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Signal-to-noise ratio and capture effect of microwave photonic links operating under small- and large-signal modulations in random noise

S. Saied Shojaeddin, S. Esmail Hosseini *, H. Abiri

Department of Communications and Electronics Engineering, School of Electrical and Computer Engineering, Shiraz University, Shiraz, Iran

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ABSTRACT

Signal-to-noise power ratio (SNR) and capture effect of intensity-modulation direct-detection (IMDD) microwave photonic links (MWPLs) operating under small- and large-signal modulation in noise have been studied. Arbitrary N sinusoidal signals in random noise are applied at radio frequency (RF) input port of the IMDD MWPL and the output spectrum is derived using a nonlinear analytical approach. General expressions for signal and noise powers at output of the IMDD MWPL are derived. From these expressions SNR and capture effect for all values of input signal power ratios can be determined. It is shown that a) the output noise and signal power for strong and weak input signals can severely be affected by the interaction of input signals with themselves, input signals with noise and input noise with itself due to the effects of nonlinearity of the MWPL combined with sum of several input signals in noise, b) the capture effect of the IMDD MWPL in noise depends on the link input back-off, the power ratio of input signals and on the number of input signals and this dependence is severe in the large-signal regime, c) the capture effect does not depend on the noise and in the presence and absence of noise are the same, d) output SNR for strong and weak input signals depend on input SNR, power ratio of input signals and input back-off. We have shown that when MWPLs are operating in the absence of noise, our theoretical predictions for the capture effect approach the already published results on this case. Besides, we have shown that the general behavior of the ratio of the input SNR to that of the output in small- and large-signal regime, is the same as the case of one input signal in random noise (or noise figure) that have been previously published.

1. Introduction

Photonic components have a lot of advantages such as broad bandwidth, immunity to electromagnetic interference (EMI), low loss and low frequency-dependent loss, etc. Microwave photonics is a multidisciplinary field that uses the advantages of photonic technology for radio frequency (RF), microwave and mm-wave applications, such as generation, transmission, distribution, control, detection, processing and measurement. Over the last decade, a lot of research activities have been done in the field of microwave photonics and a few tutorial and survey papers [1–17] and books [18–24] have been published that overview the progress in this field.

Microwave photonic link is one of the main blocks in most of the microwave photonic applications, including radio over fiber (RoF) [25], satellite communications [17,26], optically controlled phased array antennas [7], optoelectronic oscillators (OEO) [27–29], photonic signal processing of microwave signals [30], microwave photonic mixers [31], optical phase shifters [32], photonic measurement of microwave signals [12,16] and optical time delays [33–35].

The most commonly used MWPLs are based on intensity modulation with direct detection (IMDD) links due to the receiver simplicity. The basic architecture of the IMDD MWPL that is considered in this paper is shown in Fig. 1 which consists of a continuous wave (CW) laser source, an external electro-optic intensity modulator (Mach–Zehnder type, MZM), a long single mode fiber (SMF) and a photodetector.

RF performance of MWPLs and their most important parameters, which are link gain, small-signal noise figure (NF), and dynamic range have already been extensively studied [18,20,25]. The capture effect concept in the absence of noise and large-signal NF of an IMDD MWPL were introduced and studied in our previous works [36,37]. The capture effect or the small-signal suppression is the ratio of the strong-to-weak signal power ratio at the output of the MWPL to the corresponding power ratio at the input [36].

To the best of our knowledge, signal-to-noise ratio and capture effect of MWPLs operating under small- and large-signal modulation when its input consists of a sum of several unequal-power sinusoidal signals in random noise have not already been studied. This problem is of

* Corresponding author.
E-mail address: se.hosseini@shirazu.ac.ir (S.E. Hosseini).

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particular importance in many applications that IMDD MWPLs operate in their linear (such as RoF) or nonlinear (such as OEO) regime with multicarrier.

As mentioned before, microwave photonic link is one of the main blocks in most of the microwave photonic applications. In some of these applications the link is operating in small-signal regime, such as RoF [25], optically controlled phased array antennas [7], etc., and some is operating in large-signal regime, such as OEO [27–29], microwave photonic mixers [31], etc. So investigation of SNR and capture effect of MWPL under small- and large-signal modulation in random noise are important.

For example, in an OEO in order to reach ultralow phase noise performance, the length of the optical delay line must be long, so mode spacing of the oscillating modes will be quite narrow so that some of them fall in the bandwidth of the mode selection filter. As consequence, there are some sinusoidal input signals with different amplitudes (due to the frequency response of the mode selection filter) in random noise to the input of the MWPL under large-signal modulation, so the SNR and capture effect must be considered for this application. For another example, in the RoF, the MWPL is operating in small-signal regime, if for example a signal with frequency modulation (FM) goes through the MWPL, capture effect should be considered.

In this paper, SNR and capture effect of IMDD MWPLs operating under small- and large-signal modulation in random noise are studied. Arbitrary N sinusoidal signals in random noise are applied at RF input port of the IMDD MWPL and the output spectrum is derived using a nonlinear analytical approach. General analytic expressions for signal and noise powers at output of the IMDD MWPL in small- and large-signal regime are derived. From these expressions we will be able to determine signal-to-noise power ratios and capture effect for every values of input signal power ratios.

2. Analysis of an IMDD MWPL operating under N input signals in random noise

As shown in Fig. 1, N independent sinusoidal signals plus a narrowband white Gaussian noise with its spectrum close to the signal frequencies are applied to an IMDD MWPL. At the end of the link, a bandpass filter is used to select the desired frequencies. Signals plus noise at the input of the IMDD MWPL can be expressed as,

$$x(t) = n(t) + s(t) = n(t) + \sum_{n=1}^{N} A_n \cos\left(\omega_n t + \phi_n\right) \qquad (1)$$

where $n(t)$ is filtered white Gaussian noise (with zero mean) in vicinity of the carrier frequencies and A_n, ω_n and ϕ_n are amplitude, angular frequency and phase of the nth signal which are independent of the input noise. Input signals in random noise modulate the optical carrier and pass through optical fiber. At the end of the MWPL electric voltage and noise are extracted by a photodetector. The electrical voltage at the output of the photodetector in the IMDD MWPL can be expressed as [20]

$$y_{out}(t) = V_{ph}\left(1 + \cos\left(\pi v_{in}(t)/V_\pi\right)\right) \qquad (2)$$

where, $v_{in}(t) = V_B + x(t)$ is the input signal plus noise to the link, V_B is the bias voltage of the MZM, V_π is its half-wave voltage, V_{ph} is defined as $V_{ph} = P_{in} T_{ff} \rho R_L/2$, where P_{in} is input power of the optical carrier,T_{ff} is insertion loss of MZM, R_L and $\rho$are load impedance and responsivity of the photodetector, respectively.

2.1. Autocorrelation function and spectrum at the output of the IMDD MWPL

Here, signal plus Gaussian noise are passed through an IMDD MWPL which has a nonlinear input–output characteristic function. So to calculate the output autocorrelation function and power spectral density for an IMDD MWPL in response to N sine waves plus Gaussian noise input, noise analysis methods in nonlinear systems should be used.

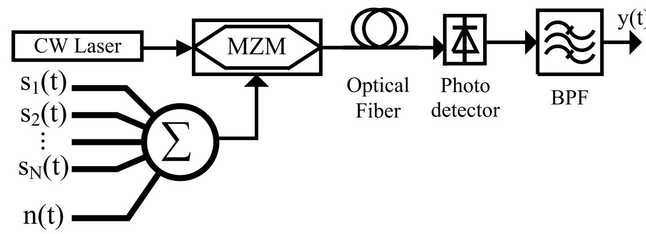

Fig. 1. IMDD MWPL with N input signals in noise, CW: Continuous wave, MZM: Mach–Zehnder modulator, BPF: Bandpass filter.

Using statistical parameters of input noise and the transfer characteristic function of the nonlinear system, autocorrelation function of the system output can be determined. By taking Fourier transform of this function, output voltage spectral density can be calculated.

Output RF bandpass filter is set to fundamental spectral zone (at frequencies in the vicinity of input signal frequency), in order to remove harmonics and also intermodulation outside the scope of the system output. For calculating the effect of output intermodulation, components which fall inside fundamental spectral zone and dominant in power are considered in the analysis.

Davenport's technique [37–41], calculates autocorrelation function of the output of a nonlinear device when its input is one sinusoidal signal plus Gaussian noise. By extending it to N sinusoidal signal plus Gaussian noise input, autocorrelation function $R_y(\tau)$ of the unfiltered output of an IMDD MWPL can be expressed as

$$R_y(\tau) = \sum_{k=0}^{\infty}\sum_{m_1=0}^{\infty}\cdots\sum_{m_N=0}^{\infty}\Big[R_n^k(\tau)\,\varepsilon_{m_1}\varepsilon_{m_2}\cdots\varepsilon_{m_N} h^2\left(k, m_1, \ldots, m_N\right) \times R_{s_1}(\tau) R_{s_2}(\tau)\cdots R_{s_N}(\tau)/k!\Big] \qquad (3)$$

where, $R_n^k(\tau)$ is kth power of autocorrelation function of input noise, ε_m is Newman coefficient ($\varepsilon_0 = 1$, $\varepsilon_{m,m>0} = 2$), $R_{s_i}(\tau)$ is autocorrelation function of ith input sinusoidal signals and coefficients $h\left(k, m_1, \ldots, m_N\right)$ are as follows

$$h\left(k, m_1, \ldots, m_N\right) = j^{(k+m_1+m_2\cdots+m_N)}\int_{-\infty}^{+\infty}\Big[f(\omega)\times\omega^k e^{-\sigma^2\omega^2/2} \times\Big(J_{m_1}\left(A_1\omega\right)\cdots J_{m_N}\left(A_N\omega\right)\Big)d\omega\Big]/2\pi \qquad (4)$$

where, $\sigma^2 = N_{in}R_L$ is variance of the input noise voltage, J_m is the mth order Bessel function of the first kind and $f(\omega)$ is Fourier transform of the system's transfer function, that can be calculated from (2) as

$$f(\omega) = \pi V_{ph}\Big[2\delta(\omega) - \delta\left(\omega - \pi/V_\pi\right)e^{j(\pi V_B/V_\pi)} - \delta\left(\omega + \pi/V_\pi\right)e^{-j(\pi V_B/V_\pi)}\Big]. \qquad (5)$$

By substituting (5) into (4), coefficients $h\left(k, m_1, \ldots, m_N\right)$ can be expressed as

$$h\left(k, m_1, \ldots, m_N\right) = V_{ph} j^{(k+m_1+m_2+\cdots+m_N)} \times \begin{cases} \prod_{s=1}^{N} J_{m_s}(0) - 0.5e^{\frac{-\sigma^2\pi^2}{2V_\pi^2}}\prod_{s=1}^{N} J_{m_s}\left(\beta_s\right) \\ \times\left(e^{j\Gamma_0} + (-1)^{m_1+m_2+\cdots+m_N}e^{-j\Gamma_0}\right) & ; k = 0 \\ 0.5e^{\frac{-\sigma^2\pi^2}{2V_\pi^2}}\left(\pi/V_\pi\right)^k\prod_{s=1}^{N} J_{m_s}\left(\beta_s\right) \\ \times\left(e^{j\Gamma_0} + (-1)^{m_1+m_2+\cdots+m_N+k}e^{-j\Gamma_0}\right) & ; k \neq 0 \end{cases} \qquad (6)$$

where, $\Gamma_0 = \pi V_B/V_\pi$ and $\beta_s = \pi A_s/V_\pi$.

As it is clear from (3) and (6), output autocorrelation function is dependent on input signal and noise power, optical source power and parameters of the devices of the link such as modulator, photodetector,