Very high bit rate access on HFC: Requirements and alternatives

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1. Introduction

The cable industry has been undergoing rapid changes these recent years with the introduction of digital TV and the massive deployment of interactive services in the CATV networks. The latter has required major efforts both in order to upgrade the plants for two ways and master the impairments problem, and to standardize the protocol layers for data and telephony services.

The standardization work has been successfully achieved under the leadership of CableLabs, with the successful launch of DOCSIS 1.0 products, the upcoming arrival of DOCSIS 1.1 systems, and the pending finalization of the DOCSIS 2.0 specification. The worldwide endorsement of these specifications has allowed the MSOs to achieve significant cost reduction in their deployment, and therefore to accelerate the penetration of multimedia services to the subscriber.

Recent trends such as the popular utilization of streaming audio and streaming video can drive the bandwidth requirements far higher than originally projected by email and web browsing usage. In addition the ability to generate high volume upstream traffic (Napster, video instant messenger, and the personal server applications) is becoming an important customer requirement

Furthermore the evolution to deep fiber architectures, and redundancy of network elements, have increased the network reliability to a level where telephony and more generally business applications can be introduced in the HFC network.

All these trends push the bit rate requirement to a higher end: as will be highlighted below, the penetration of high bit rate applications containing video, and of professional application can drive the subscriber bit rate requirement from the current 100 kbps range to the Mbps range.
Indeed this could drive the system capacity requirements to the 100 Mbps range upstream (therefore 12-18 MHz upstream bandwidth using currently achievable modulation efficiencies).

Therefore it is interesting to evaluate the capability and performances of different physical layer alternatives in order to provide such high bit rates and bandwidth.

The paper is subdivided into the following sections:

- A brief of Traffic Requirements;
- Plant capacity analysis;
- A Plant Impairment analysis;

- The different Physical layer alternatives, more particularly single carrier and multicarrier techniques;
- Performance analysis in noisy and clean plant;
- System analysis and conclusions.

2. Traffic requirements

Different applications profiles are expected to drive the traffic evolution:

- Asymmetrical residential applications containing video:
    - VOD type of applications requiring a high downstream bit rate (4-8 Mbps);
    - Video Napster types of applications requiring a high upstream bit rate.
- Symmetrical residential applications like Visio-conference;
- Symmetrical and asymmetrical professional applications.

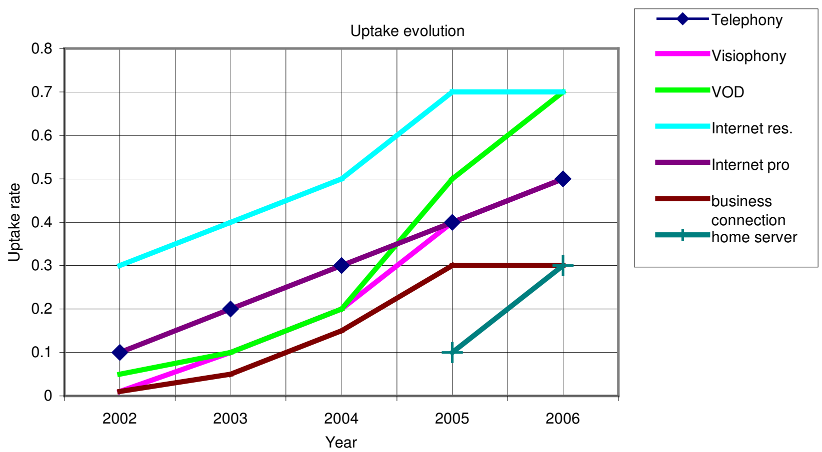

Figure 1: Possible future services penetration

As shown in the example below, aggressive penetration hypothesis can drive the average traffic requirement from the current 100 kbps range to several Mbps downstream and upstream per home passed, with a reduction of a traffic asymmetry.

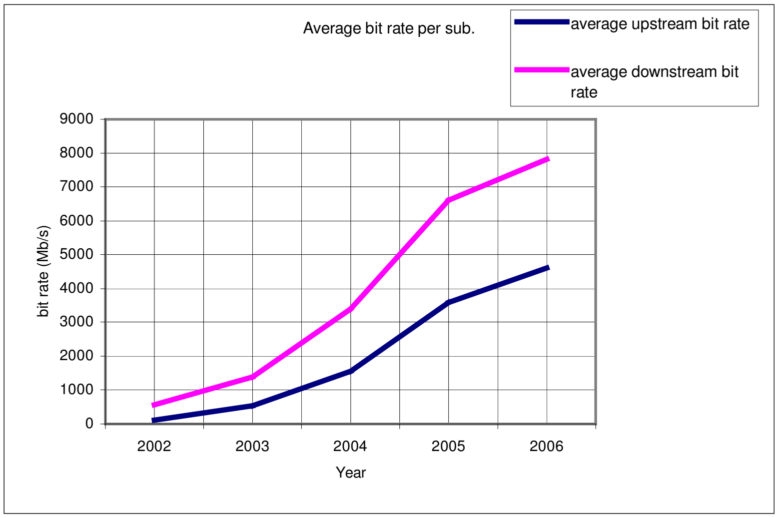

Figure 2: Probable evolution of the average bit rate per subscriber

We can define the system performance objectives as follows:

- Average bit rate upstream: 1-10 Mbps;
- Peak bit rate upstream: 100 Mbps;
- Average bit rate downstream: 2-20 Mbps;
- Peak bit rate downstream: 150-200 Mbps.

This paper focuses on the upstream requirement only. According to the maximum achievable efficiency (6 to 8 bits/Hz), the required upstream spectrum available to a user will be 16 MHz to achieve these performance objectives.

3. Plant capacity upgrade analysis

Both current plant downstream and upstream upgrade may support the bit rate defined above:

- In upstream, the available upstream spectrum may vary from 5-42 to 5-65 MHz. Both an evolution of the band size to 5-200 MHz (midsplit architecture) and a decrease of the cell size may be envisaged;
- In downstream, narrowcasting transmitters can be installed either by using WDM or through an additional fiber. The splitting ratio of this narrowcast band will determine the available bit rate per subscriber.

The diagram below presents the capacity per home passed versus cell size for downstream and upstream.

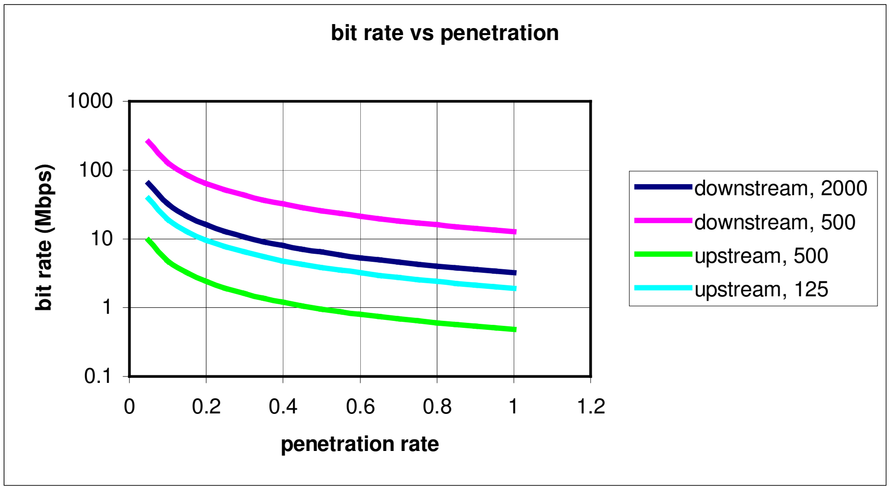

Figure 3: capacity per home passed vs. cell size (hypothesis: 8 b/Hz downstream – 4 b/Hz upstream efficiencies)

The conclusions are the following:

- Optimizing the current upstream band capacity 5-65 MHz will enable a high upstream bit rate per passing and delays further plant upgrades;
- There is no major limitation in downstream if narrowcast transmitters serving 500 to 2000 passing are added in the future;
- WDM becomes cost effective and will allow optimizing the fiber usage downstream and upstream.

Other complementary alternatives such as the use of >1GHz frequency spectrum may be possible, but are not treated in this paper because they require significant modifications of today's two-way HFC physical plant. This paper studies the alternatives for delivering high bandwidth-per-subscriber in current HFC physical plant.

4. Plant impairment analysis

The objective of this section is to make a synthesis on the type of channel model that a high bit rate system will have to encounter, and to draw some general system conclusions.

The 3 mains categories of disturbances that have to be considered are:

4.1 Impulse noise

Impulse noise is defined as including Impulse length of limited duration (<300 µsec for instance). The impulses are therefore broadband in nature and disturb the whole return band. The impulse amplitude can be high enough to saturate the return amplifier or the return laser transmitter and destroy all the information transmitted in the band during the impulse; but also medium amplitude Impulse can exist, acting more like a temporary gaussian noise added to the signal.

The impulsive noise is mainly generated by man-made devices and to a minor extent by Nature. Among the man-made noise sources, we can mention power switching, high power dimmers, electrical motors, engine ignitions, digital equipment, switching of domestic equipment. The rate of occurrence of such Impulse has been observed as being multiple of the AC line frequency, i.e. relatively low repetition rate.
A second type of Impulse noise can also be created by bad contacts in the cable network interrupting from time to time the cable amplifiers AC power supply, lightning, atmospherics, and galactic noise.
A third type of Impulse is produced by the upstream optical transmitter clipping as explained below.

Extensive analysis [1] of Impulse noise has been performed in other papers and supports the following characterization of impulse noise statistics:

- Impulse length of less then 10 µsec occur most frequently with a low repetition rate (< 1 kHz); the Impulse length limitation can be explained by the fact that most of the Impulses are filtered by the upstream band;
- Impulse length of 10µsec to 100 µsec occur less frequently;
- Impulse noise can be sometimes observed to occur at given time in the day;
- The spectrum of these Impulses is not flat across frequency but can have a repetitive nature [1] as shown below.

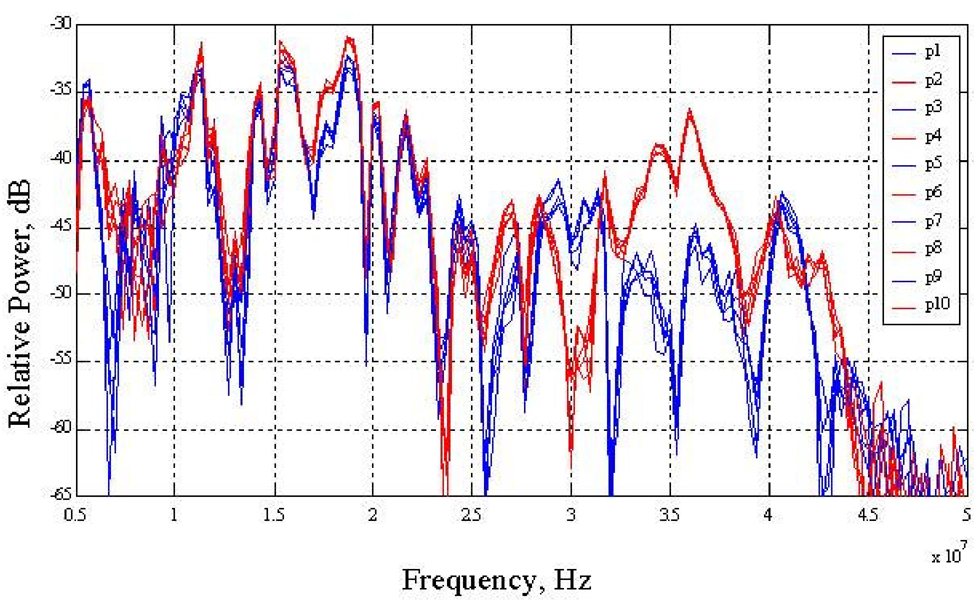

Figure 4: example of consecutive Impulse spectrum measurements[1]

4.2 Ingress noise

Ingress is defined as frequency selective impairment in contrast with Impulse noise, and can be categorized as follows:

- Narrowband Ingress injected in the cable network itself: the major causes are identified as being AM short-wave, amateur band, maritime radio transmission; the amplitude of the injected Ingress vary during the day according to the propagation condition; this slow amplitude variation can be as high as 20 dB
- Location specific interference: electronic equipment in the subscriber premise can inject a high level of Ingress in a poorly shielded coaxial installation.

The relative degree of importance of these 2 sources of Ingress will vary according to the cable network architecture; for instance:

- A cable network with aerial cabling will be more sensitive to Narrowband ingress, whereas man made noise will be of primary importance in an "underground" network;
- Some networks with a passive return path (working therefore at low operating levels) will be more sensitive to Narrowband Ingress.

4.3 Common Path Distortion

Common Path distortion (CPD) is produced by poor contacts in the cable network; these contacts create a rectifier effect, which produces mainly second order non-linear distortion product (and to a minor extent third order products) coming from downstream carriers. The main frequencies at which CPD will occur will are the multiple of channel frequency spacing (multiple of 6, 7 or 8 MHZ according to the frequency plan).

In general the CPD effects can be accurately calculated using a limited Volterra series (see [2]); in practice a good simplified model has been developed in [1], assuming that the non linear behavior did not depend on frequency (Taylor-expansion), and that the major part of the analog channels energy is located at the vision and sound carrier frequencies.

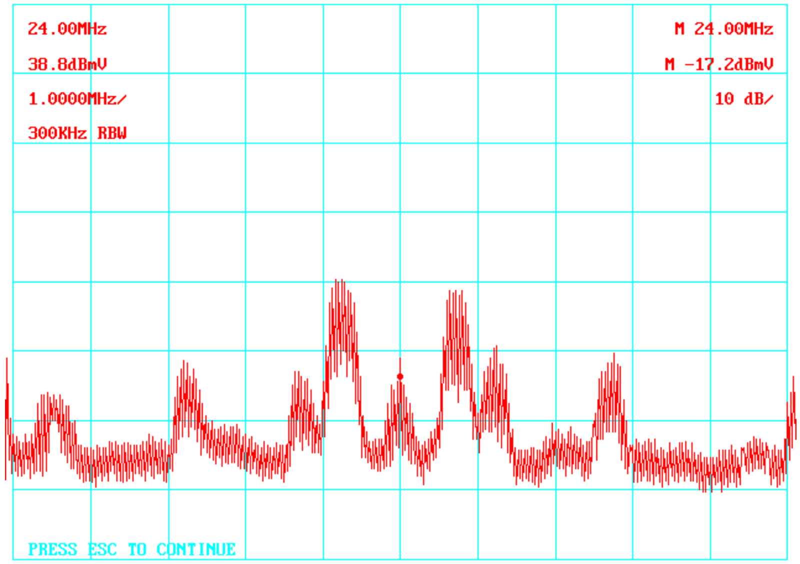

Figure 5: example of CPD spectrum measurement at 24 MHz (SCTE)

In summary the CPD frequencies are well determined as fixed by the downstream frequency plan, and the level of CPD can vary broadly during the day.

4.4 Clipping

Two non-linear devices will contribute to distortion and clipping in the upstream:

- Upstream amplifiers, which can be characterized by CTB, CSO and noise figure for 2^{nd} and 3^{rd} order non-linear distortion and noise respectively.
- Upstream laser transmitters can use uncooled Fabry-Perot or DFB, with and without optical isolators. A detailed description is out of scope but let us recall that:
  - Lasers diode show a hard clipping behavior under the threshold current;
  - The noise and non linear distortion behavior of the laser diode is complex and will depend on both on the amplitude and frequency of the incoming signals according to the following optical phenomena:
    - Discrete reflections to the laser diode can change both the noise and distortion characteristics;
    - Fabry-Perot external cavity created by 2 reflections will create non linear effect (due to the laser chirping);
    - Fiber combined double backscattering associated with homodyne detection at the receiver will induce an 1/f frequency dependant noise in the lower part of the spectrum;
    - Mode partition noise associated by Fiber dispersion and Polarization mode dispersion can also affect the optical transmission characteristic.

As a result a return path optical system is better characterized by its Noise Power ratio (the NPR) which will determine the range of total input power that is acceptable for a given C/(N+I).

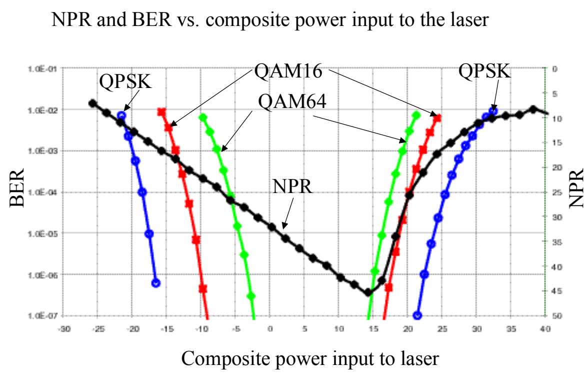

Figure 6: curve showing example of NPR, and BER for different constellations

The NPR approximates the acceptable operating level for a given spectral efficiency (via the C/(N+I) requirement).

The NPR estimation is accurate when the input signal to the laser is gaussian, i.e. for instance if the signal is composed of a sufficient number of similar QAM carriers;
Some slight corrections be made in the following cases:

- The additional power introduced by Ingress and Impulse noise may be significant and may require to add an additional margin;
- The total signal can differ slightly from a gaussian profile. This can be the case of an heterogeneous upstream spectrum containing different type of carriers, for example CDMA and TDMA carriers;
- The amount of Error correction applied on each carrier, linked with the service availability requirement, will also require some correction.

An enhanced NPR curve can take into account these situations, and will determine more exactly the required laser operating level.

The Ingress noise power can be significantly higher than the useful carrier power; in such case:

- The most frequent situation is where the Ingress situated between 5 and 10 MHz is the most disturbing; a low pass filter can be placed at the input of the impaired transmitters;
- If Ingress is mainly produced by the subscriber, Filters or Noise blockers can be used at the subscriber premises.

4.5 Noise Impairments Summary

A high bit rate system using a bandwidth of 12-18 MHz has to deal with the following parasitic:

1. Ingress and CPD:

- Narrowband Ingresses (bandwidth <20 kHz) with slowly variable amplitude during the day;
- Narrowband Ingresses (< 20 kHz) with slowly variable envelope during the day, and rapidly variable amplitude;
- Broadband Ingresses (100 KHz and above);

The number of Ingresses can be evaluated from 5 to 10 in the band.

2. Impulse noise:
   - Impulse of 1 to 100 □sec with low repetition rate (<1-10 kHz);
   - Impulse spectrum having non-flat spectrum in the band.

The described Impairments have a 2 dimensional (time, frequency) nature and can be represented as such; therefore in order to optimize the system capacity, the system should be able to adapt to this 2 dimensional Impairment amplitude variation with time and frequency.

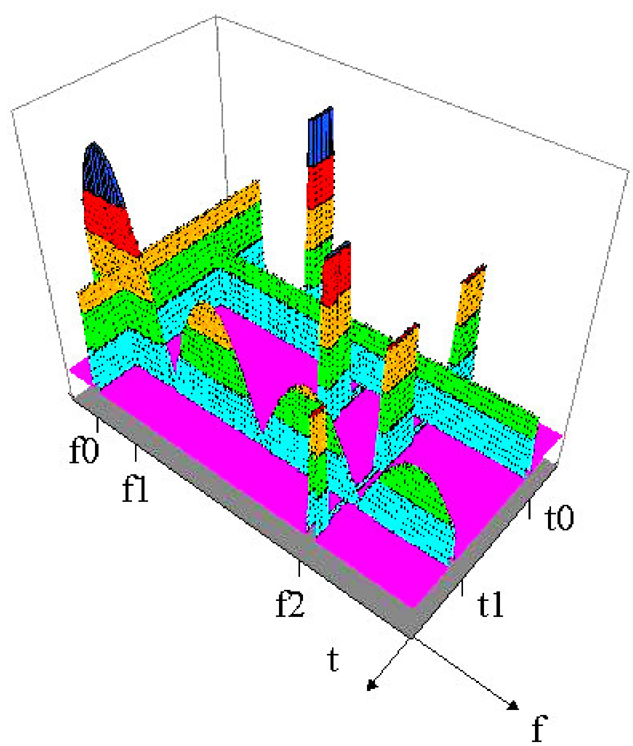

Figure 7: Simplified time frequency representation of Ingress and Impulse noise

The simplified diagram above highlights the main impairments:

- Narrowband CPD at f0 appearing as a continuous tone
- AM modulated tone at f_2
- Spurious tone at f_1
- Broadband pulse (short duration) at t_o, impairing the whole band
- Pulse with a sinx/x spectrum at t_1.

5. Modulation - Access techniques

The different possible techniques to mitigate the plant impairments have been extensively analyzed for low to medium bit rate transmission in Docsis 1.1 and Docsis 2.0 committees.
Docsis 2.0, which specifies symbol rates as high as 5.12 MS/s, has chosen a priori a mix of TDMA and SCMDA access on the same band. For higher bit rates access Multicarrier can also be reconsidered as an alternative access method.

5.1 Single carrier TDMA

As emphasized in various papers on the topic, TDMA is not specifically resistant to Ingress and CPD, but the use of specific equalizers dramatically improves the performances; however the technique has limitations both against the number of Ingresses and the bandwidth of the Ingresses. The overall equalization can become complex when still increasing the bandwidth and constellation size.
Therefore it is little interest to increase the bandwidth of the single carrier TDMA method.

In order to improve the efficiency in presence of highly variable Ingress, it is useful to plan to use several upstream carriers in order to avoid the most impaired bands; in addition some Ingress cannot be anticipated and will appear sporadically.
In consequence spare carriers have to be used, and both frequency and symbol rate agility are required. For instance 6 or 8 carriers can be used in the lower part of the spectrum to cope with high level Ingress and CPD as shown in the diagram below. The appearance / disappearance of an Ingress will lead to the bandwidth decrease of the affected carrier, and the addition of a spare upstream carrier in the spectrum as shown below.

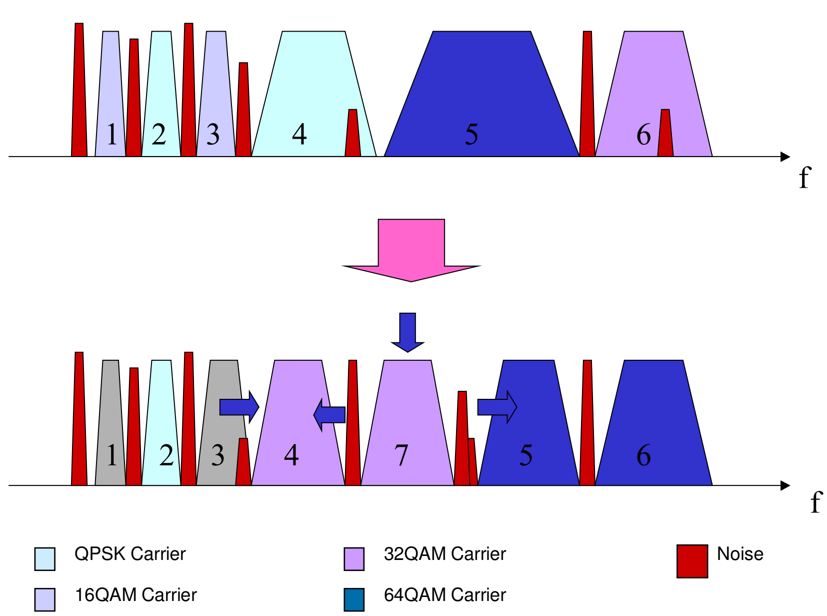

Figure 8: example of dynamic spectrum management (FDMA/TDMA)

Of course the system requires a relatively sophisticated level of plant management and has limited flexibility, as the number of spare carriers may be hard to predict.
The second issue, if very high bit rate upstream has to be obtained, may be the need of several upstream channels per Customer Premise Equipment (CPE).

The resistance of Single carrier TDMA to short Impulse is very good thanks to the use of a RS error correction scheme; the resistance to long Impulse is ensured by using interleaving at the price of the well known issue of an increased latency. The figure below shows the efficiency and latency for different Impulse cases:

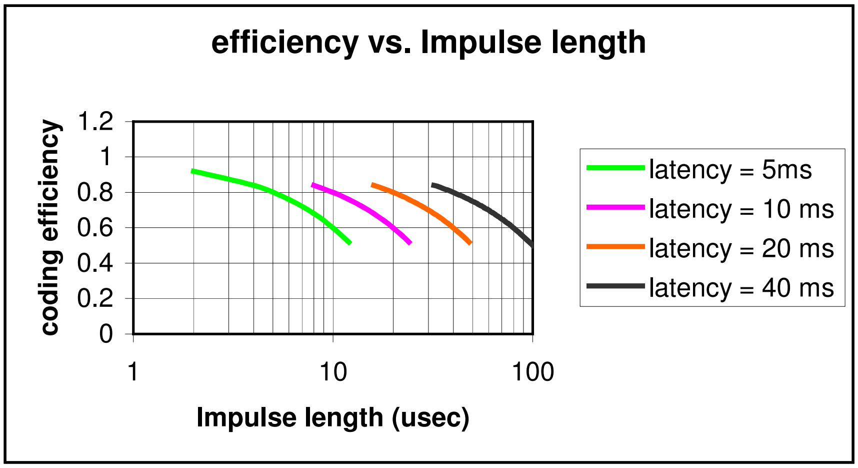

Figure 9: coding efficiency vs. Impulse length for different pulse repetition periods (64QAM, 5.12 MS/s)

The latency is calculated assuming that 100 users are active; the curves show that a good efficiency can be maintained even for long Impulse if additional latency can be accepted.

5.2 Mixed TDMA-SCDMA

To enter in a full discussion of the technique is not the purpose of the paper; some general remarks can be made:

The advantages and issues as for TDMA apply to the mixed TDMA-SCDMA technique; in addition when using SCDMA, the system provides an increased resistance against long bursts.

When higher bandwidth is searched, the same above limitations apply, and a decrease of carrier bandwidth to optimize the spectrum capacity can be applied as well to the system, leading to an FDMA/TDMA-SCDMA scheme like described above.

5.3 Multicarrier modulation

Multicarrier is now commonly utilized and standardized in low frequency wireless and wireline (DSL,..) applications thanks to its capacity to cope with variable echo/multipath phenomena, and variable narrowband Ingress in the VHF band. In cable the technique has also the following advantages:

- The frequency granularity will allow to fight and isolate Ingress;
- Short and Long Impulses can both be corrected, thanks to the long symbol time.

Moreover in order to optimize the system to each particular plant configuration, it is possible to work in several modes (different number of carriers, different carrier bandwidth). For instance:

- A mode with a high number of carriers can be chosen when narrowband ingress is the main phenomenon, in order to optimize the bandwidth usage
- In the case of short impulses with very high repetition rate being the main disturbance, the system can be configured with a low number of carriers and a symbol length matching the Impulse length.

Another important operational advantage of multicarrier is its ease of operation when working in a noisy plant:

- The system naturally detects and records the main Ingress disturbances, and either suppresses the perturbed carriers, or uses these carriers to carry low priority data;
- No complicated frequency planning has to be done for each cable area: the system has just to cover the whole band and will determine the available capacity and the unusable carriers;
- A marginal use of this frequency granularity may be to intermix a multicarrier spectrum with existing legacy carriers as shown below.

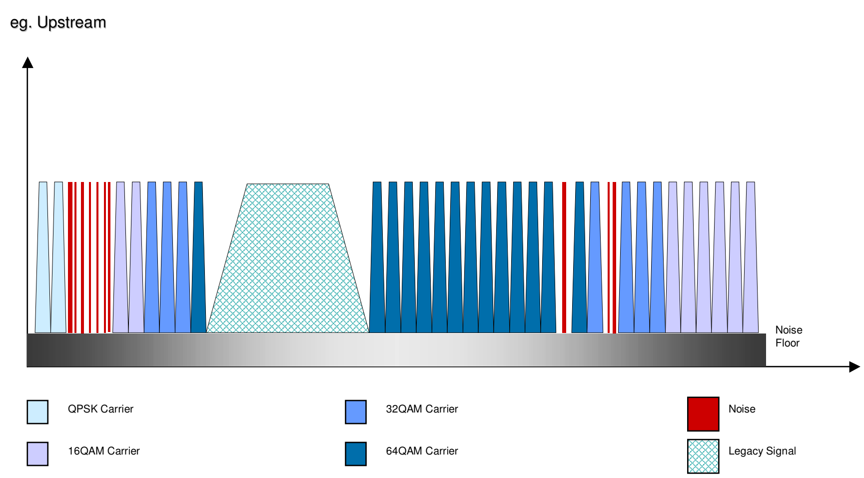

Figure 10: simplified representation of multicarrier spectrum in upstream

The potential known issues are the following:

- The technique is more sensitive to low power unpredicted Ingress, which can result in a slight efficiency decrease in a clean plant; however the difference can be reduced by using less carriers in that case;
- The latency is increased according to the lower symbol rate of each carrier; however this physical latency can be reduced to the order of 1-2 msec, which is acceptable (100 kHz carrier width, 100 bytes segments).

Several types of multicarrier technique can be used:

- OFDMA presents the advantage of low complexity but has the following issue:
    - As using an IFFT, the energy of each carrier is scattered in the band, increasing the sensitivity of neighbor carrier to a narrowband Ingress tone
- Therefore multicarrier schemes with a better discrimination between bands are required; various techniques can be imagined:
    - A known and standardized one is SFMDA (Synchronized FDMA) which a simple FDMA scheme implemented with an IFFT; the drawback of this method is a slight spectral efficiency decrease according to the excess bandwidth chosen;
    - Several variations with overlapped carriers have proven to be realizable, leading to the best efficiency but an increased complexity and tighter requirements on bands stability and carriers synchronization, which is necessary if high order modulations are to be used.

5.3.1 Multicarrier performances

The following presents the performances of multicarrier modulation for several representative tests cases for high bandwidth access:

- 4 narrowband Ingresses (bandwidth< 100 kHz);
- 10 Narrowband Ingress tones (bandwidth < 100 kHz);
- The broadband Ingresses cases can be easily extrapolated, as just the subcarriers situated in the Ingress band will be affected.

In order to present a general case, relative capacity curve are presented; a capacity of one will correspond a constellation of 64 or 256QAM, i.e. a bit rate of around 100 Mbps for an upstream bandwidth of 16 MHz.

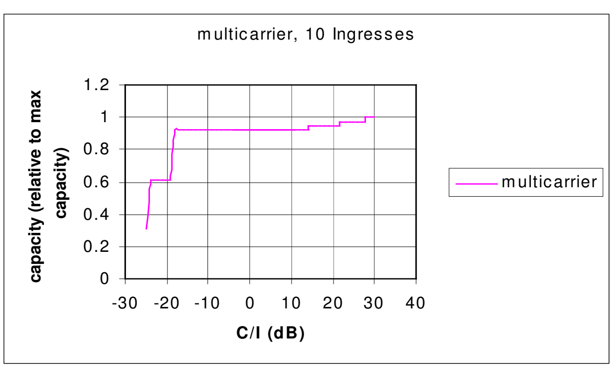

Figure 11: relative capacity vs. C/I, 4 narrowband Ingresses (128 carriers)

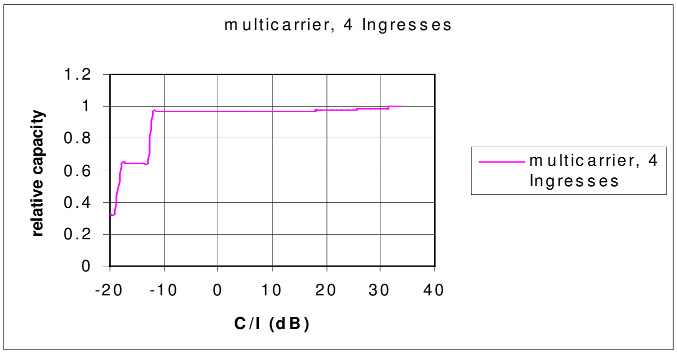

Figure 12: relative capacity vs. C/I, 10 narrowband Ingresses (128 carriers)

The behavior of multicarrier is simple: as stated before some carriers will be rejected at a relatively high C/I ratio, therefore the capacity in a clean plant is slightly lower then single carrier; when C/I decreases, the capacity remains constant until very negative C/I ratios whereas single carrier techniques will begin to degrade at C/I comprised between 10 and 0 dB.
Additional equalization technique can still be used to notch large amplitude Ingress and to slightly improve the performances of the system.

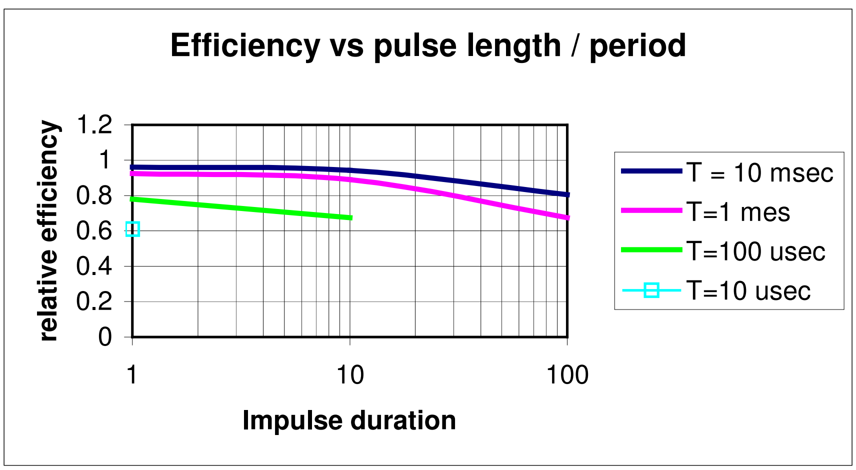

Figure 13: coding rate vs. Impulse duration for different Impulse repetition rates (T is the pulse repetition period) (conditions 64QAM, RS coding, C/I = -10 dB)

The diagram above shows the system relative capacity (a capacity of one corresponds to 100% efficiency for FEC) for different Impulse noise cases.

The following observations can be made about the results:

- The system latency is not affected by long Impulse as the symbol duration is long;
- One mode can correct almost all the Impulse noise cases with a simple Reed Solomon coding scheme; only the last case (1 sec, 10 % duty cycle has to use a mode with less carriers);

- The efficiency remains high in all the cases, whereas a combination of access techniques adapted to each different case would have to be used for example in the TDMA-SCDMA case.

5.4 Utilisation of Turbo product codes

The results for multicarrier have assumed the use of classical RS coding which is efficient in the case of a channel impaired by impulse noise. Turbo product codes are known for their outstanding performances in presence of gaussian noise, but show very good results as well in a channel affected by Impulse.

Performances of long Hamming TPC are can outperform those of similar (TCM+RS) in the case of gaussian noise; it is interesting to evaluate the performances of shorter codes in presence of both Noise and Impulse.

A shortened (64,57)*(32,26), R=0.704 code has been selected for the test.

The graphs presented in annex A, show the 2 following curves :

- BER vs Eb/No in a channel affected by gaussian noise;
- BER vs Impulse rate per packet in the case of regularly spaced Impulses.

Additional simulation will be performed in order to examine more finely how TPC can be used in HFC, but the first results are encouraging :

- TPC behave very well in a noisy channel
- TPC show at least equivalent performances then RS in the case of Impulse

Combination of RS and TPC may also be interesting to evaluate and can optimize the channel efficiency.

6. System strategies - choices

If very high bandwidth has to be provided, the results presented above lead us to several possible solutions:

6.1 "Single carrier techniques"

- Widen the bandwidth of current single carrier TDMA or SCDMA (or a mix) systems may be difficult:
  - The protection against ingress can become a critical issue;
  - To find a band free of legacy carriers would become challenging;
  - The system capacity would decrease.

6.2 FDMA/TDMA scheme

- Using "multicarrier TDMA" (several single TDMA carriers) is a good scheme; as stated before some optimization can be performed with that scheme:
  - Mitigation of plant impairment by avoiding the known impaired bands will lead to better spectral use;
  - Bandwidth and frequency agility in conjunction with the use of spare carriers for dynamic reallocations will allow to cope with unpredicted dynamic Ingress;
  - In the time domain, when Impulse noise can be predicted, optimization of the capacity can be done by increasing the modulation order between the Impulses.

  However the flexibility of the system may be limited in the frequency space and full optimization is difficult especially when using high bandwidth carriers.

6.3 Multicarrier technique

- Multicarrier modulation may be an attractive possible alternative:
  - The frequency granularity permits to easily cope with any Ingress situation;
  - Impulse noise can be easily mitigated with a simple configuration;
  - The system has the required 2 dimensional time frequency aspects which allows to optimize the upstream spectrum usage;
  - The system can even coexist with In band legacy carriers.

  Also a main advantage of the technique is the simplicity of management, as the system will automatically configure for the best upstream efficiency.

  The issues to solve are the following:

  - System performances in a clean plant are slightly lower;
  - Currently this physical layer is not standardized for cable and would need to gain acceptance among manufacturers and MSOs.

7. Conclusions

The paper has shown that providing very high bit rate to the subscriber with current cable architecture is achievable with minor plant upgrade:

- Current HFC architectures are scalable to predicted very high bit rate demand without major upgrades; WDM introduction allows to optimize downstream and upstream fiber number;
- Current access techniques are offering powerful techniques for Ingress cancellation and allow to optimize the existing upstream spectrum capacity, and to use the lower part of the band;
- Using FDMA/TDMA is possible; sophisticated network planning, traffic and carrier management have to be performed in order to optimize the cable plant capacity;
- Multicarrier appears to be a simple and powerful alternative when very high bit rate applications are targeted:
    - The plant management is very simple as multicarrier has the required 2 dimension time- frequency aspect;
    - The performances versus Ingress and Impulse are very good, and the advantage is that a single system configuration can mitigate all the plant disturbances;
- As bringing additional features in the case of high bit rate access, it may be interesting to add a multicarrier scheme as an option in the future releases of Docsis.

References

[1]: “Daniel Howard, Detection and classification of RF impairments
For higher capacity upstream using advanced TDMA; NCTA, 2001”.
[2]: “J. C. Point: 1 GHz Multichannel Analog Transmission through Optical Fiber, Montreux 1991”.

Acknowledgements

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I would like to thank Jacky Tousch from Turbo Concept for his simulations on Turbo Codes.

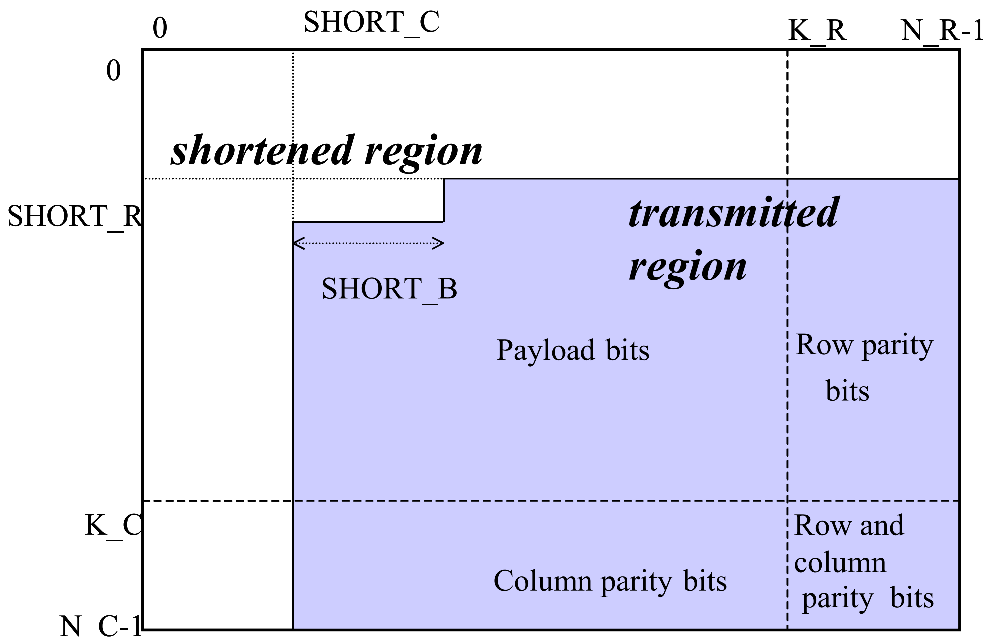
Glossary

HFC: Hybrid Fiber Coaxial
CSO: Composite Second Order
CTB: Composite Triple Beat
RS: Reed Solomon
WDM: Wavelength Division Multiplexing
OFDMA: Orthogonal Frequency Division Multiple Access
SCDMA: Synchronized Code Division Multiple Access
TPC : Turbo Product Code

Annex A : TPC performances

The structure of a 2-dimensional TPC is shown below. The code is defined by :
(1) its two constituent codes :

- a row code with parameters (N_R, K_R)
- a column code with parameters (N_C, K_C)



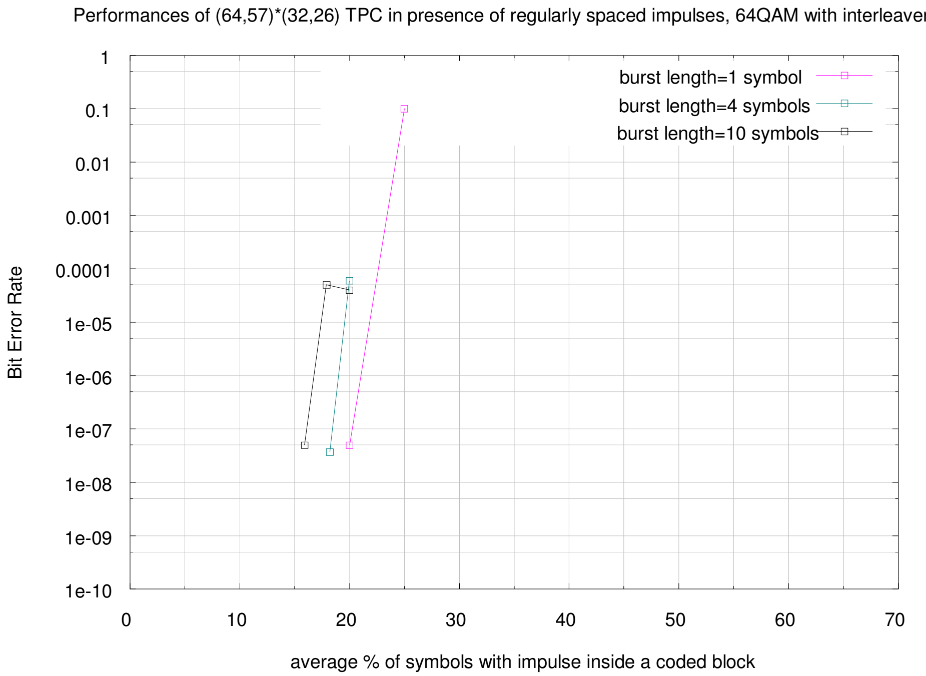
(2) Shortening parameters :

- SHORT_R gives the number of shortened rows
- SHORT_C gives the number of shortened columns
- SHORT_B gives the number of additional shortened

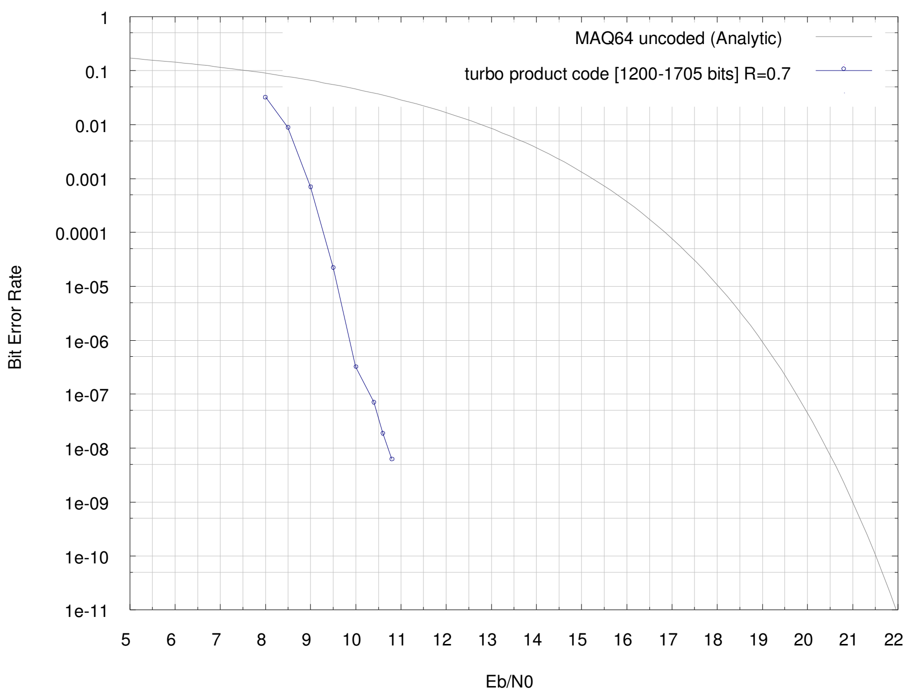
The following code is selected for simulations :

- (64,57) row code
- (32,26) column code
- Shortening parameters (1, 9, 0) following the order defined above.

This leads to a coded size of 1705 bits and R=0.704.



Performances of (64,57)*(32,26) TPC in presence of regularly spaced impulses, 64QAM with interleaver
burst length=1 symbol
burst length=4 symbols
burst length=10 symbols
Bit Error Rate
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
0
10
20
30
40
50
60
70
average % of symbols with impulse inside a coded block



MAQ64 uncoded (Analytic)
turbo product code [1200-1705 bits] R=0.7
Bit Error Rate
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
Eb/N0