AD-A247 618

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Subcarrier-Multiplexed Coherent Optical Video Transmission Using Direct Frequency Modulation of Semiconductor Lasers

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1991

N00014-91-J-1857

Abstract

An analog subcarrier-multiplexing (SCM) coherent optical system for video transmission using direct frequency modulation of semiconductor lasers is analyzed. Receiver sensitivity, corresponding to a 56 dB SNR at the output video ports, is approximately -38 dBm for 50 channels and -25 dBm for 100 channels using the FM subcarrier modulation format. These results are obtained for realistic values of receiver thermal noise (3.31×10^{-22} A^2/Hz), laser linewidth (40 MHz), RIN (-150 dB/Hz), and optical bandwidth (20 GHz). Linewidth-induced performance degradation is found to be negligible for up to 50 channels.

Introduction

The simultaneous transmission of many video channels through subcarrier multiplexing (SCM) on a single optical carrier is feasible using the high available bandwidths of distributed-feedback (DFB) lasers and PIN photodiodes. The use of subcarrier multiplexing in coherent optical systems for analog and digital video distribution has been explored experimentally; using phase modulation of the optical carrier, receiver sensitivities of -32 dBm and -27 dBm have been achieved for 60 FM video channels and 20 frequency-shift-keyed (FSK) video channels, respectively [1], [2]. Direct frequency modulation of the optical carrier is also an attractive modulation format due to the avoidance of external modulation and to the high output signal-to-noise ratio (SNR) attainable through FM enhancement [3]. Way *et al.*[4] used an optical frequency discriminator followed by a direct-detection receiver to demodulate a directly frequency-modulated optical signal with FM video subcarriers. This letter reports the results of a theoretical analysis of an SCM coherent system using direct frequency modulation of the optical carrier and FM video subcarriers.

System Description

Fig. 1 shows a block diagram of the system analyzed. FM video signals on microwave subcarriers are combined, generating a signal which is used for direct frequency modulation of a laser. The transmitted optical signal travels over single-mode fiber to a coherent receiver, where it is combined with an optical local oscillator signal using a directional coupler. The resulting signal is heterodyne-detected by a PIN photodiode, amplified, and demodulated. After the first FM demodulator, the SCM channels are separated using a bandpass filter array, downconverted to a common frequency, and amplified. A set of FM demodulators and lowpass filters recovers the baseband video signals.

Analysis

The goal of this analysis is to evaluate the optical receiver sensitivity, defined as the received optical power (P_s) required to achieve a 56 dB peak-to-peak SNR at the output video ports. Tables 1 and 2 contain definitions of variables and numerical values of parameters used in this analysis.

The SCM signal g(t) used to frequency modulate the optical carrier is given by

$$g(t) = \sum_{k=1}^{N} \beta_k \cos(2\pi f_k t + 2\pi f_d \int_{t_0}^{t} d_k(t')dt' + \varphi_k). \qquad (1)$$

Modulation indices $\{\beta_k\}$ are chosen such that $|g(t)| \le 1$. For simplicity, $\{\beta_k\}$ are set equal to a common value β.

The signal and LO fields are mixed by the photodiode, giving a detected photocurrent

$$i(t) = R\left(P_s + P_{LO} + 2\sqrt{P_s P_{LO}}\cos(2\pi f_{IF} t + 2\pi f_\Delta \int_{t_0}^{t} g(t')dt' + \phi_p(t))\right). \qquad (2)$$

The dc terms P_s and P_{LO} will contribute to the photodetector shot noise and to the total relative-intensity noise (RIN). The third term is the useful signal. The phase noise process $\phi_p(t)$ is assumed to have a power spectral density [5]

$$S_\phi(f) = \frac{\Delta\upsilon}{\pi f^2} \qquad (f > 0). \qquad (3)$$

After amplification, the signal and noise enter the radio frequency (RF) demodulator. The carrier-to-noise ratio (CNR) at the input of the frequency demodulator is given by

$$CNR = \frac{2R^2 P_s P_{LO}}{\sigma_W^2 + \sigma_{RIN}^2}, \qquad (4)$$

where the white noise power (consisting of shot, thermal, and amplifier noise powers) and RIN power are given by

$$\sigma_W^2 = \left(2qR(P_s + P_{LO}) + \frac{4kT}{R_L} + \frac{4\{v_a^2\}}{3R_L^2}\right)B_{IF} \qquad (5)$$

$$\sigma_{RIN}^2 = R^2(P_s + P_{LO})^2 10^{\frac{RIN}{10}} B_{IF}. \qquad (6)$$

B_{IF} is given by Carson's rule:

$$B_{IF} = 2(D+1)f_h, \ D > 10 \text{ and } D < 2 \qquad (7)$$

$$B_{IF} = 2(D+2)f_h, \ 2 < D < 10. \qquad (8)$$

The optical frequency deviation ratio D is analogous to the modulation index in tone modulation.

We evaluated the SNR at the output of the intermediate frequency (IF) demodulator by performing an analysis similar to that in [3, pp. 428-443]. The fundamental impact of the FM demodulation on the noise sources is (a) the conversion of additive white noise at the input to parabolic noise with a zero at dc at the output and (b) the conversion of the frequency noise at the input to white noise at the output. The noise enhancement which occurs as FM demodulator operation breaks down for CNR below the FM threshold (approximately 10 dB) is quantified using the threshold model of Rice [6].

The CNR after the bandpass filter for channel N is

$$CNR_N = \frac{0.5 f_\Delta^2 \beta^2}{(\sigma_W^2 + \sigma_{RIN}^2)\dfrac{f_h^2 B_T}{2R^2 P_s P_{LO} B_{IF}} + \sigma_P^2 + \sigma_T^2}, \tag{9}$$

where the phase noise [7] and threshold noise powers are

$$\sigma_P^2 = \frac{\Delta \upsilon}{\pi} B_T \tag{10}$$

$$\sigma_T^2 = \left(\frac{4\pi^2 B_{IF} \operatorname{erfc}(\sqrt{CNR})}{\sqrt{3}} + 4\pi^2 \sqrt{2} f_\Delta \exp(-CNR) \right) B_T. \tag{11}$$

Carson's rule for $2 < D < 10$ is used to find B_T in our numerical calculation. Channel N, the channel with the highest subcarrier frequency, has the lowest CNR at the input to the subcarrier FM demodulator due to the parabolic noise spectrum, which has f^2 frequency dependence. The impact of the noise on channel N is approximated by white noise with density equal to that of the parabolic noise at f_h, the highest frequency of the SCM signal.

Using a similar analysis, it can be shown that the SNR at the output of the FM demodulator for channel N is

$$\mathrm{SNR_N} = \frac{3f_\Delta^2 f_d^2 \beta^2}{\left(\sigma_W^2 + \sigma_{RIN}^2\right)\frac{f_h^2 f_v^3}{2R^2 P_S P_{LO} B_{IF}} + \left(\sigma_P^2 + \sigma_T^2\right)\frac{f_v^3}{B_T} + \sigma_{T2}^2 f_v^2}, \qquad (12)$$

where the threshold noise power for the second demodulator is

$$\sigma_{T2}^2 = \left(\frac{4\pi^2 B_T \mathrm{erfc}(\sqrt{\mathrm{CNR_N}})}{\sqrt{3}} + 4\pi^2\sqrt{2} f_d \exp(-\mathrm{CNR_N})\right) f_v. \qquad (13)$$

Assuming an emphasis improvement factor of 13.1 dB as per international (CCIR) standards for FM video transmission systems [8], an SNR_N of 42.9 dB is required for a destination SNR of 56 dB. The threshold noise due to the subcarrier FM demodulator is negligible because CNR_N must be on the order of 20 dB to achieve an output SNR of 56 dB.

Results and Discussion

Figs. 2 and 3 show samples of our results for the system parameters given in Table 2. In both figures, the optical receiver sensitivity is plotted versus the number of channels; constant optical bandwidth is assumed. The values of sensitivity were obtained using an iterative numerical technique to solve equation (12) for P_s. Inspection of Fig. 2 reveals that increasing linewidth reduces the maximum number of SCM channels which one can transmit with a reasonable sensitivity. However, receiver sensitivity is only weakly dependent on linewidth for lower channel counts, since the linewidth is much smaller than the optical bandwidth per channel. A receiver sensitivity of approximately -40 dBm can be achieved for up to 50 channels, even with 100 MHz linewidth. This is comparable to the fundamental limit on sensitivity for the assumed optical bandwidth (-45 dBm) and the fundamental limit for 50-channel coherent transmission of analog FM SCM video channels using intensity modulation of the transmitter (-35 dBm) [9]. The sensitivity is also comparable to that reported for FM-SCM video using phase modulation of the transmitter for about the same number of channels [1],[10]. The leveling off of achievable receiver sensitivity for low channel counts is due to the threshold effect of the first FM demodulator.

Inspection of Fig. 3 shows that performance is degraded for high values of transmitter and local oscillator RIN. As RIN increases beyond -150 dB/Hz, local oscillator relative-intensity noise becomes increasingly dominant. For example, a sensitivity loss of nearly 10 dB for low channel counts occurs as RIN increases from -140 to -130 dB/Hz. RIN degradation can be softened using a balanced receiver [11].

Summary

Analog coherent systems for transmission of subcarrier-multiplexed FM video have potential for excellent sensitivity. For example, a receiver sensitivity of approximately -30 dBm is attainable in an 80-channel system with 100 MHz linewidth. For up to 50 channels, receiver sensitivity is essentially independent of laser linewidth up to 100 MHz. This effect results from the phase noise suppression in a receiver employing double FM demodulation and is similar to that in digital ASK and FSK systems [14]. Relative-intensity noise effects are more severe than linewidth effects, particularly for low channel counts, where the local oscillator RIN is dominant. For example, a degradation in the sensitivity floor of about 15 dB occurs as RIN increases from -150 dB/Hz to -130 dB/Hz. A balanced receiver may be used to reduce the impact of RIN on system performance.

Acknowledgements

This work was partially supported by ONR under contract number N00014-91-J-1857, by a gift from GTE Corporation, and by the National Defense Science and Engineering Graduate (NDSEG) Fellowship Program. The authors are grateful to Drs. R. Gross and R. Olshansky of GTE Labs for their support and helpful discussions.

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Figure Captions

Fig. 1. Block diagram of a coherent SCM system using direct laser frequency modulation to transmit FM video channels. The N branches after the downconverters are identical.

Fig. 2. Receiver sensitivity (for output SNR = 56 dB) versus the number of transmitted channels for several values of linewidth; RIN=-160 dB/Hz. The linewidths shown ($\Delta\upsilon$) correspond to the sum of the transmitter and LO laser linewidths. Numerical values of system parameters are shown in Table 2.

Fig. 3. Receiver sensitivity (for output SNR = 56 dB) versus the number of transmitted channels for several values of RIN. The sum of the linewidths of the transmitter and LO lasers is 40 MHz. Numerical values of system parameters are shown in Table 2.

Table 1 - Definitions of Variables

P_s	Optical signal power
f_s	Optical signal frequency
f_Δ	Single-sided maximum optical frequency deviation
N	Number of channels
β_k	Modulation index for channel k
f_k	Subcarrier frequency for channel k
f_d	Single-sided maximum subcarrier frequency deviation
$d_k(t)$	video signal for channel k (baseband)
φ_k	Phase of channel k (subcarrier)
P_{LO}	Optical local oscillator power
$f_{IF} = f_s - f_{LO}$	Receiver intermediate frequency
$\phi_p(t)$	Combined phase noise of received signal and optical local oscillator
B_{IF}	IF bandwidth
RIN	Relative-intensity noise (in dB/Hz)
f_h	Highest frequency in SCM signal
$D = f_\Delta/f_h$	Optical frequency deviation ratio
$\Delta\upsilon$	Sum of linewidths of optical transmitter and LO

Table 2 - Parameter Definitions and Values

$R = 0.7$ A/W	Photodiode responsivity
$q = 1.6\times10^{-19}$ C	Charge of electron
$k = 1.381\times10^{-23}$ J/°K	Boltzmann's constant
$T = 300°$ K	Room temperature
$R_L = 50\ \Omega$	Amplifier load resistance
$\{v_a^2\} = 4\text{x}10^{-20}\ A^2 / Hz$	Amplifier voltage noise
$B_T = 50$ MHz	SCM channel bandwidth
$f_d/f_v = 2.68$	Subcarrier frequency deviation ratio

Optical LO power = 1 mW
Subcarrier separation = 60 MHz
Lowest subcarrier frequency = 100 MHz
Optical bandwidth = 20 GHz

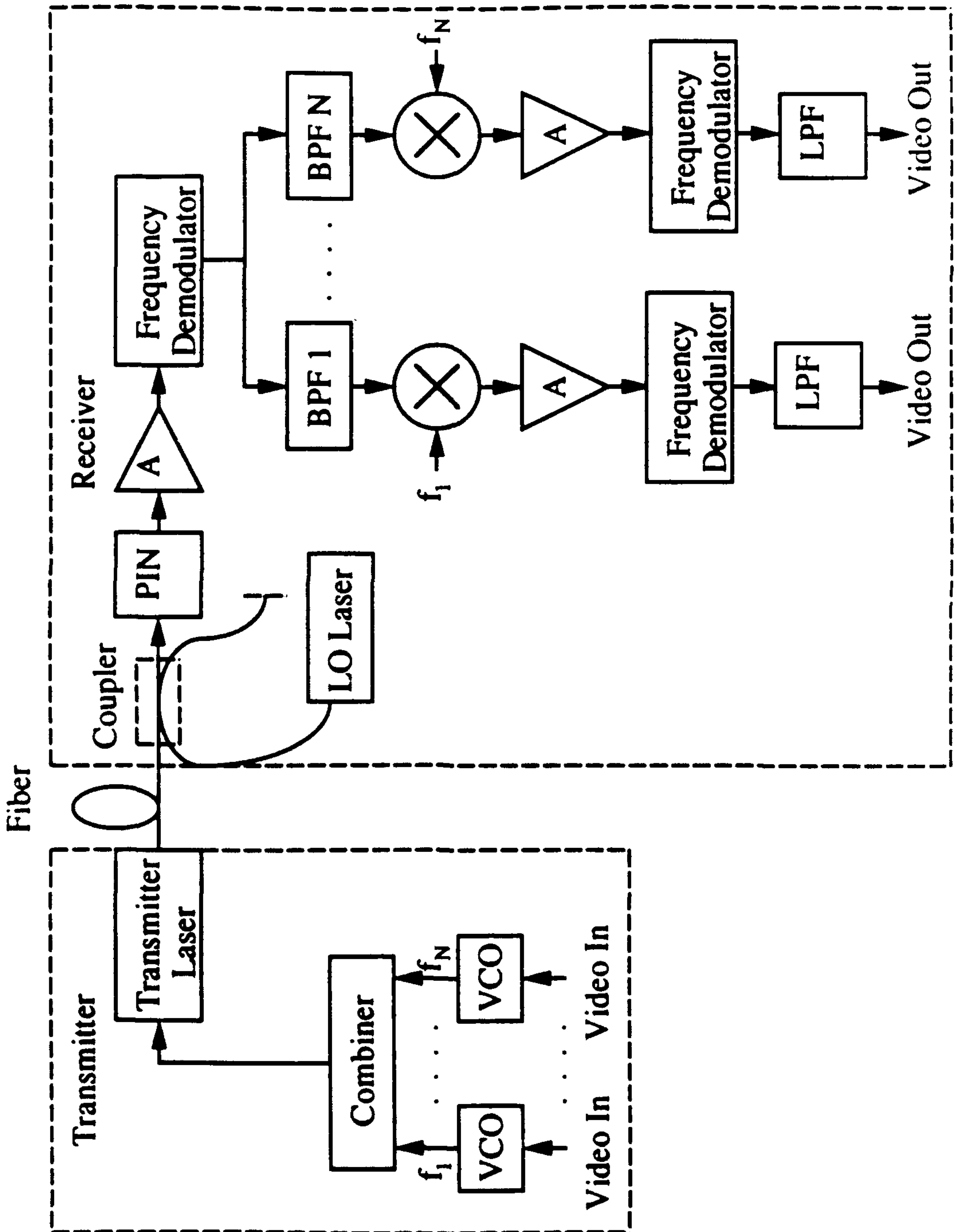
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Fig. 1

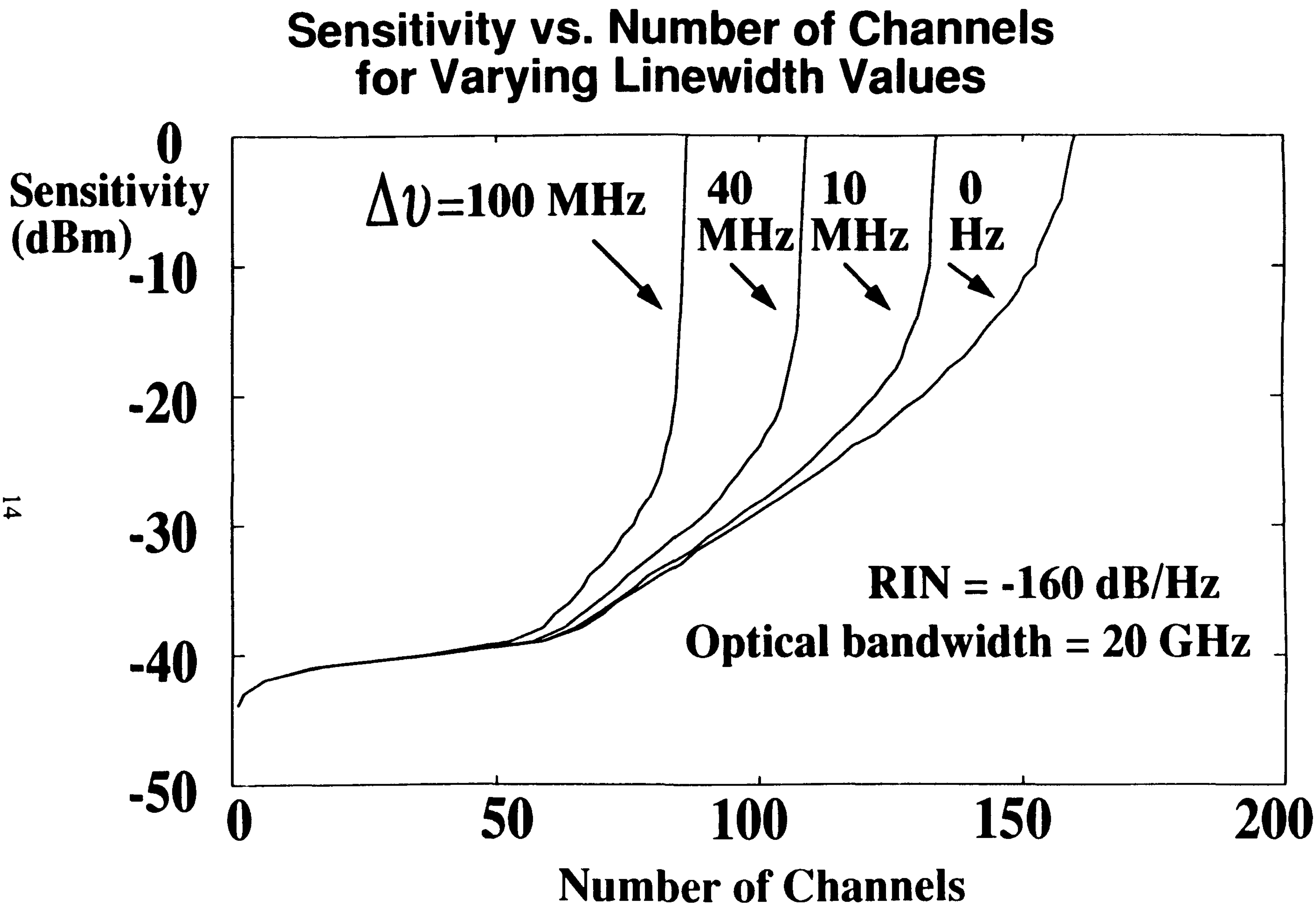
Sensitivity vs. Number of Channels
for Varying Linewidth Values
Sensitivity (dBm)
0
-10
-20
-30
-40
-50
Δυ=100 MHz
40 MHz
10 MHz
0 Hz
RIN = -160 dB/Hz
Optical bandwidth = 20 GHz
0
50
100
150
200
Number of Channels

Fig. 2

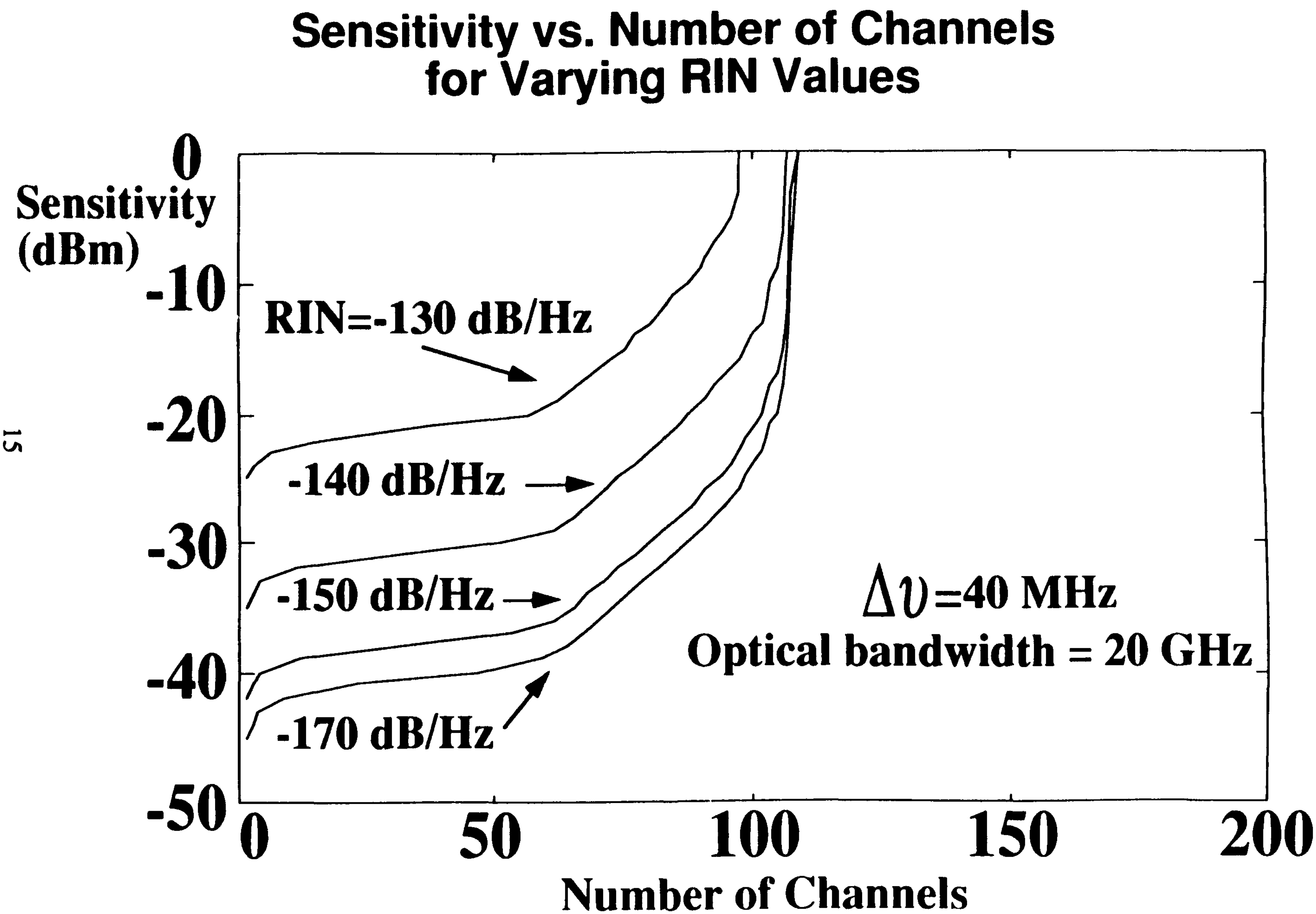
Sensitivity vs. Number of Channels
for Varying RIN Values
Sensitivity
(dBm)
0
-10
-20
-30
-40
-50
RIN=-130 dB/Hz
-140 dB/Hz
-150 dB/Hz
-170 dB/Hz
Δυ=40 MHz
Optical bandwidth = 20 GHz
0
50
100
150
200
Number of Channels

Fig. 3