Low-Bandwidth Photonics-Assisted Receiver for Broad-Bandwidth Wireless Signals

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ABSTRACT

This paper introduces a photonics-assisted receiver that enables the reception of high-bandwidth wireless signals with low-bandwidth electronics. The receiver down-converts the input signal into parallel low-bandwidth sub-signals, employing photonics-based orthogonal sampling. This sampling is based on a multiplication and not switching, so, it does not introduce additional aperture jitter. Therefore, the photonics-assisted analog-to-digital converter (ADC) converts the wireless signal with a higher signal-to-noise-and-distortion ratio (SINAD), which improves the Q-factor for the detection. This Q-factor improvement is especially high, when the orthogonal sampling is carried out with low-jitter oscillators. Compared to the direct detection with 30 GHz, the simulation demonstrates a 2.2 dB Q-factor enhancement for the detection of a 30 GHz signal, with 10 GHz electronics. The same improvement is revealed in the experiment for the detection of 12 GHz signals with 4 GHz electronics.

INDEX TERMS

Orthogonal sampling, photonics-assisted receiver, photonic sub-sampling, wireless communications.

I. INTRODUCTION

Along with new radar, sensing, and communication applications, the signal bandwidth increases drastically [1]. The development of 6G and beyond, for instance, is expected to enable peak data rates of up to 1 Tbit/s [2]. Dependent on the parallelization, modulation format and shaping, this may require bandwidths of several tens of GHz [3]. With such high bandwidths the receiver, and specifically the analog-to-digital conversion (ADC), may encounter difficulties [4]. Furthermore, the bandwidth of electronic ADCs is a severe bottleneck for the detection and measurement of broadband signals [3].

In electronic ADCs, the initial stage is sampling, which is typically executed by sample-and-hold circuits [5], [6], [7]. However, at high bandwidths, clock and aperture jitter, as well as noise, can diminish the resolution of the ADCs, resulting in a decrease in the signal-to-noise-and-distortion (SINAD) ratio. This lower SINAD may increase the power consumption for the subsequent digital signal processing [5], [6], [7]. To mitigate the impact of jitter and sampling errors, as well as to reduce the requirements on subsequent electronic signal processing, the signal can be down-convert into several parallel low-bandwidth sub-signals. These sub-signals may then be detected and processed by low-bandwidth electronics. In [8], this down-conversion was carried out in the electrical domain by a fast sample-and-hold switch, for instance. However, this switching introduces an extra aperture jitter [9], which reduces the signal quality.

Due to its high bandwidth, low power consumption, immunity to electromagnetic interference, and the ability to be integrated [10], photonics-assisted signal processing may be a promising solution for such down-conversion. An optical solution can be spectrum slicing [11], where the
high-bandwidth input spectrum is sliced into low-bandwidth sub-spectra by a bank of filters. However, this method has very high demands on the filters and subsequent high bandwidth post-processing. An alternative may be provided by temporal magnification [12], [13]. For these methods, the high-bandwidth input signal is first sliced in the time domain and then the slices are timely stretched and processed with low-bandwidth electronics in parallel branches. However, a time magnifier typically requires a strong first-order dispersion, that is difficult to integrate and is accompanied by higher-order dispersions that may distort the signal.

Here, we demonstrate a photonics-assisted receiver based on orthogonal sampling for the down-conversion of the high-bandwidth signal into low-bandwidth sub-signals. These sub-signals are then sampled and processed in parallel branches using conventional low-bandwidth electronic ADCs [14]. The orthogonal sampling multiplies the incoming signal with a sinc-pulse sequence, which is generated and multiplied simultaneously by a low-bandwidth optical modulator driven with one or several equidistant sinusoidal radio frequencies. Since orthogonal sampling is based on a multiplication and not a switching, like in electronic sample and hold circuits, there will be no additional aperture jitter. Additionally, it can be shown mathematically [14] that each bandwidth limited signal is the superposition of time shifted sinc pulse sequences, periodically weighted with the sampling points. Due to the orthogonality between the sequences, for ideal components the retrieving of the periodic sampling points would be possible without any error. But even for non-ideal devices, the sampling is very accurate. We have successfully presented this method for the detection of high-bandwidth optical communication signals with low-bandwidth detectors [15]. Here we extend the idea to wireless signals.

The main difference in detecting wireless signals is that the signal-to-noise ratio (SNR) is predominantly determined by the input noise of the receiver [16]. Additionally, the wireless input must be converted to an optical signal, which allows for parallel processing in $N$ parallel branches without dividing the signal power by $N$. A simulation analysis and preliminary experiments will be presented. Such a low-bandwidth photonics assisted receiver may be of great interest for the next generation of wireless communications, radar, and measurement applications.

**II. PRINCIPLE OF OPERATION**

The basic concept of the photonics-assisted receiver is shown in Fig. 1. First, the wireless signal $s(t)$ is detected and converted into the baseband by a mixing with the carrier frequency [17]. Subsequently, the in-phase (I) and quadrature (Q) components of the baseband signal are directed to an optical I/Q modulator. However, for amplitude modulated signals below 300 GHz, down-conversion to the baseband may not be necessary. In such cases, an antenna-coupled optical intensity modulator with a bandwidth of 300 GHz can be adequate. Such high-bandwidth modulators have been shown as integrated devices [18].

The I/Q modulator converts the wireless signal with bandwidth $B_s$ into $p$ identical optical signals, each with an optical bandwidth of $B = 2B_s$. In Fig. 1 each of the $p$ signals has another wavelength to avoid the power splitting for a single source but, instead just one single laser with $p$-times the optical power can be used. A wavelength division demultiplexer copies the optical waves modulated with the wireless signal into $p$ branches. The information conveyed by the wireless signal $s(t)$ remains identical in each of the branches.

An intensity modulator, like a Mach-Zehnder modulator (MZM) driven with one or a number of $n = (p-1)/2$ sinusoidal radio frequencies (RFs), is employed for the
orthogonal sampling of $s(t)$ [19], [20]. To get the whole information from the signal, in each of the $p$ branches, the same signal is sampled with the same sampling rate but, at a different sampling time. The adjustment of the sampling time is achieved by a phase shift of the RF frequencies between the branches of $\phi = 2\pi/p$ [21], [22], [23].

In the frequency domain, the modulator convolutes the signal spectrum with a rectangular frequency comb with the bandwidth $B = p\Delta f$, with $\Delta f$ as the frequency spacing between the comb lines and $p$ as the number of lines. In the equivalent time domain, this results in a multiplication of the input signal with a sinc-pulse sequence with bandwidth $B$ and a repetition rate of $B/p$. Therefore, no pulse or high bandwidth source is necessary. The generation of the sinc pulse sequence and its multiplication with the signal is done simultaneously in the modulator, driven with the sinusoidal radio frequencies. The radio frequencies can be generated with integrated oscillators with jitter values of 20 fs [24]. In the single branch, the signal is sampled with a sampling rate of $B/p$. The sampling can be very fast and it does not depend on any switching, which means that there is no additional aperture jitter and the low jitter of integrated oscillators can be directly transferred to the sampling.

For $p = 3$ and a single modulator in each branch, the required electrical bandwidth of the modulator and that of the RF oscillator is just $\Delta f$ and the total real-time sampling rate of the $p$ branches together is $3\Delta f$. Thus, a sampling rate of three times the RF bandwidth of the modulator and the oscillator can be achieved. However, with integrated silicon modulators even up to six times the bandwidth of the modulator has been shown in experiments [15]. Thus, with 100 GHz integrated modulators and just three branches, 150 GHz or even 300 GHz wireless signals can be sampled.

Since each signal limited to the bandwidth $B$ can be seen as the superposition of sinc-pulse sequences with the same bandwidth $B$, time-shifted to each other by $1/B$ and weighted with the sampling points and due to the orthogonality of these sequences, the periodic sampling can be error-free. This periodic sampling is just the multiplication of the signal $s(t)$ with a sinc-pulse sequence with the right bandwidth and time shift, leading to a frequency down-conversion of the high bandwidth input signal. The down-converted signals are then further processed in each branch by a coherent detector (CD) and an ADC of bandwidth $B/(2p) = B_c/p$.

### III. SIMULATION AND EXPERIMENTAL RESULTS

To study the effect of jitter and the influence of noise on the detection, simulations with the Optisystem software from Optiwave were carried out.

#### A. SIMULATION RESULTS

The simulation setup is shown in Fig. 2. To compare the photonics assisted low bandwidth receiver with a conventional broad bandwidth device, for the simulation as well as for the experiment the broadband signal will first be directly detected with a high-bandwidth receiver, as shown in Fig. 2(a). This will then be compared with the proposed method, which is depicted in Fig. 2(b). For the wireless signal, we have assumed, that it has already been detected by the antenna and down-converted to the baseband. Thus, we employ a 60 Gbd binary phase shift keying (BPSK) electrical baseband signal, limited to its Nyquist bandwidth of 30 GHz. For the direct measurement (Fig. 2(a)), an MZM converts the signal into the optical domain at a frequency of 193.1 THz (C-band of optical telecommunications). A CD and an ADC with a bandwidth of 30 GHz are utilized to detect and process the signal. To analyze the SNR behavior of the receiver, an optical signal-to-noise ratio (OSNR) component (provided by the software) adds white noise of different power to the signal directly before detection.

The proposed low-bandwidth photonics-assisted receiver is simulated with the setup depicted in Fig. 2(b). Here the signal is modulated to three multiplexed laser beams at optical frequencies of 193.1 THz, 193.2 THz, and 193.3 THz (C-band of optical telecommunications) by a single modulator and then copied to three branches by a wavelength demultiplexer (DMUX). In each branch, a single MZM driven with a 20 GHz sinusoidal radio frequency (RF) from an oscillator samples the 60 Gbd Nyquist signal by a sinc-pulse sequence, generated simultaneously in the same modulator. The RF defines the sampling rate of the single branch to 20 GSa/s. In the next branch, the same signal is sampled with a time-shifted version of the sinc-pulse sequence. For the time shift, the electrical phases of the RF frequency in the three branches are 0°, 120°, and 240°, respectively. As revealed by simulations, slight changes in phase of a few degrees will not have a significant effect on the signal detection. A CD and ADC with only 10 GHz bandwidth detect and process 1/3rd of the 30 GHz signal in each branch. Optical amplifiers followed by bandpass filters for noise reduction are used, to make the simulation similar to the experiment. For each optical amplifier, a noise figure of 6 dB has been assumed. These amplifiers and filters are not needed if the optical power of the laser diodes would be high enough.

![FIGURE 2. Simulation setup for the reception of a 60 Gbd BPSK signal with Nyquist shape (30 GHz) using (a) a 30 GHz receiver and (b) the 10 GHz photonics-assisted receiver. Here again, the black lines represent the electrical and the colored ones the optical signals at different wavelengths. RF: oscillator, providing one single sinusoidal radio frequency, SG: signal generator, AMP: optical amplifiers, BPF: optical bandpass filter, OSNR: optical signal-to-noise ratio, OSC: oscilloscope.](image-url)
The proposed system has two sampling stages, first the orthogonal sampling in the MZM and then the second sampling in the electronic ADC with a sample and hold switch. Since the first sampling is based on multiplication with a sinc pulse sequence and not a switching, it shows no aperture jitter and the low jitter values of the oscillator can be directly transferred to the sampling. Therefore, for the jitter analysis, the jitter value of the oscillator and the ADCs have been swept. For a fair comparison between both methods, the optical powers at the points (p1) and (p3) in Fig. 2 are equal, the same holds for the points (p2), (p4), and (p5). The relative intensity noise (RIN) of the lasers was assumed to be -140 dBc/Hz and the linewidth was 1MHz.

Figure 3(a) depicts the transmitted and received signal reconstructed from the three sub-signals (Fig. 3(b, c and d)) with the black and red trace, respectively. As shown, both signals are basically the same. The root mean square error for the difference between the signals was calculated as 2.18%.

To analyze the quality of the system, we performed a Q-factor analysis of the received signal. The Q-factor as a function of jitter is shown in Fig. 4(a) and (b). The blue curve demonstrates the direct measurement with a high-bandwidth electronic ADC and the red one represents the photonics-assisted method proposed here. As can be seen from Fig. 4(a), if the jitter of the first and second stage is the same, there is an improvement by the proposed method up to a jitter value of 850 fs. This is mainly due to the fact, that the first sampling stage down-converts the bandwidth of the signal by 3, which enhances the resolution of the subsequent electronic ADC [25]. For jitter values below 100 fs, the improvement is around 2.3 dB.

As mentioned above, for the proposed method the low jitter of clock sources can be directly translated to the sampling in the first stage but, electronic ADC will have an additional aperture jitter. So, for the same jitter of the clock source, the jitter of the first stage can be much lower than that of the second. Therefore, for Fig. 4(b) the jitter of the first stage was kept constant at 100 fs, (even integrated oscillators can have jitter values of 20 fs [24]), whereas the jitter of the electronic ADC was swept. As can be seen, the achievable improvement increases with the jitter of the electronic ADC, and above 2 ps the 60 Gbd signal cannot be detected anymore by the broadband receiver, since the resolution becomes too low. But if the signal is down-converted to 10 GHz by orthogonal sampling, even electronic ADCs with a jitter of 8 ps are still able to process the signal.

In Fig. 4(c) the Q-factor improvement for a 100 fs jitter of the first and second stage in dependence of the OSNR is shown. We have started with an OSNR value of 25 dB, since the output power of our noise source in the experiment was quite low. Please note that this improvement comes additionally. The main advantage of the method is, that it enables the processing of high-bandwidth signals with low-bandwidth electronics.
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FIGURE 5. Experimental setup for the detection of the 24 GBd Nyquist shaped QPSK signal (12 GHz bandwidth) with a 12 GHz receiver (a), and the proposed method (b) utilizing just 4 GHz. Please note that for the 4 GHz case the same detector was used. The bandwidth was restricted to 4 GHz by a software filtering of the detected baseband signal. The whole signal was detected by changing the phase of the RF signal subsequently by 0°, 120°, and 240°. AWG: arbitrary waveform generator, EDFA: erbium doped fiber amplifier, PC: polarization controller, VA: variable attenuator, NS: noise source, and LO: local oscillator.

B. EXPERIMENTAL RESULTS

The experimental setup, as shown in Fig. 5, follows in principle the simulation setup. We assumed that the wireless signal has already been detected by an antenna and down-converted to the baseband. The main difference between simulation and experiment is that due to a lack of equipment, we have investigated just one of the branches. Since pseudo-random bit sequences (PRBS) are periodical, the information from the whole signal can be taken subsequently by changing the phase of the RF frequency driving the MZM. We assume this as justified, since the only difference to the parallel detection is, that the signal has to be periodic. However, periodic signals like PRBS sequences are widely used in laboratory experiments. Additionally, in the experiment, we have used a 24 GBd QPSK signal limited to its Nyquist bandwidth of 12 GHz, generated by two arbitrary waveform generators (AWGs) (Tektronix AWG70001A) with a sampling rate of 50 GS/s. An I/Q modulator is used to convert the signal to the optical domain at a wavelength of 1550 nm. The laser diode has a RIN of around -140 dBc/Hz and 0.1 MHz linewidth.

For the direct measurement (Fig. 5(a)), the signal is directly detected and processed using a CD followed by an ADC of 12 GHz bandwidth. To analyze the noise performance, white noise from a broadband light source (NS) is added directly to the input of the receiver. The amplitude of the noise is varied by a programmable variable attenuator (VA).

For the proposed method (Fig. 5(b)), the 24 GBd QPSK Nyquist signal is sampled with an MZM, driven by an 8 GHz sinusoidal RF frequency and an input RF power of 15 dBm, generated by a radio frequency generator (RFG) (Agilent E8257D) with approximately 76 fs measured timing jitter. After sampling, the 12 GHz signal can be measured and processed by a CD and an ADC of only 4 GHz bandwidth. However, the CD and ADC were the same as for the direct measurement, but the bandwidth was restricted to 4 GHz after down-conversion by a software filter, provided by the measurement device. We expect even better performance if low bandwidth detectors and ADCs are used. In this case, the transimpedance amplifiers after the photodiodes can have higher quality and the electronic ADCs may have a higher resolution.

The Q-factor measurement has been done by an electrical sampling oscilloscope (Tektronix DP073304SX). To allow a fair comparison between the methods, the powers at points (p1) and (p2) in Fig. 5 are kept identical during the experiments. The Q-factor of the I and Q components of the 24 GBd QPSK signal (48 Gbit/s data rate and 12 GHz bandwidth) directly measured with a 12 GHz receiver (blue trace) and with a 4 GHz receiver by the proposed method (red trace) are shown in Fig. 6(a) and (b). For comparison, the blue trace
represents the detection of a 24 Gbd QPSK Nyquist signal (12 GHz bandwidth) with a 12 GHz detector. The proposed photonics-assisted receiver of just 4 GHz bandwidth shows a 2.2 dB Q-factor enhancement. This improvement can as well be seen in the constellation and I/Q eye diagrams in Fig. 6(c) and (d).

The required bandwidth of the detectors and electronics can be further reduced by increasing the number of branches, which leads to a further improvement of the Q-factor for the detection. Such a higher parallelization may be especially interesting for integrated systems.

It should be noted that the parallelization of the signal and the insertion loss of the MZM for down-conversion results in a power penalty for the detection. However, this loss can be compensated for by increasing the power of the laser or by higher amplification. Since we assume, that for the wireless signal the main noise comes from the detector, this amplification will not reduce the signal to noise ratio. Additionally, the electrical power consumption of the single electronic signal processing is reduced with bandwidth, the overall power consumption might increase with the number of additional components required for parallelization. This requires further investigations.

The implementation of standard, stand-alone photonic components in such a receiver system can be quite costly and power consuming. However, since the method only needs standard optical and electrical components, all of which with low bandwidth, integrating the complete photonic and electronic functionality on the same electronic-photonic platform can be possible [26], [27].

IV. CONCLUSION

In conclusion, a concept for a low-bandwidth photonics-assisted receiver for detecting and processing wide-bandwidth wireless signals based on orthogonal sampling was demonstrated. Since orthogonal sampling just needs sinusoidal signals from an oscillator and shows no aperture jitter, the very low jitter values of integrated oscillators can be directly transferred to a performance enhancement of the detection. Hence, this method is particularly useful if the oscillator has lower jitter than the electronic ADC. Additionally, since only off-the-shelf low-bandwidth devices are required, the method can be integrated into any electronics-photonics platform and offers a solution to keep up with the rising data rates and bandwidths in wireless communications, radar, sensing, and measurement applications.

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REFERENCES


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