Phase-Noise Degradation of an Optically Distributed Local Oscillator in a Radio Access Network

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Abstract. *The experimental evaluation of the phase-noise degradation of an optically distributed opto-electronic oscillator (OEO) signal is presented. The assembled setup is simulating a possible topology for a 5G radio access network (RAN), in which the local oscillator (LO) signal is distributed from the central-office to the base-stations via an existing optical distribution network (ODN). The OEO in our experiment has a phase noise of −105 dBc/Hz and −124 dBc/Hz at 1 kHz and 10 kHz offsets from the 10.5 GHz carrier, respectively. The degradation of the phase noise of the signal distributed to the base-station within a distance of 20 km is within 4 dB and 6 dB for 1 kHz and 10 kHz offsets from the carrier, respectively. These are promising results for further research and the development of the 5G RAN with a centralized OEO signal distribution.*

Keywords

Opto-electronic oscillator, phase-noise degradation, microwave, radio access network, optical distribution network

1. Introduction

High-frequency oscillators are key components in various engineering and scientific fields such as radar technology, satellite communications, radio communications, and particle physics. Phase noise (often referred to as short-term stability) is one of the significant parameters reflecting oscillator performance. An opto-electronic oscillator (OEO) is a superior solution for producing a low-phase-noise signal in the microwave and millimeter-wave ranges by employing a long delay line as a resonator [1,2]. Adding to its attraction, the phase noise of the OEO is independent of the oscillating frequency [3]. The converging optical and electronic technologies in the OEO provide the optical and electrical output simultaneously [4]. The lowest phase noise achieved with an OEO is −163 dBc/Hz at a 6 kHz offset from the carrier frequency (where a 10 GHz signal is generated by employing a 16 km optical fiber) [5].

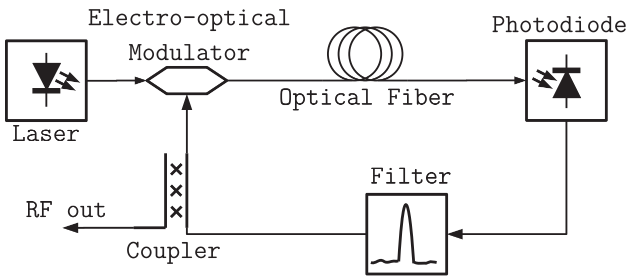

Fig. 1. Basic conceptual topology of single-loop OEO.

The simplest configuration of the OEO is shown in Fig. 1. In its simplest form, a delay line in the OEO's loop is implemented with an optical fiber that acts as a resonator with a high quality factor. Such a simple OEO consists of a modulated light source, usually a continuous wave (CW) laser with an external electro-optic Mach-Zehnder modulator (MZM), a photodiode, and an electrical bandpass filter (BPF), as shown in Fig. 1. The electrical end of the chain is connected back to the MZM, thus completing the OEO's loop. The real components in Fig. 1 have some insertion loss, which means an electrical amplifier has to be inserted to achieve the oscillating conditions. Such an OEO starts to oscillate at the central frequency defined by the bandpass filter when the Barkhausen condition is satisfied. The spectral power density of the OEO is then [3]:

$$S_{\mathrm{RF}}(\Delta f) = \frac{\delta}{(\delta/2\tau)^2 + (2\pi)^2(\tau\Delta f)^2}. \tag{1}$$

For $2\pi\Delta f\tau << 1$, where τ is the total group delay of the OEO loop, Δf is the frequency offset from the oscillation frequency of the OEO and δ is the noise-to-signal ratio [3]. The noise-to-signal ratio is [3]:

$$\delta = \frac{\rho_{\mathrm{N}} G}{P_{\mathrm{osc}}} \tag{2}$$

where ρ_{N} is the sum of the noise power density contributions, G is the power gain of the electrical amplifier and P_{osc} is the RF power of the OEO [3].

Even though an OEO provides benefits compared to electrical oscillators, some drawbacks need to be considered.

The multi-mode operation of the oscillator is one such drawback. The OEO oscillates at frequencies separated by the free spectral range (FSR), which is defined by the length of the delay. The desired frequency is selected with the electrical BPF in the OEO loop. However, since the FSR is in the range of ∼1 kHz up to few 100 kHz the BPF is not able to select a single frequency, thus unwanted side modes are present in the output spectrum. The dual-loop (or the multi-loop) OEO configuration is proposed to improve the side-mode suppression ratio (SMSR). An additional optical delay line is added in parallel with the loop to suppress the side modes [6–8]. A microwave photonic mixer is proposed to enhance the free spectral range of the OEO [9]. A whispering-gallery-mode resonator or optical filters can also be used to improve the SMSR [10–12].

Another challenge when designing an OEO is the long-term stability, also known as the frequency drift. This is mainly due to ambient-temperature variations and the component aging. To improve the long-term stability of the OEO signal, a feedback-control loop [13] or a phase-locked loop [14] can be used. As an alternative to the bulky implementation using an optical fiber, the fully-integrated OEO was also presented [15], thus minimizing the size of the OEO, where the phase noise was experimentally measured to be -91 dBc/Hz at 1 MHz offset from the carrier. Nevertheless, the simple single-loop OEO is still widely used. In this paper, we propose the use of a simple single-loop OEO in the central-office of a 5G RAN.

The rest of this paper is organized as follows. In the next section we introduce the implementation of the centralized OEO signal distribution in a 5G RAN. Section 3 presents the experimental work measuring the phase-noise degradation of the OEO signal in the presence of the optical distribution network between the central-office and the base-station. The influence of distance from the central-office on the signal's noise is also presented here. The concluding remarks and further work can be found in Sec. 4.

2. OEO Implementation in a 5G RAN

In the current 4G RAN the data signal is delivered from the central-office to the base-station using a radio-over-fiber system. At the base-station the received optical data signal is converted to the electrical signal by a photodiode. Electrical amplifiers and filters are used to compensate for the losses and suppress the unwanted responses. An electrical local oscillator (LO) is used for the frequency up and down conversion of the data signal [16]. This requires each base-station to have its own LO. In order to keep the base-station simple and cheap, electrical microwave oscillators are deployed with inferior phase-noise characteristics. Phase noise has a direct impact on the quality of the up and down converted data signal [17]. Unfortunately, the use of frequency multiplication for the high-quality quartz-crystal oscillator is limited due to the phase-noise increase by 6 dB with each doubling of the frequency [18]. Millimeter-wave bands are expected to be used in a 5G RAN [19]. One of the main aims of the 5G RAN is to improve the spectral purity. The centralized oscillator signal distribution was introduced in [20, 21]. This reduces the complexity of the base-stations, lowering the cost and reducing the constraint on temperature stabilization. We propose to employ the OEO as a centralized LO that is distributed to multiple base-stations for frequency up and down conversions. The main advantage here is that the OEO already has the oscillating signal in the optical domain and thus an additional electrical-to-optical conversion is not required. The proposed topology of the 5G RAN with a centralized OEO is presented in Fig. 2.

In the proposed RAN configuration the OEO placed in the central-office is performing the task of the LO in the base-station. The OEO can generate the mm-W signal with a high spectral purity, thereby improving the performance of the 5G RAN. Taking into account that only one OEO is needed for several base-stations, a more complex configuration of the OEO is possible than the one presented in the following. The OEO in a real system would need at least temperature stabilization or some other kind of control loop to provide the long-term stability.

The data signal and the LO signal can be delivered via the same optical fibre using dense wavelength-division multiplexing (DWDM). In other words, the existing infrastructure can be used to distribute the data signals and the OEO signal. The current 4G RAN uses digital radio-over-fiber technology (D-RoF) [22] to deploy the data to the base-station. Our proposal uses analog radio-over-fiber (A-RoF) technology for the OEO signal distribution. Compared to a D-RoF system, no digital signal processing is required in the base-station, providing low latency and, as mentioned, it reduces the complexity and cost. We measured the phase noise of the microwave OEO signal located in the central-office and the distributed OEO signal in the base-station. To the best of our knowledge, we present the first experimental study of a centralized OEO signal distribution to base-stations via an optical distribution network (ODN). In the next section the experimental results are presented and discussed.

3. Experimental Work

A simple single-loop OEO was assembled for the experiments. It must be emphasized that the OEO was assembled with components available in the laboratory and was subsequently treated as a black box, so the parameters were predetermined rather than chosen and no attention was paid to optimizing the OEO. As a result, the carrier frequency of the OEO is 10.5 GHz, which is determined by the available electrical BPF. The authors are aware that this frequency is not included in the proposed standards for 5G RAN. However, since the OEO has stable and frequency-invariant phase-noise characteristics, we believe that the results obtained for the microwave OEO should also be valid for the millimeter-wave

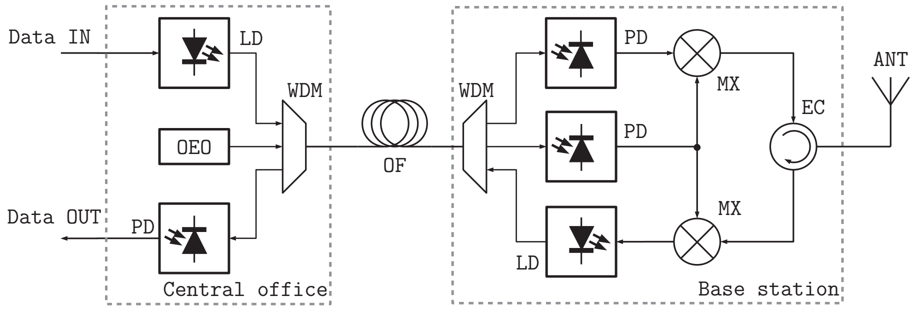

Fig. 2. Proposal of radio access network with centralized OEO distributed over an optical network. LD: laser diode, PD: photodiode, WDM: wavelength division multiplexer, OF: optical fiber, MX: mixer, EC: electrical circulator, ANT: antenna.

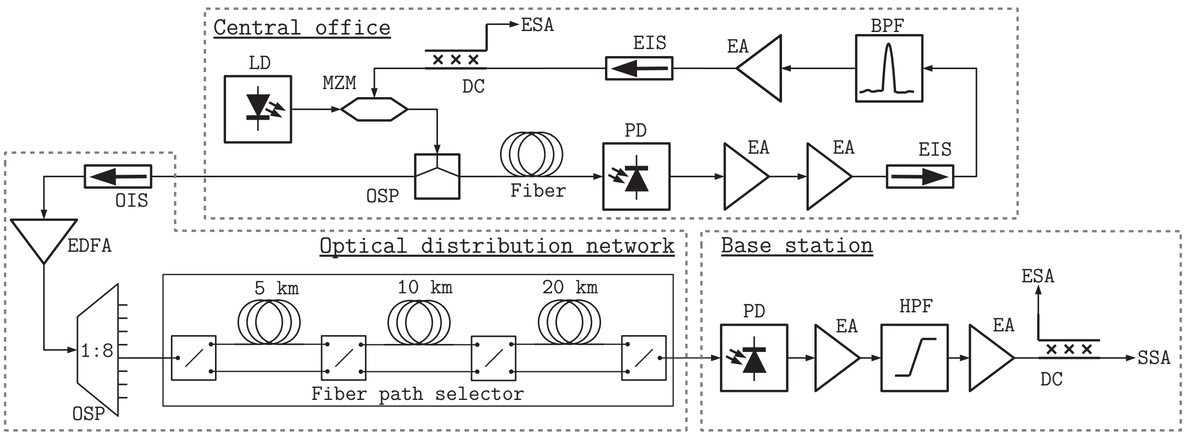

Fig. 3. Phase-noise degradation over an optical distribution measurement setup. LD: laser diode, MZM: Mach-Zehnder modulator, DC: directional coupler, ESA: electrical spectrum analyzer, EIS: electrical isolator, EA: electrical amplifier, BPF: bandpass filter, HPF: highpass filter, OSP: optical splitter, PD: photodiode, OIS: optical isolator, EDFA: erbium-doped fiber amplifier, SSA: signal source analyzer.

OEO. The experimental setup consists of three parts: central-office, ODN, and base-station. The centralized OEO signal is distributed from the central-office to multiple base-stations via the ODN. The main aim of the experiment is to measure the phase-noise degradation of the signal received by the base-station at various optical distances. This means that to support the preliminary idea of a centralized OEO signal distribution, the base-stations should receive oscillator signals that have the same or similar phase-noise characteristics, where they have different distances from the central-office due to their geographical location. The complete configuration of the experimental setup is shown in Fig. 3. The central-office employs a single-loop OEO consisting of a 1550 nm DFB laser with a MZM, an optical splitter, 15 km of optical fiber spool, a photodiode with a 11.5 GHz bandwidth, electrical amplifiers, and an electrical BPF. The optical splitter is inserted after the MZM in the oscillator's loop. The optical signal is taken to the ODN. This is realized with a 1:8 splitter and a preceding erbium-doped fiber amplifier (EDFA) to compensate for the insertion loss of the splitter. Following the 1:8 splitter is an optical path selector (which has 5 km, 10 km and 20 km optical fiber spools), which makes it possible to change the length of the fiber from 5 km to 25 km with a step of 5 km. The optical isolator is also used to separate the ODN from the central-office and prevent any potential reflections from interfering with the OEO. Even though only one base-station is implemented, the 1:8 splitter is placed in the ODN to include the possibility of distributing the signal to multiple base-stations. As mentioned, the optical path selector is used to provide a variation of the optical distance between the central-office and the base-station, thus enabling an observation of the phase-noise measurements as a function of the distance. Finally, the base-station is implemented simply as a photodiode, followed by a high-pass filter and amplifiers, which lift the signal to the appropriate level to be analyzed by a Keysight 5052B signal-source analyzer (SSA). The electrical amplifiers can also be understood as a necessary part of the distribution system, given the fact that the microwave mixer requires sufficient power to drive the LO input. Electrical spectrum analyzers (ESAs) are used in both the central-office and the base-station to manually observe the precise frequency and output power of the OEO signal. The phase-noise measurement of the centralized OEO is given in Fig. 4. The measured phase noise is −105 dBc/Hz and −124 dBc/Hz at 1 kHz and 10 kHz offsets, respectively. Even though these values are considered promising results for a central frequency of 10.5 GHz, a number of publications reported better phase-noise results for the OEO at the same or comparable central frequencies. However, the aim of this paper is not to provide an optimized solution for the OEO, yielding a phase noise better than that achieved until now, but rather to propose a prototype of the system topology in order to study the phase-noise degradation of a signal being optically distributed. Fig. 5 shows the phase-noise measurement of the OEO signal received at the base-station that is 20 km from the central-office.

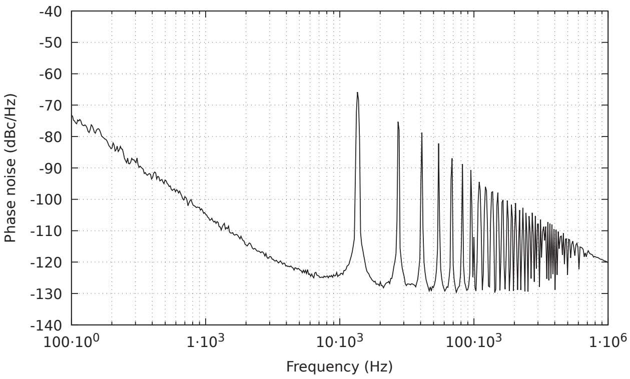

Fig. 4. Phase noise measurement of the single-loop OEO implemented in the central-office of the 5G RAN.

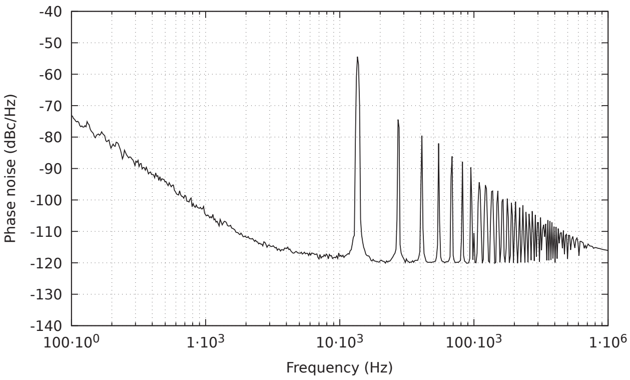

Fig. 5. Phase noise measurement of distributed OEO signal at the base station 20 km from central station.

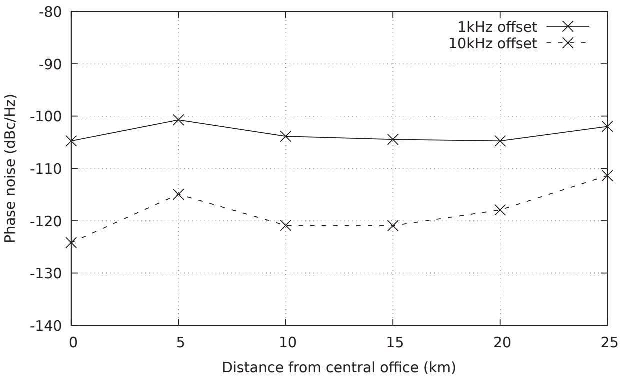

Fig. 6. Phase noise at the base station at 1 kHz and 10 kHz offsets from the carrier for different optical distances from the central office. NOTE: 0 km measurement is taken in the central office without ODN.

The phase noise is measured to be −105 dBc/Hz and −118 dBc/Hz at 1 kHz and 10 kHz offsets from the carrier, respectively. The combination of phase-noise measurements at different optical distances from the central-office is given in Fig. 6.

The measurements show that the phase-noise degradation for distances up to 20 km is within 4 dB and 6 dB for 1 kHz and 10 kHz offsets from the carrier, respectively. Current optical distribution networks rarely exceed distances of 20 km from the central-office, which is favorable for the achieved result. We believe that the Rayleigh scattering and interferometric noise might cause the phase-noise degradation for optical signal distribution. Since the generation of millimeter-wave signals is not an easy task and the phase noise is the crucial limitation of the signal purity [23], we believe that the implementation of an OEO in a 5G RAN could be a beneficial approach to deliver the required LO signal to the base-stations.

With the distribution of the millimeter-wave signal using a C-band wavelengths carrier, the problem of a power penalty due to the chromatic dispersion arises. To overcome the power penalty, SSB distribution could be implemented by employing a dual-drive MZM [24] or an optical filter [25], or applying a phase-shift method [26]. In [27] we propose a flexible solution employing a tunable dispersion compensation module (TDCM) to compensate for the chromatic dispersion. With that approach, the power-penalty-free signal distribution is obtained from 10 MHz to 45 GHz. However, adding the TDCM to the base-station increases its complexity. As only one antenna is shown in Fig. 2, time-division duplexing [28,29] is one possible solution for multiplexing different users.

4. Conclusion

The phase-noise measurement of a single-loop OEO and its distribution to the base-station via an ODN is experimentally demonstrated. The phase-noise results indicate the feasibility of using an OEO as a centralized LO for a 5G RAN. The OEO prototype is implemented due to the availability of the components and equipment for experimental research in the microwave domain. Phase-noise degradation is achieved within 4 dB and 6 dB for the 1 kHz and 10 kHz offsets from the carrier signal to an optical distance of 20 km. Although the experimental studies were performed in the microwave range, the measurements should also be valid for the millimeter-wave range since the phase-noise characteristics of the OEO do not change with the operating frequency.

In the future, the work can be extended with experimental studies on the power penalty due to chromatic dispersion, which is a limitation of the OEO signal distribution in the millimeter-wave range. The techniques to combat the chromatic dispersion of the distributed signal should also be addressed in future research. Our goal is to extend the experiment to also include a data signal and have its integrity measured in terms of the bit error rate (BER) and the throughput. This, together with the use of standardized 5G frequencies, would give a more complete insight into the behavior of the proposed RAN.

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