# 21-GHz Single-Band OFDM Transmitter with QPSK Modulated Subcarriers

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**Abstract:** We present a single-band OFDM transmitter that allows the generation of signals with a bandwidth of up to 21 GHz. Transmission experiments over up to 641 km without optical dispersion compensation demonstrate the performance with coherent reception.
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## 1. Introduction

With the introduction of multilevel formats for 40G and 100G transmission not only the bitrate of a single wavelength was increased, but also the spectral density of the optical signals was improved by a factor of 4 and 10, respectively. As a matter of fact it is to a large extend the increase of spectral efficiency with its potential for cost savings that drives the development of higher data rates on a single wavelength. Due to its compact optical spectrum Orthogonal Frequency Division Multiplexing (OFDM) is considered as a promising modulation format to raise the spectral efficiency on optical single mode fiber even further. Spectral efficiencies as high as 7 bit/s/Hz were achieved with OFDM [1].

There are different versions of optical OFDM that can be classified with respect to the way the subcarriers are modulated and demodulated. The optical approach modulates/demodulates the subcarriers individually [2], whereas the electrical variant generates and demodulates all modulated carriers in the electrical domain very efficiently by means of Fast Fourier Transforms (FFT) employing a single modulator and optical frontend for the conversion into an optical signal and vice versa. Due to the smaller optical complexity the electrical approach allows a higher number of subcarriers, which is (in combination with a suitable cyclic extension) beneficial for an inherently parallel, low complexity receiver architecture. In contrast, the optical variant of OFDM requires large scale optical integration even for a small number of subcarriers to allow a cost efficient and reliable product.

A key technology of future FFT-based OFDM systems is the ability to generate fast analogue signals from their digital image (i.e. very high speed digital-to-analogue (DA) converters are required) to allow the modulation of high bitrates with a single optical modulator. Up to now all OFDM signals of a bandwidth beyond 16 GHz have been generated by some multi-band approach, a juxtaposition of independently modulated sub-bands in the frequency domain [3, 4].

This paper presents the generation of a broadband OFDM signal with a bandwidth of up to 21 GHz using an FPGA based setup with high speed DA converters (Micram Vega DAC25) running at a sampling rate of 25 GSamples/s. This is faster than what was shown before and allowed the transmission of 27 Gb/s on a single polarization with QPSK modulation.

## 2. Experimental setup

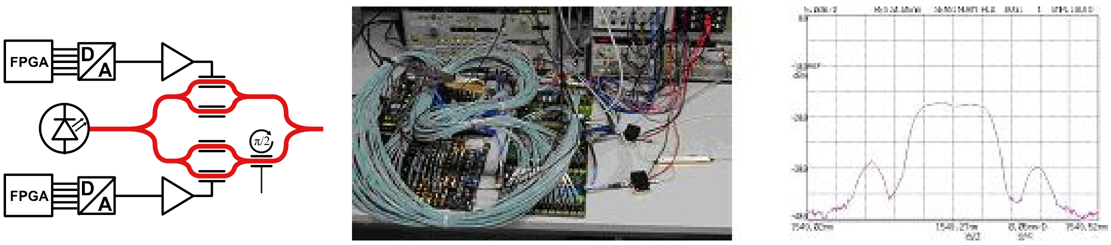


Fig. 1. OFDM transmitter setup block diagram (left), physical bench-top setup (center), and transmit OFDM spectrum for 42 modulated carriers (right).

The OFDM-transmitter setup is shown in Fig. 1: Two Xilinx Virtex-4 FX140 FPGA evaluation boards provide real-time digital data with a width of 6 bit and a rate of 6.25 Gb/s for the in-phase (I) and quadrature (Q) component of the transmit signal, each driving a DAC via 6×4=24 balanced connections. The DACs have a 4:1 multiplexing stage included and convert the data into an analogue signal. Then the outputs of the DACs are amplified and fed into the I- and Q-arms of a Cartesian Mach-Zehnder-modulator. The OFDM-signal is pre-calculated for I and Q component and read periodically and synchronously out of RAM tables in the FPGAs. Bandwidth limitations of the DACs, amplifiers and the modulator were taken into account by a pre-emphasis of the stored signals. The transmitted data was taken from a PRBS sequence of length $2^{11}$-1.

Automatic skew alignment between the FPGAs and DACs as well as a phase alignment of the I- and Q-arms of the modulator were ensured by specific start-up procedures in the VHDL-code. In the experiments described in this paper the OFDM signal was based on an FFT-length of 64. Optionally 32, 42 and 52 subcarriers were modulated with QPSK signals, where 4 of them (more or less equally distributed) served as pilot-tones for the phase noise estimation with mock data (i.e. just 28, 38 or 48 carriers transmitted real data). To allow AC-coupling two central carriers of the OFDM spectrum were suppressed. After inverse fast Fourier transformation (IFFT) the 64 time samples were extended by the cyclic continuation of 21 extras samples. Each frame of 46 OFDM symbols was headed by two additional identical training symbols for timing synchronization, channel estimation and frequency offset estimation [5]. As a result the transmitted net-bitrate was 15.8, 21.4 or 27 Gb/s (including the overhead for forward error correction), depending on the number of modulated subcarriers.

The experimental set-up is shown in Fig. 2. Two External Cavity Lasers (ECLs) with a linewidth of approx. 100 kHz each were used as transmitter laser diode (LD) or local oscillator (LO) in the coherent receiver, respectively. In the transmission experiments no dispersion compensation modules were inserted into the links. The EDFA output power was set to +1dBm and 11 unmodulated WDM channels were transmitted in addition to the OFDM signal. In front of the receiver the optical signal to noise ratio (OSNR) could be adjusted by additive noise loading. The receiver itself consisted of a conventional 90° hybrid, two balanced photodiodes and a DPO72004 sampling scope from Tektronix with a sampling rate of 50 GS/s. The polarizations of the signal and the LO were aligned manually by a polarization controller (PC). Neither wavelength locking between LD and LO nor any kind of external clock synchronization was implemented between transmitter and receiver. The received signal was sampled in traces of $10^6$ samples and subsequently post-processed with Matlab.

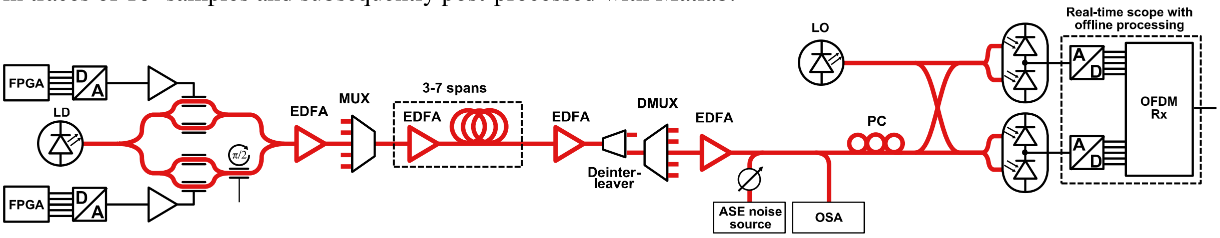


Fig. 2. Experimental set-up showing the transmitter, channel filters, transmission link and the coherent frontend with receiver (offline).

The off-line processing stages invert transmit processing and parts of the channel influence with a compensation of the estimated residual intermediate frequency (IF) offset and the removal of the cyclic extension, followed by the FFT, channel estimation and inversion, phase noise estimation and compensation, and data detection. A key to a good performance on noise limited channels is the reliable estimation of the residual IF and the channel, which can be achieved by averaging the estimation over many frames (for the IF) and a decision directed improvement of the initial channel estimation from the pilot symbols.

## 3. Experimental results

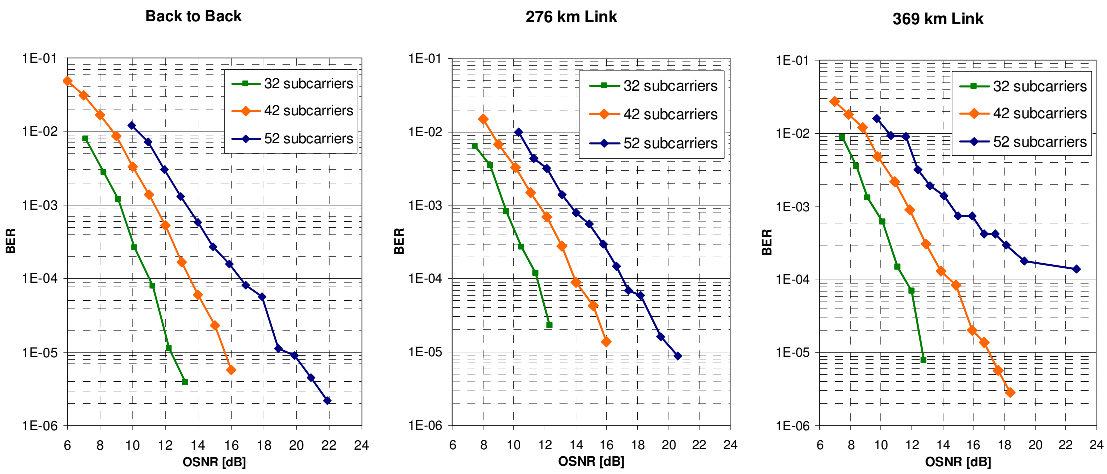


Fig. 3. BER versus OSNR: a) back-to-back b) 276 km link length c) 369 km link length

Fig. 3a) shows the back-to-back performance of all three OFDM-configurations, i.e. with 32, 42 and 52 modulated subcarriers (including 4 pilot-tones). As expected, the performance degrades the more, the higher the bandwidth of the corresponding OFDM signal is. For 32 subcarriers (net-bitrate: 15.8 Gb/s, bandwidth: 13.5 GHz) the required OSNR at a bit error rate (BER) of $10^{-3}$ is 9.2 dBm, whereas it is 11.3 dBm for 42 subcarriers (net-bitrate: 21.4 Gb/s, bandwidth: 17.4 GHz) and 13.2 dBm for 52 subcarriers (net-bitrate: 27 Gb/s, bandwidth: 21.3 GHz). Since the performance degradation is around 1 dB higher than one would expect purely due to the increase in bandwidth, there are additional bandwidth dependent effects present in the set-up, which cannot be eliminated by straightforward power leveling (e.g. the phase response or a bandwidth dependence of the effective resolution of the DACs).

Fig. 3b) and 3c) shows the BER versus OSNR-performance for all subcarrier configurations along 276 km and 369 km link lengths respectively. All three subcarrier configurations exhibit only negligible degradations over these distances. This is in very good agreement to the approximation given in [6], where it is estimated that with the 52-subcarrier-configuration a transmission over 290 km SMF should be feasible.

It should be emphasized that the achievable transmission distance depends linearly on the length of the cyclic extension, which is a design parameter. With fixed FFT-length and a cyclic extension of 42 samples approx. twice the transmission distances are possible at the cost of an increased overhead. The overhead does not change if the FFT-length is also doubled to 128, which tends to increase the sensitivity to the laser phase noise, however.

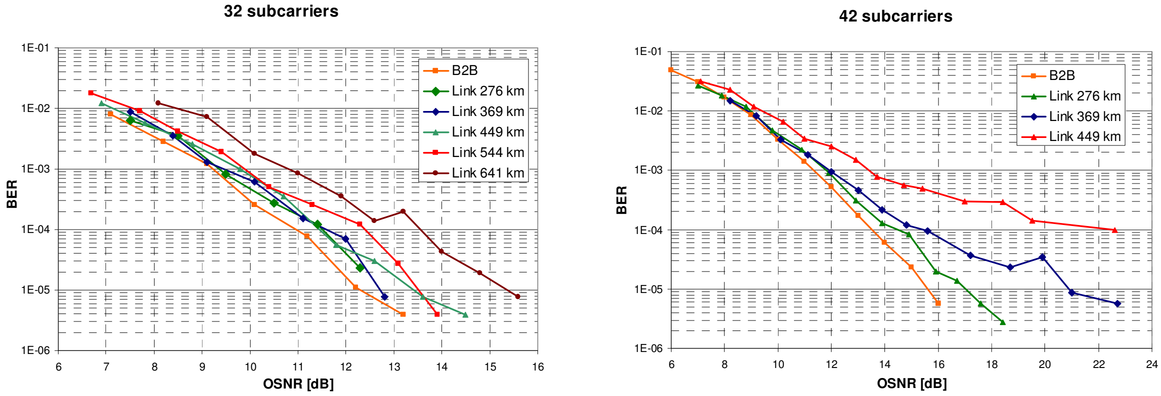


Fig. 4. BER as a function of the OSNR for several link lengths with 32 and 42 QPSK-modulated subcarriers.

The degradation with increasing transmission distance for a cyclic prefix of 21 samples is shown in Fig. 4. For 32 subcarriers 544 km and for 42 subcarriers 369 km can be reached within a penalty of 1 dB at an error rate of $10^{-3}$. Thus the results for 32 subcarriers indicate a slightly better performance than the 465 km which could be expected from [6], whereas the performance of the 42-subcarrier-configuration is in good agreement with the theoretical figure of 360 km. Similar to the penalty in the back-to-back configuration also the transmission results indicate some additional penalty for signals with higher bandwidth.

## 4. Conclusion

We have demonstrated for the first time a single-band OFDM transmitter capable to generate signals with a bandwidth of up to 21 GHz. We successfully verified the expected performance of various configurations with QPSK-modulated subcarriers in transmission experiments using coherent detection, where a maximum net-bitrate of 27 Gb/s was achieved.

## Acknowledgement

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## 5. References

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