# Distortion and noise problems of subcarrier multiplexed optical systems

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**Abstract — In this paper investigation of subcarrier multiplexed optical subsystems for optically supported communication systems is presented. Noise and spurious free dynamic range are the main parameters, which are determined by the applied optical transmission. The frequency dependence of these parameters and optimal frequency chosen is presented.**

*Keywords — wireless communications, distortion and noise problems, subcarrier multiplexed optical subsystems.*

## 1. Introduction

In many applications of analog fiber optic links the link noise figure or output signal to noise ratio and intermodulation free dynamic range are two of the most important parameters. Great dynamic range and high linearity are necessary in the subcarrier multiplexed optical transmission system to have good system performance and avoid channel cross-talk. These parameters can be determined by the optical transmitter and depend on frequency and level of optical reflection. This dependence has not been satisfactory investigated, here some measurement results and noise calculations are presented in connection of realization of an optically supported millimeter wave (MMW) cellular radio system.

## 2. Optical link in radio systems

One possible radio system can be seen in Fig. 1. This proposed system is based on the simultaneous transmission of the information and the reference signal via intensity modulated optical distribution system. The reference and information signals are placed in the low microwave frequency range (about 1 GHz). In this approach instead of transmitting the millimeter-wave signal, one of its subharmonic is optically transmitted and at the reception side the millimeter-wave is generated utilizing the subharmonic signal as a reference frequency. A single mode laser is intensity modulated by the subharmonic reference signal and several subcarriers, which are used for the optical transmission of the information channels [1]. Hence, the key parameters of the optical transmission system are noise and linearity which can be dominant in the whole system.

## 3. Optical noise sources

A typical microwave fiber optic link consists of a laser source may be with an external modulator (Mach-Zehnder or electro-absorption modulator), the fiber optic transmission medium, optical amplifier (fiber or semiconductor) and an optical detector. These components are the noise sources of the optical link. Because these noise sources are independent, they can be simply added.

Conventional direct modulation of laser diodes has the problems with an adverse frequency spread (chirp) and with a frequency response, which is limited by the internal resonance between the electrons and photons. The amplitude, power and frequency of the laser as an oscillator have some fluctuations. The semiconductor laser source is characterized by the relative intensity noise ($RIN$) and the equivalent electrical noise power ($N_L(f)$) is generated in the laser:

$$RIN(f) = \frac{\langle \Delta P^2(f) \rangle}{P_L^2}, \quad N_L(f) = RIN(f) \cdot P_L \cdot B, \quad (1)$$

where $\langle P^2(f) \rangle$ – spectral density of the square of the laser optical power fluctuation, $P_L$ – steady-state optical power output from laser, $B$ – bandwidth.

The frequency dependence of the $RIN$ is rather high, it can change more than 10 dB in the lasers bandwidth (Fig. 2). This way in the data sheet given usual value, 140 dB/Hz cannot be always used for accurate calculations. The $RIN$ also changes with biasing, to eliminate this effect as high bias current should be applied as possible. This is also good for laser stability and linearity also.

The linearity of the direct modulated laser source depends on bias current, level of optical reflection in the system, and frequency. This is shown in Fig. 3, where a conventional Fabry-Perot laser was biased over 1 mW optical power in the single mode fiber, the RF power was 0 dBm which created $m = 23\%$ modulation depth. The measurement was done by two carriers with 1 MHz spacing, and the level of the third order mixing product was measured. The $3 - 5$ dB proving effect of the isolator can be observed. In the $1 - 1.6$ GHz range the linearity changes a lot with frequency, it even overtakes the non-isolator case. This effect was reproducible, and therefore 1.6 and 1 GHz was chosen for the system as optimum frequency for the optical transmission. The laser $RIN$ was also lower than in higher frequencies.

Two types of the external modulators are widely used. The first one is the electro-optic (EO) LiNbO$_3$ Mach-Zehnder modulator and the second one is the multiple-quantum-well (MQW) electro-absorption optical modulator. For an
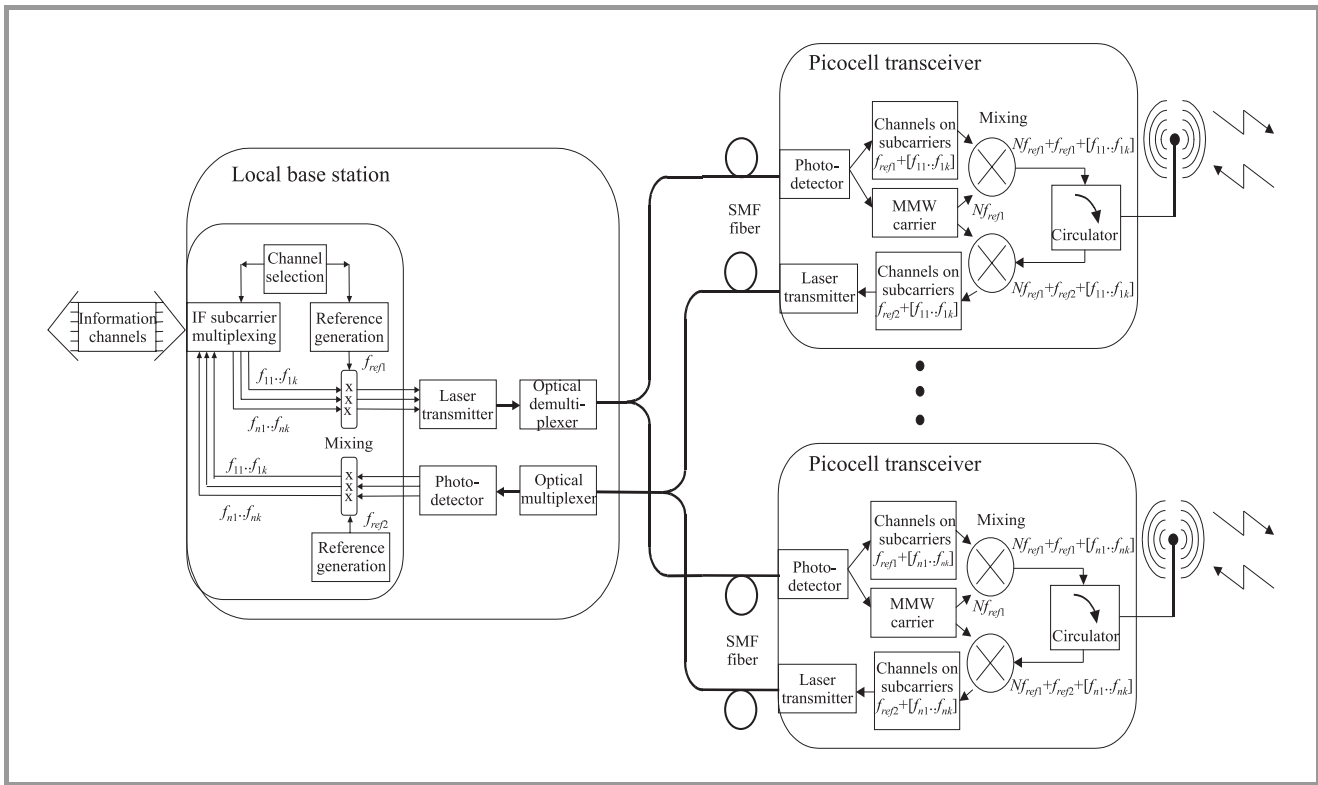
**Fig. 1.** Optical supported fiber radio system.

externally modulated link the noise figure decreases with increasing laser power. The shot noise of photodiode in-

creases linearity, while the link gain increases as the square of the laser power. This is because the modulation depth depends only on the external modulator RF input power. However, for a direct modulated optical transmitter the noise figure increases, because the link gain is independent of laser power, it depends only on the RF power [2].
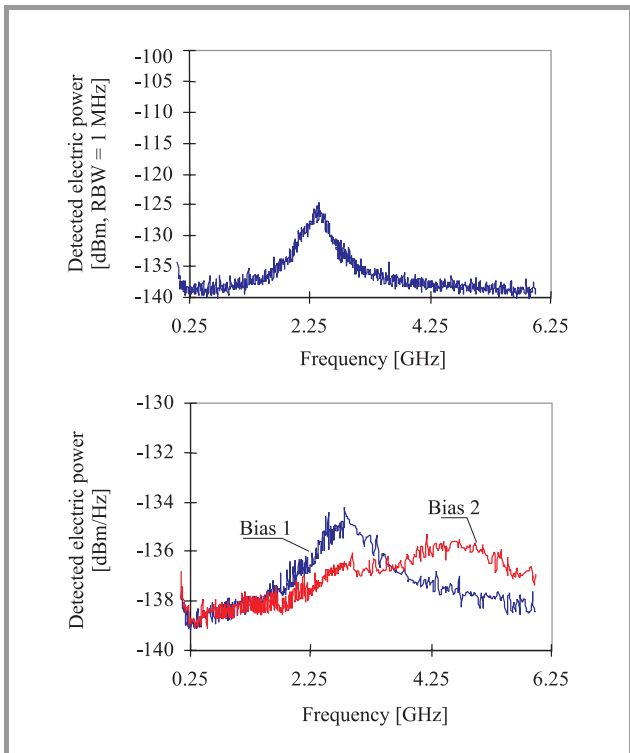


**Fig. 2.** The frequency and bias dependence for two different laser diodes.
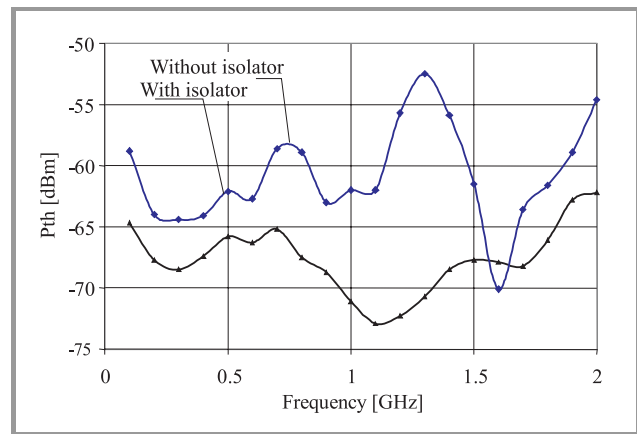


**Fig. 3.** Third order distortion product dependence on modulation frequency.

The drawback of a MZ modulator is, that it requires high RF power, and has low linearity. In the experiments a HP 83422A external modulator was used, which had less than 8% modulation depth with 10 dBm input power. The

linearity was measured at 8 and 25% modulation depth, and the result was 40.93 dBm and 31.07 dBm respectively for the third order mixing product (Fig. 4).
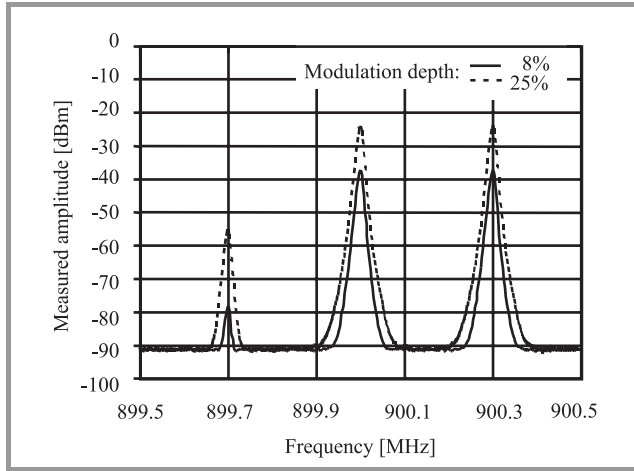


***Fig. 4.*** Third order distortion products of MZ.

The optical loss is very high in case of long optical link or usage of several optical dividers for several cellular transceivers. Hence, some optical amplifiers may be needed to compensate this optical loss. The spontaneous emission is the source of noise in semiconductor optical amplifier and it is a random process, which is statistically stationary and will cause fluctuations in both amplitude and phase of optical signal. In addition, the spontaneous emission photons can interact directly the signal. So several type of noises (the shot noise owing to spontaneous emissions, beat noise between signal and spontaneous emissions, beat noise between spontaneous emissions components and excess noise owing to incoherence of the input signal) can be observed, when the output photons are detected by a photodetector. So the resulting noise power at the detector with load resistance $R_p$ and bandwidth $B$ with perfect coupling is:

$$N_A(f) = \frac{\langle \Delta N_p^2(f) \rangle}{\tau_{p2}^2} \cdot R_p \cdot B \cdot \eta_Q^2 \cdot e^2, \qquad (2)$$

where $\langle \Delta N_p^2(f) \rangle$ – second-order moments of photon number, $\eta_Q$ – quantum efficiency of the photo-detector, $\tau_{p2}$ – photon lifetime.

In practical three main applications are used. In first method, SOAs operate as a post-amplifier to optical transmitter. In a non-regenerative repeater the incoming optical signals are directly amplified and so this process is compensate the fiber loss. Finaly, the SOA can be used as a pre-amplifier to the receiver, it can amplify the incoming weak signal, thereby improving the sensitivity of receiver. For these applications SOAs with a wide bandwidth and low noise figure are required.

If $M$ pices of identical SOAs are used as in-line repeaters, each specified by an amplifier gain ($G$) and noise fig-

ure ($F$), we can derive the signal to noise ratio of the optical receiver [3]:

$$SNR_r = \frac{SNR_t}{F + \frac{F}{G} + \frac{F}{G^2} + \cdots + \frac{F}{G^{M-1}}}, \qquad (3)$$

where $SNR_t$ is the signal to noise ratio of the transmitter. It can be seen that the noise figure of the first amplifier is the most significant contribution to $SNR_r$. So when different SOAs can be used, the minimum noise figure amplifier should be the first in the chain [4]. The typical value of the noise figure of semiconductor optical amplifier is $6-8$ dB, but the theoretical limit is 3 dB.

Several sources of optical loss along the link are indicated:

- $L_{TF}$: optical transmitter to fiber coupling loss (typical value: 3 dB),

- $L_F$: optical fiber loss (0.3 dB/km),

- $L_C$: connector and splice losses ($0.1-0.4$ dB),

- $L_{FR}$: fiber to optical receiver coupling loss ($< 3$ dB),

- $L_{FA}$: fiber to optical amplifier coupling loss (3 dB),

- $L_{AF}$: optical amplifier to fiber coupling loss (typical value: 3 dB).

Hence the whole optical insertion loss of the link:

$$L_{opt} = P_L / P_P, \qquad (4)$$

where $P_P$ is the optical power delivered to photodiode. The electrical insertion loss ($L$) which is proportional to the square of the optical loss of the link:

$$L = \frac{P_{tr}}{P_{rec}} = \frac{I_{tr}^2 \cdot R_L}{I_P^2 \cdot R_P} = \left( \frac{L_{opt}}{\eta_L \cdot \eta_P} \right)^2 \cdot \frac{R_L}{R_P},$$
$$L[\text{dB}] = 2 \cdot L_{opt}[\text{dB}]. \qquad (5)$$

Here $P_{tr}$ and $P_{rec}$ are the electrical power supplied to the laser diode and delivered by the photodiode, respectively. $R_L$ is the laser diode incremental drive impedance about its point of bias, $R_P$ is the photodiode load impedance, $I_{tr}$ is the modulation current of the laser diode, $I_P$ is the photo current of the photodetector and finally $\eta_L$ and $\eta_P$ are the responsibility of laser diode and photodiode, respectively. Supposing a pin diode photo receiver the electrical noise power in the photodiode output comes from shot noise of average photocurrent ($N_q$), dark current ($N_d$), leakage current ($N_l$) and the Johnson noise of photodiode equivalent resistance ($N_T$). Although the main noise source are the thermal noise and the shot noise, which are due to the quantum statistic nature of photons and electrons. The noise sources are statistically independent, so they can be added and the resultant electrical noise power of photodetector ($N_P$) is:

$$N_P = N_q + N_d + N_l + N_T \cong N_q + N_T =$$
$$= 2 \cdot q \cdot I_{ph} \cdot B \cdot R_P + k \cdot T \cdot B, \qquad (6)$$
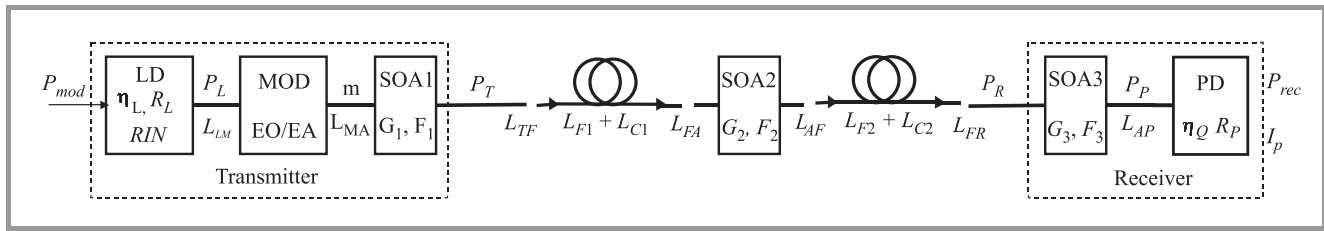
**Fig. 5.** Block diagram of the optical link.

where $q$ is the electron charges, $k$ is the Boltzmann constant, $T$ is the absolute temperature, $B$ is the bandwidth and $I_{ph}$ is the average photo current.

Summarizing the noise performance and signal power of the optical link (the block can be seen in Fig. 5):

$$L_{opt} = \frac{L_{LM} \cdot L_{MA} \cdot L_{TF} \cdot L_{F1} \cdot L_{C1} \cdot L_{FA} \cdot L_{AF} \cdot L_{F2} \cdot L_{C2} \cdot L_{FR} \cdot L_{AP}}{G_1 \cdot G_2 \cdot G_3}, \tag{7}$$

where $L_{LM}$, $L_{MA}$, $L_{TF}$, $L_{FA}$, $L_{AF}$, $L_{FR}$, $L_{AP}$ are the optical coupling loss between the different blocks and $L_{F1}$, $L_{C1}$, $L_{F2}$, $L_{C2}$, are the fiber and connectors loss in the different sections.

Examining the electrical signal power in the output of photodiode a sinusoidal modulating signal is assumed:

$$i_{rms} = \frac{1}{\sqrt{2}} \cdot I_P = \frac{1}{\sqrt{2}} \cdot \frac{q \cdot \eta_Q \cdot P_P}{h \cdot \nu}, \tag{8}$$

where $h$ is the Planck constant and $\nu$ is the light frequency. Hence the signal to noise ratio is in the output of receiver:

$$\frac{S}{N} = \frac{\left(\frac{1}{\sqrt{2}} \cdot \frac{q \cdot \eta_Q \cdot P_L \cdot L_{opt}}{h \cdot \nu}\right)^2 \cdot R_P}{\frac{N_L}{L} + \frac{\frac{N_{mod}}{L}}{\left(L_{LM}\right)^2} + \frac{\frac{N_{A1}}{L}}{\left(L_{LM} \cdot L_{MA}\right)^2} + \frac{N_{A2}}{\left(L_2\right)^2} + \frac{N_{A3}}{\left(L_{AP}\right)^2} + N_P}, \tag{9}$$

where $N_L$, $N_M$, $N_A$ and $N_L$ are the noises of laser diode, external modulator, optical amplifier and photodiode respectively, $L$ is the electrical loss of the whole optical link and $L_2$ is the optical loss from optical amplifier to photodiode.

## 4. Conclusion

In the paper sources of nonlinearity and noise in subcarrier multiplexed optical transmission were investigated. The different types of optical modulation methods were experimentally compared. The external modulation is advantageous when high dynamic range is more important than linearity. The direct modulation has higher linearity and needs lower driving signal. The frequency and optical reflection dependence of linearity was presented. Calculation method of the signal to noise ratio in optical transmission including optical amplifiers was also presented.

## Acknowledgment

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