A Programmable, Flexible Headend for Interactive CATV Networks

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***Abstract* – Cable networks are in transition to digital two-way broadband networks. The Data-over-Cable Service Interface Specifications (DOCSIS) and the Digital Video Broadcasting (DVB) standards for cable (DVB-C) and return channel for cable (DVB-RCC) were developed for the delivery of high-speed interactive services across these cable networks. A common platform which can be configured according to both standards is presented in this paper. The new concept of Software Cable and Software Headend is introduced. Then, the architecture of a Software Headend using flexible digital signal processing is described. Three different classes of Software Headends are derived from this architecture, which are subdivided into modules and functional units.**

I. Introduction

Cable television (CATV) networks are currently being upgraded towards digital two-way broadband networks. A return path is installed where not yet available and the frequency range in downstream direction is extended up to 1 GHz . These new CATV networks can be used to transmit all kinds of high-speed interactive services, such as video, audio, data or even voice.

Several organizations have been working on open standards for digital two-way transmission on cable networks to enable these new services. Two major systems have evolved: U.S. CableLabs issued the Data-over-Cable Service Interface Specifications (DOCSIS), whereas the European Digital Video Broadcasting (DVB) consortium developed the standards for cable (DVB-C) and return channel for cable (DVB-RCC) used by the EuroModem and EuroBox devices [1-8]. These two systems are incompatible, although there is an extension to DOCSIS called Euro-DOCSIS, which adapts DOCSIS to the European cable environment, but changes are only at the physical layer.

Therefore, there is a need to develop devices that can handle both standards. The devices should be very flexible and a solution similar to the Software Radio principle from mobile communications is applied in this paper.

First, the functional requirements for these devices will be assembled in section II. Then, we will define the new terms "Software Cable," "Software Terminal" and "Software Headend" in section III. In section IV, the Software Headend architecture will be presented, whereas the focus is on the digital signal processing in upstream direction. The architecture will be subdivided into elements such as functional units and modules which leads to different classes of Software Headend. Three classes, the Modular Software Headend, the Parallel Software Headend and the fast Fourier transform (FFT)-based Software Headend are investigated in section V.

II. Functional Requirements

This paper refers to the standards DVB-C, DVB-RCC, DOCSIS and Euro-DOCSIS [1-6]. DVB-C was adopted by the European Telecommunications Standards Institute (ETSI) as EN 300 429 [1] as well as by the International Telecommunication Union (ITU) as ITU-T Rec. J.83 Annex A [4]. DVB-RCC was adopted by ETSI as ES 200 800 [2] and by the ITU as ITU-T Rec. J.112 Annex A [5]. There are currently two versions of DOCSIS available. Reference [3] is the physical layer specification for DOCSIS 1.0 and DOCSIS 1.1, respectively. DOCSIS was adopted as ITU-T Rec. J.112 Annex B [5] and the version of DOCSIS which includes the Euro-DOCSIS extensions by ETSI as ES 201 488 [6].

A general CATV network environment is shown in Fig. 1. The headend, in terms of CableLabs and DVB called cable modem termination system (CMTS) or interactive network adapter (INA), is connected to the cable network via two paths in downstream direction, the broadcast channel and the forward interaction channel. The forward interaction channel can be used for additional user-specific data besides the broadcast channel. The return path provides upstream transmission of data from the end user to the headend. The device at the end user's home is called cable modem (CM) or set-top-box (STB).

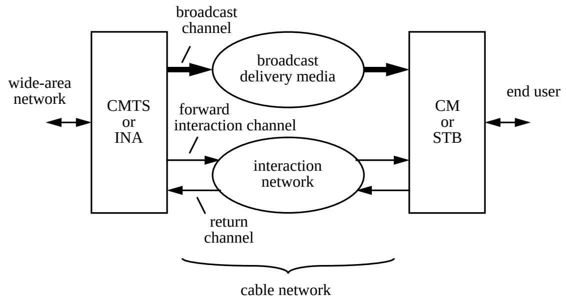

Fig. 1. CATV network environment

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Duisburg, ITG-Fachbericht 171, 28.02.-01.03.2002, pp. 247-251

Our considerations are largely focused on upstream transmission. The signal processing of the received upstream signal at the headend is most challenging because of the point-to-multipoint architecture of existing CATV networks. A flexible digital signal processing in downstream direction at the headend is rather straightforward as the headend acts as a transmitter of a certain number of data signals.

The required signal processing elements for upstream transmission according to the standards DOCSIS and DVB-RCC are[1]:

- Combination of time division multiple access (TDMA) and frequency division multiple access (FDMA).
- Upstream frequency range: 5 - 42 MHz for DOCSIS, 5 - 65 MHz for DVB.
- Supported channel widths: 200 kHz, 400 kHz, 800 kHz, 1.6 MHz and 3.2 MHz for DOCSIS, 200 kHz, 1 MHz, 2 MHz and 4 MHz for DVB.
- Modulation schemes: quadrature phase-shift keying (QPSK) and quadrature amplitude modulation (QAM), with QPSK or 16-QAM for DOCSIS, differential QPSK (and 16-QAM under study) for DVB.
- Differential-coded and Gray-coded symbol mapping for DOCSIS.
- Spectral shaping: square-root raised cosine with roll-off factor $\alpha = 0.25$ for DOCSIS and $\alpha = 0.3$ for DVB.
- Randomization: polynomial $1 + x^{14} + x^{15}$ for DOCSIS and $1 + x^5 + x^6$ for DVB, with programmable seed value for DOCSIS.
- Forward error correction (FEC): Reed-Solomon (RS) decoder with variable input length and variable error protection ($18 \ldots 255$ bytes data input, $0 \ldots 10$ bytes error protection) for DOCSIS, RS(59,53) decoder for DVB.
- Upstream burst: programmable preamble with variable length for DOCSIS, unique word for DVB.

The novel Software Headend that is introduced in the following sections has to comply with this multitude of requirements.

III. Definition of the Terms "Software Cable," "Software Terminal" and "Software Headend"

The terms "Software Defined Radio" and "Software Radio" were recently introduced in mobile communications to handle different standards with one and the same hardware platform [9]. For more information on the Software Radio architecture please refer to [10].

In the following, we introduce the new definition "Software Cable" which ties up to the Software Radio principle. Instead of addressing mobile communication standards, Software Cable is related to bi-directional transmission in CATV networks. Software Cable consists of "Software Terminal," the software driven CM / STB, and "Software Headend," the software driven CMTS / INA.

Software Headend and Software Terminal devices should have the following characteristics:

- Implementation of multiple standards on the same hardware platform. In case of the Software Headend and the Software Terminal, DOCSIS / Euro-DOCSIS specifications and DVB specifications (DVB-C, DVB-RCC) are considered.
- Analog to digital (A/D) and digital to analog (D/A) conversion is done as close to the cable outlet interface as possible. Therefore, most of the headend's and terminal's functionality is realized in software.
- Programmable and flexible devices such as digital signal processors (DSPs) and field programmable gate arrays (FPGAs) shall be used for digital signal processing.

Software Cable provides the same flexible solution for cable as Software Radio does for mobile communications. Standards can easily be exchanged by setting the appropriate configuration without changing hardware. Thus, a Software Headend or a Software Terminal can be installed in a DVB and DOCSIS environment. This is very important because most probably multi standards will dominate. Furthermore, Software Headends and Software Terminals can easily handle future enhancements or changes in specifications by replacing the software for the DSPs or FPGAs via software download.

IV. Software Headend Architecture

Fig. 2 illustrates the connection of a Software Headend to the coax cable and the wide-area network. Downstream and upstream signals are separated by a splitter. A wideband digital-to-analog converter (DAC) is used to produce the complete downstream spectrum in the range of 70 to 860 MHz. This signal includes all downstream signals, i.e. broadcasting channels as well as forward interaction channels. The signal is filtered and amplified before it is passed to the splitter.

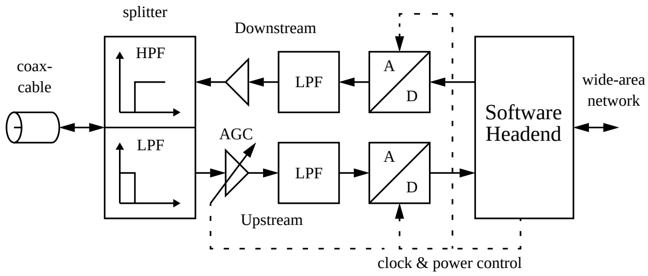

Fig. 2. Connecting the Software Headend to the cable outlet

[1] Please note that the Euro-DOCSIS physical layer is equivalent to the DVB-RCC physical layer.

The upstream signal after the splitter is fed into an automatic gain control (AGC) circuit, an anti-aliasing lowpass filter and then a wideband analog-to-digital converter (ADC) digitizes the complete upstream spectrum in the range of 5 to 65 MHz .

In the following, we investigate the part of the Software Headend that is responsible for upstream transmission. The input signal is therefore the completely digitized upstream spectrum that includes the return signals of all active Software Terminals.

An example of a possible upstream frequency spectrum allocation is shown in Fig. 3. DVB channel spacing is used in this example. Certain frequency bands may also not be occupied due to narrowband ingress.

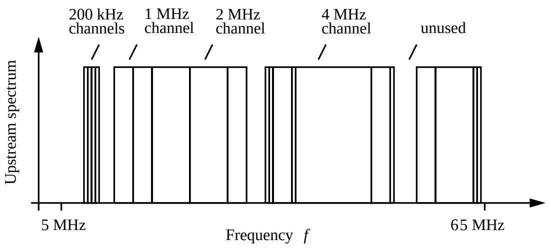

Fig. 3. Upstream spectrum allocation (e.g. for a DVB system)

Fig. 4 shows the digital signal processing elements required to demodulate and decode one specific channel out of the upstream spectrum. Functional units (FU) in Fig. 4 are configurable elements with a set of parameters according to the requirements of the different standards as described in section II.

Channel selection is done by downconverting the radio frequency (RF) spectrum around the carrier frequency $f_{c,i}$ to baseband if the i-th channel is considered. This carrier frequency is generated by a numerically controlled oscillator (NCO) at the headend. The FU for the matched filter has to provide all possible roll-off factors and bandwidths. As indicated in Fig. 4, grey arrows inside a FU mark one possible way how the signal passes through the FU.

Then, downsampling can be performed after filtering. As the Software Headend uses a fixed sampling frequency f_s, the sampling rate can be decreased by different factors D_i, $i = 1 \dots 8$, for the different bandwidths.

A signal detection FU is necessary to detect the arrival of an upstream burst. This unit analyzes the data signal with respect to the occurrence of a transmitted preamble or unique word.

Two more control units are used for carrier and timing recovery and tracking. Techniques with feedback loop (as in the case of carrier recovery in Fig. 4) or feed-forward processing (for the timing recovery in Fig. 4) can be applied [11]. The carrier recovery unit passes data to the NCO, the timing recovery unit to a resampling unit, respectively. The resampling unit is comprised of interpolators and decimators to regain the exact sampling point of time. Tracking algorithms in these units monitor the signal throughout the duration of the upstream burst so that derivations will be automatically adjusted.

After resampling, the FUs for symbol decision, demapping and differential decoding follow. Finally, the FU for derandomization and a FEC decoding unit supply the output bitstream of the selected channel. Because FEC according to the DVB-RCC specification is a subset of the DOCSIS specification, no standard-specific functionality is needed for this purpose.

V. Classification of Software Headends

In this section, the architecture of the Software Headend described above is widened to support all return channels in the

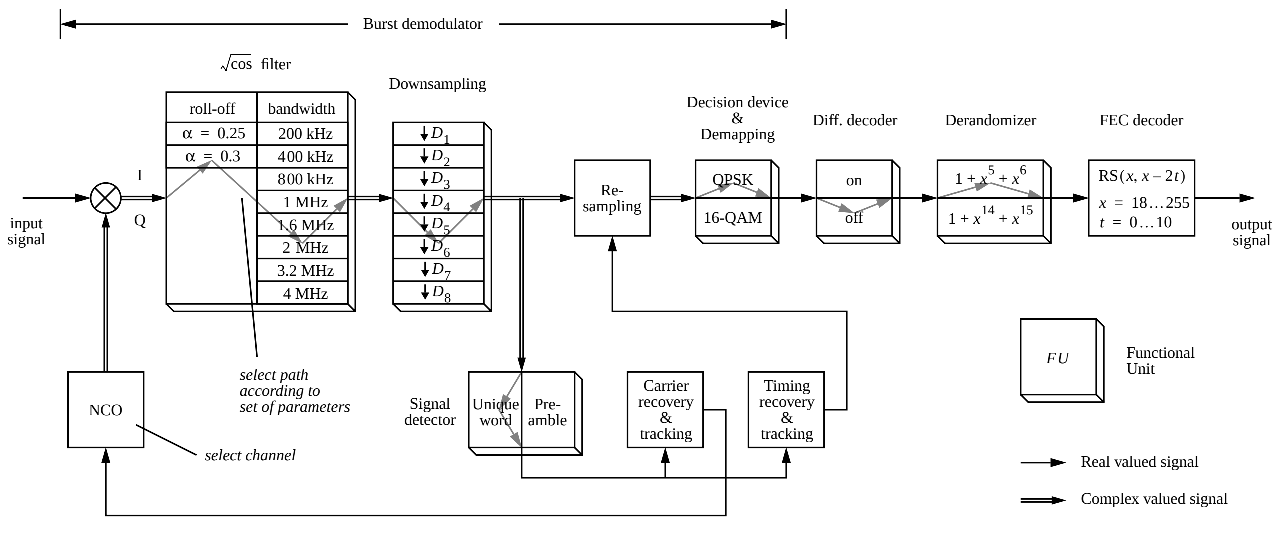

Fig. 4. Software Headend architecture: digital signal processing for a single channel

upstream spectrum. Three different classes of Software Headend will be presented that each use different techniques to separate the upstream channels. First, the Modular Software Headend and then the Parallel Software Headend are described. Thirdly, an FFT-based Software Headend approach follows.

A. The Modular Software Headend

The Modular Software Headend is the most obvious form of a Software Headend that supports all upstream channels. The architecture for one channel is simply manifold N times to support N upstream channels. Fig. 5 illustrates this, whereas the complexity of Fig. 4 is graphically reduced in order not to exceed Fig. 5 and point out the difference to the Parallel Software Headend. All signal processing elements for one specific upstream channel are grouped into a module. In the case of the Modular Software Headend, a module is thus identical to the signal processing as described in the previous section.

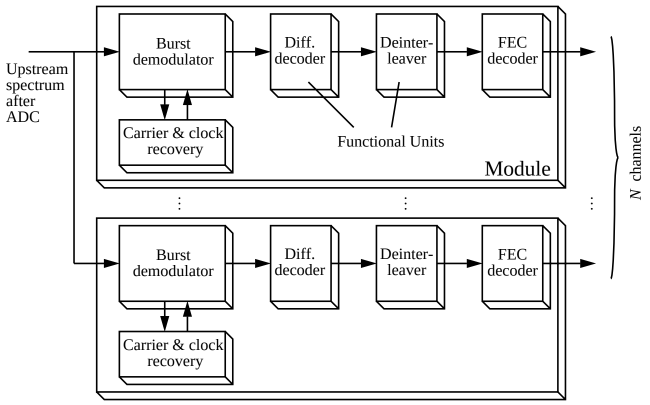

Fig. 5. Modular Software Headend

The Modular Software Headend offers most flexibility regarding the number of upstream channels because modules can simply be added or removed. But the main disadvantage of this solution is the large amount of identical FUs if many upstream channels have to be supported. This disadvantage leads to the second type of Software Headend, the Parallel Software Headend.

B. The Parallel Software Headend

In contrast to the Modular Software Headend a module in the Parallel Software Headend is associated with a functional unit as shown in Fig. 6. Therefore only one implementation of each FU is required resulting in less hardware amount, but significantly faster circuits.

A TDMA scheme is used to process the different upstream channels as shown in the lower part of Fig. 6. Each module has got N parallel inputs and N parallel outputs. The inputs are switched to the selected functionality. Of course, it has to be taken into account that each upstream channel requires its own

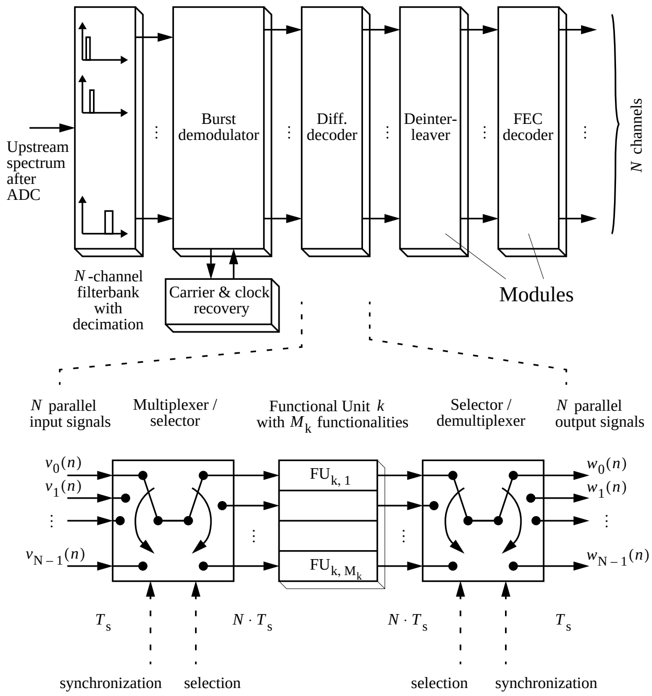

Fig. 6. Parallel Software Headend

set of parameters, i.e. synchronization and selection in the modules have to be set properly.

Another feature of the Parallel Software Headend is a flexible N-channel filterbank with decimation, realized as a polyphase filterbank. The filterbank has to be flexible, because the matched filters must support the different bandwidths and the center frequencies have to be adjustable to currently used carrier frequencies.

Filtering and decimation are now pulled out of the burst demodulator. This results in a modified burst demodulator with less complexity that is completely clocked with the decimated sampling frequency.

C. The FFT-based Software Headend

The FFT-based Software Headend makes use of one or more FFTs to separate the upstream channels. It's possible to transform the first signal processing elements of a Modular or Parallel Software Headend to a structure with an FFT only with few restrictions concerning frequency allocation.

First, we assume that all upstream channels in a certain frequency band use the same modulation format. This assumption is valid because the Software Headend assigns center frequency, modulation format and other parameters to each CM or STB in both, the DVB and DOCSIS systems. This yields to an upstream frequency allocation with several ranges with bandwidth B_i. An example is shown in Fig. 7. The number and arrangement of these ranges remains of course flexible.

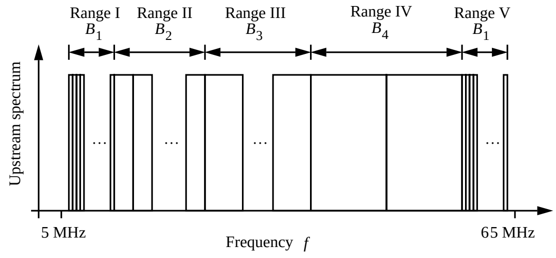

Fig. 7. Upstream spectrum allocation for the FFT-based Software Headend

The interesting signal processing elements are illustrated again in Fig. 8(a). $x(n)$ denotes the received FDMA upstream signal, $h_x(n)$ is the impulse response of the variable matched filter for set x of parameters, and $y_i(n)$, $i = 0 \ldots N-1$, are the demultiplexed output signals for the N channels. D_x is the appropriate decimation factor. Ω_i is the normalized carrier frequency of the i-th carrier with respect to the sampling frequency f_s, given by $\Omega_i = 2\pi f_i / f_s$. With the upstream spectrum separated in several ranges or subbands, a uniform carrier frequency spacing is now feasible to achieve a structure necessary for the FFT. In this case $\Omega_i = \Omega_B + i \cdot \Delta\Omega$ must hold, where Ω_B denotes the base frequency of the range and $\Delta\Omega$ the uniform carrier spacing equivalent to the bandwidth of the modulated signals in this subband.

A mathematical way is described in [11] to convert the structure in Fig. 8(a) into a structure as shown in Fig. 8(b). Instead of filtering each branch with $h_x(n)$, only one multiplication with one coefficient of $h_x(n)$ in the block windowing element is necessary before executing the FFT. Each subband requires an own FFT path with N_1 upstream signals in range I, N_2 upstream signals in range II, and so on. All possible modulation formats can be set up by providing several FFT paths.

VI. Conclusions

We have investigated architectures for headends in CATV networks with advanced digital signal processing. First we have defined Software Cable, Software Terminal and Software Headend. These new architectures allow the implementation of DOCSIS and DVB standards on a single hardware platform. With wideband ADCs at the beginning of the signal processing chain, all functional requirements can be realized with DSPs and FPGAs. This provides a very flexible solution for CATV networks. The Software Headend architecture was presented next, with focus on the signal processing in upstream direction. Elements necessary to process the digitized upstream spectrum to produce the demodulated and decoded output signals for all upstream channels were described. Moreover, we have subdivided the Software Headend into the Modular Software Headend with modules corresponding to upstream channels, into the Parallel Software Headend with modules corresponding to functional units and into the FFT-based Software Headend that requires a special upstream frequency spectrum allocation.

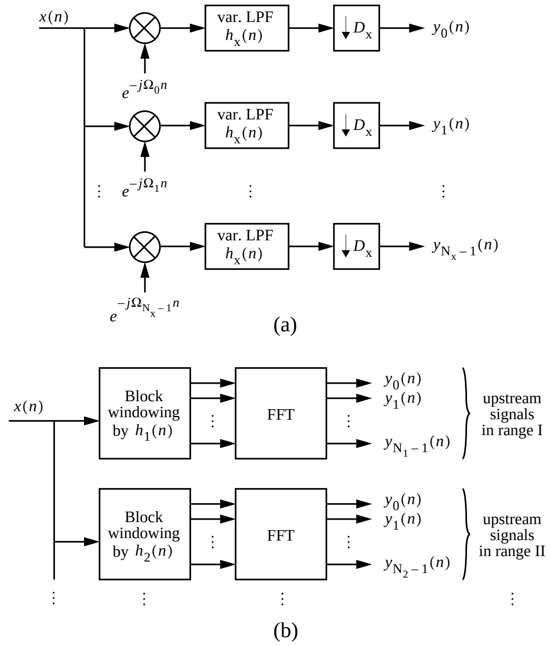

Fig. 8. (a) Basic structure; (b) Structure with FFT

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