Power penalty and CNR penalty Performance in Single-Tone Radio-over-FiberTransmissionsystemusingOSSB Techniquedue to Phase Noise from Laser-Spectral Width

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***Abstract*—Inthispaper,we analysedtheeffect of noise due tolinewidths of laser on single-tone radio-over-fiber (RoF) transmission system.A Mach–Zehnder modulator (MZM) and a phase shifter are employed to externally generate an optical single sideband (OSSB) signal since the OSSB signal is tolerable for power degradation due to a chromatic fiber-dispersion effect.ItisshownthatPower penalty and CNR penalty is increased exponentiallywhen we changelaserlinewidth(γ_{RF})from 10MHzto 624MHz.Theresultsare calculated for transmissiondistance (L_{FIBER}) 10kmto40kmfor opticalsinglesideband (OSSB)–RoFtransmissionsystem.We investigate the effect of laser linewidth with30-GHz RF carrier(f_{RF}), fiber dispersion parameter (D) 17 ps/nm·km, and 1550-nm laser (λ) with zero linewidth.**

Key words—carrier-to-noise ratio(CNR), direct detection, fiber,Bandwidth, laser, line width, Dual electrode Mach–Zehnder modulator (DEMZM), optical single sideband (OSSB), oscillator, phase noise, power spectral density (PSD), radio.

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1. Introduction

Wireless broadband, fixed and mobile, can be found almost everywhere, and it became a part of our modern life style. The data traffic in telecommunication networks has been growing tremendously over recent years, and experts predict accelerating data volumes from today three Exabyte a year to ninety Exabyte per year by 2015, where an Exabyte is equal to one million terabytes [23].For fulfilling the demands, wideband communication systems arenecessary in both wired link and wireless link.Radio-over fiber (RoF) systems have been good candidates for broadband services. This is a technology, which modulates light into radio frequency and transmits it via optical fiber to facilitate wireless access. Radio signals are carried over fiber utilising distributed antenna systems in fiber-optic cellular and micro-cellular radio networks. Radio signals in each cell are transmitted and received to and from mobile users by applying a separate little box that is connected to the base station via optical fiber. Cells are divided into microcells to enhance the frequency re-use and support a growing number of mobile users.

The introduction of microcells has the following advantages Firstly, the microcell is able to meet increasing bandwidth demands; secondly, reduces the power consumption also the size of the handset devices. The high-power radiating base station antenna is replaced by a divided antenna system connected to the base station via optical fiber [24].However,theperformanceofRoF systemsdependsonthemethodusedtogeneratethe optically modulatedradiofrequency(RF)signal,powerdegradationdueto fiber chromaticdispersion,nonlinearityduetoanoptical power level, andphasenoisesfromalaserandanRFoscillator [1-14].There are two techniques to generate the optically modulatedRF signal: Direct and External modulation. The direct modulation scheme is simple but suffers from a laser-frequency chirp effect, and this chirp effect results in severe degradation of the system performance. However, this can be eliminated by using the external-modulation scheme instead of the direct modulation scheme [2]. Although the external-modulation scheme is employed, the conventional optical double sideband (ODSB) signal can degrade the received RF signal power due to fiber chromatic dispersion drastically. For overcoming the power degradation, an optical single sideband (OSSB) signal, generated by using a phase shifter and a dual-electrode (DE) Mach–Zehnder modulator (MZM), is employed [2].

In addition to these two effects, the nonlinearity of an optical fiber can give a large penalty on the long-haul transmission and multichannel system using a high-power signal. For the high-power transmission, the nonlinear effect should be managed by utilizing a modulation format [3], and by controlling the launched power level [4]. The nonlinear effect, however, can be negligible in short and low optical power less than 0dBm, especially for a single channel transmission.Unlike those parameters, phase noise isone of the practical and decisive factors in high-quality servicesthat require high signal-to-noise ratio (SNR), because it resultsin a bit error rate (BER) floor in a high SNR value [6]. This phenomenonis serious to RoF systems because the purpose of RoFsystems is to provide a service of high data rate and high quality,which require a large SNR. Thus, the system performance canbe more sensitive to the phase noise in these services.The influence of the phase noise on optical communicationsystems has been investigated [5]–[10]. Kitayama et al. analyzedthe system performance for an ODSB signal includinglaser phase noise and suggested how to compensate the differentialdelay by using a dispersioncompensating fiber (DCF).He focused on how to compensate fiber chromatic dispersionfor the ODSB signal experimentally and analytically. Barry and Lee [6] and Salz [7] analyzed the performanceof coherent optical systems with laser phase noise by utilizinga Wiener process, since coherent detection provides bettersensitivity than that of direct detection, while direct detectionhas a simple structure [21]. Gallion and Debarge [8] andTkach [9] used an autocorrelation function and a PSD functionfor evaluating the effect of the laser line width and fiber chromaticdispersion on the system performance. Gallion analyzedthe power spectral density (PSD) function of a photocurrentincorporating the laser phase noise in detail. Gliese applied theresult in [8] to study the influence of chromatic fiber dispersion on the transmission distance of fiber optic microwave and millimeter wave links [10]. For the tolerance to fiber chromaticdispersion, dual correlated lasers were employed to generatean OSSB signal in [10]. In this paper, we will analyse the CNR penalty and Power penalty due to fiberchromatic dispersion and phase noises from a laser using an OSSB signal and a direct-detection scheme.For the analysis of the Power penalty and CNR penalty, the autocorrelation andthe PSD function of a received photocurrent are evaluated. Thebandwidth of an electrical filter is dealt in the Penaltiessince the phase noises result in an increase of the requiredbandwidth and the increased bandwidth causes an additionalCNR and Power penalty. It is shown that the phase noise from the Laser Diode is more dominant in long haul transmission because differential delay is more (>100ps) at 40km as compared to 2km, as the distance increases Power penalty and CNR increases exponentially, Since at short distances the phase noise due to laser is not much as compared to RF oscillator.

2. R-o-F Architecture

In a RoFsystem anopticallymodulatedradioFrequencysignalis generated fromacentral office(CO)toabasestation(BS)via anopticalfiber.AnOSSBsignalisproduced byusingaDual-Electrode Mach–Zehnder modulator (DEMZM)and a90° phase shifter, and optically modulated by LASER diode and DEMZM.TheopticallymodulatedsignalistransmittedtoBSwheret hereceivedRFsignalisrecoveredbyusing aphoto detector(PD)andaBPFarrivesatauserterminal(UT) throughawirelesschannel as shown in fig.1.

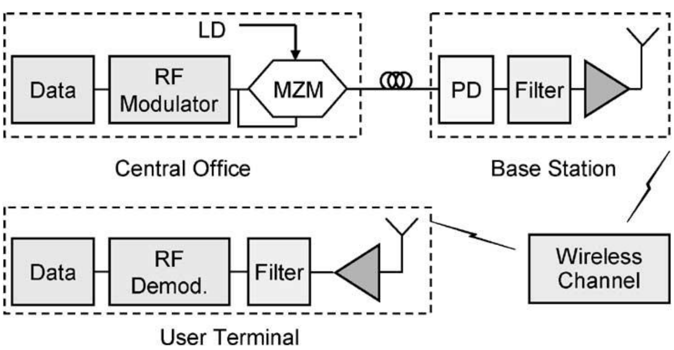

Fig.1

Theopticalsignalsfromthelaserand theRFoscillatorarerepresentedmathematicallyas

$$x_{LD}(t) = A\,.\,expj(\omega_{LD}(t) + \Phi_{LD}(t)) \quad (1)$$

$$x_{RF}(t) = V_{RF}\,.\cos(\omega_{RF}(t) + \Phi_{RF}(t)) \quad (2)$$

Where A and V_{RF} areamplitudesofsignalsfromtheLDandtheRF oscillator respectively, ω_{RF} and ω_{LD} areangularfrequenciesofthesignals fromtheLDandtheRFoscillator, $\Phi_{LD}$and$\Phi_{RF}$are phase-noise processesandΦ_{LD} ischaracterizedbyaWienerprocess[6] as

$$\Phi_{LD}(t) = \int_0^t \Phi_{LD}'(\tau)d\tau \quad (3)$$

The time derivative$\Phi_{LD}(t)$is not flat at low frequencies due to1/f noise [6]. The white phase noise, however, is the principalcause for line broadening and is associated with quantumfluctuations [7]. Thus, $\Phi_{LD}(t)$can be modeled as a zero-meanwhite Gaussian process with a PSD [6]

$$S_{\Phi_{LD}'}(\omega) = 2\pi\Delta v_{LD} \quad (4)$$

Where v_{LD} is Laser linewidth

After opticallymodulating $x_{LD}(t)$ by $x_{RF}(t)$ withaDEMZMandbycontrollingthephaseshifter,theOSSBsignalisgenerated by setting θ(phase shift)and γ (normalized dcvalueofLD)to 90° and 0.5, respectively,andthisOSSBsignalattheoutputofDEMZMis representedas

$$E(0,t) = A.L_{MZM}\left[J_0(\alpha\pi).expj\left(\omega_{LD}(t) + \Phi_{LD}(t) + \frac{\pi}{4}\right)\right] - \sqrt{2}J_1(\alpha\pi).expj(\omega_{LD}(t) + \Phi_{LD}(t) + \omega_{RF}(t) + \Phi_{RF}(t)) \quad (5)$$

Where $\alpha = V_{RF}/\sqrt{2}V_{\pi}$ is thenormalizedacvalue, V_{π} is the switching voltageoftheDEMZM. L_{MZM} is theinsertionlossofthe DEMZM,and θis thephaseshiftbythephaseshifter. Generally , $V_{\pi} \gg V_{RF}$, thus,thehigh-ordercomponentsoftheBesselfunction areneglected.

2. Power Penalty and Carrier to Noise Ratio Penalty Analysis

AftertransmittingtheOSSBattheoutputof DEMZMthroughstandardsingle-modefiber(SSMF) ofL_{FIBER}Km is representedas

$$E(L,t) = A.L_{MZM}.L_{LOSS}.10^{-\frac{\alpha_{FIBER}\,\cdot\,L_{FIBER}}{20}}.J_0(\alpha\pi)\left[expj\left(\omega_{LD}(t) + \right.\right.$$

ΦLDt−τ0−Φ1+π4−2J1απJ0απ.expjωLDt+ΦLDt−τ++ωRFt+ΦRFt−τ+−Φ2 (6)

Where L_{LOSS} denotesanadditionallossintheopticallink line, α_{FIBER} is the SSMF loss, L_{FIBER} is thetransmissiondistanceoftheSSMF,and τ_0 and τ_+ define groupdelaysforacenterangularfrequencyof $\omega_{LD}(t)$, andanuppersidebandfrequency of $\omega_{LD}(t) + \omega_{RF}(t)$, Φ_1 and Φ_2 are phase-shiftparametersforspecificfrequenciesdueto the fiber chromaticdispersion.Byusingasquare-lawmodel,thephotocurrent i(t) canbeobtainedfrom(6)asfollows

$$i(t) = R|E(L,t)|^2 = RA_1^2[B + 2\alpha_1\cos(\omega_{RF}(t) + \Phi_{LD}(t - \tau_+) - \Phi_{LD}(t - \tau_0) + \Phi_{RF}(t - \tau_+) - \Phi_2 + \Phi_1)] \quad (7)$$

Where $A_1 = A.L_{MZM}.L_{LOSS}.10^{-\frac{\alpha_{FIBER}.L_{FIBER}}{20}}.J_0(\alpha\pi)$

$\alpha_1 = \frac{\sqrt{2}J_1(\alpha\pi)}{J_0(\alpha\pi)}$, $B = 1+\alpha_1^2$, $R = Responsivity\ of\ PD$

From (7), theautocorrelationfunction $R_{AF}(\tau)$isobtainedas

$$R_{AF}(\tau) = \langle i(t).i(t+\tau) \rangle \quad (8)$$

$$\frac{R_{AF}(\tau)}{R^2.A_1^4} = B^2.\begin{cases} 2.\alpha_1^2.\cos(\omega_{RF}\tau)\exp(-2\gamma_1|\tau|), & |\tau| \le \tau_1 \\ 2.\alpha_1^2.\cos(\omega_{RF}\tau)\exp(-2\gamma_{LD}\tau_1 - \gamma_{RF}|\tau|), & |\tau| > \tau_1 \end{cases} \quad (9)$$

WhereΔv_{LD} and$\Delta v_{RF}$are the line widths for the laser and the RF oscillator, respectively, $2\gamma_{LD}$ (= $2\pi\Delta v_{LD}$)and $2\gamma_{RF}$ (= $2\pi\Delta v_{RF}$) are the angular full-line width at half-maximum (FWHM) of the Lorentzian shape for the laser andthe RF oscillator, respectively, and $2\gamma_t$ is related to the total line width. Note that the $2\gamma_t$ is given not as $2\pi\Delta v_{LD} + 2\pi\Delta v_{RF}$ but $2\pi\Delta v_{LD} + \pi\Delta v_{RF}$. Now τ_1 (= $\tau_+ - \tau_0$) is the differential delay due to the fiber chromatic dispersion and is dependent on the wavelength λ, the carrier frequencyf_{RF} , the fiber chromatic dispersion D, and the optical transmission distanceL_{FIBER}. It is given by [10]

$$\tau_1 = D\ .\ L_{FIBER}\ .\ \lambda^2\ .\ \frac{f_{RF}}{c} \quad (10)$$

where$c$ is the light velocity.

The shot noise term at the PD is omitted here since the noise power can be evaluated by the product of bandwidth and noise density level.The PSD function of the photocurrent is given by the Fourier transform of Autocorrelation Function.

$$S(f) = F \langle R_{AF}(\tau) \rangle$$

$$\frac{S(f)}{R^2A_1^4} = B_2\ .\delta(f) + G(f - f_{RF}) + G(f + f_{RF})$$

Where

$$G(f - f_{RF}) = S_1 + S_2 + S_3$$

After getting the three terms, S_1 and S_2 defines the broadening effects due to the fiber chromatic dispersion and the line width of the laser and the RF oscillator. By using Fourier Transform the received RF carrier power $P_{RECIEVED}$ is approximately represented as follows

$$P_{RECIEVED} = \frac{4R^2A_1^4\alpha_1^2}{\pi}e^{-2\gamma_t\tau_1}.\tan^{-1}\left(\frac{\pi\ .\ B_{RF}}{\gamma_{RF}}\right) \quad (11)$$

Where $2\gamma_t\tau_1 \ll 1$and $\gamma_t \ll \gamma_{RF}$. This is because the laser linewidth is much greater than the RF oscillator linewidth. The received RF carrier power is a function of the differential delay τ_1 , the laser and the RF oscillator linewidths, and the Bandwidth of the electrical filterB_{RF}. The ratio between the bandwidth and the linewidth of the RF oscillator is one of the dominant parameters for the carrier power. Practical systems employ various types of bandwidth as the required power, such as half-power bandwidth, fractional-power containment bandwidth (99% of signal power), and so on [17].For evaluating the total RF power excluding dc power, we utilize theAutocorrelation Function.

$$P_{TOTAL} = R_{AF}(0) - R^2A_1^4B^2$$

$$P_{TOTAL} = 2R^2A_1^4\alpha_1^2 \quad (12)$$

By using (12), we define the ratio p between the total carrier Power and the required power as follows

$$p = \frac{P_{RECIEVED}}{P_{TOTAL}} \quad for\ 2\gamma_t\tau_1 \ll 1\ and\ \gamma_t \ll \gamma_{RF}$$

$$p \cong \frac{2}{\pi}e^{-2\gamma_t\tau_1}.\tan^{-1}\left(\frac{\pi\ .\ B_{RF}}{\gamma_{RF}}\right) \quad (13)$$

Required bandwidth for ratio p is

$$B_{RF} = \frac{\gamma_{RF}}{\pi}.\tan\left(\frac{\pi}{2}e^{2\gamma_t\tau_1}p\right) \quad (14)$$

When we need more received signal power the required bandwidth increases. We use $2B_{RF}$ instead of B_{RF} because received power is in real and also in imaginary part. Similarly noise is evaluated. Now and Carrier to noise ratio can be calculated by using (11)and (14).

$$\frac{C}{N} = \frac{Carrier\ Power}{Noise\ Power}$$

$$\frac{C}{N} = \frac{P_{RECIEVED}}{2B_{RF}\frac{N_0}{2}}$$

$$\frac{C}{N} = \frac{2R^2A_1^4\alpha_1^2p}{N_0\frac{\gamma_{RF}}{\pi}\tan\left(\frac{\pi}{2}e^{2\gamma_t\tau_1}p\right)} \quad (15)$$

Now from (13) and (15) the Power penalty, CNR penalty induced by the Differential delay from the fiber chromatic dispersion by varyinglaser linewidth is as

$$Power\ Penalty = \frac{1}{p} = 1/\left(\frac{2}{\pi}e^{-2\gamma_t\tau_1}.\tan^{-1}\left(\frac{\pi\ .\ B_{RF}}{\gamma_{RF}}\right)\right) \quad (16)$$

$$carrier\ to\ noise\ ratio\ penalty = \Delta\frac{C}{N}$$
$$= 10\ log_{10}\left(\frac{(C/N)_0}{(C/N)}\right)$$
$$= 10\ log_{10}\left(\frac{p_0\ .\gamma_{RF}\tan\left(\frac{\pi}{2}e^{2\gamma_t\tau_1}p\right)}{p\ .\gamma_{RF_0}\tan\left(\frac{\pi}{2}e^{\gamma_{RF_0}\tau_1}p_0\right)}\right)$$

(17)

To calculate the CNR_0, set p_0=0.5 ,$\gamma_{RF_0} = \pi$, it means 1-Hz linewidth of the RF oscillator, and zero laser linewidth.we set D=17 ps/nm · km, λ=1550-nm.

3. Results

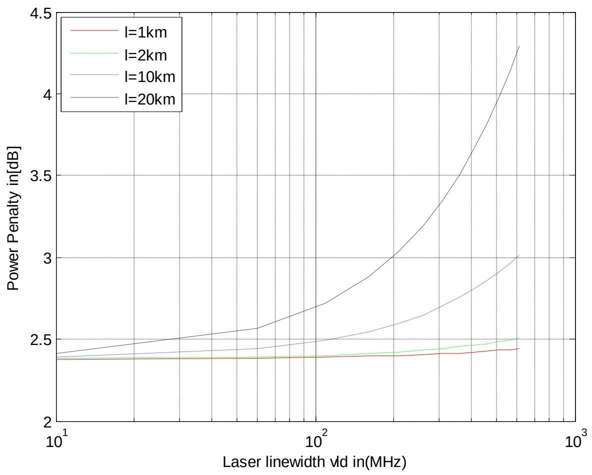

Fig.2

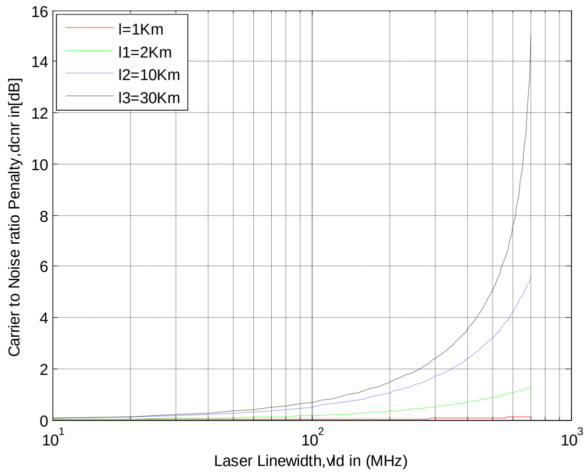

Fig.3

The result of the laser-line width effect is described in Fig.2&3 using (16) and (17). The penalties are observed for laser line width from 10 to 624 MHz since 10 and 624 MHz are typical line width values of a distributed-feedback (DFB) laser and a Fabry–Pérot (FP) laser [18].ΔCNR and power penalty exponentially increases as the laser linewidth. Therefore, the RoF system relatively suffers from both penalty for a long transmission, such as 30 km, while both are almost unchanged for the FP laser in the short-transmission case (=2 km). We can say that the FP laser can be used in a practicalmicrocell boundary because the radius of the microcell is from 0.2 to 1 km [20].

4. Conclusion & Discussion

We have seen that the Power Penalty and carrier-to-noise ratio (CNR) penaltydue to the limits of the fiber chromatic dispersion in the standardsingle-mode fiber (SSMF) and the phase noises of the laser in the radio-over-fiber (RoF)system. In order to investigate the penalties, we evaluate thepower spectral density (PSD) function, and the PSD function isidentical with the previous result in [8], when the phase noiseof the RF oscillator is 0.A practical laser having nonzero linewidthinduces penalties by the multiplication with nonzero differential delayin the RoF system that uses external modulation with a(DEMZM)dual-electrode Mach–Zehnder modulator and directdetection. However, the penalty due to the laser linewidthis much less than the penalty due to the RF-oscillatorlinewidth at short distance.The penalties come from the power degradation due tophase noises and the differential delay caused by fiber chromaticdispersion. The filter bandwidth at an electrical receivershould be selected carefully considering tradeoff between the penalties and required signal power ratio p, especially forp greater than 0.9, since the increase of bandwidth causes the increase ofnoise power. The penalties for the use of a 99% bandwidthfilter are 15.1 dB, as compared to the case using the half-powerbandwidth.The CNR penalty due to the FP laser linewidth is only 0.22 dB in a microcell (2 km) even though it becomes relatively severe in a long distance (30 km).The long-haul transmission is different because the initial phase difference is not maintained at the end of the optical fiber anymore. The observed linewidth due to the laser at the PD will be twice that of an initial laser linewidth Φ_{LD} since the differential delay is much greater than the coherence time. Therefore, the phase noise processes of Φ_{LD} and $\Phi_{LD}(t+\tau_1)$ are completely uncorrelated [9]. In that case, the system performance will suffer from the laser linewidth in a long-haul case seriously while the laser-linewidth effect can be ignored in a short transmission.In conclusion, the bandwidth of an electrical filter at the receiver should be carefully chosen considering minimum required signal power ratio p and CNR penalty at the same time.

7. References

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