Deliverable D21

Performance evaluation of next generation HFC physical layer systems

30 June 2010
ReDeSign – 217014
Research for Development of Future Interactive Generations of Hybrid Fiber Coax Networks

Information for Publication:
Version: 1.0
Status: Public (PU)
# Table of contents

1. Abbreviations and symbols ................................................................. 3  
2. Scope and Objectives ........................................................................ 4  
3. Introduction ...................................................................................... 5  
4. HFC System Performance Simulations ............................................ 6  
   4.1 Cable Network Interference .......................................................... 6  
      4.1.1 Narrow Band Interference .................................................. 6  
      4.1.2 Burst Noise ..................................................................... 7  
      4.1.3 Impulsive Noise ............................................................... 8  
   4.2 Impact of the Interference on DVB-C2 ........................................ 9  
      4.2.1 Narrow Band Interference .................................................. 9  
      4.2.2 Burst Noise ..................................................................... 10  
      4.2.3 Impulsive Noise ............................................................... 12  
5. Analysis of Impact on HFC Systems ............................................. 14  
   5.1 HFC RF spectrum considerations .............................................. 14  
   5.2 Optimized Frequency Utilization .............................................. 16  
   5.3 Spectral implications of the Absolute OFDM mechanism .......... 16  
   5.4 HFC capacity estimations ......................................................... 17  
   5.5 DOCSIS integration issues ......................................................... 19  
6. Summary and Outlook .................................................................... 20  
7. Bibliography .................................................................................. 21
1 Abbreviations and symbols

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>μs</td>
<td>Microseconds</td>
</tr>
<tr>
<td>B</td>
<td>Bandwidth</td>
</tr>
<tr>
<td>BER</td>
<td>Bit-Error Rate</td>
</tr>
<tr>
<td>C/I</td>
<td>Carrier-to-Interference Ratio</td>
</tr>
<tr>
<td>C/N</td>
<td>Carrier-to-Noise Ratio</td>
</tr>
<tr>
<td>CSO</td>
<td>Composite Second Order</td>
</tr>
<tr>
<td>CTB</td>
<td>Composite Triple Beat</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>CPE</td>
<td>Customer Premises Equipment</td>
</tr>
<tr>
<td>DOCSIS</td>
<td>Data Over Cable Service Interface Specification</td>
</tr>
<tr>
<td>DTG</td>
<td>Digital Terrestrial Group</td>
</tr>
<tr>
<td>DVB</td>
<td>Digital Video Broadcasting</td>
</tr>
<tr>
<td>DVB-C(2)</td>
<td>DVB for Cable (second Generation)</td>
</tr>
<tr>
<td>DVB-T</td>
<td>DVB for Terrestrial Reception</td>
</tr>
<tr>
<td>FEC</td>
<td>Forward Error Correction</td>
</tr>
<tr>
<td>FDM</td>
<td>Frequency Division Multiplex</td>
</tr>
<tr>
<td>FM</td>
<td>Frequency Modulation</td>
</tr>
<tr>
<td>FTTLA</td>
<td>Fiber to the Last Amplifier</td>
</tr>
<tr>
<td>Gbps</td>
<td>Gigabit per Second</td>
</tr>
<tr>
<td>HD</td>
<td>High Definition (Television)</td>
</tr>
<tr>
<td>HFC</td>
<td>Hybrid Fiber Coax</td>
</tr>
<tr>
<td>HIS</td>
<td>High Speed Internet</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>K</td>
<td>Index of Absolute OFDM Sub-Carrier</td>
</tr>
<tr>
<td>kHz</td>
<td>Kilohertz</td>
</tr>
<tr>
<td>L1</td>
<td>High Level Signaling Information in DVB-C2</td>
</tr>
<tr>
<td>LDPC</td>
<td>Low Density Parity Check</td>
</tr>
<tr>
<td>log</td>
<td>Logarithm</td>
</tr>
<tr>
<td>MHz</td>
<td>Megahertz</td>
</tr>
<tr>
<td>ms</td>
<td>Milliseconds</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplex</td>
</tr>
<tr>
<td>PAL</td>
<td>Phase Alternate Line</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadratur Amplitude Modulation</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>SDTV</td>
<td>Standard Definition Television</td>
</tr>
<tr>
<td>SECAM</td>
<td>Séquentiel couleur à mémoire</td>
</tr>
<tr>
<td>TV</td>
<td>Television</td>
</tr>
<tr>
<td>VOD</td>
<td>Video on Demand</td>
</tr>
</tbody>
</table>
2 Scope and Objectives

The development of DVB-C2 was successfully completed more than a year ago. The preparation of a document covering DVB-C2 Implementation Guidelines was continued until its completion by the DVB TM-C2 experts group. ReDeSign WP5 was involved in this activity and provided significant contributions, several of which were received via computer simulations carried out in the course of the project work. These simulations covered transmission investigations and confirmed the superior performance of the technology in terms of spectral efficiency and flexible applicability. First simulation results of ReDeSign WP5 were described in ReDeSign Deliverable D15 (Performance simulation of advanced modulation and channel coding). Deliverable D16 (Topology transmission report) produced by WP6 confirmed that DVB-C2 would be a good candidate for future use of the technology in next generation cable architectures such as deep fiber architectures i.e. FTTLA (Fiber to the Last Amplifier). As commercialization of DVB-C2 seems to happen in the coming months and years, it was concluded that it may not make sense to investigate in further physical layer technologies next to DVB-C2 as originally considered when the project was set up. The original objectives of the actual Deliverable D21 read:

“This report will include a comparison of advanced physical layer signal processing algorithms investigated by means of software simulations. The simulations will be carried out in coordination with the research work of WP6 and will take account of related results such as those described in D16. The transmission performances of these techniques will be analyzed and the results of the performance analysis will be explained.”

Because of this market development, ReDeSign slightly modified the deliverable focusing more on DVB-C2 as the physical layer technology of the future and engaged deeper in related simulation investigations as well as in an analysis on HFC system level. These two aspects are covered by chapters 4 and 5, respectively. Chapter 4 elaborates simulation results of DVB-C2 being an advanced physical layer signal processing algorithm whereas chapter 5 provides an analysis of possible impacts on HFC systems caused by an introduction of DVB-C2 in these HFC systems. Aspects of integration of DVB-C2 in DOCSIS, for instance, are taken into account.
3 Introduction

The preparation of the DVB-C2 Implementation Guidelines resulted in the DVB Bluebook A147 [10] and is currently (June 2010) in the ETSI ratification process which will result in the ETSI TS 102 991 [11]. These DVB-C2 Implementation Guidelines are supplemented by a publication with the title "DVB-C2: High Performance Data Transmission on Cable – Technology, Implementation, Networks – which is issued in terms of a monograph as part 13 of "Mitteilungen (Communications) des Instituts für Nachrichtentechnik der Technnischen Universität Braunschweig [12]. The publication is emerged from the Implementers’ Seminar which ReDeSign jointly organized with ANGA Verband Deutscher Kabelnetzbetreiber and the DVB Project in September 2009. Various simulation results described in chapter 4 and results of the HFC analysis introduced in chapter 5 have been used for the preparation of these and other publications such as in [13] and [14].

The simulation results carried out in the course of ReDeSign WP5 activities are described in chapter 4 of this deliverable. Focus was put on Interferences, Impulse Noise and Burst Noise. All disturbances were simulated with the presence of additional additive Gaussian noise. The different parameters were tuned to get a feeling about the performance characteristics of DVB-C2. In some investigations the carrier-to-noise level was changed while keeping the carrier-to-interference level constant and vice versa. The results of the investigations confirmed the very good transmission performance of DVB-C2, which was also indicated in earlier simulations.

The analysis of the impact which the introduction of DVB-C2 in HFC networks could have is laid down in chapter 5 of this deliverable. It is shown that the RF characteristics of DVB-C2 provide significant increase of the digital bandwidth of a network. The flexible frequency utilization capabilities of DVB-C2 allow the complete new kind of frequency occupation which makes the traditional channel grid obsolete. A new channel planning based on the OFDM sub-carrier index is suggested. This idea was communicated to CENELEC [9] as input to the European standardization work for HFC networks. Depending on the business requirements of cable operators, introduction of the new technology may start with Video on demand and HD services and smoothly involve further cable services. The use of DVB-C2 for television services provides a significant increase of digital bandwidth for IP services transmitted by a traditional DOCSIS system. Finally the integration of DVB-C2 in all cable technologies leads to a very flexible and high performing cable network infrastructure which can fulfill technical requirements of cable operators for several years to come.
4 HFC System Performance Simulations

This chapter introduces the simulation results of WP5. Sub-chapter 4.1 describes the interference types implemented and sub-chapter 4.2 explains the actual simulation results.

4.1 Cable Network Interference

HFC networks use fiber technologies in the backbone as well as increasingly in the access areas. With deep fiber architectures, optical nodes are moved closer to the customer. Nevertheless, coaxial cables are used in the so called last mile to finally connect the customer premises to the network. The combination of fiber systems and coaxial cables provide rather good transmission conditions and channel characteristics which are far better than those of e.g. terrestrial channels. Therefore it could be considered that disturbances occurring during transmission would not cause any problems to the very robust LDPC error protection mechanisms of DVB-C2. However, as DVB-C2 employs very high spectral efficiencies by applying high QAM constellation of up to 4096 stages, even small interference has to be taken into account when evaluating the overall transmission performance of DVB-C2. Various cable specific impairments, which were described in ReDeSign Deliverable D8 [1], were already investigated by simulations in ReDeSign Deliverable D15 [2]. These results are complemented by the results presented in this document. In particular, the impact of three kinds of impairments is explained consecutively: Narrow-band interference, Burst Noise and Impulsive Noise.

4.1.1 Narrow Band Interference

Narrowband Interference can be caused by several means. For instance the electromagnetic power of narrow-band terrestrial signals transmitted at a typical cable channel frequency can be injected into cable networks and is referred to as ingress. Another example is given by the Composite Triple Beats (CTB) and Composite Second Order (CSO) intermodulation products generated by the picture carrier of analogue TV signals which can be caused by the non-linear transmission behavior of the broadband cable amplifiers installed in HFC networks as analyzed in detail in ReDeSign Deliverable D14 [3]. CTBs have a bandwidth of some 30 kHz depending on the frequency stability of the carriers themselves, which is far less than the typical bandwidth of 7.61 MHz of a DVB-C2 signal.

Figure 1 shows the simulated power spectral density of a DVB-C2 signal with a narrow-band interferer of 100 kHz bandwidth. Within this bandwidth, the carrier-to-interference ratio is equal to $C*/I = -10$ dB whereas the carrier-frequent signals power $C*$ refers to the 100 kHz band of the signals affected by the interferer. The negative value indicates that the interference is 10 dB stronger than the DVB-C2 signal within the interference bandwidth, which is clearly visible within the figure.

Sources of such interference may be caused by ingress of terrestrial signals. Due to strong ingress naturally all OFDM sub-carriers within the interferer bandwidth are completely destroyed. However, the remaining sub-carriers are hardly affected. Hence, only a small percentage of the data is lost, which can be recovered by the FEC in case its correction power is not eaten up due to the noise occurring in the channel. A further increase of the power of the interfering signal would not worsen the situation since only a limited number of OFDM sub-carriers are affected. This is a typical effect of the OFDM scheme.
4.1.2 Burst Noise

Burst noise is an additional kind of interference occurring in cable networks. It is characterized by individual pulse events. Under certain conditions, these pulse events can have strong power levels with durations being in the order of magnitude of an OFDM symbol length or beyond. Furthermore, the frequency spectrum of burst noise is generally not white, but has a limited bandwidth. A typical source of burst noise can be e.g. mobile phones. Interference to cable services caused by mobile communications services are currently in discussion of the so-called Digital Dividend, thus may get more important in the future.

![Figure 1: Spectrum of a DVB-C2 signal with narrow-band interferer of 100 kHz bandwidth, $C/I_{B=100kHz}=-10dB$ within the interferer bandwidth and a payload noise signal of a $C/N=25dB$.](image1)

![Figure 2: Power ramp of GSM burst that shows the allowed transmission level in the uplink of the GSM standard](image2)
Figure 2 lines out a typical time response of a burst caused by a mobile phone in the uplink of the cellular system GSM [3]. Such a burst was used for the simulation of burst-noise impact to a DVB-C2 transmission. Naturally, also other systems, e.g. the currently upcoming LTE [5], could be used for such an analysis. Unfortunately the simulations based on a UMTS interference have not been completed at the end of the project but will be continued after the project’s closure. The length of each GSM burst is approx. 550 µs, which is in the order of an OFDM symbol in DVB-C2, the length of which is 448 µs. Thus, one burst typically affects two OFDM symbols. However, the bandwidth of these signals is limited to approx. 200 kHz, which means that only a part of the spectrum is disturbed by the impulses.

Due to the fact that the bandwidth of the bursts is limited, only a subset of the data within the OFDM symbols is disturbed. Typically, the bandwidth of the Data Slices in DVB-C2 will be 7.61 MHz. Consequently, less than 3% of the overall OFDM subcarriers of the Data Slice will be directly affected by the 200 kHz wide bursts. However, due to the fact that the receiver uses windowing in the time domain for the separation of the different OFDM symbols, the noise will also affect carriers outside the original burst bandwidth of 200 kHz.

4.1.3 Impulsive Noise

The new cable transmission standard DVB-C2 is no longer based on single-carrier, but on the multi-carrier modulation OFDM. It is well-known from literature that OFDM is sensitive to impulsive noise. This noise can, for instance, be generated by switching events occurring in the mains as reported in [1]. It is characterized by very short impulses in the regions of nanoseconds. However, the impulses can have power levels significantly higher than the desired signal power, which may cause negative C/I values. In case of single-carrier modulation, as used in DVB-C for instance, only a few bits are affected. However, in case of OFDM the noise energy is collected over the complete OFDM symbol duration, and almost equally spread over all data transmitted within the affected OFDM symbol. Due to this collecting structure, the effect is called noise-bucket effect [6].

![Impulse noise model](image)

Figure 3: Temporal behavior of the DTG-6 impulse noise model

The disturbance of impulsive noise was studied for instance in the United Kingdom during the introduction of DVB-T. Several impulse noise models have been created. One of the most demanding ones is the impulse noise model 6 of the DTG (Digital Terrestrial Group). Its temporal response is depicted in Figure 3.

The modeled disturbance consists of bursts which have a distance of 10 ms. The distance is caused by the frequency of the mains of 50 Hz, which causes zero crossing of the electrical
current every 10 ms. Furthermore, each burst consists of a specific number of impulses, each pulse having a fixed length of 250 ns. The number of pulses per burst is given by the model parameters. The most demanding model is the model 6 where each burst consists of 40 short impulses. The maximum length is approximately 40 µs, while the effective length (i.e. the accumulated duration of all 40 impulses) is 10 µs. Consequently, the length of the complete burst is significantly shorter than the useful OFDM symbol length of 448 µs for DVB-C2. The fact that the signal consists of multiple short bursts with non-equidistant spacing causes a white spectrum in the frequency domain, which then affects all OFDM subcarriers equally.

4.2 Impact of the Interference on DVB-C2

The impact of the previously described interference has been simulated within a DVB-C2 simulation chain. Therefore, an ideal QAM de-mapper in addition to an LDPC decoder using the sum-product algorithm [7] with 100 iterations has been employed. Furthermore, the receiver had perfect channel knowledge about the linear channel distortions.

As the LDPC decoder requires the probability of each bit to reach its full performance, the QAM de-mapper has to include the noise variance when de-mapping each QAM symbol. Figure 4 depicts the approach that was used during the simulations.

Besides the data path, an additional interference/noise path was implemented (see Figure 4), which allows for the estimation of the noise variance of each individual OFDM subcarrier. However, within the noise variance estimation block the noise has been estimated in 7 sub-bands of approx. 1 MHz bandwidth each. Obviously, the presented approach cannot be used in reality, as a separate noise path does not exist in real systems. However, due to the estimation within sub-bands it should give similar results to realistic algorithms for estimating the noise variance, e.g. the usage of the frequency domain pilots. The following subsections will give simulation results for the interference models described in the previous section. These results are presented in terms of bit-error rates (BER) received after FEC when imposing different carrier-to-noise ratios (C/N) in addition to the impairment investigated.

4.2.1 Narrow Band Interference

Several simulations were performed to estimate the impact of narrow-band interference on DVB-C2 signals. A snapshot of these simulations is depicted in Figure 5, which shows the results for 256-QAM with varying code rates of the FEC. The dotted lines show the BER after the FEC without the presence of interference. In this case, the signal was disturbed by additive Gaussian noise only. The solid lines show the BER including the additional narrow-band interferers of 100 kHz bandwidth within the 7.61 MHz wide DVB-C2 signal. As already shown in Figure 1, the interference level was 10 dB stronger than the level of the payload signal within the interference bandwidth. The total carrier-to-interference ratio measured within the complete signal bandwidth of 7.61 MHz is equal to

![Figure 4: Block diagram of the used simulation chain and its noise variance estimation](image-url)
The additional degradation caused by the interference was equal to 0.2 dB measured for a BER limit of $10^{-4}$ and using a code rate of 3/4. This gap increases to approximately 1 dB in case code rate 9/10 is applied. If the signal-to-noise ratio is sufficiently high, the signal can still be decoded without any errors. Furthermore, the degradation to the reference curve which shows the behavior with the absence of interference is very limited.

4.2.2 Burst Noise

The burst noise simulations assume a similar temporal behavior as the burst of the uplink signal transmitted by a GSM cell-phone, which was described in sub-chapter 4.1. The carrier-to-interference level occurring in the watched frequency spectrum was again chosen to be equal to $C^*/I = -10$ dB, which is significantly stronger than the expected interference level in real networks. The ration $C^*/I$ describes the power ration between the portion of the DVB-C2 signals which is affected by the interfering burst thus considering a bandwidth of some 200 kHz and a time period of some 550 µs. The overall $C/I$ values can be approximated from the $C^*/I$ figures by taking account of the different bandwidth and time period figures of the two signals as shown in the following formula:

$$\frac{C}{I} \approx \frac{C^*/I \times \text{BW}_{\text{DVB-C2}}}{\text{BW}_{\text{interfering burst}}} \times \frac{\text{time}_{\text{DVB-C2}}}{\text{time}_{\text{interfering burst}}}$$

with $n = \text{number of OFDM symbols considered (e.g. 4, 8, 16)}$

This results in the total signal-to-interference figures of:
Performance evaluation of next generation HFC physical layer systems

Figure 6 a) to d) depicts 4 diagrams with the simulation results for different DVB-C2 parameter sets, including 1024-QAM.

a)

b)

c)

d)

Figure 6: Simulation results for GSM like burst noise with different interleaver depths, C*/I = -10 dB, DVB-C2 signal bandwidth = 7.61 MHz, parameters: a) 256-QAM with code rate 3/4, b) 256-QAM with code rate 5/6, c) 256-QAM with code rate 9/10, and d) 1024-QAM with code rate 3/4

Obviously, the application of time interleaving increases the robustness in all parameter sets. Using the longest time-interleaver depth of 16 OFDM symbols, less than 1 dB increased SNR is required for error-free reception of the data. Furthermore, it turns out that the time-interleaver depth of 8 OFDM symbols gives almost the same performance as the longest possible time-interleaver depth. These 8 OFDM symbols correspond to approx. 3.5 ms, which is close to the repetition rate of the cell-phone bursts. Hence, for the 8 and the 16 OFDM symbols time-interleaving depth almost the same number of data is disturbed. The
usage of shorter time-interleaving leads to strong degradation, especially for the higher code-rates, as the low number of parity bits cannot correct the destroyed data.

4.2.3 Impulsive Noise

The performance of DVB-C2 in case of impulsive noise has been simulated using the previously described DTG-6 impulse noise model. In order to show the robustness of the new system against these disturbances, very strong noise impulses have been assumed. Figure 7 shows the results of simulations using different combinations of QAM constellations and code rates. The maximum time interleaving depth of 16 OFDM symbols was applied. The carrier-to-interference ratio during the active impulse events was again set to $C^*/I = -10$ dB. This means that the interference was 10 dB stronger than the payload signal during the individual impulses. Such strong impulses had the effect that practically almost all payload data were destroyed within the affected OFDM symbols. However, especially for the lower code rates only a small degradation of approx. 1 dB can be observed compared to the reference case without the presence of any impulsive noise. In contrast, the degradation increases for the higher code rates. The reason for this effect is simply that the codeword does not have sufficient parity bits available for compensating the disturbed bits. A first analysis may lead to the recommendation for cable operators to use the higher constellation schemes in combination with lower code rates as shown in Figure 7. The mode using 1024-QAM and code rate 3/4 offers higher payload bit rate than the mode using 256-QAM and code rate 9/10. However, in case of the impulsive noise channel the higher constellation shows better results due to the lower code rate.

In further studies very strong impulsive noise was not found in networks as reported in ReDeSign Deliverable D08 [1]. Therefore, Figure 8 shows simulation results for different C/I levels for the parameter set 256-QAM code rate 9/10, which has shown the worst performance in Figure 7. Again the maximum time-interleaving depth was used. Only the very strong impulsive noise leads to an increased SNR of several dBs for error-free reception. The penalty for $C^*/I = 0$ dB (impulses have similar strength as the payload signal within the observed frequency band) is, however, less than 1 dB.

Figure 7: Simulation results for the DTG-6 impulse noise model with $C^*/I = -10$ dB for different DVB-C2 parameter sets: (boxes) 256-QAM, code rate 3/4; (circles) 256-QAM, code rate 5/6; (crosses) 256-QAM, code rate 9/10; (stars) 1024-QAM, code rate 3/4; time interleaver depth of 16 OFDM symbols, signal bandwidth 7.61 MHz, the solid lines indicate the performance without impulsive noise.
Some applications require low-latency, e.g. Internet gaming. Hence, a long time interleaver cannot be used, as its buffering leads to increased latency. Therefore, also the influence of the time-interleaving depth for the mode using 256-QAM and code rate 9/10 has been simulated. Figure 9 depicts the results for $C^*/I = 10$ dB.

Without time-interleaving, the required SNR for error-free reception increases by approx. 1 dB. Furthermore, the application of short time-interleaving (i.e. 4 OFDM symbols) increases the robustness significantly. Longer time interleaving depths can additionally increase the robustness, while this increase is quite limited. Hence, already short time interleaving of 4 OFDM symbols may be sufficient in most cases. However, the usage of no time interleaving for very low-latency application is possible, showing an acceptable degradation.

![Figure 9: Simulation results for the DTG-6 impulse noise model with varying time-interleaving depths, DVB-C2 parameters: 256-QAM, FEC code rate 9/10, signal bandwidth 7.61 MHz](image)

![Figure 8: Simulation results for the DTG-6 impulse noise model with varying interference levels, DVB-C2 parameter 256-QAM, code rate 9/10, interleaving depth of 16 OFDM symbols, signal bandwidth 7.61 MHz](image)
5 Analysis of Impact on HFC Systems

The following results of investigations analyze the possibilities for the utilization of DVB-C2 in HFC networks and the potentials provided by the new technology. In the first section, state of the art RF characteristics of HFC networks are explained to an extent important to understand the impacts caused by and the limitations for DVB-C2. Three basic methods are explained which show how DVB-C2 signals could be transmitted in compliance with the existing RF spectrum. The physical characteristics of DVB-C2 can be configured in a very flexible manner, which allows deviating from the traditional cable channel pattern of 6 MHz and 8 MHz, respectively. Instead of a channel number, a new characteristic frequency value is introduced which takes account of the new approach implemented in DVB-C2 called Absolute OFDM. Further to requirements in the frequency domain, the evaluation of future usage scenarios for DVB-C2 requires the consideration of the actual network load in association with the different architectures implemented in the last mile of HFC networks. A more detailed investigation of which network load could be transmitted through which topology is described in ReDeSign Deliverable D14 [3].

5.1 HFC RF spectrum considerations

HFC networks carry different kinds of broadcast and broadband downstream signals from headends to customers as well as broadband upstream signals in reverse direction. Next to analogue FM radio, analogue and digital TV as well as DOCSIS signals are transmitted in an RF spectrum ranging from 5 to maximal 65 MHz (upstream) and from 87.5 MHz to 862 MHz (downstream). Current investigations to extend the two frequency bands to higher frequencies are underway but not described hereafter. A Frequency Division Multiplex (FDM) system is applied to allow a distinct signal separation at the receiving end. Because of these arrangements, RF spectrum diagrams are well suited for an analysis of transmission scenarios in a network. Figure 10 shows an example of such an RF spectrum. The spectra of the individual signals traditionally transmitted e.g. FM radio, analogue PAL, DVB-C and (Euro)DOCSIS are arranged in the FDM manner with an equidistant channel pattern provided by the network. Frequency gaps are noticeable in the higher frequency sub-bands, particularly in Band IV and V (see Figure 10). In many HFC networks these sub-bands have been occupied to a large extent and are used today for the introduction of new services such as HDTV, VOD, Catch-up TV etc.
The introduction of DVB-C2 signals in such a scenario needs to take account of a number of technical requirements; however, the most important one certainly is the demand to prevent any reduction of technical quality of the traditional signals. This important requirement can be fulfilled if DVB-C2 signals comply with the transmission parameters defined by the relevant standards published by IEC and CENELEC. In particular channel frequencies and power levels are of interest which means that a DVB-C2 signal is to be injected in the existing channel raster at a defined power level. For the following discussion it is assumed that a sub-band of the RF frequency spectrum is occupied with signals as indicated in Figure 11 a) by means of an example. A simple means introducing DVB-C2 is a one-to-one exchange of an individual signal such as analogue TV or DVB-C with a DVB-C2 signal while keeping the signal power at the dedicated level. The resulting RF spectrum of such a simple example is depicted in Figure 11 b). Two DVB-C signals transmitted in adjacent channels and one analogue TV signal are replaced each by a DVB-C2 signal. Figure 11 c) shows the possibility to transmit a wide-band DVB-C2 signal of a bandwidth equivalent to two cable channels (e.g. 16 MHz in Europe, 12 MHz in the U.S.). The benefit arising from the injection of wide-band signals in two or more adjacent channels consists of an increase of spectral efficiency caused by an active use for data transmission of the frequency Guard Band traditionally applied between two adjacent signals. In Figure 11 c) such frequency band is marked by the coloured ellipse. Compared to this example of a combination of two channels, the spectral efficiency can be further accelerated by either transmitting signals of even wider bandwidths and combining a higher number of channels or by injecting individual DVB-C2 signals adjacent to each other and without making use of any frequency Guard Band. Such a close

Figure 11: Opportunities for RF spectrum utilization
packet signals line-up can be achieved if the signals comply with the pre-requisites defined for the special case of an Optimized Frequency Utilization. The pre-requisites are illustrated further down in this chapter. An example of the resulting RF spectrum is depicted in Figure 11 d).

As described already in various chapters above, DVB-C2 receivers using tuners with a traditional receiving bandwidth (of 8 and 6 MHZ, respectively) are capable of receiving individual Data Slices or bundles of Data Slices transmitted in related frequency bands. Guided through the DVB-C2 Signalling Information, the CPE will be tuned to the Data Slice which carries the service of interest, e.g. an HD program.

5.2 Optimized Frequency Utilization

The pre-requisite for the application of an Optimized Frequency Utilization is the establishment of a mode requiring the full synchronization of all DVB-C2 signals being part of a DVB-C2 ensemble. The synchronization has to be created in both time and frequency domain. It is necessary to ensure that the physical behavior of all synchronized DVB-C2 signals of the entire ensemble is identical with the behavior of a single wide-band DVB-C2 signal. In fact the orthogonality of the OFDM sub-carriers applied in the frequency domain has to be guaranteed not only within an isolated OFDM symbol but also among the sub-carriers being part of each adjacent OFDM symbol and thus of each OFDM symbol contributing to the ensemble of DVB-C2 signals. This synchronization requirement needs to be fulfilled at least during the active symbol duration (excluding the temporal Guard Interval). Therefore the DVB-C2 signals of the ensemble have to be synchronized in time domain as well.

The spectrum of such an ensemble is shown in Figure 11 d). While the bandwidth of a single DVB-C2 signal can be assigned in a very flexible manner, the bandwidth of such an ensemble of DVB-C2 signals can vary significantly and has only a lower limit which is equal to the minimal bandwidth of a single DVB-C2 signal.

5.3 Spectral implications of the Absolute OFDM mechanism

The introduction of the so-called Absolute OFDM concept (see above and sub-chapter 10.4) entails the definition of a new set of RF parameters corresponding to the traditional RF channel numbering: The OFDM Sub-carrier Index and the L1 Channel Number. As shown in Figure 12, the entire RF frequency band used for up- and downstream transmission in HFC networks is subdivided for this purpose in sub-bands of the OFDM sub-carrier bandwidth $f_{SC} = 1/448$ MHz $\approx 2.232$ Hz and parameterized with a running index $k$. The Sub-carrier Index $k$ starts with a value of 0 indicating the frequency sub-band at DC (0 Hz) and ends at a value of 386,176 which corresponds with a frequency of 862 MHz. The interrelationship between the index $k$ and the medium frequency of the related frequency sub-band is given by the formula:

$$f_{sc,k} = \frac{k}{448}\text{MHz} \quad \text{with} \quad f_{SC,\text{min}} = 0\text{MHz} \quad \text{and} \quad f_{SC,\text{max}} = 862\text{MHz}$$

As explained already in previous chapters (e.g. sub-chapter 10.3), L1 Blocks are aligned to a fixed 7.61 MHz frequency grid which corresponds to 3408 OFDM sub-carriers. The theoreti-
cal concept arranges for the first L1 Block starting at 0 Hz whereas the subsequent L1 Blocks starting at sub-carrier indexes of a multiple number of 3408. They can be calculated as follows:

\[ k_{L1, \text{Start}} = n \cdot 3,408 \quad \text{for} \quad n = 0, 1, 2, ..., 113 \]

Assuming that the FM radio band will be continuously used for analogue audio transmission, the first entire L1 Block transmitted starts at \( k_{L1, \text{Start, min}} = 15 \) corresponding to 114.1 MHz. However, parts of the L1 Block could also be transmitted below this frequency but above 108 MHz which is the upper frequency limit of FM radio. A protection distance between DVB-C2 and the FM signal needs to be taken into account when introducing DVB-C2 in these frequency bands. The required protection ratio is currently investigated by ReDeSign and under standardization by CENELEC and IEC [9].

### 5.4 HFC capacity estimations

With the knowledge gained by the simulations and investigations regarding Optimized Frequency Utilization, explained in the above sub-chapters, calculations were carried out to estimate capacity gains which an introduction of DVB-C2 may generate.

For a first estimation of capacity available in cable networks for digital signals, data were taken from the results of a survey which the ReDeSign project conducted among European cable operators in 2008. From the responses of the cable operators representing almost a third of the entire European operators' community, in terms of numbers of operators and subscribers served by their networks, average scenarios were derived and dealt with as the basis for the following calculations ReDeSign Deliverables D03 [1] and D04 [8].

Scenario 1 describes an average service portfolio transmitted through cable networks today. The number of occupied channels was chosen to be 95 – corresponding with a fully loaded frequency spectrum in downstream – with 40 channels being used for the provision of analogue TV services. Further 44 channels were assigned to digital TV signals and correspond to a total capacity of 1.9 Gbps of which 0.9 Gbps were used for STDV using DVB-C with 64-QAM and 1 Gbps for HDTV and VOD services based on DVB-C with 256-QAM. 11 DOCSIS channels provide High Speed Internet (HSI) and other IP based services. Respective bit-rate figures are given in Table 1.

<table>
<thead>
<tr>
<th>Service</th>
<th>Technology</th>
<th>No of channels x constellation</th>
<th>Digital capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analogue TV</td>
<td>PAL, SECAM</td>
<td>40</td>
<td>n.a.</td>
</tr>
<tr>
<td>SDTV</td>
<td>DVB-C</td>
<td>24 x 64-QAM</td>
<td>0.9 Gbps</td>
</tr>
<tr>
<td>HD &amp; VOD</td>
<td>DVB-C</td>
<td>20 x 256-QAM</td>
<td>1.0 Gbps</td>
</tr>
<tr>
<td>HIS/IP</td>
<td>DOCSIS</td>
<td>11 x 256-QAM</td>
<td>0.5 Gbps</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>95 channels</strong></td>
<td><strong>2.4 Gbps</strong></td>
</tr>
</tbody>
</table>

Table 1: Estimation of digital capacity for a today's channel line-up

In Scenario 2, the number of analogue TV signals was reduced to 25. The freed spectrum was used either to introduce new services such as HD and VOD via DVB-C2 or to migrate the existing services to the new technology. Assuming that a 4096-QAM could be applied, the 120 MHz frequency slot (equivalent to fifteen 8 MHz channels) makes an additional digi-
tal capacity of approximately 1.25 Gbps available. This capacity allows converting the entire HD and VOD services from 20 DVB-C channels to 15 DVB-C2 channels while providing opportunities for service extensions through the introduction of new services.

In a next step, the 20 DVB-C channels occupied with 256-QAM signals were upgraded to DVB-C2 using 1024-QAM. This step increased the capacity of the corresponding 160 MHz band from 1 Gbps to some 1.4 Gbps and allowed a migration of the SDTV service to DVB-C2. Since the composite bit rate of all SDTV programs was smaller than the capacity available, either the SDTV service or another TV service using DVB-C2 technology could be extended by introducing new programs. Eventually, the spectrum freed from the 24 SDTV channels could be entirely used by DOCSIS – for instance for the introduction of an IPTV service – while enlarging the DOCSIS capacity from 0.5 Gbps to 1.4 Gbps (see Table 2). The bit rates which can be achieved with DVB-C2 for dedicated C/N figures are known from various deliverables and publications and thus are not explained again at this stage.

<table>
<thead>
<tr>
<th>Service (technology)</th>
<th>Technology</th>
<th>No of channels x constellation</th>
<th>Digital capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analogue TV</td>
<td>PAL, SECAM</td>
<td>25</td>
<td>n.a.</td>
</tr>
<tr>
<td>SDTV</td>
<td>DVB-C2</td>
<td>15 x 4096-QAM</td>
<td>1.3 Gbps</td>
</tr>
<tr>
<td>IPTV</td>
<td>DOCSIS</td>
<td>24 x 64-QAM</td>
<td>0.9 Gbps</td>
</tr>
<tr>
<td>HD &amp; VOD</td>
<td>DVB-C2</td>
<td>20 x 1024-QAM</td>
<td>1.4 Gbps</td>
</tr>
<tr>
<td>HIS/IP</td>
<td>DOCSIS</td>
<td>11 x 256-QAM</td>
<td>0.5 Gbps</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>95 channels</strong></td>
<td><strong>4.1 Gbps</strong></td>
</tr>
</tbody>
</table>

Table 2: Estimation of digital capacity for a system using DVB-C2 for TV and DOCSIS for HIS/IP services

The final scenario used DVB-C2 as an integrated portion of DOCSIS for downstream transmission. If the remaining 25 analogue TV channels were replaced by DVB-C2, the entire downstream channel line-up would be filled with DVB-C2 signals. Assuming that again a 4096-QAM constellation could be used in these former analogue TV channels and a 256-QAM DVB-C2 signal in the former SDTV channels, the spectrum would be occupied as indicated by Table 3. The entire digital capacity of the cable network reached a figure of almost 6.9 Gbps.

<table>
<thead>
<tr>
<th>Service (technology)</th>
<th>Technology</th>
<th>No of channels x constellation</th>
<th>Digital capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band I</td>
<td>DOCSIS</td>
<td>40 x 4096-QAM</td>
<td>3.4 Gbps</td>
</tr>
<tr>
<td>Band II</td>
<td>DVB-C2</td>
<td>24 x 256-QAM</td>
<td>1.3 Gbps</td>
</tr>
<tr>
<td>Band III</td>
<td></td>
<td>31 x 1024-QAM</td>
<td>2.2 Gbps</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>95 channels</strong></td>
<td><strong>6.9 Gbps</strong></td>
</tr>
</tbody>
</table>

Table 3: Estimation of digital capacity provided by an integrated DVB-C2/DOCSIS system utilized in the entire cable downstream spectrum
5.5 DOCSIS integration issues

The rough estimations carried out in the last sub-chapter demonstrate how significant the capacity assigned to digital signals can be increased when introducing DVB-C2 and finally integrating the technology in DOCSIS for downstream transmission. For example, the combination of twelve 8 MHz channels to a single 96 MHz DVB-C2 downstream pipe using 4096-QAM would allow the establishment of a 1 Gbps downstream connection mode via HFC. Such enormous capacity per connection has of course many operational side effects. For instance, it paves the way for the creation of an integrated solution for full service provision based on IP. Bandwidth could be dynamically assigned to different service types in an easy manner. On the other hand, the integration of DVB-C2 in DOCSIS requires some additional specification and standardization work. For instance, CMTS and Edge Resource Manager have to be aware of the advanced capacity figures provided by the new technology and also timing and synchronization between upstream and downstream needs to be established within the existing DOCSIS requirements.
6 Summary and Outlook

The preparation of the DVB-C2 Implementation Guidelines was completed by DVB with support from ReDeSign. The results are published in the DVB Bluebook A147 [10] which is currently ratified by ETSI for publication as TS 102 991 [11]. The purpose of the Implementation Guidelines is to give engineers supplementing information on DVB-C2 implementation issues. Additional information is provided by a ReDeSign publication with the title “DVB-C2: High Performance Data Transmission on Cable – Technology, Implementation, Networks” which is issued in terms of a monograph as part 13 of “Mitteilungen (Communications) des Instituts für Nachrichtentechnik der Technnischen Universität Braunschweig [12]. The publication is emerged from the Implementers’ Seminar which ReDeSign jointly organized with ANGA Verband Deutscher Kabelnetzbetreiber and the DVB Project in September 2009 and contains several of the results of this work documented in this deliverable.

The performance simulation results described in chapter 4 of this deliverable have a focus on Narrow-band Interferences, Impulse Noise and Burst Noise. All disturbances are elements of intermodulation products generated by interaction among many digital signals such as DVB-C and analogue signals as analyzed in WP4. The characteristic of intermodulation products among DVB-C2 signals has not yet been identified comprehensively however, related studies are ongoing and will be continued after the end of the project life-time. The simulation platform is in preparation for reflecting such disturbances. The execution of laboratory validation will, however, take some time since sufficient hardware is not expected to be available in sufficient quantities shortly.

The performance simulations of DVB-C2 impaired by Narrow-band Interference, Burst and Impulse Noise, and with the presence of additional additive Gaussian noise were carried out considering strong interference cases. The carrier-to-interference ratios chosen for the affected signal portions (i.e. frequency bands and time periods affected) had values of minus 10 dB. Nevertheless quasi error-free transmissions could be achieved. One important observation was that configurations of the DVB-C2 signal using a high constellation grade combined with a lower code rate seemed to be superior to configurations using a lower constellation grade in combination with a higher code rate. This phenomenon was particularly observed in case of the occurrence of impulse noise. Such results will be communicated in terms of recommendations for the use of DVB-C2 signals in HFC networks.

The analysis of the impact of DVB-C2 in HFC networks carried out in chapter 5 of this deliverable showed that operators are able to generate serious bandwidths savings when introducing DVB-C2. As a typical value for a digital bandwidth operated at a fully loaded network, 2.4 Gbps was considered. Be it that a business case for the introduction is based on the introduction of DVB-C2 for VOD services with a later conversion of HD and SD services to DVB-C2, the digital bandwidth can be increased to above 4 Gbps. Due to the freed frequency spectrum, the capacity used for DOCSIS services can be increased from 0.5 to 1.4 Gbps without changing anything of the current DOCSIS systems. The integration of DVB-C2 in DOCSIS was considered as final scenario resulting in a use of the complete RF spectrum with DVB-C2 signals. Although the mechanism of an Optimized Frequency Utilization was not seriously considered, the digital bit rate increased to almost 7 Gpbs.

Also a new approach for a channel line-up was introduced, which supports the frequency agility of DVB-C2. The traditional channel raster based on 6 MHz, 7 MHz, and/or 8 MHz channels would not allow for a flexible use of DVB-C2 in the frequency range which would permit the optimized exploitation of the spectral efficiency available. The new approach is based on the utilization of the OFDM sub-carrier index as a spectral reference rather than a channel grid with equidistant channel spacing. This approach was communicated to CENELEC for standardization purpose [9].
7 Bibliography


[4] Digital cellular telecommunications system (Phase 2+); Multiplexing and multiple access on the radio path (GSM 05.02 version 8.5.1 Release 1999); ETSI EN 300 908, V8.5.1, November 2000


