DETECTION AND CLASSIFICATION OF RF IMPAIRMENTS FOR HIGHER CAPACITY UPSTREAMS USING ADVANCED TDMA

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Abstract

Mitigation of ingress, common path distortion (CPD) and impulse/burst noise is of great interest to cable operators. Advanced physical layer technologies such as frequency agility, enhanced error correction, ingress cancellation and FFT processing have created new tools for mitigation of impairments. Impairments can now be canceled, reduced or avoided by intelligent adapation of both signaling and system parameters. A detailed knowledge of RF impairments is required however, to both characterize the impairment and to determine the best mitigation strategy.

In this paper, detailed models of common path distortion (CPD), ingress, and impulse/ burst noise are presented based on first principles and verified by plant measurements. The models were developed to optimize the detection, classification, and mitigation and/or avoidance of such impairments by advanced DOCSIS TDMA physical layer technology [1]. The result is higher upstream performance and capacity. A link between plant monitoring and communication system configuration is made that can significantly improve availability and overall plant maintenance. The approach is applicable to existing as well as deep fiber architectures.

INTRODUCTION

Advanced TDMA improves upstream capacity and performance via greater bits/Hz, more robust signaling, and higher signaling bandwidth. In clean upstream channels, a threefold increase in capacity is provided by operation at 64 QAM at 5.12 Megasymbols per second (Msps). In impaired channels, advanced TDMA provides cancellation of ingress and common path distortion (CPD), mitigation of high rate and long duration impulses by greater FEC (T=16) and Reed Solomon byte interleaving. Coupling these advanced features with upstream monitoring in both the spectral and time domains creates a new capability for operators to simultaneously report problems and to adapt the signaling to the impairment in order to maintain the capacity of the system as high as possible.

Previous measurements have concentrated on long term statistical characterization, or capture of short time traces of the upstream only. Further, many of the models currently available are still basic in nature. For example CPD is usually consider to produce beats or at most triplets every 6 MHz. Many more frequencies exist in the CPD spectrum however, and proper design of cancellation filters requires knowledge of this additional spectral structure. Hence, in this paper, more detailed models of common RF impairments are provided in terms of parameters needed by advanced TDMA systems to obtain the maximum capacity from the HFC system. The new models are verified by plant measurements, and then applied to an advanced TDMA system to show how the system may be adapted to the impairments.

MODELING RF IMPAIRMENTS

Common Path Distortion

Common path distortion (CPD), also termed common path intermodulation distortion (CPID) arises in cable plants from several mechanisms, but the most common source is oxidation of contacts which leads to diode-like behavior. A second mechanism is improper balancing of actives leading to nonlinear behavior. In general, the impairment produces second and third order nonlinearities which lead to mixing products of downstream frequencies . These products are located in the upstream frequency band. The most common of these products are at difference frequencies of the downstream video carriers: 6 MHz, 12 MHz, and so on up to 42 MHz. However a complete characterization of CPD reveals many more frequencies in the upstream spectrum, and also the different bandwidths of these frequencies.

The mechanical discussion of common path distortion (CPD) has been covered texts such as Ciciora et al [2] and will not be repeated here. We begin by assuming that second and higher order mixing products have been produced in the cable plant, and seek to derive the frequencies, relative amplitudes, and fine structure of CPD in the upstream frequency band. It will be shown that there are three scales of CPD spectral structure:

Coarse

Main CPD frequencies that depend on whether the plant is set up for harmonically related carriers (HRC), incrementally related carriers (IRC) or standard carriers (STD). These include the well-known 6 MHz beats in the upstream spectrum.

Medium

Sidebands around each coarse CPD frequency that result from the use of offset carriers in certain cable channels as per FCC regulations for avoiding aeronautical radio communications. These offsets are either 12.5 kHz or 25 kHz away from the nominal downstream frequencies.

Fine

Spreading of CPD coarse and medium frequencies with occasional tone-like peaks that result from carrier frequency inaccuracy in downstream modulators. Typical carrier frequency accuracy of cable modulators is on the order of +/- 5 kHz to +/- 8 kHz.

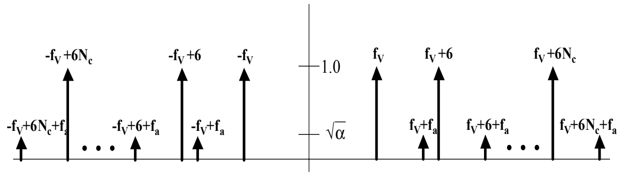
An NTSC downstream signal has two main peaks, at the video and audio carriers. If f_V is the frequency of the video carrier, then the audio carrier will be at $f_A = f_V + 4.5$ MHz. Generally speaking, subsequent carriers for other downstream cable channels will be at f_V + m*6 MHz, f_A + m*6 MHz, where m=1,2,3, and so on.

To determine the CPD frequencies that result from second order mixing products, we need only take sum and difference frequencies, f_j-f_i. , where both positive and negative frequencies of the original spectrum must be considered. The result is CPD beat frequencies at 6, 12, 18…m*6 MHz, with sidebands at +/-1.5 MHz around every 6 MHz beat. Thus, the main, or coarse CPD frequencies from second order mixing products in the upstream band are at 6.0, 7.5, 10.5, 12.0, 13.5, 16.5, 18.0, 19.5, 22.5, 24.0, 25.5, 28.5, 30.0, 31.5, 34.5, 36.0, 37.5, 40.5, and 42.0 MHz. Since these frequencies are invariant to downstream carrier shifts due to frequency plan, they will always be present when CPD exists.

In order to determine relative amplitudes of the CPD frequencies, and for greater detail in modeling, a formalism for the above will be used which is based on the fact that multiplication in the time domain is equivalent to convolution in the frequency domain. Since the frequency domain representation of a real carrier at f_V is ½ [$\delta(f+f_V) + \delta(f-f_V)$], where δ is the Dirac delta function, if we represent the entire cable downstream spectrum as only the video and audio carriers, the spectrum can be written as

$$S(f) = \sum_{\substack{n=-N_c \\ n\neq 0}}^{N_c} \{\delta(f-nf_c) + \alpha\delta(f-[nf_c+f_a])\}$$

where N_c is the number of downstream cable channels, f_c is the spacing between channels (6 MHz), α is the amplitude of the audio carrier relative to the video carrier (-8.5 dB) and f_a is the spacing between the audio carrier and the video carrier (4.5 MHz). This spectrum is depicted in the figure below:



Simplified Downstream Spectrum Model

The second order mixing products can then be determined from

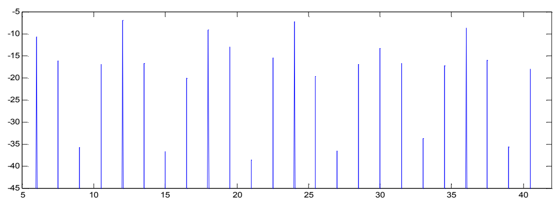
$$S_2(f) = S(f)*S(f)$$

where ∗ denotes convolution. A similar approach is used to derive the 3rd order mixing products:

$$S_3(f) = S_2(f) * S(f) = S(f) * S(f) * S(f)$$

Additional CPD frequencies are produced, for example at $f_k+f_j-f_i$, and also at $2f_j-f_i$ and f_j-2f_i. For HRC systems, these additional frequencies are at multiples of 1.5 MHz since the original carriers are at multiples of 6 MHz + (0 or 4.5 MHz).

A simple MATLAB routine to calculate the upstream band of CPD 2nd and 3rd order frequencies was used to predict CPD for an HRC system:

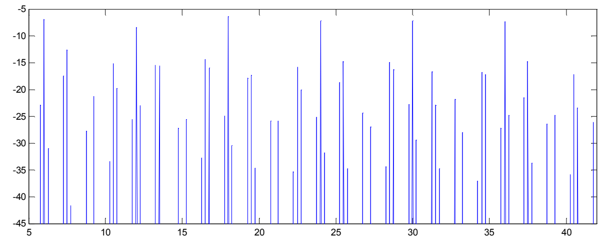


Coarse CPD Frequencies for an HRC plant

The CPD frequencies at 9, 15, 21, 27, 33, and 39 MHz are solely due to 3rd order products, while the remaining frequencies are due to both 2nd and 3rd order products.

Note that STD and IRC plans have carrier frequencies which are offset by 0.25 MHz from those of HRC plans. While this does not affect the location of the 2nd order mixing products, it will affect the location of 3rd order products. For example, in an IRC or Standard plant, the audio carrier of Chanel 19 will be at 151.25 + 4.5 = 155.75 MHz. Twice the video carrier of Channel 4 is 2*67.25 = 134.5 MHz. The difference between the two is 21.25 MHz. Hence, a key visual cue for whether the plant is HRC or Standard/IRC is the presence of CPD frequencies at x.25 MHz or X.75 MHz locations; only Standard and IRC plans will produce these coarse CPD frequencies. It is possible that on an IRC plant, the 3rd order frequencies can be much higher due to more coherent summing of the mixing products, however this has yet to be verified with measurements [5].

The MATLAB routine was rerun with IRC frequencies, with the resulting spectrum shown at the top of the next column:



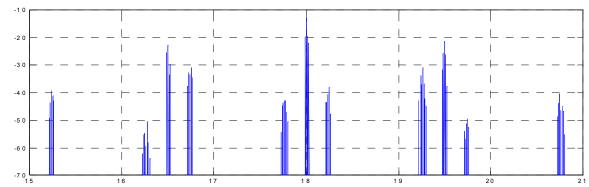
Coarse CPD Frequencies from IRC Plant.

<u>Derivation of Medium CPD Frequency Structure</u>

There are additional medium scale CPD frequencies which are produced by the fact that the FCC requires cable operators to offset the carriers in certain bands by either 25 kHz or 12.5 kHz to prevent any leakage signals from interfering with aeronautical radio communications in those bands. The rules are as follows [3]:

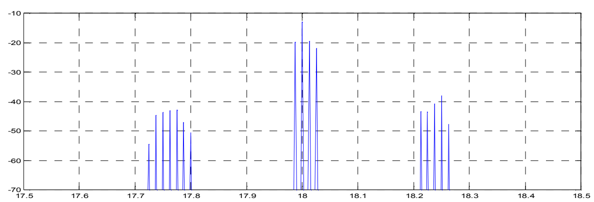
> Cable in the aero radiocom bands 118-137, 225-328.6 and 335.4-400 MHz must be offset by 12.5 kHz.
>
> Cable channels in the aero radiocom bands 108-118 and 328.6-335.4 MHz must be offset by 25 kHz.

Second order difference frequencies between an offset carrier and a non offset carrier will thus produce CPD frequencies at 12.5 and 25 kHz offsets from the previously predicted frequencies. Third order offset products will produce additional CPD frequencies at 37.5 kHz, 50 kHz, 62.5 kHz, etc. from the non offset products, which will be lower in amplitude due to the fact that the number of cable channels which must be offset is less than the number which are not offset. The MATLAB routine was rerun for IRC frequency plans using positive offsets for the FCC regulated cable channels with the following result:



Medium Scale CPD Structure on STD Plant

The FCC offsets result in widening the CPD tones via additional tones from the offset frequencies. The resulting bandwidth can approach 100 kHz, as seen below in a magnified view near 18 MHz:

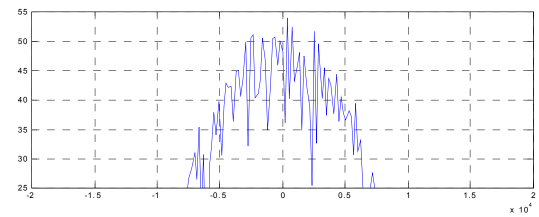


Three CPD Spectral Peaks Near 18 MHz

Derivation of Fine CPD Frequency Structure

Finally, in standard cable plants (STD), the modulators are not locked to a comb generator, and hence do not always produce carriers of exactly the specified frequency. The frequency accuracy specifications for typical modulators are f_{acc} = +/- 5 kHz or +/- 8 kHz [4]. Hence the actual carrier frequency of any particular modulator will be that specified by the STD frequency plan plus the specified FCC offsets if applicable, and finally plus a very slowly varying random frequency offset selected from a probability distribution with rough limits of either +/- 5 kHz or +/- 8 kHz. Since this is a significant fraction of the medium CPD frequency structure (at increments of 12.5 kHz), one would expect that the result will be a spreading of CPD frequencies about the nominally predicted frequencies, by about half the spacing between CPD medium frequency structure tones.

A separate MATLAB routine was developed to simulate the effect of summing many carriers with random frequencies normally distributed about zero frequency with a standard deviation of 1500 Hz (which gives a 3σ value of 4500 Hz:

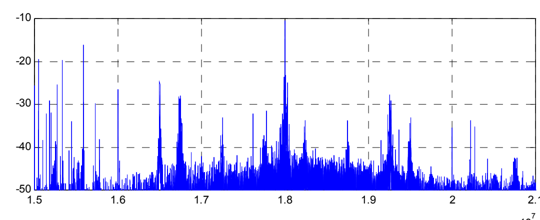


Predicted Fine CPD Spectrum

CPD Measurements

Measured data from a plant using a STD frequency plan and known to have CPD was analyzed and compared to the models described above. The results show complete agreement with the model for coarse, medium, and fine frequency structure, as seen below.

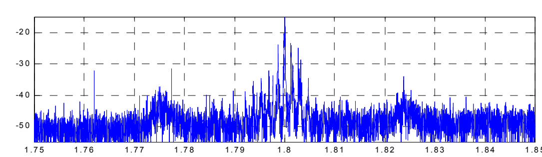
A measurement snapshot of a 6 MHz band centered on 18 MHz is shown below:



Measured CPD Coarse Frequency Structure

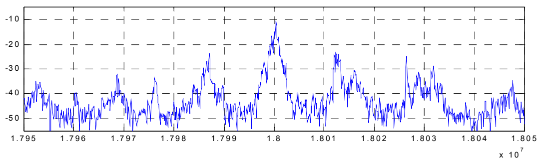
Note the presence of the coarse CPD frequencies at 15.25, 16.25, 16.75, 17.75, 18.0, 18.25, 19.25, 19.5, and 20.75 MHz, in agreement with the model.

The figure below shows the medium CPD frequency structure in the measured data. The two coarse side tones at 17.75 and 18.25 MHz are low enough that it is difficult to discern the medium frequency structure, but at 18.0 MHz, the four strongest medium CPD tones are clearly seen, in complete agreement with the model.

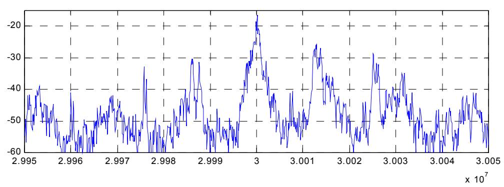


Measured Medium CPD Structure

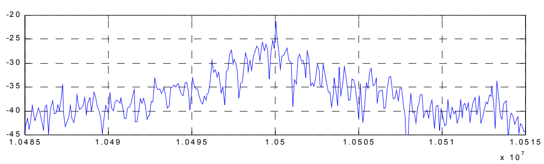
Further detail of the medium and fine CPD structure are shown in the next three figures, where the fine CPD structure can be seen via the non uniform shapes of the medium CPD tones spaced at 12.5 kHz. As discussed above, this is due to frequency inaccuracy in the downstream modulators.



Measured Medium and Fine CPD at 18 MHz

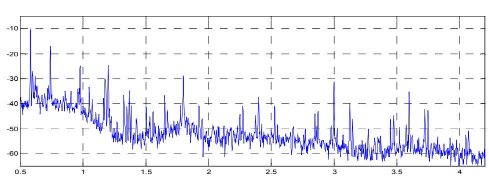


Measured Medium and Fine CPD at 30 MHz



Measured Fine CPD Structure at 10.5 MHz

Finally, a plot was generated of the entire upstream spectrum from the measured data using the PWELCH function in MATLAB. The resulting spectrum is plotted below:



Entire CPD Spectrum for STD Plant.

Ingress

Ingress of off-air communications has previously been modeled using stationary carriers with Gaussian noise modulation [6]. However actual ingress comes in a variety of forms:

Strong, stationary HF broadcast sources such as Voice of America

Data signals with bursty characteristics

Intermittent push-to-talk voice communications such as ham and citizen's band (CB) radio signals

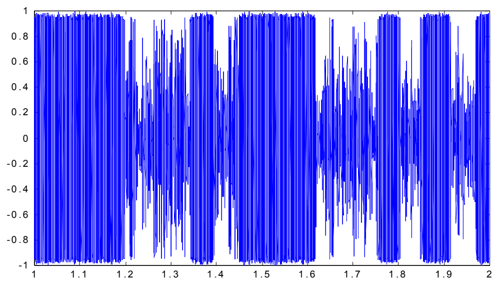
Slow Scan Amateur TV, allowed anywhere amateur voice is permitted, but usually found at these US frequencies: 7.171 MHz, 14.230 MHz, 14.233 MHz, 21.340 MHz, and 28.680 MHz.

Plus other, less frequent ingress signals such as radar and other military signals

It is relatively straightforward to generate models of all of the above communications using tools such as MATLAB with the signal processing toolbox, since it includes most of the commonly used forms of modulation for such signals. However, the time variation of the signals' power level must be developed. This time variation comes from three main sources: the fluctuations in atmospheric propagation (multipath, ducting, etc.), fluctuations from vehicular movement (in the case of ham and CB radio signals), and fluctuations from the fact that the ingress typically enters the plant in multiple locations. From the evidence that significant reductions in ingress levels occurred after high pass filters were installed throughout the plant, it may be conjectured that ingress typically enters the plant via the subscribers house [7].

From measurements by the author, fluctuations in the signal power of at least 20 dB have been frequently seen with the time scale of fluctuations on the order of tens of milliseconds. Hence, a time varying, random envelope with power variation of up to 20 dB can be impressed on the signals above to generate realistic ingress models for testing new technologies.

For the Morse code communications, captured traces show the on off cycles of such signals to be on the order of tens of ms (‘dots’) to hundreds of ms (‘dashes’). An example trace is shown on the next page:



One Second of Morse Code Trace

A simple model involves gating a CW signal on and off with a 10 Hz rate to emulate such signals. A more complex model includes specific durations for ‘dots and dashes’, as well as variations.

Models of voice conversations abound in the telecommunications literature, and can be used for detailed modeling of voice signals. Spaces between words (tens of milliseconds) as well as larger silence intervals (seconds) can be applied to the signal models for single sideband and other common ham and CB voice signals.

The bandwidths of ingress signals range from extremely narrowband on-off keyed Morse code signals, to voice and slow scan TV signals of bandwidth on the order of 20 kHz, to specialized data signals with bandwidths of hundreds of kHz.

The last point in modeling ingress signals is to determine how many ingress signals can occur in band during cable modem signals. This depends highly on whether certain bands are avoided. The DOCSIS specification recommends avoiding the following broadcast bands:

Broadcasting Allocations in 5 - 42 MHz

No. From	**To**	**Bandwidth**
1. 5.95 MHz	6.20 MHz	250 kHz
2. 7.10 MHz	7.30 MHz	200 kHz
3. 9.50 MHz	9.90 MHz	400 kHz
4. 11.65 MHz	12.05 MHz	400 kHz
5. 13.60 MHz	13.80 MHz	200 kHz
6. 15.10 MHz	15.60 MHz	500 kHz
7. 17.55 MHz	17.90 MHz	350 kHz
8. 21.45 MHz	21.85 MHz	400 kHz
9. 25.67 MHz	26.10 MHz	470 kHz

However, this list was developed before advanced TDMA DOCSIS was available. When measurements of upstream ingress are compared with advanced TDMA capabilities, it turns out that many of the above bands have few enough ingressors that advanced TDMA permits cancellation of the ingress. On a typical plant, for example, bands 2, 5, and 7-9 in the previous table can turn out to have relatively few strong ingressors, and thus are candidates. A scan of measured data indicates that with judicious placement of DOCSIS carriers, a typical maximum number of ingress zones to be canceled is about 4-6. The term ‘zone’ is used, as frequently ingressors occur in groups and must be canceled as a group rather than individually. It is for this reason that the bandwidth to be canceled can often exceed 100 kHz.

Thus, a reasonable model for ingress to use for developing and characterizing advanced TDMA DOCSIS systems is:

4-6 ingressors zones in band
Power levels with up to 20 dB fluctuations over tens to hundreds of ms
Bandwidths in three ranges:
- 100’s of Hz for OOK-CW
- 20 kHz for voice, data, SSTV, etc.
- 100 kHz for special signals or for groups of ingress signals to be canceled as a group

Impulse Noise

Random impulse noise has been extensively studied in the past, with the following representing current thinking on the subject [8]:

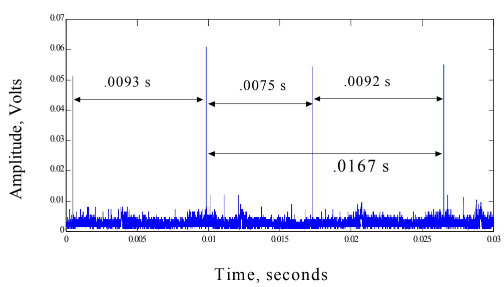
1 µs impulse duration (dominant case)
10-50 µs burst duration (infrequent case)
100 µs and above (rare)
Average interarrival time: 10 ms

As for the spectral characteristics, Kolze [6] gives the following model for random impulse noise:

Each burst event is AM modulated, zero mean, Gaussian noise with a 1 MHz RF bandwidth, carrier frequency of 5-15 MHz (according to measurements) and amplitude ranging from zero to 60 dBmV.

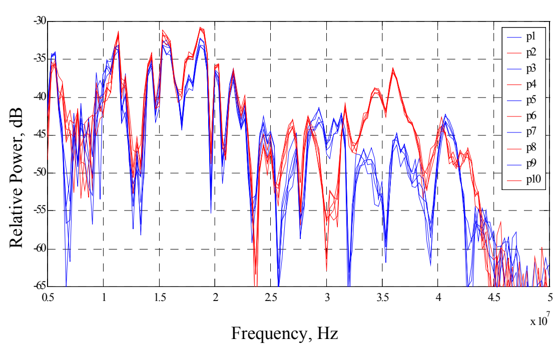
However, periodic impulse noise has been frequently found by the author in measurements on at least one node per headend, and to date no specific models for this phenomenon have been given. These impulses are often quite large in amplitude, and appear to occur with different pulse recurrence frequencies which are usually harmonics of the power line frequency of 60 Hz.

The figure below shows a captured trace of impulses with apparent period of 120 Hz.



Interleaved Periodic Impulses

From the time trace, it appears that the trace is actually two interleaved 60 Hz waveforms. To check, the FFT's of ten successive impulses were captured and plotted below:



FFT's of Successive Periodic Impulses

Clearly, the even impulses are from one element, and the odd impulses from another, perhaps different element. Spectra such as the above are representative of such events captured from multiple nodes and headends.
Hence, in addition to the current models for random impulse noise and periodic noise with period of 60 Hz, 120 Hz, and so on, we should add to the model interleaved periodic trains of 60 Hz recurrence frequency with varying offset intervals between them.

ADAPTATION TO RF IMPAIRMENTS USING DOCSIS ADVANCED TDMA

DOCSIS advanced TDMA provides the operator with several new methods of handling RF impairments. Ingress and CPD may be detected using FFT-based spectrum analysis techniques and then removed using ingress cancellation technologies. Random and periodic impulse noise can be mitigated via greater FEC and interleaving. Both ingress, CPD, and impulse noise can also be mitigated via adapting the modulation order, symbol rate, frequency, and power level. Periodic impulse noise can also be mitigated via detection in the time domain and either avoidance by scheduling around the impairment or mitigation via changing the burst parameters during the expected periodic events. By only changing the burst parameters during the expected impulse events, one can achieve much higher capacities in the upstream than if all upstream packets were forced to use the more robust signaling parameters. Some examples of adaptation are presented below to show how these new features may be used.

Adaptation to CPD

Since CPD has well known and predictable frequencies, it is possible using FFT's of the entire upstream to detect the presence of CPD and move the frequency of upstream signals. The optimum choice would be to move carriers such that the strongest CPD tones (at 6 MHz, 12 MHz, 18 MHz, etc.) lie beyond the edges of DOCSIS upstream carriers. The remaining CPD tones can then be removed by ingress cancellation technology. Note that if CPD is detected, the system should report this event to the operator so that the impairment can eventually be eliminated from the plant. Until then, the detected CPD frequencies can be maintained in a table, and used for more intelligent frequency hopping if ingress occurs.

Adaptation to Ingress

Ingress cancellation technology makes possible the elimination of ingress from the signal spectrum. Based on the above modeling, a good ingress canceller should be able to cancel 4-6 ingress zones, with occasional cancellation bandwidths of over 100 kHz possible. A key initial decision is whether to notch all ingress frequencies detected by spectrum analysis of the upstream band, or to move the carrier frequency such that strong and/or wideband ingressors are eliminated first from the signal spectrum entirely, leaving fewer and/or more narrowband ingressors to be canceled. The algorithms to make such decisions will depend on the capabilities of each advanced TDMA implementation, and will thus be proprietary in nature.

It is interesting to note that both advanced and conventional DOCSIS TDMA signals can achieve "negative SNR" performance against ingress using the detect and adapt strategy. For example, suppose an advanced TDMA system is using the full 6.4 MHz spectrum for 5.12 Msym/sec signaling and a strong ingressor turns on in band with a power level of +10 dB relative to the cable modem signal. By reducing the symbol rate to 2.56 Msps and moving the carrier frequency to avoid the ingressor, the cable modem system can be considered to operate at 50% capacity using only half of the original 6.4 MHz band where the overall SNR is "-10 dB". This is actually superior to the capacity vs. robustness tradeoff made in a CDMA system where the modem uses the full 6.4 MHz bandwidth, but reduces the number of active codes to provide "negative SNR" operation, albeit at reduced capacity. The difference is that in the TDMA system, the "negative SNR" is almost limitless since the interferer is avoided entirely, whereas the CDMA system spreads the interferer onto the desired signal.

Adaptation to Random Impulse Noise

With the proposed advanced TDMA waveform which incorporates stronger FEC (up to T=16) and RS byte interleaving, mitigation of strong impulse/burst noise is possible, as shown in the table below.

16 QAM @ 1.28 Mbaud, CIR=0 dB		
Interleaver Depth (I)	RS(N,K)=(74,54), T=10	
	Max Impulse/Burst Duration	Max Repetition Rate
I=1	15.6 µsec	8.6 kHz
I=2	31.3 µsec	4.3 kHz
I=4	62.5 µsec	2.3 kHz
64 QAM @ 5.12 Mbaud, CIR=0 dB		
Interleaver Depth (I)	RS(N,K)=(86,54), T=16	
	Max Impulse/Burst Duration	Max Repetition Rate
I=1	4.2 µsec	45 kHz
I=2	8.3 µsec	22 kHz
I=4	16.7 µsec	11 kHz

Adaptation to Periodic Impulses

The periodicity of powerline related impulse noise raises a new possibility for mitigation: scheduling around the impulses. For example, a typical powerline impulse/burst noise waveform might be strong enough to require a low order of modulation such as QPSK, full FEC and interleaving capability, have a repetition frequency of 60 Hz, and a pulse width as high as a few ms. This gives a duty factor (ratio of pulse width to pulse period) of about 1/8. Allowing for error in tracking, an effective duty factor of ¼ could be used, which means that 25% of upstream minislots would require QPSK with maximal robustness, while the remaining 75% slots could use a much higher order modulation such as 64 QAM. This is possible in advanced TDMA due to the ability to alter modulation order on a burst-by-burst basis. The result would be more than twice the upstream capacity than if QPSK were used on all upstream packets.

CONCLUSION:
APPLICATION TO HFC NETWORKS

The combination of advanced signal processing features, spectrum monitoring, and intelligent algorithms for adaptation in advanced TDMA technology has application to a wide variety of HFC architectures. In large node systems, the robustness provided by advanced TDMA will open up new spectrum that was previously un-useable due to RF impairments. Advanced TDMA permits operation in the presence of im-pulses, raised noise floor, multiple ingressors, and common path distortion.

On more moderately sized nodes, advanced TDMA will provide a threefold increase in ca-pacity per channel due to doubling the signal bandwidth per channel and 50% more bits/Hz per channel with 64 QAM. In both large and small node systems, the integration of spectrum moni-toring, impairment detection and classification, and on-the-fly adaptation of signaling parameters will guarantee that quality of service is main-tained for applications such as VoIP.

Finally, in proposed deep fiber architectures such as mini fiber node, the ability to support all of these features in the CMTS means the functional-ity can be migrated into the mini fiber node itself. In this application, low power consumption, small form factor, and low system complexity are all important to making the mini fiber node archi-tecture cost effective.

References

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