Basics of telecommunications technology

Orthogonal Frequency Division Multiplexing – Cool Communications

The technical article describes how orthogonal frequency division multiplexing (OFDM) works, which allows the data rate to be adapted very flexibly to the conditions of the transmission channel. OFDM has a very broad field of application in both wireless and wire-bound communications technology. By Dr. Alexander Adams

The advent of a sedentary lifestyle went congruent with the domestication of grain and the consequent definition of a farmer's job description to produce the hard earned, daily bread. However, mankind turned engineer when the bread-cutting machine was invented, to segment the fresh, steaming loafs into slices of equal length and breadth, to maximize the spreading area for jam and marmalade, invented shortly after bread.

OFDM as „cutting machine"

Landing back in the world of communications technology after this phantastic and sumptuous excursion, it can be stated that Orthogonal Frequency Division Multiplexing (OFDM) indeed poses as the communications engineering equivalent of a bread-cutting machine. However, its calling is not the efficient segmentation of doe-produce, but the optimal utilization of frequency spectrum in the wire-bound and wireless transmission of information. OFDM is a modulation technique, segmenting the frequency spectrum into thousands of narrowband "subcarriers", all of which are individually and independently addressable and configurable with their own modulation order. This allows for a granular approach to adjust and optimize data throughput to the conditions across the spectrum. Not without reason it is said that "OFDM is the coolest thing since bread comes sliced". Cool Communications!

Orthogonal Frequency Division Multiplexing is a digital modulation approach. For many years, it has found widespread application in mobile technologies such as 4G LTE, as well as 5G, WLAN and Digital Video Broadcasting (DVB) – and it stepped into cable with the advent of DOCSIS 3.1 technology in HFC-networks. OFDM offers a multitude of advantages, making it an approach especially suited for modern communications networks, as shall be exemplified below.

Modulation – a basic principle of communications systems engineering

Firstly, the concept of modulation shall be considered, before jumping into modulation techniques themselves. Modulation poses as a fundamental concept in communications systems engineering. A modulation impresses the informational content of a message signal upon a high frequency carrier signal. The carrier signal is often chosen to be sinusoidal. This idea is illustrated in Figure 1. Here, the information contained in the message signal at the top is either transmitted by changing the amplitude (AM), or the frequency (FM) of the carrier signal. The purpose of modulation is the transfer of information between a transmitting and a receiving end, across a defined medium (air, glass, copper) and frequency. Modulation of different messages upon different carrier frequencies facilitates the simultaneous transferal of these different messages, without them interfering with each other during the process of transmission. Modulation can be compared to guiding cars along a highway system on designated lanes, allowing for an efficient use of the road.

Comparison between SC-QAM and OFDM

In wire-bound and wireless communications, modulation techniques facilitate the efficient utilization of spectral bandwidth and the transmission of data across large distances. There are different approaches to modulation, focusing on

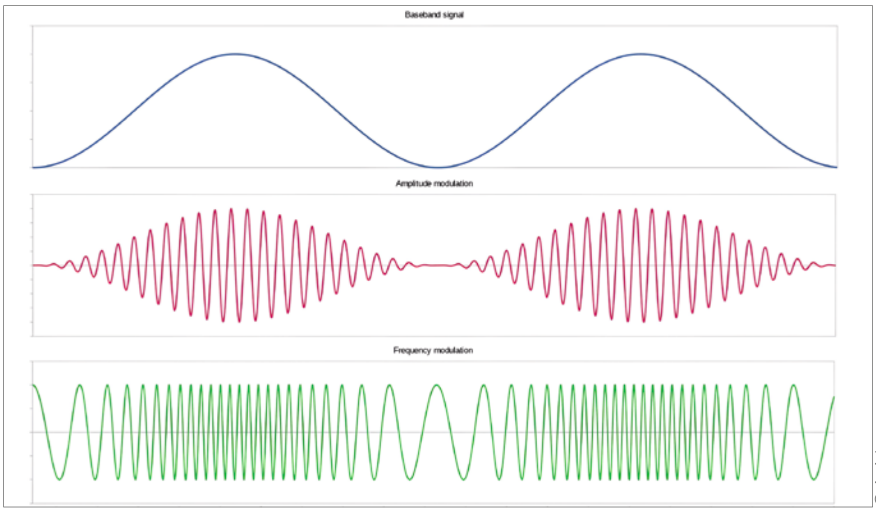

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Figure 1: AM- and FM-modulation

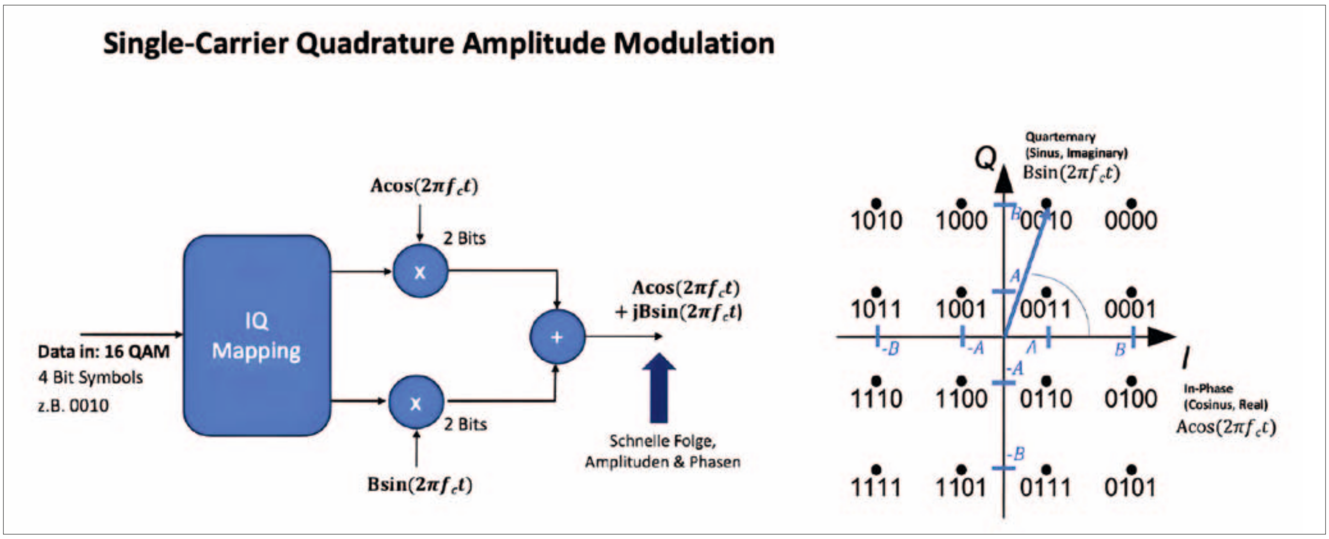

Figure 2: Single-Carrier Quadrature Amplitude Modulation (SC-QAM) Principle

different aspects of the carrier wave to contain and transport the information. In DOCSIS systems up to (and including) version 3.0, modulation of digital data was achieved by use of a Single-Carrier Quadrature Amplitude Modulation (SC-QAM). The following comparison between SC-QAM and OFDM in DOCSIS technology underlines the technological advantages OFDM brings to market. European networks largely use 8 MHz wide channels for the transmission of SC-QAM modulated signals. Since the bandwidth of a channel is equivalent to its maximum symbol rate, it means that a maximum of 8 million symbols per second can be sent across an 8 MHz channel. However, within the frequency spectrum, a little distance is kept to adjacent channels on either side, to avoid interferences. Therefore, a range of 6.9 MHz is being used for actual transmission, hence a symbol rate of 6.9 million symbols is effective on an 8 MHz channel. The number of bits on the symbols are not significant in this matter. It's 6.9 million symbols per second, no matter whether there is one bit or twelve bits per symbol transmitted in the process. A downstream 256 QAM DOCSIS 3.0 transmission uses eight bits per symbol, resulting in 55.6 Mbit/s on a 6.9 MBaud symbol rate. Therefore, a bit takes 18 nanoseconds to transmit, an eight-bit symbol takes 144 nanoseconds. With 8 MHz bandwidth, SC-QAM symbols occupy quite a bit of frequency spectrum, but the short symbol times make the signal susceptible to errors. An impulse noise event of one or two microseconds might render a few consecutive symbols useless.

In a practical sense, a SC-QAM signal is being transmitted by using a sine as well as a cosine waveform on the same frequency in the middle of the designated 8 MHz transmission channel. The amplitude of the cosine designates the x-coordinate, the amplitude of the sine the y-coordinate of a bit combination – the principle resembles the designation of locations on a map with latitude and longitude. Since the signal is transmitted as the sum of the sine and cosine components, it can be displayed as a vector with a phase angle, as shown in Figure 2. Sine and cosine signals can be successfully transmitted on the same frequency without interference, since for these two functions the mathematical definition of orthogonality holds. This definition is given in Figure 3. However, this only serves informational purposes at this point and will not be elaborated upon any further.

Orthogonality certainly plays a critical role in OFDM as well, indicated by the fact that it is carried in the modulation technique's somewhat clumsy name. Nonetheless, in a system engineering sense, OFDM follows a significantly different approach than SC-QAM does. Instead of using a very fast bitstream with short symbol times, with OFDM that fast bit stream is principally fanned out into thousands of long, narrowband, mathematically orthogonal, parallel bitstreams. Figure 4 illustrates this idea. A segmentation into n parallel bitstreams increases symbol times at the individual ports by a factor n. Therefore, the system architecture of an OFDM-system is based upon thousands of narrowband "subcarriers" on harmonic frequencies. These subcarriers do not pose much bandwidth, merely 25 KHz or 50 KHz in DOCSIS 3.1 and 4.0 systems. This design offers the advantage of long symbol times of 40 or 20 microseconds, respectively, which is significantly longer than 144 nanoseconds in the case of a SC-QAM transmission. However, the informational content per symbol in both modulation techniques stays comparable. Therefore, the effects of ingress and impulse noise

Mathematical orthogonality: $$\langle f, g \rangle = \int_a^b f(x)g(x)dx = 0$$

Holds for f(x) unequal g(x)
If f(x) equal g(x), result is unequal 0

Figure 3: Mathematical Definition of Orthogonality

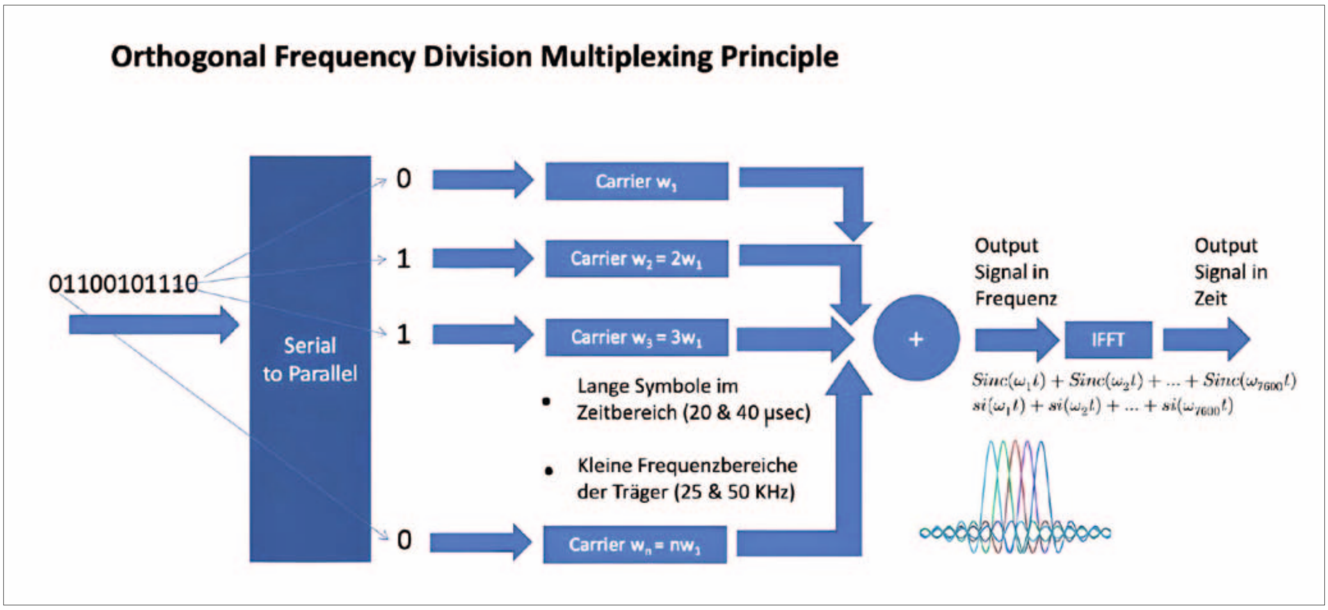

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Figure 4: Orthogonal Frequency Division Multiplexing (OFDM) Principle

as well as microreflections have less of a disturbing effect of the longer symbols, making OFDM an inherently robust modulation technique.

Sinc-functions: Overlaping without correlation

OFDM-systems do not use sinusoids modulation carriers, but so-called sinc-functions. Contrary to their sinusoidal cousins, OFDM-carriers do extend in frequency, as shown in Figure 5. Modulation carriers overlapping in frequency during transmission interfere with each other. Exceptions to the rule pose orthogonal functions, as shown above for a sine and a cosine of the same frequency. Mathematical orthogonality, as defined in Figure 3, can also hold for more than two functions. Figure 5 depicts a graphical representation of orthogonal OFDM-carriers. The individual carriers are set to harmonic frequencies, whole-number multiples of a base frequency. This arrangement results in the maximum of each carrier coinciding with zero crossings of the x-Axis (frequency axis) of all other carriers. This way the carriers overlap “smartly”, without correlating with each other.

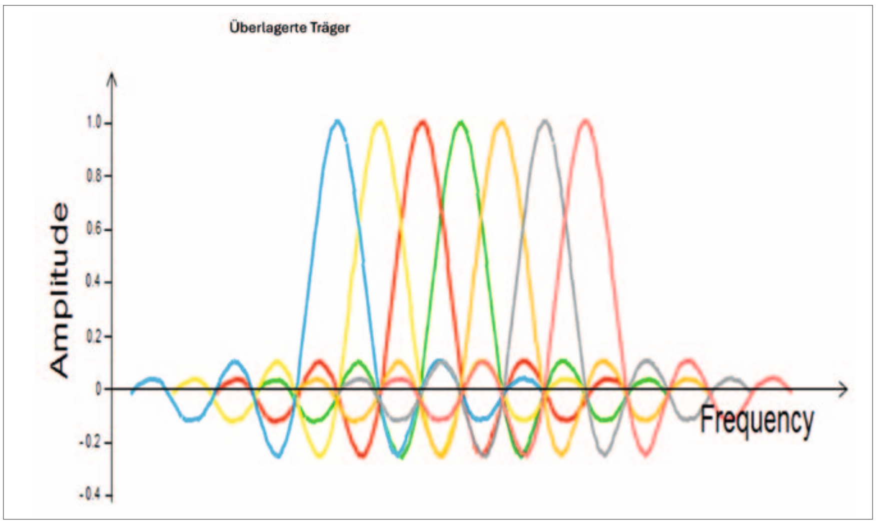

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Figure 5: Superposition of Sinc-Functions

More efficiency and flexibility

By making use of overlapping, orthogonal subcarriers in this fashion, OFDM can utilize the available frequency spectrum a lot more efficiently than traditional modulation techniques, such as SC-QAM. This results in higher data rates over a given part of the spectrum. Furthermore, the segmentation of the spectrum into narrowband subcarriers aids in the optimization of data throughput within the modulated OFDM-spectrum. In a DOCSIS 3.1 system, 160 subcarriers of 50 KHz, or 320 subcarriers of 25 KHz bandwidth can fit into an 8 MHz wide channel, an idea illustrated in Figure 6. Theoretically, every single subcarrier in a DOCSIS 3.1 downstream OFDM-channel can be individually addressed and sent to a different modem. Practically however, this is done with small groups of subcarriers, whose modulation order is optimized to the conditions on the group’s transmission path to the destination modem.

OFDM-systems can flexibly react to changing conditions of the quality of the transmission path and adjust individual subcarriers’ modulation orders to these changes, as well as forward error correction parameters and coding rates. Orthogonality of subcarriers therefore allows for a very granular approach to data throughput optimization. Further, orthogonality

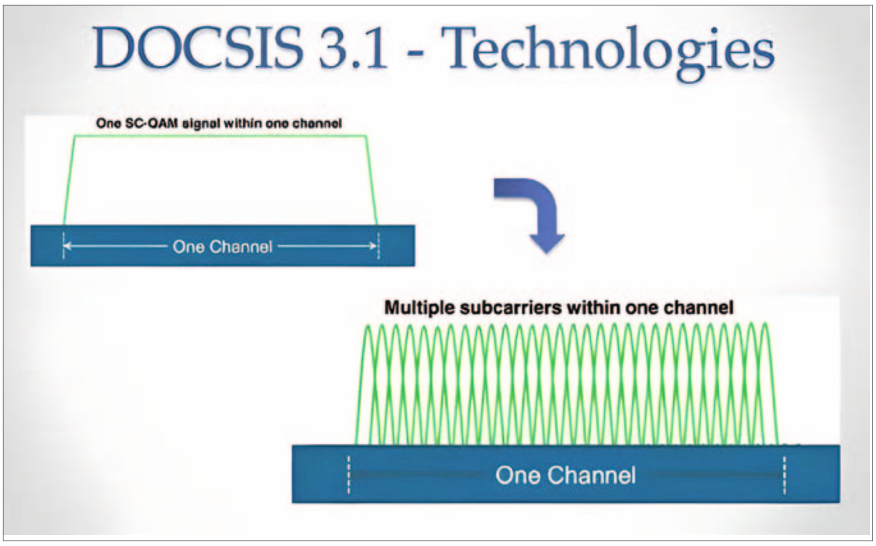

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Figure 6: OFDM-Subcarriers in 8 MHz Spectrum

aids in the design of OFDM-receivers, for their engineering is simplified based on the orthogonality condition, and hence less complex in technical and financial means. Additionally, the FFT-based (Fast-Fourier Transform) implementation of OFDM-systems allows for efficient realization in hardware.

The following example is meant to underscore the flexibility of OFDM-technology: Within a geographical region, supplied by a DOCSIS 3.0 CMTS upstream/downstream port pair, a modulation order needs to be used that all modems can receive. In the downstream, 256 QAM is only possible, if all connected modems to this port can reliably receive and decode 256 QAM symbols (8 bits). If there is only one modem that cannot receive this, the entire region needs to be reduced in modulation order, consequently resulting in overall wasted capacity.

OFDM-based technology, such as DOCSIS 3.1 and 4.0, divide the spectrum up into granular, narrowband slices, allowing to supply each modem with the optimal data rates possible on the individual transmission paths between CMTS and modems. Figure 7 gives a graphical representation of this idea.

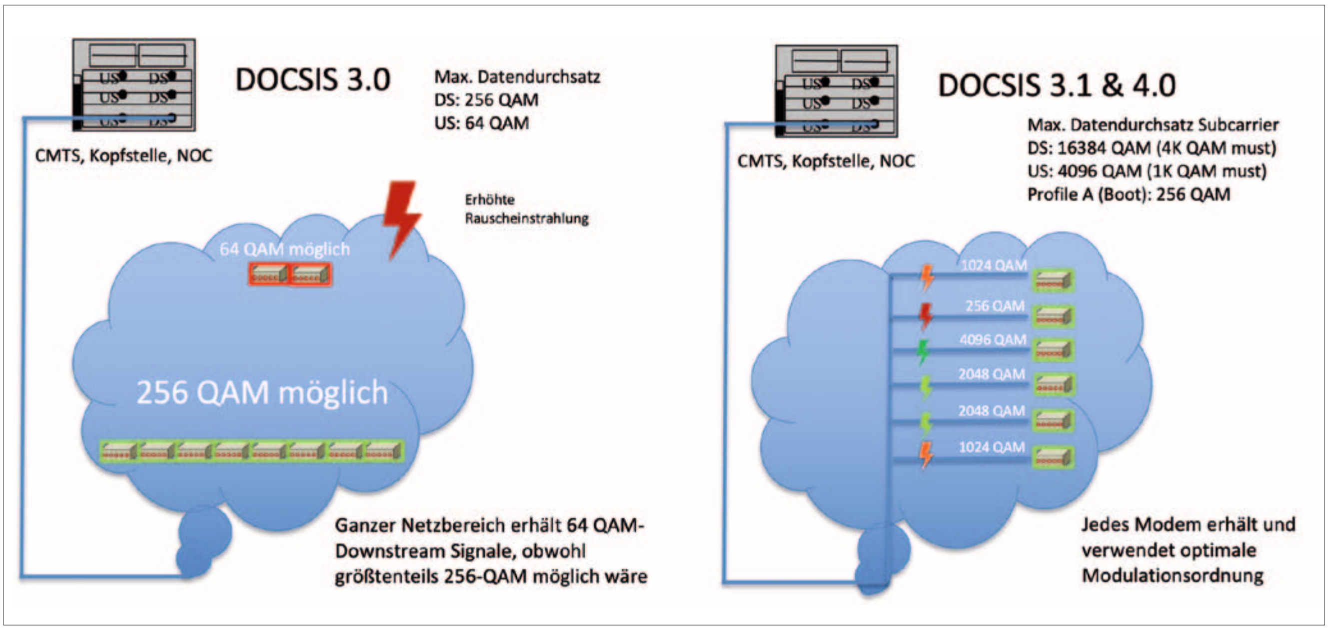

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Figure7: Individual Adjustment of Modulation Orders to Transmission Path Quality

Summary

OFDM is a robust technology. It uses long signals in time and a granularly adjustable frequency spectrum. It was developed under boundary conditions set by the application in mobile networks, where highly noisy environments and multi-path transmissions are to be considered. Coaxial cable on the other hand poses a wonderfully shielded environment for signals to dwell in, such that the robust constitution of OFDM is not truly necessary for systems operation. The metal shielding of the outer conductor of a coaxial cable forms a so-called "Faraday cage" on the inside of the cable, in which the adoption of OFDM leads to a significant increase of the number of bits modulated upon a single symbol. Using OFDM in cable therefore does not mean that installation and service work may now be executed with less care than before, since the robustness introduced by OFDM is being invested into up to 50 percent higher data throughput per Hertz of spectrum, resulting again in higher susceptibility to ingress and impulse noise as well as microreflections.

OFDM enables the high data rates needed for applications such as high-definition streaming services, online gaming, Internet-of-Things applications, WLAN and 5G networks. It was extrapolated, how OFDM makes optimal use of the available spectrum by spreading information over many parallel subcarriers of small bandwidth. In an industry, where spectrum is a rare and valuable resource, this type of efficiency is and will be a decisive factor in the future. OFDM is inherently robust against a multitude of channel impairments, occurring in wireless as well as wire-bound systems. This robustness improves upon the reliability of data transmission in different communication environments. Further, OFDM allows for flexible reaction to channel conditions, by adjusting the number of subcarriers and their parameters, a scalability that can support a multitude of different services, ranging from broadband internet to digital broadcast.

OFDM works very well in conjunction with multiple-input-multiple-output antenna systems (MIMO), which are decisive for increasing data-rates and signal quality in mobile networks. The combination of MIMO-systems with OFDM poses as the base of modern mobile technology. The advent of cutting-edge communications technology, such as 5G and 6G systems, as well as the growing hunger for mobile bandwidth of industry 4.0 applications, autonomous driving systems, and a world connected in an Internet-of-Things, require and demand an efficient, reliable and flexible transmission technology. Orthogonal Frequency Division Multiplexing offers a solid base to meet the current requirements of wireless and wire-bound communications technology and steps up to the plate to be very useful still in the future. ■

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Dr. Alex Adams has 23 years of experience in the German and international broadband communications industry. He is associate professor at Jade Hochschule in Wilhelmshaven, European representative of SCTE, a Subsidiary of CableLabs, and their specialist for DOCSIS-technology, as well as an auditor for dibkom – German Institute for Broadband Communications. Alex holds both a Bachelor- and Master-degree in Electrical Engineering from the University of Hawai'i, he received his Doctorate degree from the Technical University of Darmstadt, Germany.