However, for a Gaussian with the same mean and variance as the NB, as $n \to \infty$,

$$P_N(n) = \exp\left[-(n - \langle n_{th}\rangle)^2/(2\langle n_{th}\rangle^2)\right]/[\sqrt{(2\pi)}\langle n_{th}\rangle)$$
$$\propto \exp(-n^2)$$

Thus, the right tails of the two distributions differ in form, as is readily seen in Fig. 2.

As is also evident in Fig. 2, as $n \to 0$ the left tail of the NNB distribution decays more rapidly than the left tail of the equivalent Gaussian. Indeed for $n = 0$, $P_{SN}(0)$ for the NNB is

$$P_{SN}(0) = \exp\left[-g\langle N\rangle/(1 + \langle n_{th}\rangle)\right]/(1 + \langle n_{th}\rangle)^M$$
$$\approx \exp(-3b\langle N\rangle)[\exp(-b\langle N\rangle)/\langle n_{th}\rangle^M]$$

with $b = g/(4\langle n_{th}\rangle)$, whereas for a Gaussian with the same mean $g\langle N\rangle$ and variance $2g\langle N\rangle\langle n_{th}\rangle$ as the NNB (assuming $\langle N\rangle$ very large),

$$P_{SN}(0) = [\langle N\rangle^{-1/2}/(4\pi g\langle n_{th}\rangle)^{1/2}] \exp\left[-g\langle N\rangle/(4\langle n_{th}\rangle)\right]$$
$$\approx \langle N\rangle^{-1/2}[\exp(-b\langle N\rangle)/(4\pi g\langle n_{th}\rangle)^{1/2}].$$

Thus, even as $\langle N\rangle$ becomes very large, the left tail of the NNB cannot be approximated by a Gaussian.

UNIFORM CNR DESIGN RULES FOR COHERENT SUBCARRIER MULTIPLEXED SYSTEM WITH MULTIOCTAVE FREQUENCY ALLOCATION

Indexing terms: Multiplexers and multiplexing, Phase modulation

For a CSCM system with multioctave configuration, the CNR difference among channels is significant and needs to be taken into consideration. Here we take 'equal optimal CNR of the first and central channels' as a criterion, then we derive a design rule to reduce CNR difference significantly. The example shows that it can be lessened from 7 to 1·5 dB with lower received signal power to achieve the same CNR requirement.

Introduction and system description: For a coherent subcarrier multiplexed (CSCM) system as shown in Fig. 1, the degree of nonuniform CNR in a multioctave configuration may be large as reported in Reference 1. Usually in a multioctave system,

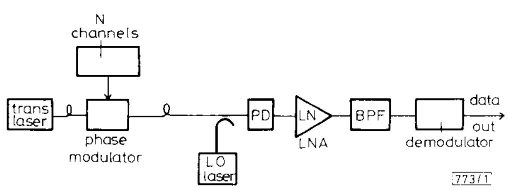

Fig. 1 *System block diagram of CSCM*

the second-order intermodulation (IMD_2) contaminates the first channel mostly, but the third-order intermodulation (IMD_3) contaminates the central channel mostly.[1] In this letter, we first obtain the optimal CNR expressions of both the first and the central channel and use the criterion 'equal optimal CNR of the first and central channels' to equalise the CNR performance approximately. Then we can obtain the phase modulation (PM) index in terms of channel spacing, the total number of channels, and the 'octave-number' with corresponding received power to meet the CNR requirement of the first channel (worst case in a multioctave system). The optical CSCM system consists of N equispaced channels with signal bandwidth B and channel separation Δf. To reduce IMD_2, we locate the frequency of the ith channel ($i = 1, \ldots, N$) at $f_i = (i - 1)\,\Delta f + F_{min}\,\Delta f + \Delta f/2$, where F_{min} is an integer. The offset frequency $\Delta f/2$ is employed to let IMD_2 degrade the channel signal least. The power spectra of IMD_2 and IMD_3 can be taken as the convolution of the power spectrum of each channel[2] and their magnitudes are determined by the signal power level and the phase modulation (PM) index.

Derivation of CNR and optimum PM index: The CNR for large local oscillator power which suppresses the thermal noise can be derived by using the first-order approximations of $J_0(\beta)$ and $J_1(\beta)$ as[1]

$$CNR = (4qB/(RP_S\beta^2) + h_2K_2\beta^2/4 + h_3K_3\beta^4/16)^{-1} \tag{1}$$

where q is the electron charge, R is the photodiode responsivity, P_S is the received signal power, and β is the PM index (assumed equal for all channels). h_2 and h_3, related to the power spectra of IMD_2 and IMD_3 in the neighbourhood of the signal band, are the fractions of the power within the passband of the bandpass filter. Under the condition of equal channel spacing, the value of h_2 for the ideal rectangular signal spectrum can be expressed as $h_2 = (3 - \Delta f/B)^2/8$ for $\Delta f < 3B$, and $h_2 = 0$ for $\Delta f \geq 3B$. The value of h_3 for the ideal rectangular signal spectrum is 2/3. $K_2(i)$ and $K_3(i)$ represent the numbers of IMD_2s and IMD_3s contaminating the ith channel, respectively. They can be expressed for a multioctave configuration as in References 3 and 4, case (A) ($1 < X \leq 2$): $K_2(i) = N(1 - 1/X) - i + 1$ for $1 \leq i \leq N - F_{min}$, $K_2(i) = 0$ for $N - F_{min} + 1 \leq i \leq F_{min} + 1$ and $K_2(i) = (i - N/X - 1)/2$ for $F_{min} + 2 \leq i \leq N$; case ($B$) ($2 < X$): $K_2(i) = N(1 - 1/X) - i + 1$ for $1 \leq i \leq F_{min} + 1$, $K_2(i) = [N(2 - 3/X) - i + 1]/2$ for $F_{min} + 2 \leq i \leq N - F_{min}$ and $K_2(i) = (i - N/X - 1)/2$ for $N - F_{min} + 1 \leq i \leq N$. For both cases ($A$) and ($B$), $K_3(i) = i(N - i + 1)/2 + [(N - 3)^2 - 5]/4$, where $X \equiv N/F_{min}$ (the 'octave-number') and $X = 2, 3, \ldots$, etc. represent the two-, three-, ..., octave configuration.

Here we define the CNR difference, $\Delta(i, j)$, between channels i and j from eqn. 1 as

$$\Delta(i, j) = 10\log_{10}\frac{CNR(i)}{CNR(j)}$$
$$= 10\log_{10}\frac{1 + [h_2K_2(j) + h_3K_3(j)\beta^2/4]/[16qB/(RP_S\beta^4)]}{1 + [h_2K_2(i) + h_3K_3(i)\beta^2/4]/[16qB/(RP_S\beta^4)]} \tag{2}$$

We can obtain the optimal PM index that maximises the CNR of the ith channel as $\beta_{opt} = \langle 0{\cdot}5\{-y + \sqrt{[y^2 + (64/3h_3K_3(i)CNR)]}\}\rangle^{1/2}$, where $y = [8h_2K_2(i)]/[3h_3K_3(i)]$.[1] The corresponding receiver sensitivity is $P_S = (4qB/R)/[\beta_{opt}^2/CNR - h_2K_2(i)\beta_{opt}^4/4 - h_3K_3(i)\beta_{opt}^6/16]$. Then we can express this maximum obtainable CNR for this channel in terms of β_{opt} as $CNR_{opt} = [h_2K_2(i)\beta_{opt}^2/2 + 3h_3K_3(i)\beta_{opt}^4/16]^{-1}$.

The design rules: We usually have the same received power P_S and unified system PM index β_{sys} for all the channels in the CSCM system with total N_{sys} channels. We also need to keep the CNR of all channels above a specific value. Therefore, we may choose the appropriate P_S, β_{sys} and Δf to meet the requirement. Here, we are concerned about 'uniform CNR for all channels' and will solve this problem as follows: first, we take channels 1 and $N_{sys}/2$ as the worst channels under the consideration of IMD_2 and IMD_3, respectively. We apply 'equal optimal CNR of channels 1 and $N_{sys}/2$' as a criterion, that is, $CNR_{opt}(1) = CNR_{opt}(N_{sys}/2)$, to obtain the corresponding $\beta_{sys} = 2(3 - \Delta f/B)[K_2(1) - K_2(N_{sys}/2)/N_{sys}(N_{sys} - 2)]^{0{\cdot}5}$. Then we may simplify it as $\beta_{sys} = 2(3 - \Delta f/B)(1 - 1/X/N_{sys} - 2)^{0{\cdot}5}$ (case (A)), and $\beta_{sys} = (3 - \Delta f/B)[(1 + 2/X)/N_{sys} - 2)]^{0{\cdot}5} + 0{\cdot}016$ (case (B)). Hence, the unified system PM index can be obtained from the given total channel number and octave-number; together with the specified channel spacing Δf to achieve the required CNR value with the corresponding P_S.

Numerical examples and conclusion: Consider a multioctave system with digital data rate 100 Mbit/s ($B = 100$ MHz) and $R = 1$ A/W. Here we consider the two- and four-octave systems (that is, $X = 2$ and 4) with total channel number $N_{sys} = 40$. We may find that the β_{sys} and β_{opt} of channels 1 and $N_{sys}/2$ cross at some specified CNR with corresponding channel spacing Δf as shown in Fig. 2. Table 1 lists the operating conditions proposed here (A, B, C, D) and in Reference 1 (E, F, G, H). We obtain the CNR difference $\Delta(i, 1)$ between the first and ith channels against the numerical channel positions as shown in Fig. 3 with the corresponding operating conditions in Table 1. As shown in Reference 1, the CNR difference may be large for fixed channel spacing ($\Delta f = 2B$) in a multioctave system when only the first channel's optimisation is considered. Given the octave-number and the total channel number, we can select the unified system PM index β_{sys} to achieve an approximately uniform CNR. Finally, we can choose the required channel spacing to achieve a given CNR value with the corresponding received signal power. Therefore, we can reduce the CNR difference from 7 to 1·5 dB with lower received power to achieve the same CNR requirement.

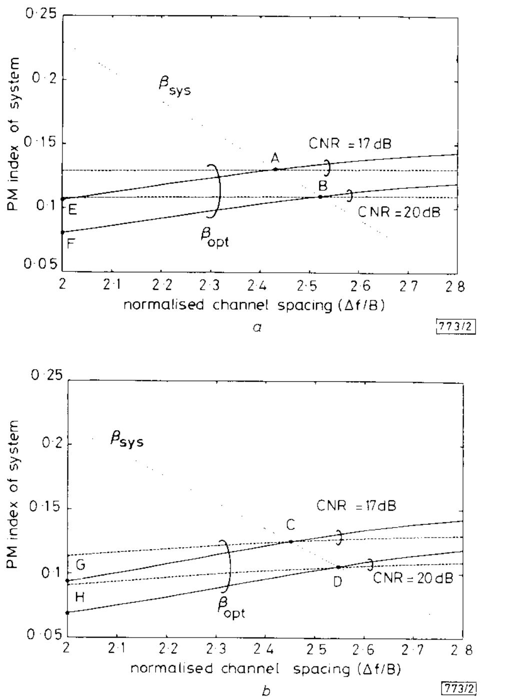

Fig. 2 *PM index of channels 1, $N_{sys}/2$ and system against the normalised channel spacing with $N_{sys} = 40$, $B = 100$ MHz*

a Case (*A*): X = 2
b Case (*B*): X = 4
——— channel 1
– – – – channel $N_{sys}/2$

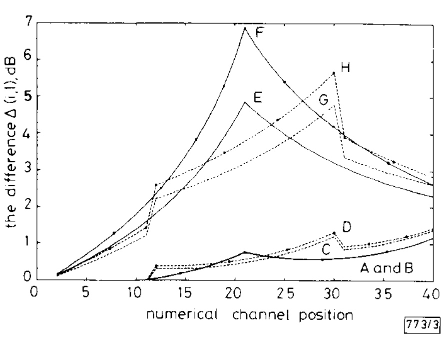

Fig. 3 *CNR difference $\Delta(i, 1)$ between channel i and 1 against the numerical channel position for the operating conditions in Table 1 with $N_{sys} = 40$ and $B = 100$ MHz*

CNR = 17 dB
——— Case (*A*)
– – – – Case (*B*)
CNR = 20 dB
●—● Case (*A*)
●-● Case (*B*)

Table 1 OPERATING CONDITIONS

	β_{sys}	$\Delta f/B$	*CNR* (dB)	P_s (dBm)
This letter				
A	0·1286	2·43	17	−34·3
B	0·1087	2·52	20	−29·8
C	0·1261	2·45	17	−33·8
D	0·1065	2·55	20	−29·4
Reference 1				
E	0·1065	2	17	−32·5
F	0·0804	2	20	−27·0
G	0·0935	2	17	−31·4
H	0·0695	2	20	−25·7

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References

1 GROSS, R., and OLSHANSKY, R.: 'Multichannel coherent FSK experiments using subcarrier multiplexing techniques', *J. Lightwave Technol.*, 1990, **8**, (3), pp. 406–415
2 STEPHENS, W. E., and JOSEPHS, T. R.: 'A 1·3 μm microwave fiber optic link using a direct-modulated laser transmitter', *J. Lightwave Technol.*, 1985, **3**, pp. 308–315
3 OLSHANSKY, R., LANZISERA, V. A., and HILL, P.: 'Subcarrier multiplexed lightwave systems for broadband distribution', *J. Lightwave Technol.*, 1989, **7**, pp. 1329–1341
4 ABUELMA'ATTI, M. T.: 'Carrier-to-intermodulation performance of multiple FM/FDM carriers through a GaAlAs heterojunction laser diode', *IEEE Trans.*, 1985, **COM-33**, (3), pp. 246–248

THROUGHPUT ANALYSIS OF CDMA WITH DPSK MODULATION AND DIVERSITY IN INDOOR RICIAN FADING RADIO CHANNELS

Indexing terms: Digital communication systems, Radio links

The throughput of a slotted CDMA system with DPSK modulation is derived, considering selection diversity and maximum ratio, combined in an indoor Rician fading channel. Computational results are obtained for typical values of maximum RMS delay spread and data rates. The effect of (15, 7) BCH code on the throughput is also investigated.

Introduction: We present a throughput analysis of slotted code division multiple access (CDMA) for indoor wireless communications with a differential phase shift keying (DPSK) modulation scheme and two forms of diversity methods (antenna selection diversity and maximum ratio combining) to combat the multipath fading in indoor radio channels. The