOCSIS or 5-65Mhz in EuroDOCSIS), transmission power, RS correction capability (1-16 erred bytes) and word size (18-255 bytes), interleaver parameters and framer parameters in S-CDMA mode. In addition, the headend can configure the content, length and power of the preamble sequence.

Typical Analysis Trade-offs

The channel analyzer described in this paper has to account for various trade-offs in order to recommend transmission parameters. Following are a few examples.

A typical trade-off is the choice of constellation and RS coding rate. Traditionally, the most common reaction to impulse noise in the channel is reducing the constellation size. However, this comes at the expense of upstream throughput. A better approach may actually be using larger constellations with stronger RS code. The choice should be made according to the resulting throughput.

An additional trade-off with respect to the WGN is the possibility to use higher spectral density with a lower baud rate (and hence keeping total transmission power unchanged). This results in higher signal to noise ratio and may allow the use of larger constellations.

Another example may be choosing the interleaver or spreader parameters when impulse and burst noise exists along with WGN. Assuming we use a rectangular interleaver, where the number of columns defines the RS word size and the number of rows defines the interleaver depth and hence its immunity to burst noise. If the WGN is dominant we would prefer maximal RS word size, even at the expense of interleaver depth whereas if the impulse and burst noise are dominant we may prefer larger interleaver depth, even at the expense of shorter RS word.

An even greater challenge for the upstream channel analyzer is when it is faced with the task of mitigating different types of noise simultaneously, especially when the optimal choice of parameters for each impairment are different. For example, when ingress is combined with burst noise, the DOCSIS 2.0 needs to choose between a higher baud rate that will improve the performance of the ingress cancellation, or a lower baud rate for greater immunity to long bursts.

We suggest a combination of frequency domain and time domain analysis to determine the correct set of transmission parameters, as described below.

Adaptive Algorithms, Frequency Domain Analysis

The most common impairment to be analyzed using the frequency domain analysis is the ingress noise. For frequency domain analysis we suggest an algorithm that will consist of the following steps:

1. Noise spectrum estimation.
2. Ingress and other impairment characterization.
3. Choice of frequency domain transmission parameters.

Step 1, the noise spectrum estimation can be done by wideband sampling followed by FFT calculation, or alternatively by using frequency-sweeping filter.

In step 2 we create a list of the ingresses, their center frequencies, bandwidths and powers. This can be done in several methods, such as pattern recognition.

The goal of step 3 is to choose the carrier frequency, baud rate, constellation and other relevant transmission parameters of the upstream QAM signal. For that the ingress list of step 2 and the number of channels to allocate are taken into consideration.

Another important consideration in step 3 is the ability of the receiver to handle ingresses that fall within the QAM signal band, that is, the ability for ingress cancellation [5]. Ingress noises, which are too strong for ingress cancellation, should be avoided by shifting the QAM signal to a different band, while the weaker ingresses can be ignored, assuming that the receiver will be able to cancel them.

Figure 1 describes an example of a system that employs the above 3 steps. In this case we scan through all possible carrier frequencies and baud rates. For each baud rate and carrier we transmit a QAM training sequence, used to train a Decision Feedback Equalizer (DFE).

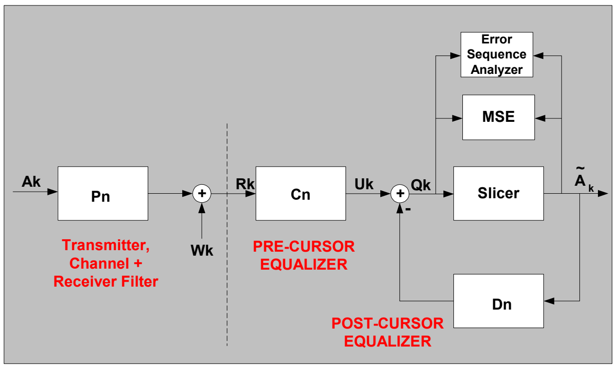


Figure 1: System block diagram

A_k is the transmitted symbols in time k and W_k is added noise. It may be colored and include ingress, burst and impulse noises.

We assume the form of the DFE shown in figure 1 above, in which the pre-cursor equalizer is anti-causal with N coefficients and the post-cursor equalizer is causal with M coefficients. Therefore, the slicer input is given by the relation:

$$Q_k = \sum_{i=-(N-1)}^{0} c_i R_{k-i} - \sum_{i=1}^{M} d_i \hat{A}_{k-i}$$

The pre-known training sequence of length *num+M+N* is transmitted and is used to optimally train the decision feedback equalizer using least square fit method. The main steps to the known method are described below:

Assuming no decision errors occurs:

$Q_k \sim \hat{A}_k = A_k$ and

hence the following equations apply

$$\begin{aligned}
A_0 &= c_{-(N-1)} \cdot R_{N-1} + \ldots + c_0 \cdot R_0 - d_1 \cdot \hat{A}_{-1} + \ldots + d_M \cdot \hat{A}_{-M} \\
A_1 &= c_{-(N-1)} \cdot R_N + \ldots + c_0 \cdot R_1 - d_1 \cdot \hat{A}_0 + \ldots + d_M \cdot \hat{A}_{1-M} \\
&\vdots \\
A_{num} &= c_{-(N-1)} \cdot R_{num+N-1} + \ldots + c_0 \cdot R_{num} - d_1 \cdot \hat{A}_{num-1} + \ldots + d_M \cdot \hat{A}_{num-M}
\end{aligned}$$

We define:

$$\underline{\theta} = [c_{-(N-1)} \cdots c_0 \ \text{-d}_1 \cdots \text{-d}_M]^t$$

$$\underline{A} = [A_0 \ A_1 \cdots A_{num}]^t$$

$$H = \begin{bmatrix} R_{N-1} & \cdots R_0 & \hat{A}_{-1} & \cdots \hat{A}_{-M} \\ \vdots & \vdots & \vdots & \\ R_{num+N-1} & \cdots R_{num} & \hat{A}_{num-1} & \cdots \hat{A}_{num-M} \end{bmatrix}$$

The equations above can be expressed as: $\underline{A} \approx H \cdot \underline{\theta}$

and can be solved using least square fit method: $\hat{\underline{\theta}}_{ls} = \left(H^t H\right)^{-1} H^t A$

Calculation of $(H^tH)^{-1}$ requires calculating the autocorrelation of R and of A, sample cross correlation between R and A, and then inversion of an (M+N) x (M+N) matrix.

After the training is complete, one can learn about the characteristics of the in-band noise by observing the nulls in the equalizer frequency response. In addition, the MSE calculation can be used to predict the expected performance of each carrier-baud rate combination assuming the receiver used implements the DFE structure described.

After scanning through all possible carrier frequencies and baud rates best transmission parameters can be determined.

Adaptive Algorithms, Time Domain Analysis

The main channel impairments that can be characterized using the time domain analysis are the impulse and burst noises. These impairments can be mitigated using the RS code, byte interleaver, S-CDMA spreader and other transmission parameters. The DOCSIS 2.0 CMTS needs to dynamically track impulse levels, and to optimally set transmission parameters accordingly. Impulse strength, as well as impulse frequency and arrival statistics can be determined by employing various power detectors that measure the signal level during quiet periods or in adjacent unoccupied frequencies. An additional important impairment to track is the white gaussian noise (WGN). Using the right choice of transmission spectral density, constellation, RS parameters and number of active codes in S-CDMA transmission can mitigate this impairment.

Returning to the example depicted in Figure 1, after the training is complete burst of errors can be identified in the error sequence analyzer. The information is used to characterize the impulse and burst noise affecting the channel and to determine transmission parameters accordingly.

Both the time domain and frequency domain algorithms, described above, are best implemented using a digital signal processor (DSP).

Simulation Results

We conclude the paper with simulation results of the method described. We simulated an upstream channel with multiple ingress as illustrated in Figure 2. We assume that the spectral density of the QAM signal is restricted to a certain total channel power.

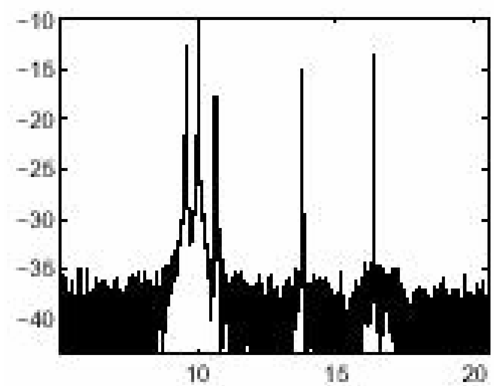
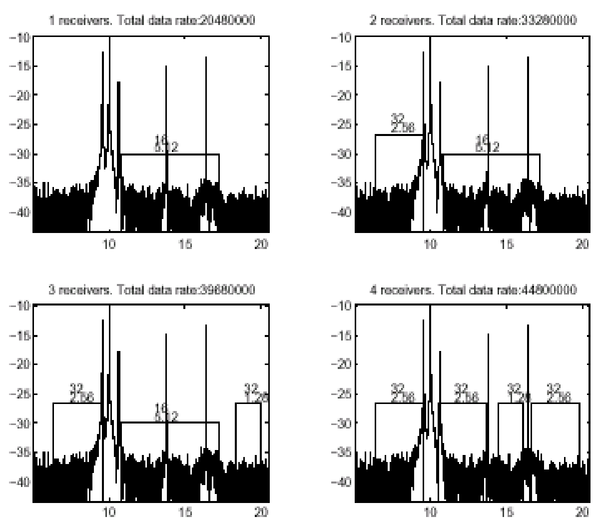


Figure 2: Upstream Channel Spectrum

In addition to ingress, this simulated channel is also corrupted by time-domain impairments, such as burst and impulse noises, which cannot be seen in the frequency-domain analysis.

Figure 3 shows the output of the channel analyzer algorithm for one up to four upstream channels. For each allocated channel the baud rate (1.28-5.12Mbaud) and constellation used (16 or 32 QAM) are defined. Note that for one upstream channel, the channel allocation algorithm determines that the highest throughput can be achieved by using the highest baud-rate of 5.12Mbaud and a 16-QAM constellation while overlapping two ingresses. The channel allocation algorithm determines that avoiding the ingress by reducing the baud-rate would not result in higher throughput even if a more spectrally efficient constellation can consequently be used. Another interesting result of the allocation algorithm can be seen when moving from 3 allocated channels to 4 allocated channels. Until the third allocated channel each new channel was allocated without affecting previous allocated channels parameters (carrier frequency and baud rate). When moving from 3 allocated channels to 4 allocated channels the allocation algorithm determined that higher total throughput could be attained if also the first and the third allocated channels were changed.

Figure 3: DUCA allocation of 1-4 upstream channels (Note that the heights of the squares do NOT represent the allocated channel spectral density)



Summary

Many contemporary communication systems allow the operators to use a variety of coding schemes, constellations, error coding capabilities and many other transmission parameters. These possibilities generate a new and challenging goal to develop adaptive algorithms that analyze channel impairments using digital signal processing methods while tracking their dynamic changes. The analysis is used in order to derive optimal transmission parameters to be used in order to maximize achieved capacity.

In this paper we have presented the need for such adaptive algorithms in several of the common communication systems available today and explored the subject in-depth in a test case from the cable upstream industry using the recently defined standard DOCSIS 2.0.

We have presented the concept of channel analyzer for selection of these transmission parameters, and which is best implemented using a dedicated Digital Signal Processor (DSP). We believe that channel analysis and parameter setting tools will be used in many of the communication systems available today and in future systems.

References

[1] "HI PHY LITE – A Pragmatic Approach to Advanced PHY" Ofir Shalvi, Noam Geri et al, NCTA 2001 Conference Proceedings

[2] ITU-T recommendation V.34: Data communication over the telephone line

[3] "Advanced TDMA Proposal for HFC Upstream Transmission", Texas Instruments Cable Broadband Communications and Broadcom Corp., Oct 1999

[4] "S-CDMA as a High-Capacity Upstream Physical Layer", Mike Grimwood and Paul Richardson (Terayon Communications Systems), IEEE 802.14a/98-017, July 7, 1998

[5] "Advanced Modulation Schemes For Cable TV Upstream Channel", Ofir Shalvi and Noam Geri, ICCE Conference Proceedings, June 2000

[6] "HFC Channel Model Submission", Thomas J. Kolze, IEEE 802.14a/012, May 26 1998

[7] INCA Technology White Paper, Texas Instruments –CBC, www.ti.com/sc/docs/innovate/cable

[8] DOCSIS 1.0 RF Interface Specification (SP-RFI-I05-991105) Nov 5, 1999

[9] "Optimizing transmission parameters in DOCSIS2.0 with a Digital Upstream Channel Analyzer (DUCA)" Noam Geri, Itay Lusky NCTA 2002 Conference Proceedings

[10] "Digital communication" Edward A. Lee, David G. Messerschmitt, chapter 11

IMPORTANT NOTICE

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products		**Applications**	
Amplifiers	amplifier.ti.com	Audio	www.ti.com/audio
Data Converters	dataconverter.ti.com	Automotive	www.ti.com/automotive
DSP	dsp.ti.com	Broadband	www.ti.com/broadband
Interface	interface.ti.com	Digital Control	www.ti.com/digitalcontrol
Logic	logic.ti.com	Military	www.ti.com/military
Power Mgmt	power.ti.com	Optical Networking	www.ti.com/opticalnetwork
Microcontrollers	microcontroller.ti.com	Security	www.ti.com/security
		Telephony	www.ti.com/telephony
		Video & Imaging	www.ti.com/video
		Wireless	www.ti.com/wireless

Mailing Address: Texas Instruments
Post Office Box 655303 Dallas, Texas 75265