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Analysis of oscillator phase noise effect on high order QAM links

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Abstract

In this work, the effect of oscillator phase noise on the bit error rate (BER) for high order QAM communication systems is analyzed. Two high frequency oscillators are designed, built and tested to get real phase noise data, and a BER simulation of a 1024 QAM signal through a super-heterodyne frequency down-converter is implemented using the measured data from the two oscillators as local oscillator sources for the down-converter. A third frequency source is also added to the simulation to visualize the dramatic effect of phase noise on the system BER analysis.

Keywords Phase noise · Oscillator · Opto-electronic oscillator (OEO) · Dielectric resonator oscillator (DRO) · Bit error rate (BER) · Frequency down-converter · 1024-QAM

1 Introduction

Modern communication systems are built by exhaustive frequency planning and optimization. These systems operate at various frequencies which are up/down converted for digital signal processing. One of the commonly used methods for frequency conversion is super-heterodyne topology [1]. In this method, the input signal (RF) to a receiver is "mixed" with a local oscillator signal (LO) for up/down conversion at multiple stages to get the sum or difference of the RF and LO signals. The resulted signal is a filtered intermediate frequency (IF) at the output of the receiver that can be digitized by an ADC for signal processing [2]. A basic down-converter block diagram is shown in Fig. 1.

Different types of oscillators can be used as local oscillator sources, and each type has various advantages and disadvantages to consider while designing an optimized RF communication system. In this manuscript, the effect of phase noise parameter of the local oscillators on bit error rate of a receiver is analyzed. For our analysis, a Dielectric Resonator Oscillator (DRO) and an opto-electronic oscillator (OEO) are designed, built and tested and the measured phase noise data of these oscillators are used in the BER analysis of a frequency down-converter using a microwave simulation tool called AWR Microwave Office.

The outline of this manuscript is as follows: The second section briefly describes the DRO design, and presents the measured phase noise results of the constructed DRO. The following third section explains OEO design and construction. The measured phase noise data for the OEO is also presented in this part. The fourth section covers the BER simulation setup, the simulation results and the discussion on how phase noise affects the performance of high order QAM communication systems.

2 DRO design

The first high frequency local oscillator source we have designed to use with the receiver simulation is a dielectric resonator oscillator that operates at around 18 GHz center frequency. The frequency is selected to match the frequency planning of a microwave receiver that is being developed for our research.

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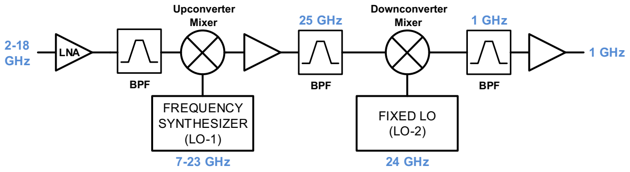


Fig. 1 Basic RF down-converter block diagram

The DRO is preferred for its small size, high stability, good phase noise performance and high oscillation frequency values. The downside is that, DROs oscillate at a single frequency, which requires both mechanical and electronic tuning to be able to get a locked, accurate and stable signal.

There are several ways to design a DRO, one of which is series feedback method, as seen in Fig. 2 [3]. This topology is chosen for its simpler structure. To build a DRO, a dielectric material and an active device are required. The dielectric material is selected according to the material's resonation frequency. The active device consists of an oscillating circuit with feedback element. In our case, we achieve the oscillation by using a high frequency transistor in its nonlinear region. The oscillation signal is reflected from the coupled line at the resonance frequency of the dielectric material, which is placed close to an RF microstrip line to achieve maximum coupling. The resonance frequency of the dielectric, hence the output of the DRO shifts when a metal surface is brought closer to the dielectric material. This action provides the mechanical – "bulk" tuning of the oscillator. For "fine" tuning and getting a stable signal locked to a reference frequency, a phase locked loop (PLL) structure should be used, that is shown in Fig. 3. By means of using a PLL, the free-running high frequency DRO output can be locked to an external reference frequency [4].

After building a free running DRO, the performance of the device is tested. A picture of the developed DRO is shown in Fig. 4. The RF spectrum and phase noise measurement results of our 18 GHz DRO are given in Figs. 5 and 6, respectively. The phase noise measurement graph starts from −95 dBc/Hz at 1 kHz offset frequency and remains nearly constant until 35 kHz offset; this behavior is typical for dielectric resonator type of oscillators. After around 40 kHz offset frequency, the phase noise decreases from − 95 dBc/Hz to − 130 dBc/Hz at 400 kHz offset. The recorded phase noise values are used in the BER simulation mentioned in section IV of this manuscript.

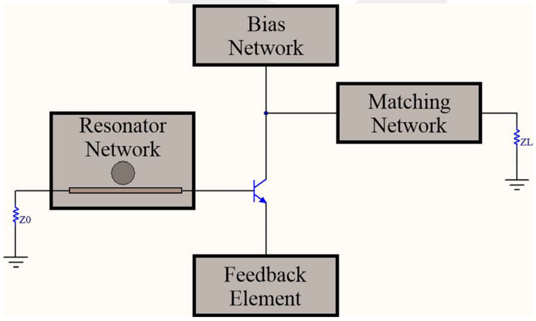


Fig. 2 Basic DRO diagram

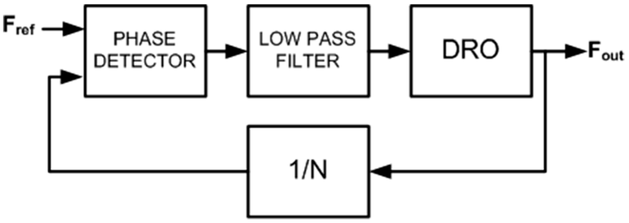


Fig. 3 DRO with a PLL

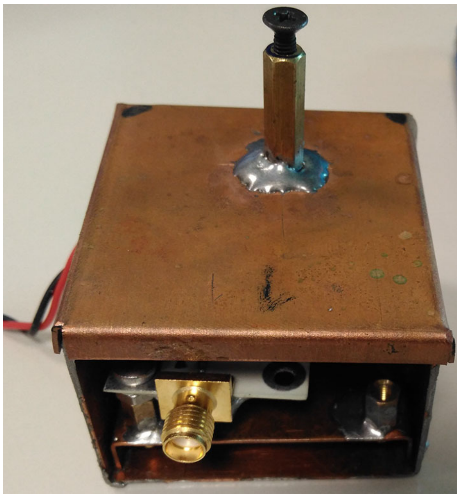


Fig. 4 18 GHz DRO picture

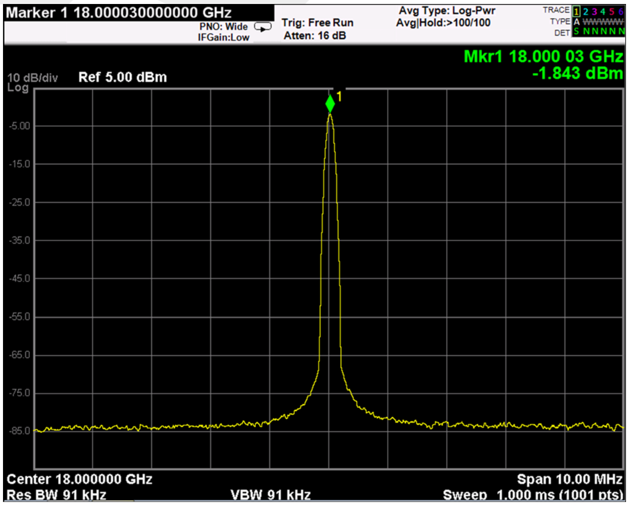


Fig. 5 RF spectrum trace of 18 GHz DRO output

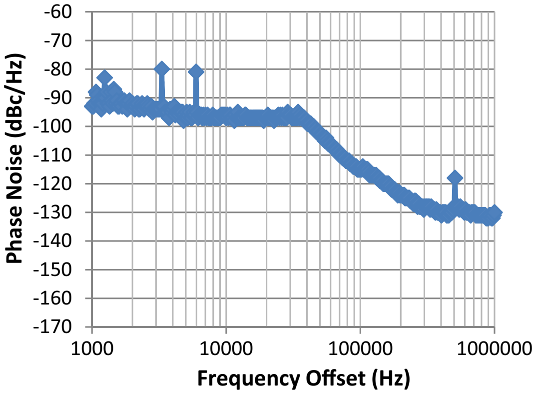


Fig. 6 18 GHz DRO phase noise

3 OEO design

The first applications of opto-electronic oscillator devices go back to 1979 [5]. The research for building a high frequency oscillator for optical communication systems started with a 380 MHz oscillator, which was considered as high frequency at that time, and nowadays it is possible to construct an OEO device with center frequency up to 40 GHz [6, 7].

The need for better phase noise performance, especially for high frequency 5G systems, have drawn the communication system designers to this particular oscillator type, despite its larger size, higher cost and more complex structure compared to DROs [8]. It is important to point out that the phase noise of an OEO is not directly related to the generated frequency value, unlike DRO and other oscillator types. The reason for this is; for an OEO, the frequency determining element (RF band pass filter) and the sources of phase noise are different. The Q factor of the OEO is dependent on the length of the optical delay line (Fig. 7). Better Q factor and phase noise performance can be achieved by using a longer delay line [9].

Operating both in optic and RF domains, OEOs provide the industry's best phase noise values for available frequencies [10]. The oscillation is achieved by the optical elements, while filtering, amplification, stabilization and lock mechanism take place in RF sub circuits. The oscillation frequency is determined by the center frequency of the RF band pass filter [11, 12].

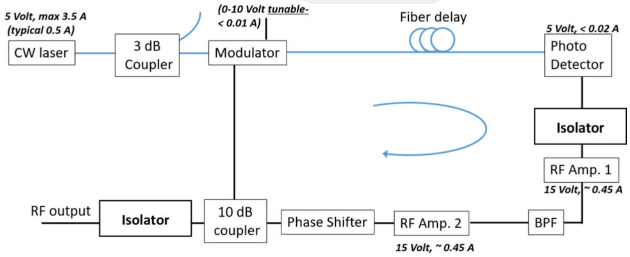


Fig. 7 Basic OEO diagram

For our research, we have designed and built a free-running OEO at 18 GHz, following the topology outlined in the block diagram in Fig. 7. The OEO consists of an optical block to generate oscillation, and an RF block for filtering and amplification of the signal. The optical delay line used for the resonator is 400 m in length. The developed OEO that is used for measurements is shown in Fig. 8.

After building the OEO, the performance of the device is tested. The RF spectrum and phase noise measurement results of our 18 GHz OEO are given in Figs. 9 and 10, respectively. The spurs on the OEO phase noise plot are the supermode noise spurs at frequencies 450 kHz and its integer multipliers. The recorded phase noise values are used in the BER simulation in section IV.

4 Simulation setup and analysis

In order to understand the effect of oscillator performance on a communication system, we have simulated a two-stage super heterodyne frequency down-converter. The simulation is intended to show the effect of an RF component on the signal processing end of a communication system. The digitization of the received signal requires lower error rates, which traces back to the hardware part of the system, to the local oscillator in our case.

As shown in the block diagram of the simulation setup (Fig. 11), the system receives a high order QAM modulated signal and up-converts it with a noiseless local

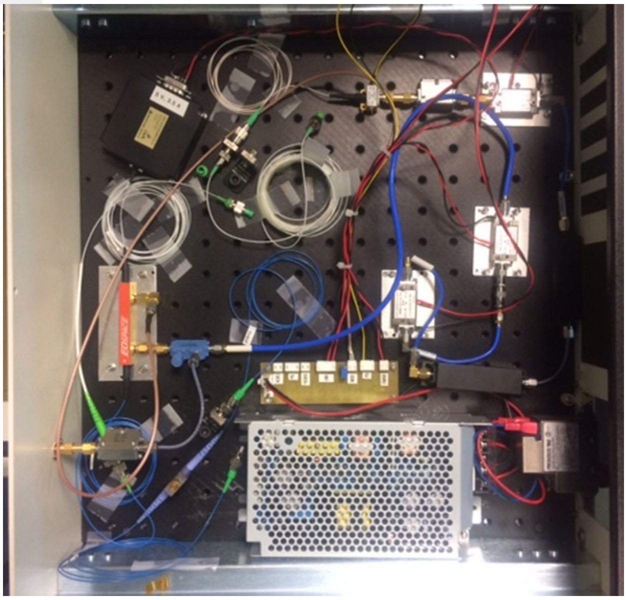


Fig. 8 18 GHz OEO picture

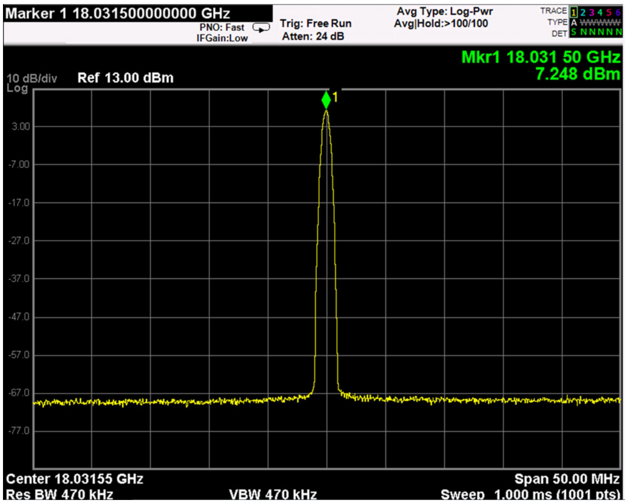


Fig. 9 RF spectrum trace of 18 GHz OEO output

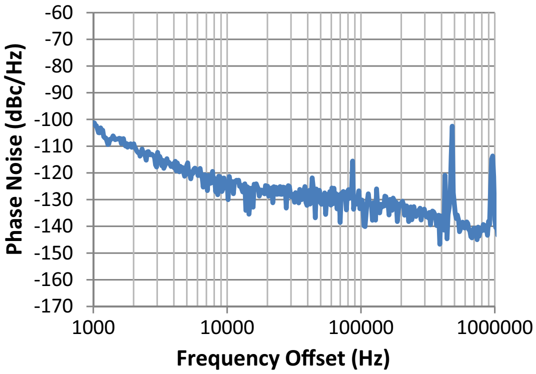


Fig. 10 18 GHz OEO phase noise

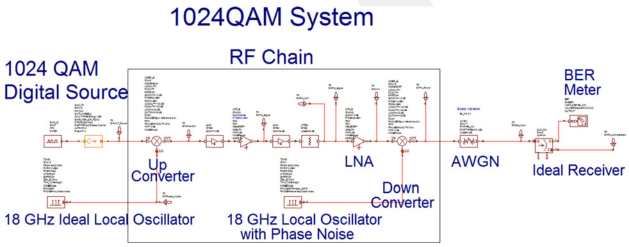


Fig. 11 1024 QAM receiver simulation setup

oscillator and a mixer. Next, the high frequency signal with modulation is down-converted to an intermediate frequency for analog to digital conversion. The second conversion is implemented with 3 different phase noise data; the measured phase noise values from the DRO, the OEO and a commercial signal generator present in our test lab. The phase noise values of the sources are given in Table 1, with phase noise data converted to jitter value in degrees RMS. The jitter of the OEO shows the best result with below 0.1° RMS value. The DRO jitter performance follows the OEO with 0.21° RMS.

Table 1 Phase noise and jitter values of local oscillators

Frequency offset	Noise level (dBc/Hz)		
	DRO	OEO	Signal generator
10 Hz	– 70	– 80	– 55
100 Hz	– 86	– 90	– 77
1 kHz	– 93	– 101	– 95
10 kHz	– 97	– 123	– 98
100 kHz	– 115	– 132	– 99
1 MHz	– 130	– 138	– 120
Jitter (°RMS)	0.21	0.064	0.41

As mentioned in [13], when the RMS jitter of a receiving system becomes higher than 0.25° RMS for a 256 QAM signal, the constellation of the signal data is intolerable. For our simulation, this specification is even lower due to the usage of 1024 QAM signal. This modulation type is chosen for our study because higher order modulation types (256 QAM and above) are considered to be potential candidates for next generation 5G systems due to their higher data rates within a limited bandwidth [14]. However, higher order modulation models are more susceptible to noise effects that can be seen in our analysis below.

The BER results of our simulation with three different frequency sources are given in Fig. 12 for comparison. Since the jitter value of OEO is below 0.1° RMS, the BER curve with OEO is very close to the reference BER curve that is achieved with a noiseless frequency source. The results with DRO are tolerable, with almost 1 dB degradation at a BER of 1e-7. However, for the third source, the jitter value of 0.41° RMS corresponds to a 2 dB degradation at the same BER values as DRO and OEO.

Since our analysis focuses on application based actual data, the theoretical background for oscillator design and phase noise modelling for a QAM channel are not included in this manuscript. However, a deduction of numerical

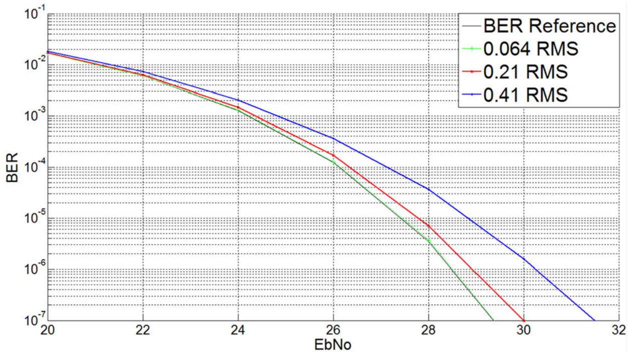
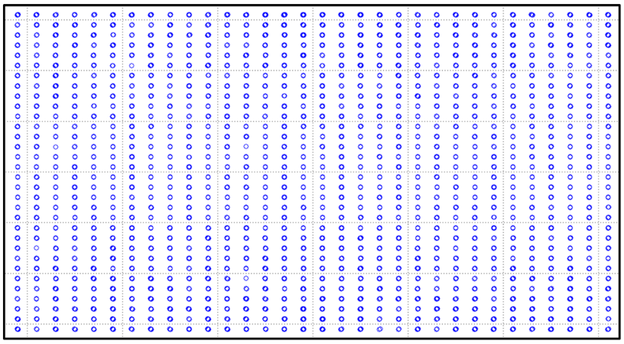


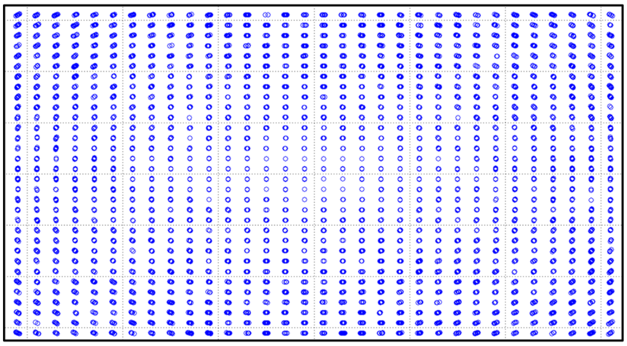
Fig. 12 1024 QAM BER simulation results

values from [15] supports our analysis. Linjian Xu et al. show that for a 16-QAM system, a 2.2° RMS degradation in phase noise corresponds to approximately 2.2 dB degradation in SNR for a BER of 1e-7. Using this result for our 1024 QAM system, to get a similar SNR degradation of 2 dB, the increase in phase noise should not be more than 2.2/(1024/16) = 0.034° RMS. A change more than that will cause the BER to get 2.2 dB worse, which is undesirable for a modern communication system, as stated in [13]. This deduction is in parallel with our simulation results, which show a 2 dB decrease in SNR for a phase noise degradation of 0.41–0.021 = 0.0346° RMS.

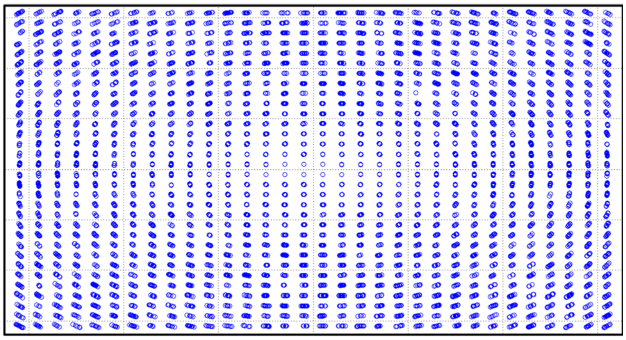
Figure 13 shows the constellation diagrams of the receivers using OEO, DRO and signal generator. It can be seen that, the symbol error rate increases as the local oscillator performance decreases and degradation becomes intolerable after 0.41° RMS jitter.



(a) 1024 QAM with OEO



(b) 1024 QAM with DRO



(c) 1024 QAM with Signal Generator (Lab Equipment)

Fig. 13 1024 QAM constellation diagrams with OEO, DRO and a commercial signal generator

We have also analyzed the error rate performance of the lowest phase noise oscillator (OEO) at different order quadrature amplitude modulations: 256 QAM, 64 QAM and 16 QAM. The error rate comparison of different order modulations is shown in Fig. 14. At a BER of 1e-5, there is almost 4 dB degradation for each QAM order change. This implies that, as the order of the modulation increases, the system becomes more vulnerable to phase noise effects. Thus, a jitter value of 0.4° may be acceptable for a system with 256-QAM, but not for a system with higher order QAM.

5 Conclusion

An analysis of the effect of phase noise on the BER parameter of a high order QAM communication system and comparison of the performance of three different types of frequency sources is presented. A DRO and OEO are designed, built and tested to get actual performance data, and the measured phase noise values are used in a frequency down-converter simulation that allows to observe the BER behavior of a 1024-QAM system with respect to the local oscillator performance. The simulation results are used to verify that the 1024-QAM system is more vulnerable to phase noise effects than a system using 256-QAM. Previous study results are mentioned to support our analysis for a next generation modulation type that can be used for 5G communication systems. Overall, the limiting values of tolerable phase noise/jitter for a given system is explored. Further study can be done on different modulation techniques such as OFDM, and other types of oscillators can be considered for advanced receiver systems.

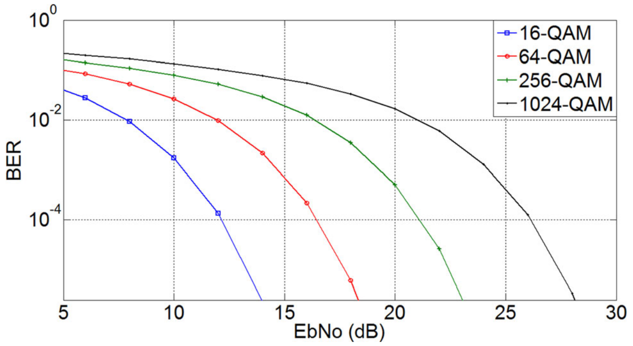


Fig. 14 BER diagrams for 16, 64, 256 and 1024-QAM (system with OEO)

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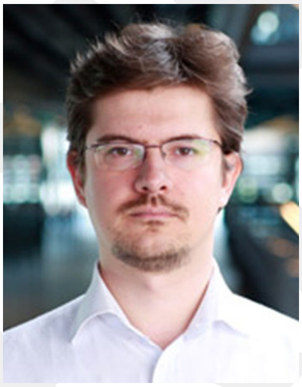

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