MultiGbit/s transmission over a fiber optic mm-wave link

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***Abstract* — Advances in broadband radio-over-fiber multigbit/s transmission links are presented. An optical double sideband with suppressed carrier (DSB-SC) spectrum is used to generate a mm-wave signal of outstanding performance. One sideband is modulated with baseband data rates of up to 10 Gbps. Transmission experiments prove this modulation scheme to be dispersion tolerant and error free transmission was demonstrated after 40 km of single mode fiber for data rates up to 5 Gbps. The limits of the setup were tested with data rates of 10 Gbps.**

***Index Terms* — Microwave photonics , optical frequency conversion, optical mixing, broadband wireless transmission.**

I. INTRODUCTION

In future cellular radio networks Radio over Fiber (RoF) is a very attractive technology to deliver microwave and millimeter-wave signals containing broad band multimedia services to numerous base stations of the network. The radio signals are placed on an optical carrier and distributed by means of an optical fiber network to the base stations (BS). The optical fiber network provides high frequency, wideband, low loss and a means of signal distribution immune to electromagnetic interference. The generation of the high frequency signals takes place at the central station (CS), where the expensive components can be shared between a number of antenna sites, and where it can be protected from environmental impairments [1], [2].

The simplest technique for the optical generation of a RF signal is a direct or external intensity modulation where the optical signal is modulated to generate an optical signal with carrier and two sidebands. At the photodiode, each sideband heterodynes with the optical carrier, thereby generating two beat signals, which constructively interfere to produce a single component at the RF frequency. Due to the chromatic dispersion of the fiber each spectral component experiences a different phase shift. These phase shifts between carrier and sidebands result in a power degradation of the detected RF signal [3], [4]. Several methods to generate dispersion tolerant optical signals have been proposed in the literature [2], [5]-[6]. The generation of a double-sideband with suppressed carrier (DSB-SC) signal described in [2] is a straightforward method due to the fact that only one microwave modulator driven at half the millimeter-wave frequency is required. The modulators optical bandwidth of approximately 40 nm allows the use of Wavelength Division Multiplex (WDM) to address the base stations in a cellular radio system. Therefore a large optical bandwidth is advantageous for supplying a high number of cells in a RoF system [1], [2].

Previous work in [5] and [7] used a Mach-Zehnder Interferometer (MZI) filtering principle but with low data rates (155 Mbps) and subcarrier modulation. In [8] the data rates were extended up to 2.5 Gbps by means of FBG filtering techniques and a self-homodyne receiver. In this paper we experimentally show broadband data transmission from 2.5 Gbps up to 10 Gbps by means of a single sideband (SSB) modulation technique with a mm-wave carrier at 33 GHz.

II. MM-WAVE GENERATION AND DATA MODULATION

To overcome dispersion effects, double sideband with suppressed carrier (DSB-SC) signals are used. As shown in [4] carrier suppression extends the transmission distance limited by dispersion power fading by many kilometers. This effect is much more dominant in high data transmission rates like 2.5 Gbps and higher. By using an optical Single Sideband approach there is no power penalty due to dispersion [6] and the signals can be transmitted over longer distances.

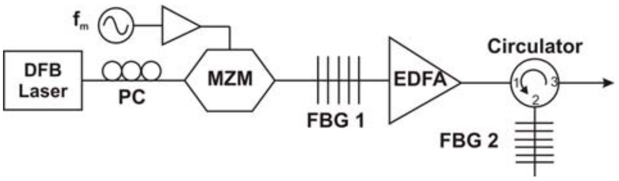


Fig. 1. Setup for the generation of the DSB-SC signal (PC: Polarization Controller, MZM: Mach-Zehnder Modulator, FBG: Fiber Bragg Grating, EDFA: Erbium Doped Fiber Amplifier).

The setup for the DSB-SC signal generation is shown in Fig. 1. By driving a Mach-Zehnder Modulator (MZM) at V_π (i.e. the minimum optical power transmission point) the carrier is theoretically completely suppressed, leaving two sidebands at $f_0 \pm f_m$. Polarization mismatches of the optical signals inside the Mach-Zehnder modulator, as well as bias instabilities make the total suppression of the optical carrier impossible. That is why the residual carrier is further attenuated by a Fiber Bragg Grating (FBG 1) specially designed for our application. With a 3dB bandwidth of f=30 GHz, the carrier is suppressed by more than 60 dB and cannot be observed in the spectrum after the optical amplification provided by the EDFA. Limiting the Amplified Spontaneous Emission (ASE) of the EDFA via the use of FBG 2 in reflection provides a high power signal with a reduced amplifier noise figure [9].

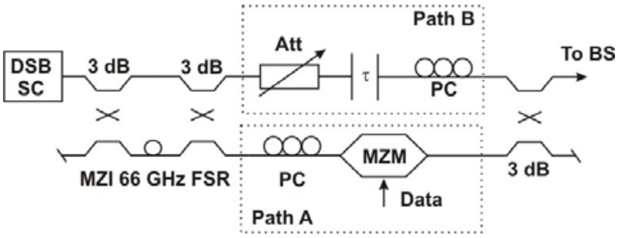


Fig. 2. Setup for the laser line separation and data modulation.

The carrier separation is carried out as shown in Fig. 2 corresponding to the setup used in [7]. By using an optical MZI with a Free Spectral Range (FSR) of $4f_m$, the two optical sidebands are guided in two different fiber paths with more than 30 dB rejection (Fig. 3a). One path (path A) is modulated in its intensity with the broadband baseband NRZ-signal while the other (path B) remains unchanged. An optical attenuator and delay line are added to path B in order to adjust the path difference and the power of the unmodulated carrier for optimum transmission. Afterwards, both signals are recombined by use of a broadband 3 dB coupler (Fig. 3b) and transmitted through an optical fiber link to the BS.

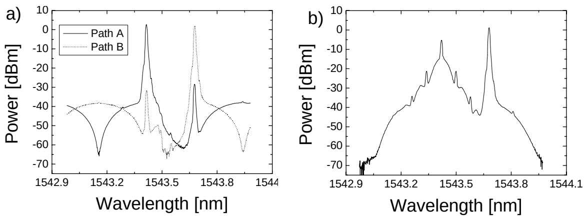


Fig. 3. Optical spectrum a) inside the MZI and b) resulting single sideband modulation of a 10 Gbps baseband data signal. The resolution was 0.01 nm in both graphs.

III. EXPERIMENTS

The setup for the transmission experiments is shown in Fig. 4. The dual wavelength source (DSB-SC in the figure) consists of a Distributed Feedback (DFB) laser modulated in its amplitude with f_m=16.5 GHz and biased at minimum transmission (as shown in Fig. 1) giving two coherent laser lines separated by $2f_m$=33 GHz with P= +5 dBm optical power and a laser linewidth of $\Delta\nu$=10 MHz each. The baseband data modulation consist of a 2^{31}-1 pseudo random binary sequence (PRBS) which is introduced by a Mach-Zehnder Modulator (MZM) in path A with a modulation index m=0.8. After recombination by a 3 dB coupler, an EDFA is used and its ASE is limited in bandwidth by an Optical Band Pass Filter (OBPF) with B=1 nm bandwidth.

The mm-wave signal is transmitted to a BS via a single-mode Fiber (SMF) link. In the BS the optical signal is converted to an ASK modulated mm-wave carrier by heterodyning in a broadband photodiode (PD) and sent through antennas to a Mobile Unit (MU). Fig. 4 shows a direct path from the BS to the MU which is used for test and back to back experiments before sending wireless data.

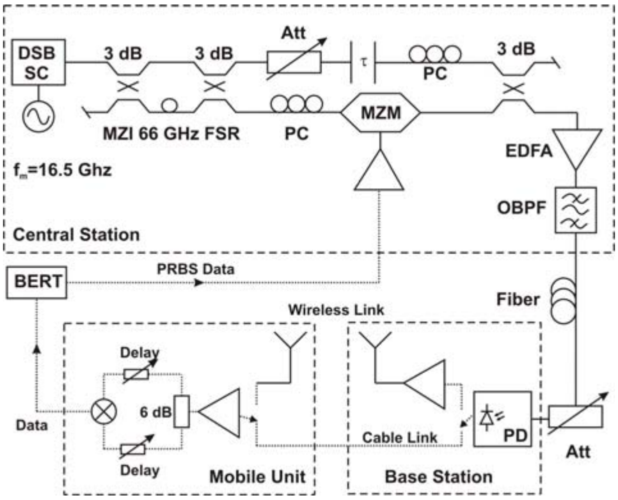


Fig. 4 Schematic of the setup used for the system experiments.

The receiver in the MU is based on the principle of self-homodyning the received signal. By splitting the mm-wave carrier in two paths with a broadband 6 dB resistive splitter and subsequent mixing of both signals, the mm-wave envelope can be detected and the baseband information retrieved independently of the actually used carrier frequency. In this configuration both electrical paths have to present equal delays for optimum mixing therefore electrical delay lines are needed. As the mixer requires a local power of P_{LO}= +12 dBm for optimum conversion, two broadband RF amplifiers (Centellax 2-50 GHz) have been included in the setup. This resulted in a baseband copy of the data being amplified which had to be filtered out. A more detailed diagram of the self-homodyne receiver is shown in Fig. 5. The cascaded Noise Figure (NF) of the system was calculated to be 5.05 dB before the 6 dB coupler according to Friis Equation [10].

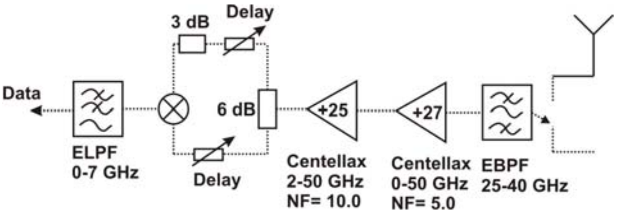


Fig. 5. Detailed setup for the self homodyne receiver in the MU (ELPF: Electrical Low-Pass Filter, EBPF: Electrical Band-Pass Filter, NF: Noise Figure)

The data rate of the baseband signal was varied from 2.5 Gbps up to 10 Gbps to test the systems susceptibility to dispersion. The mixer used (Miteq M2640W1) operates in the 26-40 GHz band so placing the mm-wave carrier at f=33 GHz limits the available baseband bandwidth to B=7 GHz. Fig. 6 shows the Bit Error Rate (BER) versus optical power at the photodiode for different fiber link lengths and data rates for the case of direct cable link between the BS and MU. No power penalty induced by dispersion could be observed and transmission distances up to 40 km were achieved. Longer fiber links could not be tested due to lack of further optical amplification.

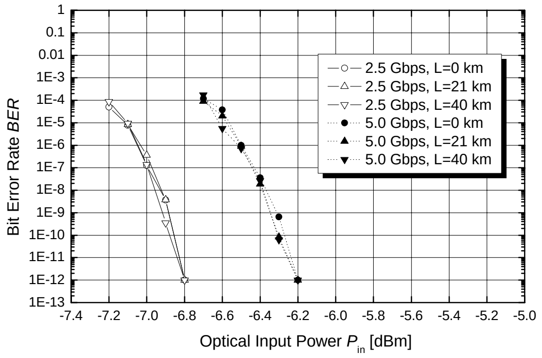
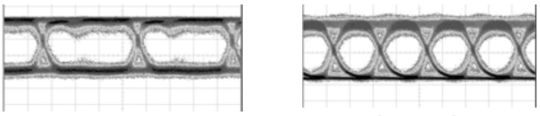


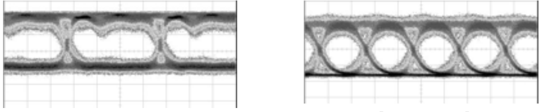
Fig. 6. BER vs. optical power at photodiode for different fiber lengths L and data rates for the cable transmission case.

Fig. 7 shows the corresponding eye diagrams for the cable transmission case at the BER Tester (BERT). There is no distortion observed even after 40 km of single-mode fiber transmission.

Fig. 8 shows the same transmission configurations as before but for the wireless transmission case. In this setup two broadband Vivaldi antennas (DRH40) with gain G=10 dB each were positioned d=1 m apart to demonstrate the principle. For direct and short air links, the path loss equals to PL=42±2 dB across the spectrum (carrier at 33 GHz±7 GHz and L=1 m) which requires usage of additional amplification.



2.5 Gbps – 0 km 5.0 Gbps – 0 km



2.5 Gbps – 40 km 5.0 Gbps – 40 km

Fig. 7. Eye diagrams for different fiber lengths for the cable transmission case

Unlike for the cable connection, the minimum error rates achieved for the air link are approx. BER= 10^{-8}, however, these values are several orders of magnitude within typical uncoded rate requirements for wireless transmission. Implementing error coding schemes, error free end-to-end data transmission can be expected.

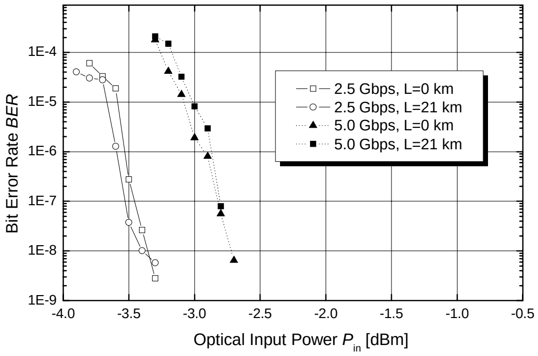
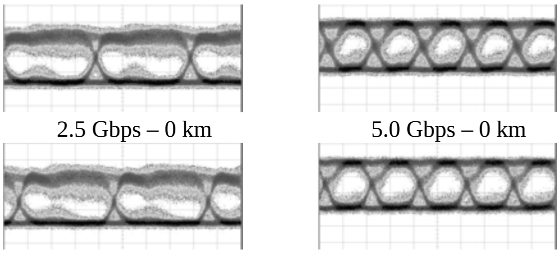


Fig. 8. BER vs. optical power at photodiode for different fiber lengths for wireless transmission over d=1 m.

The corresponding Eye Diagrams at the BERT are shown in Fig. 9. The signals appear distorted with respect to the cable transmission case which is the main cause for the increased error rates. Fiber dispersion has no evident effect in the signal, as the same performance was obtained after transmission over 21 km of single mode fiber. Wireless transmission demanded more electrical power than the cable transmission case that is why the 40 km fiber link couldn't be tested in our lab. Nevertheless, comparing the results in Fig. 6 and Fig. 8 it is reasonable to assume that with sufficient optical power or electrical amplification wireless transmission over L=40 km fiber is feasible.



2.5 Gbps – 0 km

5.0 Gbps – 0 km

2.5 Gbps – 21 km

5.0 Gbps – 21 km

Fig. 9. Eye diagrams for different fiber lengths for wireless transmission over d=1 m.

To test the limits of the setup, the data rate was increased to 10 Gbps. Error rates around 10^{-7} could be achieved, and further an air link has been realized with d= 0.7 m. For the cable link, the curves present the same slope even after 21 km of SMF still indicating immunity to dispersion effects on the mm-wave carrier. Nonetheless, dispersion effects on the baseband signal cannot be neglected, especially for data rates as high as 10 Gbps.

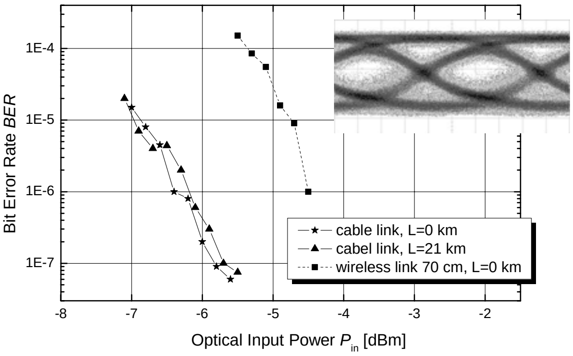


Fig. 10. BER vs. optical power at photodiode for 10 Gbps. (Inset: Eye diagram for L=0 km fiber link)

IV. CONCLUSION

This paper presents important advances made in the transmission of high bit rate mm-wave signals which are generated by heterodyning of optical signals. The data rate has been pushed as high as 10 Gbps, and was experimentally demonstrated for both a direct link as well as wireless transmission over d=1 m. After transmission distances up to 40 km of fiber, the mm-wave signal is produced in the BS by detecting an optical DSB-SC spectrum with an outstanding carrier suppression of more than 60 dB in a PD. There was no evidence of dispersion as a limiting factor for signal transmission up to 5 Gbps. The self-homodyne receiver provides independence of the mm-wave carrier frequency but requires high RF powers and a low noise figure. For 10 Gbps baseband signals the performance worsens and chromatic dispersion of the fiber may finally be a limiting factor for mm-wave transmission of broadband signals, needing further investigation. Also as mentioned in [4], the laser linewidth introduces a Carrier to Noise penalty that may prove critical for broadband signals.

ACKNOWLEDGEMENT

The authors wish to acknowledge the contributions of T. Schuster, M. Haas, N. Neumann and the kind support of Jens Peupelmann.

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