American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-6, Issue-5, pp-86-95
www.ajer.org
Research Paper Open Access

DOCSIS 3.1 and OFDM

Nataša Živić[1]
[1]*Chair for Data Communications Systems, University of Siegen, Germany*

Abstract: *Among several strategies with a view to increasing the efficiency of today's coaxial cable networks, a very attractive one includes the use of version 3.1 of Data Over Cable Service Interface Specification (DOCSIS). The technology based on this standard provides a flexible framework to cable operators with regard to the expenditures of network upgrade. Better spectral efficiency, and consequently, a higher data throughput of coaxial networks are achieved through the use of several modern techniques of data processing and modulation implemented in DOCSIS 3.1equipment. Among these techniques, on the first place is certainly the Orthogonal Frequency Division Modulation (OFDM) combined with an error-correction coding scheme customized for this type of modulation. Still, beside a significant improvement, there are some issues which should be handled properly, so the possibilities offered by DOCSIS 3.1 would be fully exploited in the real coaxial cable networks.*
Keywords: *DOCSIS 3.1, HFC network, OFDM, LDPC/BCH coding, spectral efficiency*

I. INTRODUCTION

The always increasing demands for bandwidth, now boosted by the explosion of WiFi services, then by the rise of over-the-top (OTT) content over internet and cloud applications, as well as by the start of the expansion of Internet-of-Things (IoT), resulted in the development of several technologies for the so called next generation broadband internet access. Not only bandwidth, but also other factors, such as CAPEX, OPEX, economic life of new access platforms, average revenue per user, then security, reliability and flexibility issues, have the influence on service providers when deciding which of the new technologies will be chosen to invest in. There is always a major dilemma for providers – whether to realize a capital investment to upgrade a plant completely, or to invest gradually and incrementally improve the existing plant.

Among the technologies for broadband access, Fiber-to-the-Home (FTTH) has long time been seen as the ultimate solution, but at the same time the most expensive. The alternative solutions as wireless or copper last mile connections can save providers' money for installation of new fibers, but on the other hand, their capacity is inherently limited, which on long term may restrict providers to fulfil the increasing bandwidth demands of their subscribers. The compromise offered by Fiber-to-the-x (FTTx) chosen by many providers, is the installation of fibers close to the homes and then the deployment of copper for the last 50−300 m. The new technology which fits in the FTTx concept is G.fast, which should provide download speeds of 1 Gbit/s and more. G.fast is seen as the successor of xDSL technologies operating over twisted pairs.

Parallel with the telecom operators which traditionally have used copper cables with twisted pairs (first for telephony and then also for xDSL services), cable operators which provide TV and other multimedia signals from the very beginning have used coaxial cables to reach to the end customers. Today's cable infrastructure of these operators in the most of cases assume the existence of hybrid fiber-coaxial (HFC) networks where multimedia and internet traffic is transmitted over optical fibers to the distribution nodes and then over coaxial cables to customers. A standard technology for broadband internet access implemented by cable operators is known as Data Over Cable Service Interface Specification (DOCSIS). It defines an upstream and downstream channel to enable bidirectional communications between a cable modem termination system (CMTS) in the cable operator's head end and a subscriber's cable modem (CM).

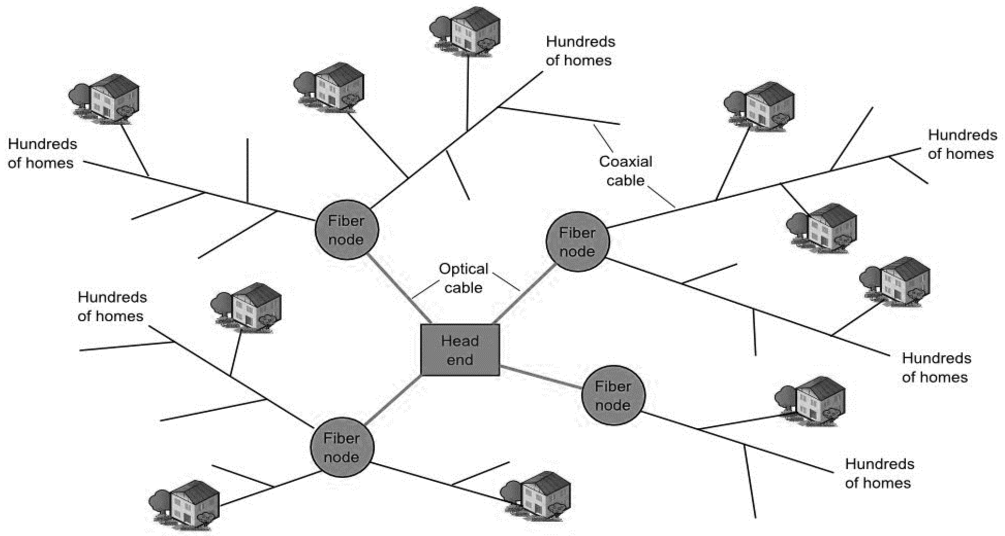

Figure 1: Hybrid Fiber-Coaxial (HFC) network

Over time, the bandwidth offered by different versions of DOCSIS was being gradually increased. In the period from 1997 to 2006 the downstream capacity of 38 Mbit/s (DOCSIS 1.x) grew to up to 1 Gbit/s (DOCSIS 3.0; with 32 bonded downstream 6 MHz wide channels), while the newest DOCSIS 3.1 specification extends downstream capacity up to 10 Gbit/s. Also, the upstream capacity is from 100 Mbit/s of DOCSIS 3.0 increased to 1 G/bit/s by DOCSIS 3.1. With such the characteristics (among others), DOCSIS 3.1 becomes a very attractive choice for cable operators, i.e. multimedia signal operators (MSOs), in order to keep their competitiveness on the market, having in mind the above mentioned factors.

II. DOCSIS 3.1 – MAIN FEATURES

2.1 Compatibility

DOCSIS 3.1 standard is backwards compatible with DOCSIS 2.0 and can coexist with DOCSIS 3.0 equipment in the same network. The transition from version 2.0 (still used by many operators) to version 3.1 brings a better quality of experience to customers and prolongs the time of usage of the outside plant without need for any change.

2.2 Multicarrier transmission

The implementation of Orthogonal Frequency Division Multiplexing (OFDM) is the biggest change introduced by DOCSIS 3.1 [1]. With OFDM the source bit stream is (after coding) split into parallel data streams of lower bit rate, whereby each stream digitally modulates different subcarrier. The subcarriers are equidistantly distributed over the frequency range while the frequencies of all subcarriers are the integer multiples of the same basic frequency. Modulated subcarriers are then summed to form OFDM signal, which is finally transmitted through coaxial cable.

Since DOCSIS 3.0 uses a single carrier within a 6 MHz wide band (8 MHz in Europe) and hence, the modulation is based on single carrier QAM (SC-QAM), the symbols are sequentially brought in the modulator. In case of a problem in the transmission or reception of a single carrier in a plant (among other carriers for various channels), the modulation must be reduced for all the carriers of all the channels in order to avoid the total interruption of data traffic. From this reason the modulations of all carriers must be optimized for the worst channel (6 MHz wide) in the plant.

Unlike in DOCSIS 3.0, the subcarriers of OFDM signal in DOCSIS 3.1 are spread across the entire dedicated bandwidth which may be wide from 24 to 192 MHz in the downstream. The distance between adjacent subcarriers can be 25 or 50 kHz, so an OFDM signal can have up to 7600 subcarriers (for 25 kHz spacing between subcarriers). The codewords with higher data rate are split over multiple subcarriers and time slots, whereby all subcarriers are synchronized and communicate together to form OFDM symbols with lower data rate. So, unlike DOCSIS 3.0 where the duration of a QAM symbol is less than 1s, the duration of OFDM symbol in DOCSIS 3.1 is much longer (40 µs for 25 kHz spacing i.e. 20 µs for 50 kHz spacing) which makes system more robust against noise and other impairments.

The allocation of symbols across different frequencies introduces more flexibility in OFDM. So, if there is a problem with a particular subcarrier, the system can exclude problematic subcarrier from OFDM signal and bridge the adjacent subcarriers together, keeping the flow of symbols over the entire bandwidth at optimal performance level.

2.3 Modulation formats and variable modulation profiles

Due to enhanced error correction methods then in the previous versions of DOCSIS standard (see next section), version 3.1 exploits the obtained robustness on errors in a way that now are possible higher modulation formats for the same Signal-to-Noise Ratio (SNR), or the same modulation format for the lower levels of SNR. In that way, the maximal modulation formats of DOCSIS 3.0 (64QAM for upstream and 256QAM for downstream) have been increased in new version, i.e. standard DOCSIS 3.1 now supports modulations up to 1024QAM (upstream) and up to 4096QAM (downstream). Also, the future optional modulation formats planned for the next versions of standard are 2048QAM and 4096QAM in the upstream, and 8192QAM and 16384QAM in the downstream.

Theoretically, the maximal modulation of 4096QAM in DOCSIS 3.1 gives a rate of 64.32 Mbit/s, which is 50 % more than 42.88 Mbit/s obtained by 256QAM (maximal modulation of DOCSIS 3.0) for the same 6 MHz bandwidth. In reality, these rates are lower due to overhead and spectral efficiencies, so the real improvement is the increase from 38.81 Mbit/s (DOCSIS 3.0) to 54 Mbit/s (DOCSIS 3.1).

OFDM obtains significant improvements in network performance not only as the consequence of higher modulations, but also because of the fact that OFDM can allow different modulations for different subcarriers. Instead of using one modulation for the entire plant, various profiles can be created, whereby a particular profile is defined by the combination of modulations used on all subcarriers.

In the previous versions of DOCSIS the same modulation had to be chosen for all cable modems in the plant, whereby the choice of the modulation is based on the modems with the lowest SNR. Different profiles of modulations which are at disposal with DOCSIS 3.1 enable the simultaneous use of lower QAM modulations for modems with lower SNR and higher order modulations for modems with a higher SNR. If the distribution of SNR is assumed to be a typical Gaussian with a mean of 36 dB and 2 dB deviation, the use of different profiles can improve network efficiency for 35 %. This improvement is illustrated on "Fig.2", where instead of use of e.g. 256QAM for all modems (choice of the modulation based on the worst SNR), the whole spectrum of modulations (equal to or higher than 256QAM) is used for different modems, according to their SNRs.

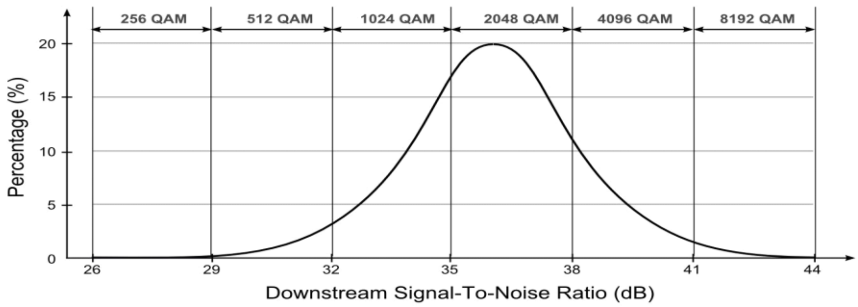

Figure 2: Typical distribution of modulations in a cable plant with DOCSIS 3.1

2.4 Error correction

In previous DOCSIS versions the dealing with errors in transmission was realized using Forward Error Correction (FEC). The FEC algorithm used in DOCSIS 3.0 is Reed-Solomon (RS) which provides BER coding gain of around 6 dB. Additional gain of 2 dB is achieved when FEC is coupled with Trellis Code Modulation (TCM), which is applied in North America.

The FEC algorithm used in DOCSIS 3.1 standard [2] is Low Density Parity Check (LDPC) which is used in WiMax, WiFi (802.11n) and Digital Video Broadcasting (DVB). LDPC requires bigger computational power than RS, but still less than Turbo Codes. On the other hand, the modern application specific integrated circuits included in cable modems and/or provider's equipment, such as Digital Signal Processors (DSPs) or Field Programmable Gate Arrays (FPGAs), are powerful enough to easily cope with LDPC FEC.

Since OFDM spreads data across multiple subcarriers and different subcarriers on every symbol, Bit-Error Rate (BER), which is relevant for the transmission over single carrier, no longer makes sense. Instead of looking for bit errors, LDPC is able to see across the entire bandwidth and looks for codeword errors. In case that codeword errors are correctable, LDPC will correct codeword, allowing in that way higher modulations. By this mechanism the need for retries is greatly reduced, so the subcarriers are able to work at optimal levels. In the downstream, the FEC scheme of DOCSIS 3.1 is LDPC concatenated with BCH, where 14,232 bits are encoded to create a single 16,200- bit codeword (the effective code rate is 0.8785).

The additional code gain of LDPC over DOCSIS 3.0 RS method is around 6 dB, so the overall spectral efficiency vs. SNR characteristic is only 1 dB away from the theoretical Shannon limit. This way spectral efficiency is improved for 2 bit/s/Hz, meaning that within a 6 MHz bandwidth in the downstream effectively can be transmitted an extra 12 Mbit/s.

As mentioned in the previous section, the increased efficiencies enabled some higher order modulations [3]. As illustration, instead of using 256QAM with RS and TCM, in DOCIS 3.1 the same SNR level allows 1024QAM using LDPC. The improvement achieved by the use of LDPC FEC can be also presented in another way: if some modulation format in DOCSIS 3.0 required minimal SNR of 27 dB, the same modulation requires only 22.5 dB in DOCSIS 3.1. Also, the SNR threshold for 4096QAM is only 36 dB, which is achievable in the most of today's cable plants.

2.5 Increased Spectrum Utilization

By combining OFDM and multiple modulation profiles, the channel bandwidths can be assigned to match the exact demands of subscribers in real time and/or channel conditions. This makes DOCSIS 3.1 much more efficient – while DOCSIS 3.0 was able to achieve maximal spectral efficiency of 6.3 bits/Hz, DOCSIS 3.1 is able to achieve 10.5 bits/Hz at 4096QAM. In a more typical situation where multiple QAMs are being used at the same time, DOCSIS 3.1 is still able to achieve 8.5 bits/Hz, which is still 35 % more efficient without changing the HFC plant.

Beside the higher order modulations, variable modulation profiles, improved FEC and increased spectrum efficiency with DOCSIS 3.1, there is also the expansion in RF domain, which additionally increases capacity. The upstream frequency range is now from 5 to 204 MHz (previous upper limit was 42 MHz), while the downstream is from 258 to 1218 MHz (optionally to 1794 MHz; see "Fig.3").

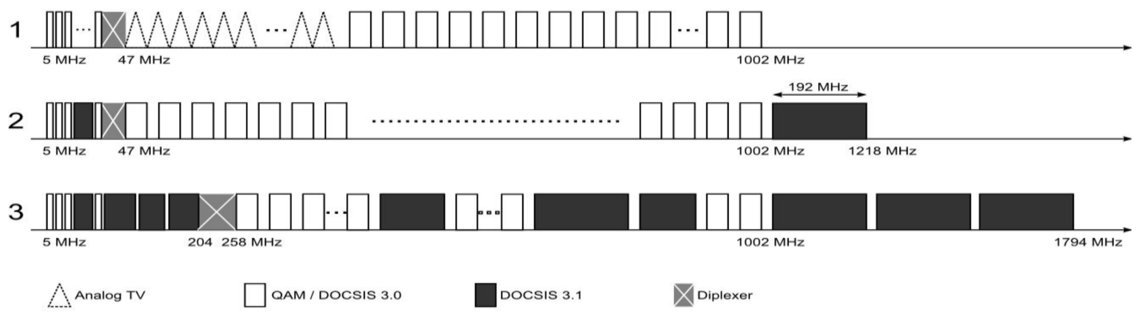

Figure 3: RF spectrum occupancy of 1) DOCSIS 3.0; 2) DOCSIS 3.1 – in the first phase of bandwidth extension (current); 3) DOCSIS 3.1 – in the second phase of bandwidth extension

The main characteristics of DOCSIS versions 3.0 and 3.1 are presented on "Table 1".

Table 1: Comparation between DOCSIS 3.0 and DOCSIS 3.1

	Downstream	Upstream	Downstream	Upstream
Version	DOCSIS 3.0		DOCSIS 3.1	
Channel bandwidth	6 MHz or 8 MHz	0.2 – 6.4 MHz	24 – 192 MHz	6.4 – 96 MHz
Modulation	single carrier		OFDM	
QAM order	up to 256 QAM	up to 64 QAM	up to 4096 QAM	
Multiple access method	TDMA, S-CDMA		OFDMA	
FEC	Reed Solomon		LDPC/BCH	
Maximal spectral efficiency	6.3 bit/Hz		10.5 bit/Hz	

III. OFDM AND CODING

Very popular in modern communications systems, OFDM can be comprehended as both multiplexing and modulation. In a simpler way observed, it consists of three stages [4]:

- Signal de-multiplexing – splitting of initial bit stream into more independent signals of lower bit rate
- Modulation – each of independent signals modulates particular subcarrier from a set of orthogonal subcarriers
- Re-multiplexing – putting together all modulated subcarriers into a composite signal which is then sent to the output stage for the transmission over physical medium (wireless, copper or optical cable)

OFDM can also be seen as FDM with orthogonal carriers. Today OFDM is used in a large number of applications, such as Digital Audio Broadcasting (DAB/DAB+ [5]), Digital Video Broadcasting – Terrestrial (DVB-T/T2 [6]), Wireless LANs [7], Worldwide Interoperability for Microwave Access (WiMAX [8]), satellite communications, then in xDSL technology in form of Discrete Multi Tone (DMT) modulation, in mobile communications (4G i.e. Long Term Evolution (LTE) [9]). Also, OFDM takes place in many new fiber optic communication systems.

The existence of many carriers gives to multicarrier systems several advantages over the single-carrier systems, especially in mobile communications:

- **Robustness against fading:**
  Single-carrier systems struggle with deep signal fades per carrier with the possibility of a temporary interruption of communication;
  In multicarrier systems, fading is handled by many neighbour carriers, which makes it almost constant per carrier (so-called "flat fading")
- **Pulse length:**
  Pulses at single-carrier systems are short because of the broad carrier bandwidth;
  Pulses in multicarrier systems are long because of narrow carrier bands, which have as a consequence:
- **Robustness against Inter-Symbol Interference (ISI):**
  Single-carrier systems are subjected to the strong ISI caused by short pulse duration;

Multicarrier systems are much more robust against ISI, as their long pulses do not influence each other.

On the other hand, the problem of a bad spectral efficiency remains in both single- and multicarrier systems, since guard-band intervals are still necessary to keep transmissions without interferences with one another.

The solution provided by OFDM, which improves spectral efficiency and saves the bandwidth, is allowing the signals of different subcarriers to overlap (in frequency domain) with each other. But the issue that has to be solved is ISI that appears just because of overlapping. ISI can be avoided only if the signals are independent of each other, i.e. if they are orthogonal. Signal orthogonality can be defined in the time and the frequency domain. OFDM signals must satisfy both time and frequency orthogonality conditions [10].

In time domain (see "Fig.4"), two functions with the period T_s:

$$f_m(t) = e^{j\frac{2\pi}{T_s}mt} \quad \text{and} \quad f_n(t) = e^{j\frac{2\pi}{T_s}nt} \qquad m,\ n \in N \tag{1}$$

are orthogonal if:

$$\int_0^{T_s} f_m(t) \cdot f_n(t) = \begin{cases} 0, & m \neq n \\ 1, & m = n \end{cases} \tag{2}$$

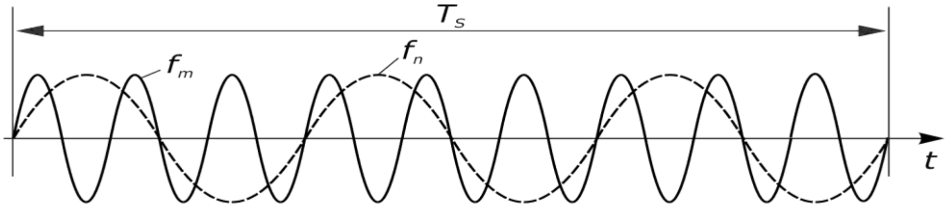

Figure 4: Time orthogonality of two periodic functions $f_m(t)$ and $f_n(t)$ (OFDM subcarriers)

In frequency domain two carriers f_k and f_m are orthogonal if:

$$f_k = \frac{k}{T_s}, \qquad f_k - f_m = \frac{k-m}{T_s}, \qquad k \in \{1, 2, ..., N-1\}, \qquad m \in \{0, 1, ..., N-1\} \tag{3}$$

Because of orthogonality, the spectrum is characterized by the maxima of carriers falling into minima of other carriers (Nyquist's first criterion – "Fig.5").

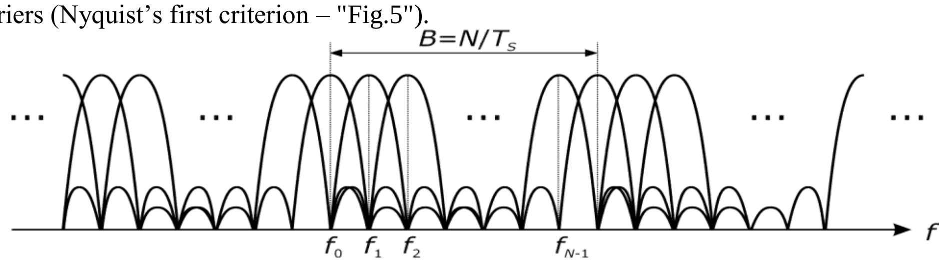

Figure 5: Spectral orthogonality of OFDM subcarriers

3.1 Transmitting and receiving of OFDM signal

Since in OFDM many subcarriers are modulated at the same time, the data stream at the transmitter has to be segmented into N parallel data streams which are fed to N orthogonal subcarriers ("Fig.5"). Because of this parallelization, the data rate of each of N data streams is reduced in comparation to the data rate of the original (non-segmented) data stream.

OFDM transmitter contains following stages (see "Fig.6" and "Fig.7"):

- Segmentation of the data stream into N parallel partial data streams.
- Sub-modulation of N partial data streams using a multilevel modulation with M levels (QPSK, 16-QAM, 64-QAM, 128-QAM,...).
- Assignment of each resulting symbol, which consists of ld(M) bits, to a complex symbol $d_n(i)$, n {0,…, N – 1} and modulation with its OFDM subcarrier; this results in an additional symbol rate reduction (the total reduction factor of the symbol rate per carrier equals 1/[N·ld(M)], due to parallelizing and sub-modulation).
- Serialization of the resulted parallel data streams into a multi-carrier signal s(t),

$$s(t) = \sum_{n=0}^{N-1} d_n(t) \cdot e^{j2\pi f_n t} \tag{4}$$

- Modulation of the multicarrier signal $s_{MC}(t)$ into a broadband multi-carrier signal x(t) using a high-frequency carrier f_{HF}.

Many modern OFDM transmitters are realized using digital signal processing (DSP) for efficient and fast calculation of mathematical functions in an OFDM transmitter. Namely, due to the similarity between expression (3) for multi-carrier signal s(t) and the definition of Inverse Discrete Fourier Transform (IDFT), the OFDM signal can be calculated in a DSP by the use of IDFT, whereby all subcarrier modulators (as well as other hardware components) are not necessary any more. This way, the modulation of orthogonal subcarriers with M-QAM or M-QPSK modulated symbols is performed implicitly during the IDFT process:

$$s(i) = \sum_{n=0}^{N-1} d_n(i) \cdot e^{j2\pi n/N} = N \cdot IDFT_{(n)}(d_n(i)) \tag{5}$$

OFDM receiver contains following stages (reciprocal of the transmitter – see "Fig.8" and "Fig.9"):

- Broadband demodulation of a received signal $\hat{x}(t)$ into $\hat{s}(t)$
- Segregation of individual carriers from the summed signal $\hat{s}(t)$
- Demodulation of each of the N partial data streams using OFDM subcarriers into the complex symbols $d_n(i)$, n {0,…, N – 1}
- Sub-demodulation of each of N symbols (QPSK, 16-QAM, 64-QAM, 128-QAM,…)
- Serialization of resulting N data streams into the original data stream.

The OFDM receiver can also be realized using DSP: the complex operations of the Discrete Fourier Transform (DFT) are performed using the Fast Fourier Transform (FFT) ("Fig.9") [10].

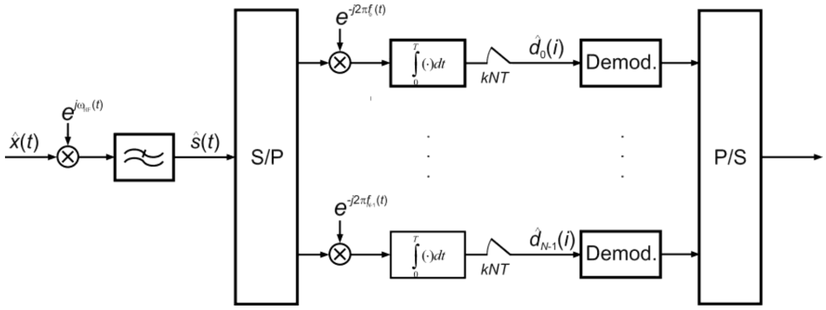

Figure 6: OFDM transmitter

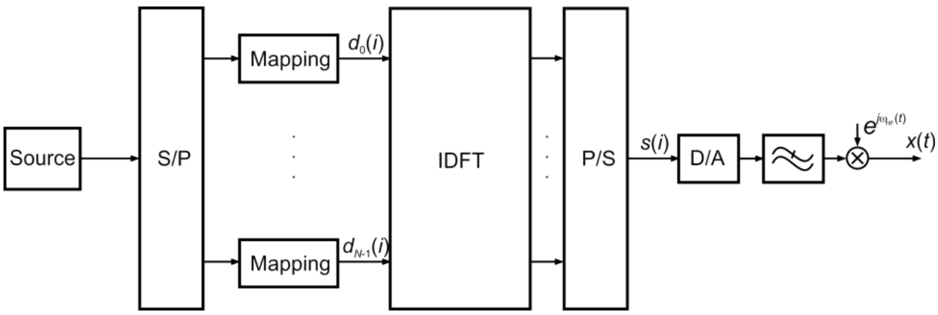

Figure 7: OFDM transmitter realized with DSP

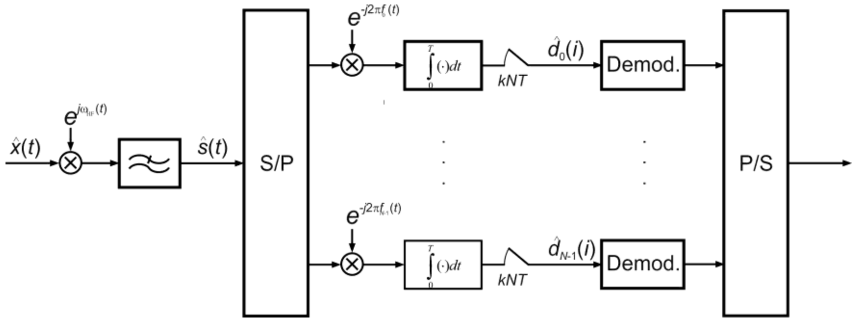

Figure 8: OFDM receiver

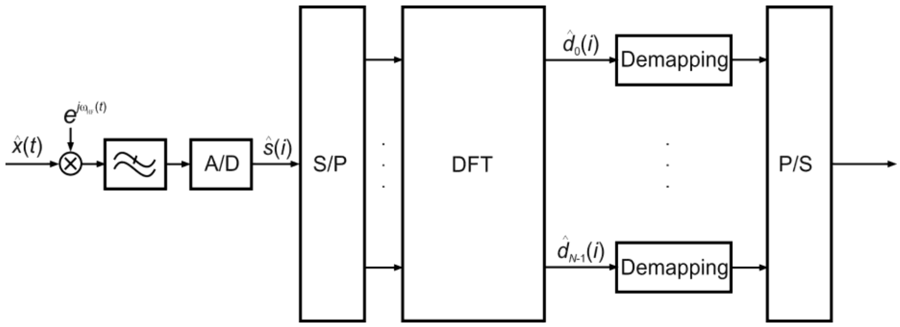

Figure 9: OFDM receiver realized with DSP

3.2 Coded OFDM

Coded Orthogonal Frequency Division Multiplexing (COFDM) is a result of the framework of the Digital Audio Broadcasting (DAB) project “Eureka 147” [11]. It is based on the usage of forward error correction (FEC) coding for erroneous channel i.e., subcarriers. COFDM is superior over OFDM in cases of extreme selective fading, i.e., in case that some subcarriers are experiencing very deep fades while the rest of subcarriers experience very low or no fading at all.

COFDM was developed as a technology for broadcast audio and video networks: DAB, Digital Radio Mondiale (DRM) and European Digital Video Broadcasting – Terrestrial (DVB-T) systems.

Different channel codes are used for COFDM: convolutional and turbo codes [12], Bose Chaudhuri Hocquenghem (BCH) codes [13], Trellis Code Modulation (TCM) [14], Reed Solomon (RS) [15], concatenation of convolutional and block codes (Reed Solomon [16] or LDPC [17] codes) etc.

In case of extreme selective fading channels, where every subcarrier is exposed to the different amount of noise, (different signal-to-noise ratio (SNR)), Soft Input Soft Output (SISO) decoding [12] achieves the best results. SISO channel decoders use the soft decision from the line decoder as soft input and deliver soft output.

The soft output is defined by so called reliability values, also called LLR (Log Likelihood Ratio) or L-values, which are generated for each output bit of the channel decoder and expressed in logarithmic form in dependence on the original bit value (the value before channel encoding):

In case of mobile communications, the Channel State Information (CSI) of subcarrier channels is mostly known i.e., measured. That means that the SNR of each channel is also known. This enables performance of the soft decision decoding, using CSIs from OFDM subcarriers as different a-priori L-values (in the case of an AWGN channel):

$$L_c = \log\left(\frac{P(\hat{x} \mid x = +1)}{P(\hat{x} \mid x = -1)}\right) = \log\frac{e^{-\frac{E_s}{N_0}\cdot(\hat{x}-x)^2}}{e^{-\frac{E_s}{N_0}\cdot(\hat{x}+x)^2}} = 4\frac{E_s}{N_0} \qquad (6)$$

where x and $\hat{x}$ denote the sent and the received bits respectively.

The information of every subcarrier is then corrected depending on the amount of noise (fading) on the channel, E_s/N_0.

- Subcarrier channels with the higher SNR are more reliable and, therefore, they get a higher L-value assigned;
- Subcarrier channels with the lower SNR are less reliable and, therefore, they get a lower L-value assigned.

The scheme of a COFDM transmitter is shown in "Fig.10" and "Fig.11" (in the case of a DSP realization). Accordingly, the scheme of a COFDM receiver using soft decision decoding is shown in "Fig.12" and "Fig.13" (in the case of a DSP realization).

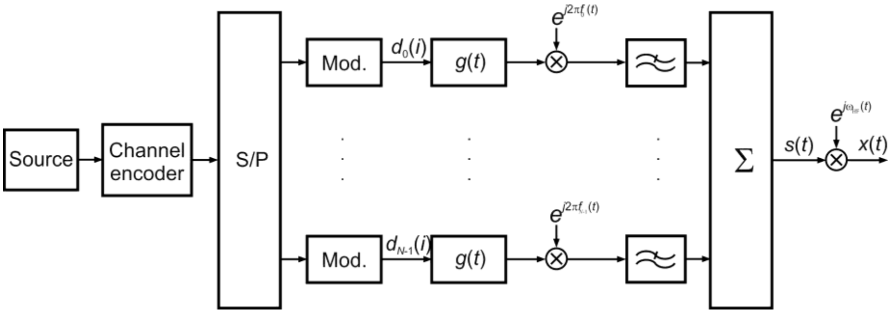

Figure 10: COFDM transmitter

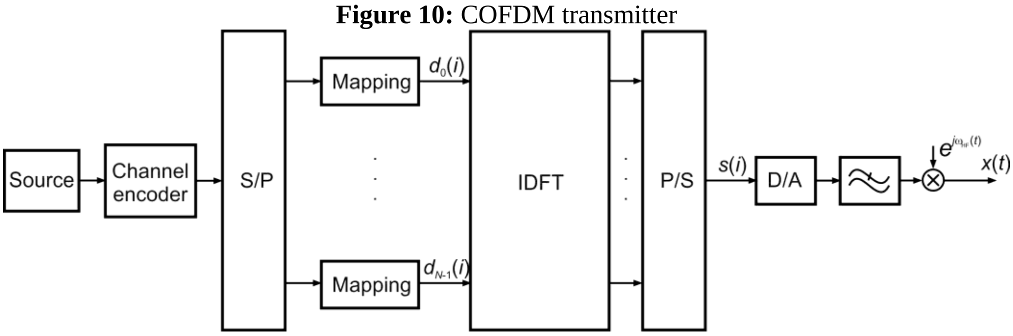

Figure 11: COFDM transmitter realized with DSP

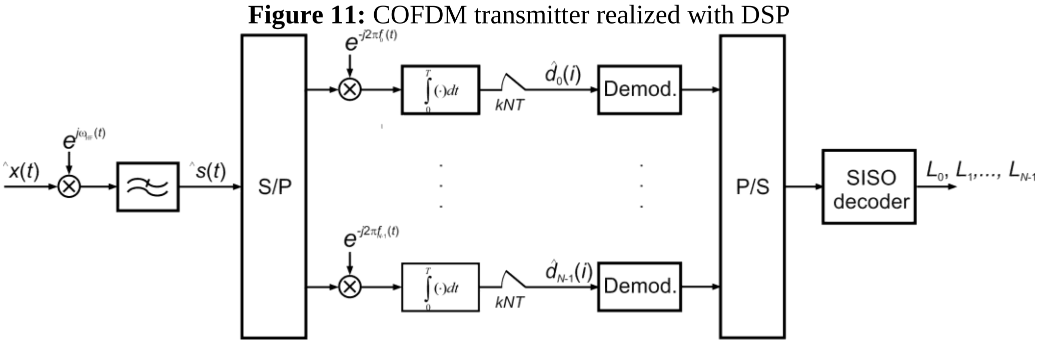

Figure 12: COFDM receiver

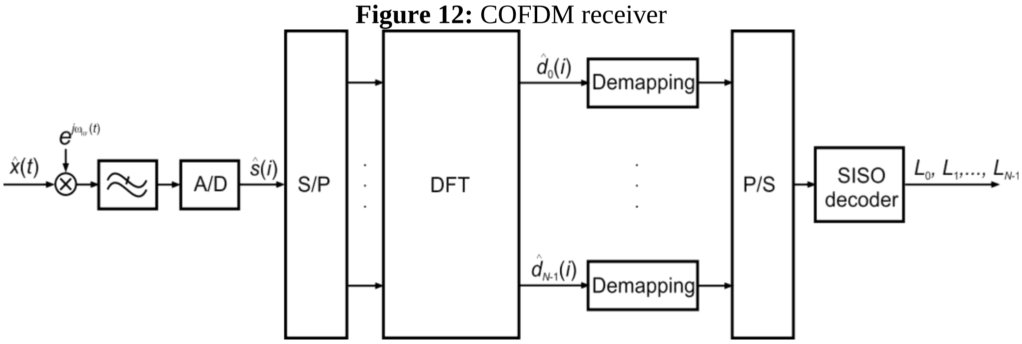

Figure 13: COFDM receiver realized with DSP

In a particular case of COFDM in the downstream channel of DOCSIS 3.1 system, coding is realized through the concatenation of outer BCH code and inner LDPC code ("Fig.14"). The BCH error protection code adds 368 redundant bits on data payload of 14232 bits. After that, LDPC inserts additional 1800 check bits (the LDPC code rate is always 8/9), creating that way codewords with the length of 16200 bits.

Codewords are interleaved in time and frequency (in order to mitigate the impact of burst noise and the effect of ingress) and mapped into OFDM symbols [18]. Since each subcarrier in an OFDM symbol can have a different QAM modulation, the codewords are first split into parallel cell words, which are then mapped into constellations based on the corresponding bit loading pattern of the subcarrier's QAM constellation (in "Fig.14" is shown only a simplified representation of the whole process). Also, more than one codeword may be mapped into one OFDM symbol and the number of codewords per OFDM symbol may not be an integer, i.e. a codeword can overflow from one OFDM symbol to another. Because of this, the transmitter has to convey to the receiver all the locations where a new codeword begins within an OFDM symbol, which is realized by the inserting of the so called Next Codeword Pointers (NCPs).

Through IDFT calculation N subcarriers are “implicitly modulated”, and the numerical results from parallel outputs of IDFT block are again serialized, i.e. turned into a sequence of symbols. After the serialization of OFDM symbols, in each time gap between two symbols is put the end part of the next symbol, i.e. the so called Cyclic Prefix (CP) is inserted. The insertion of a CP helps the receiver to mitigate the effects of ISI caused by micro-reflections in the channel. The duration of CP may be between 0.9 and 5 μs. Also, in order to maximize channel capacity, the spectral edges of OFDM symbols have to be sharpened, which is realized by the use of the windowing technique.

Now, the signal is ready to be translated onto radio frequency (RF) band (by the modulation of RF carrier) and transmitted through coaxial cable.

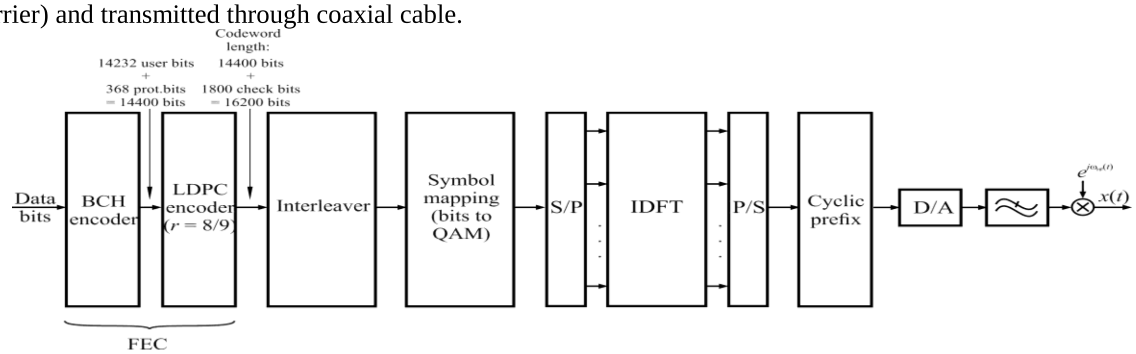

Figure 14: A simplified block scheme of COFDM transmitter in DOCSIS 3.1

IV. CHALLENGES OF ADOPTING DOCSIS 3.1

Besides obvious advantages, there are also some issues which should be handled by MSOs when introducing DOCSIS 3.1 in their networks.

One of the challenges refers to clipping as the inherent characteristic of OFDM. Clipping occurs due to the existence of high peaks in the waveform of OFDM signal when applied with nonlinear amplification, in which case various intermodulation products appear within working frequency range. To mitigate clipping in OFDM, different techniques have been developed. Some of them are already included in other systems and standards which implement OFDM. So, in Digital Video Broadcasting – Terrestrial (DVBT) two techniques are used to reduce the peak-to-average power ratio (PAPR):

1. Active Constellation Extension (ACE) in the QAM carriers and
2. Tone Reservation (TR)

While ACE reduces the PAPR by extending outer constellation points in the frequency domain, TR directly cancels out peaks in the time domain by the use of simulated impulse kernels made of the reserved subcarriers in the OFDM signal. Both ACE and TR are applicable for DOCSIS 3.1 and mutually complementary, since ACE is used in high order modulations and TR in the low order ones. Together, they provide PAPR gain of around 2 dB. On the other hand, about 1 % of OFDM subcarriers has a small increase of average power.

The second issue is related with the orthogonal condition after which OFDM technique is named. This condition assumes that channel bandwidth has to be more than the modulation rate (expressed in samples per second) – otherwise, the interymbol interference (ISI) will appear. The consequence of this condition is that improvements in spectral efficiency (obtained by higher order modulations) can be achieved only at the cost of lower tolerance on noise and nonlinearity. At first glance, this can be comprehended only as a technical requirement related to the noise ingress in cable plant and to the length of last mile to the subscribers, but for many operators it can be a big challenge, since for its solution in many cases (when higher modulations are to be applied) the interventions on cable infrastructure are necessary.

The third challenge of introducing DOCSIS 3.1 may be the interference with the signal of MoCA (Multimedia over Coax Alliance) devices which uses the same plant. In these cases operators will need to install filters in the range of 860 MHz to 1.7 GHz.

V. CONCLUSION

DOCSIS 3.1 solves a major dilemma that providers have faced for years – whether to spend money for the complete upgrade of the plant or to make gradual improvements in existing plant? With OFDM and LDPC in place, providers can make significant performance improvements, i.e. they can almost immediately gain 35 % more efficiency out of a network with few upgrades to the plant. This also buys some additional time for providers to incrementally invest in the infrastructure, which can further improve performance of the already installed DOCSIS 3.1 equipment and the quality of experience for customers.

Still, providers must be careful in the way they deploy and test DOCSIS 3.1. If done incorrectly, a network may perform no better than how it did with DOCSIS 3.0.

REFERENCES

[1]. DOCSIS 3.1 Best Practises for Peak Performance (Viavi Solutions Inc., 2016), http://viavisolutions.com

[2]. Are You Ready for DOCSIS 3.1—The Future of Cable Technology and How to Prepare Your Network (White Paper, Incognito, 2016), http://www.incognito.com/resources/areyoureadyfordocsis31

[3]. A. Al-Banna, and T. Cloonan, The spectral efficiency of DOCSYS 3.1 Systems (White Paper, ARRIS Enterprises, Inc., 2014), https://www.arris.com/globalassets/resources/white-papers/arris_spectral_efficiency_of_docsis_wp.pdf

[4]. H. Ibl, and C. Klaus, DOCSIS3.1—Application Note (Rhode&Schwarz, München, Germany), www.rohde-schwarz.com

[5]. EN 300 401, Digital Audio Broadcasting for mobile, portable and fixed receivers, 2006.

[6]. ETSI EN 300 744 V1.6.1, Digital Video Broadcasting (DVB) – Framing structure, channel coding and modulation for digital terrestrial television, 2009.

[7]. IEEE802.11, Wireless LAN Medium Access Control (MAC) and Physical Layer (OHY) Specification, IEEE-SA, 2012.

[8]. IEEE802.16, IEEE Standard for Local and Metropolitan Area Networks Part 16: Air interface for Braoadband Wireless Access Systems, 2009.

[9]. EN136101: ETSI EN 136 101 V10.3.0, LTE – Evolved Universal Terrestrial Radio Access (E-UTRA) User Equipment (UE) radio transmission and receptrion, 3GPP TS 36.101 version 10.3.0 Release 10.

[10]. N. Živić, Modern Communications Technolody (Berlin, De Gruyter Oldenburg Verlag 2016) 244-252.

[11]. T. Lauterbach, Digital Audio Broadcasting (Feldkirchen, Franzis-Verlag, 1996).

[12]. Berrou, A. Glavieux, and P. Thitimajshima, Near Shannon Limit Error Correcting Coding and Decoding: Turbo Codes, Proc. IEEE International Conference on Communication, vol. 2/3, Geneva, Switzerland, 1993, 1064-1070.

[13]. S. Reed, and X. Chen, Error-Control Coding for Data Networks (Boston, MA, Kluwer Academic Publishers, 1999).

[14]. G. Ungderboeck, Channel coding with multilevel/phase signals, IEEE Trans. Inform. Theory, vol. IT-28, 1982, 55-67.

[15]. I.S. Reed, and G. Solomon, Polynomial codes over certain finite fields, Journal of the Society for Industrial and Applied Mathematics(SIAM), vol. 8, 1960, 300-304.

[16]. R.G. Gallager, Low-Density Parity-Check Codes, Ire Transactions on Informaion Theory, 1962.

[17]. W.W. Peterson, Cyclic Codes for Error Detection, Proc. Of the IRE, vol 49, np. 1, 1961, 228-235.

[18]. CM-SP-PHYv3.1-I10-170111, Data-Over-Cable Service Interface Specifications – DOCSIS 3.1—Physical Layer Specification, Cable Television Laboratories, Inc., 2017.