Fig. 1. System model of the OCDMA-PON and noise sources.

has been reported that offers high performance, compactness, compatibility with the fiber-optic system, and potentially low cost, making it an attractive choice for coherent TS-OCDMA encoding/decoding [[26](#bookmark1)], [[27](#bookmark1)]. The improved practically of coherent TS-OCDMA has attracted a great deal of research attention.

In coherent TS-OCDMA, the coherence of the optical signal has to be maintained within the chip duration so the coherent beat noise becomes critical. The beat noise issue has been studied with respect to spectral coding OCDMA systems [[10](#bookmark1)], [[28](#bookmark1)] and 2-D OCDMA [[29](#bookmark1)]. The effect of beat noise in a TS-OCDMA system, however, has not been studied to the authors’ knowledge. This paper examines the beat noise, along with the multiple-access-interference (MAI) and receiver noise, and the effects of such noise on incoherent, coherent, and partially coherent TS-OCDMA.

This paper is organized as follows. In Section II, the system models of coherent, incoherent, and partially coherent TS-OCDMA-PON that were used are described. The noise distributions and corresponding bit-error-rate (BER) expres­sions are derived and discussed in Section III. In Section IV, the system performance of these networks and the effect of the beat noise are evaluated and possible solutions discussed. Conclusions are presented in Section V.

II. System Model

A simplified system model of a TS-OCDMA-PON is shown in Fig. 1. Three different kinds of noise source should be taken into account in this model: MAI noise arising from the net­work, beat noise at the detector, and receiver noise (thermal, shot noise, etc.). The bandwidth of the receiver is limited to the chip rate and thus is equivalent to an integrator (over one-chip interval) followed by thresholding [[2](#bookmark1)], [[7](#bookmark1)].

We assume that there are K active users asynchronously transmitting signals in the network. If there are m (0 < m < i^) interfering signals from untargeted active users at a given in­stant, the received optical field at the photodetector of the target user is

m

+yAexpj (wj ■ (t - Tj)+- Tj)) (1)

i=l



where Fd and Pi are the optical intensity of the decoded signal from the targeted (data) and untargeted users (interferers), re­spectively, ujd and uji are optical frequencies, (pd and (j)i are the

respective phase noise of these signals, and is the relative network transit delay of the interferer. We assume that (pd and pi are mutually independent Gaussian-distributed Wiener-Levy stochastic processes [[30]](#bookmark1)-[[32](#bookmark1)].

For a TS-OCDMA network employing chip-rate square-low photodetection, the output signal Z from the integrator is



-h

0

= TJkPd + TJk Y, Pi +23? Y

Data

Tc

2=1 2=1

Interference

X

J cos{{uJi 0

ojin + 4>i{t - n)

Primary data—interference beat terms m m—1

+ 29 Y.

j=i-\-l 2=1 Tc

X

0

Secondary interference—interference beat terms

Tc

— pj{t — Tj)) dt J no{t)dt (2)

0

Receiver noise

where 5R is the responsivity of the photodetector, Tc is the chip duration, and no denotes the receiver noise current. Here, it is assumed that the bandwidth of photodetector is larger than the frequency difference between the incoming signals {tOi — ujd)- The chip pulse waveform is also assumed to be constant over the chip duration Tc for simplicity. In this expression, the first term is the target signal, the second term represents the MAI noise, and the third and fourth terms are the m primary data-interfer- ence and m(m — l)/2 secondary interference-interference beat noise, respectively. The final term represents the receiver noise. Here, the polarization states of the data and interfering signals are assumed to be the same (the worst-case scenario).

Usually, in a TS-OCDMA-PON, the crosstalk level which is defined as = (Pi)/Pd (here, (•) represents the assemble average), is very small <C 1). For example, in a coherent TS-CDMA-PON with the SSFBG encoder/decoder using length ^Chip Gold code, ^ ^ 1/^chip- The ratio of the variance of primary and secondary beat noise terms is about 2/(my^^). If



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rn is not very large (rn^^ < 1), the secondary beat noise can be ignored. Generally, we can therefore focus on the primary data-interference beat terms. For the case where the secondary beat terms cannot be ignored, the discussion is similar.

In the expression of the primary beat terms (the third sum in (2)), there are three terms inside the cosine functions. The first term is (cu.; — u!j)-t= {6u))ij.t. Typically, we assume {6u))ij < 1 GHz [[32](#bookmark1)] and Tc « 10 ps [[33](#bookmark1)], [[34](#bookmark1)] in TS-OCDMA, the term {Su))ijt <C 27r within the integral duration Tc, so the first term is negligible. The second term uJiTi is approximately a constant during the integral duration, so this is also a negligible term. The third term fp{t - r^) - (p{t - tj) = 6(pij{t) strongly depends on the coherent property of the optical pulse within the integral du­ration. We will discuss the effects of this term in three different cases: an incoherent regime, a coherent regime, and a partially coherent regime.

A. Incoherent Regime (tc <C Tc)

In incoherent TS-OCDMA, it is usually assumed that Tc <€. Tc (Tc is the coherence time of the light [[32](#bookmark1)]). In this regime, S(j)ij{t) is a random process uniformly distributed over [-tt, tt] during the integral duration Tc- The integral of the cosine func­tion thus gives 0. We can simplify Z to

Z = T,?li



(3)

TS-OCDMA systems are partially coherent {kt > 1) as Tc is usually very short and Do cannot be very large. For instance, if Tc ~ 10 ps, the coherent ratio kt of a system with 2-nm bandwidth (Bo ~ 250 GHz) is only about 2.5. That is far from the incoherent regime. To attain kt = 10, an 8-nm bandwidth is required, which is prohibitively large. Therefore, it is important to determine the relationship between the beat noise and the coherent ratio kt of TS-OCDMA systems.

In the partially coherent regime, a simplification of the model is to assume that the relative phase is maintained as a con­stant within every time slot of coherent time Tc, and they are mu­tually independent random processes distributed over [-tt, tt] for different time slots. Under this assumption, Z can be ex­pressed as

Z ^ToM[Pd + J2Pt

i=l

kt

2 ^ ^ '\/PiPd

■i=l

Tc

(5)

0



Within the limit of kt = 1, (5) becomes that of the coherent regime (i.e., (4)). Within the limit of kt oo, (5) becomes that of the incoherent regime [i.e., (3)].

III. Noise Distributions and BER Expressions The average BER of the system can be written as

This means that the beat noise can be ignored by averaging throughout the detection, and the MAI noise is the dominant noise source in such systems.

A'-l

BER = ^ p(m) BER (rn) (6)

m=0

B. Coherent Regime (tc >



In contrast, in coherent TS-OCDMA (e.g., with PLCs or an ssFBG encoder/decoder), the coherence of light should be maintained at least within each chip; i.e., Tc > Tc- In this regime, 8(j>ij(t) is a small constant within the integral duration Tc- Thus, Z becomes

Z ^ToTl{Pd + Y.Pi

i=l

2 ^ ) \/PiPd cos(A4r j)

i=l

It. (4)



Here, we ignore the secondary interference-interference beat noise terms for simplicity. A4>.i = (8u!)idTc + u>iTi -|- 6(t)id denotes the overall phase noise. A<]>.; is a random process that varies over [—tt, tt] from bit to bit, which results in beat noise in coherent TS-OCDMA systems.

C. Partially Coherent Regime (Tc/tc > 1)

Usually, in an incoherent Ts-OCDMA network, the ratio Tc/tc is not very high. Here, we define the coherent ratio kt = Tc/tc to measure the coherence property of the light within the chip duration. As Tc ~ l/i?o (Po is the optical band­width of the system), kt ~ TcBo. In practice, most incoherent

where p{m) is the probability that m of the iT - 1 interfering users are simultaneously “1”s at the detection chip, which obeys the binomial distribution

p{rn)



rnl

(7)

BER(m) is the BER with m interfering signals. With equal probability binary data and chip rate detection, BER(m) can be expressed as

BER(m) = Pr(0)chip-Pe(l|0)(rrr) r(0)da,taT Pr(l)data

’r(l)chip^e(0|l)(rrr)

Tjiit J \_

Pe(l|0)(m)

' Tr

Pr(l)dataj^ TBit

Pe(0|l)(m)

2-^] Pe(l|0)(m) + ^Pe(0|l)(m)

T Bit / T Bit

(8)



where Pr(0)chip andPr(l)chip are the probabilities of chip mark “0” and “1”, respectively, while Pr(0)data and Pr(l)data are the probabilities of data mark “0” and “1”, respectively. Tuit is the bit period, and Pe(l|0)(m) and Pe(0|l)(m) are conditional error probabilities with chip mark “0” and “1”, respectively.

We can thus discuss the noise distributions from (3)-(5) for different systems and derive BER expressions of them.

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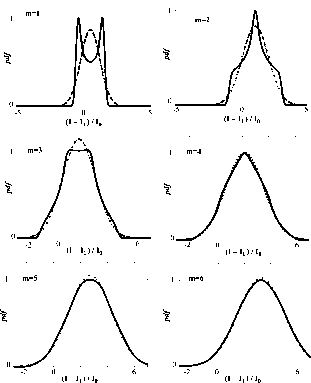


Fig. 2. Noise pdf with different values of m (/i = P^, Iq = Solid black lines: Calculate by (12). Dashed black lines: Gaussian pdf. Dotted gray lines:

Modified Gaussian pdf.

A. Incoherent Regime {kt oo)

From (3), the average received signal scaled by 1/TJR is

T.jR

= (1 +

(9)



If we assume that the MAI and receiver noise both have Gaussian distributions, the error probabilities are

Pe(l|0)(m) = ^erfc



(10a)

and

Pe(0|l)(m) = ^erfc



(10b)

where <tmad crth. and dsh are the MAI, thermal, and shot noise

variances, respectively

2 \_ 2 ^MAI — '^<^MAI-0

2 4:kBTBR ^th = —— = BnNth

o-o\_sh = 2eBR^Pdm^

al\_,,^=2eBR^Pd{l + mO^ (11b)

Here, ctmai-o is the variance of a single interfering signal; when using iVchip = 127 Gold code, ct^ai-o ^ ^ 10“^. Br =

l/(2Tc) is the receiver bandwidth, and Ath = ^ksT/RR is the thermal noise spectral density, where ks is Boltzman’s con­stant, T is the temperature, and Pi, is the load resistance. A typical value of Ath = 1 pA^/Hz is used in the following cal­culations. e is the electron charge.

where 0 < P < 1 + is the decision threshold. In addition, CTo-in and (7i\_in are the total noise variance with chip mark “0” or "1”, respectively

2 \_ 2 \_L 2 I 2

^0-in — ^MAI + ^th “T ^0-sh

2 2 I 2 I 2 1 \

<^l-in — ^MAI + ^th + <^l-sh (11a)

B. Coherent Regime (kt = 1)

Within this limit, the average received signal scaled hyl/TJR is also given by (9). When the chip mark is “0” (Pd = 0), and if the secondary beat terms are negligible, Pe(l|0)(m) is also the same as given by (10a). If the number of secondary beat terms is large enough that it is not negligible, it can also be modeled

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to have a normal Gaussiandistribution according to the central limit theorem. Therefore, Pe(l|0)(m) will have the same form as (10a) with ao-in replaced by ao-co

^2 \_ ^2 I ^2 I ^2

^0-co — ^MAI “T <^th “T <Tbeat-0

(12a)

where (ibeat-o is the variance of the secondary beat noise

^’’beat-O = - 1)U-P,I- (12b)

With chip mark "1”, the beat between each interference with the target signal has a "two-pronged” distribution [[30](#bookmark1)]-[[32](#bookmark1)]. The probability density function (pdf) of the total received signal can be expressed as

pdf(:T, m) = F\

oo

(a;) exp(-

(13a)

where M(a;) is the characteristic function of the signal [[32](#bookmark1)] and is defined as

oo

{^) = J exp(-jb

%x.

(13b)

From (4) and (13b), we can easily derive M{uj) = Jo”\*(2ViAw)exp

9 9 -\

+

(14)

X exp

where Jq is the Bessel function of hrst kind zero order. Thus, the error probability for mark "1” can be expressed as

DPd

(15)

0

We have applied two approximations for this pdf to simplify the calculation [[33](#bookmark1)]. One is to use the Gaussian distribution with

—CO

Pe(0|l)(m) = J pdf(x,m)

z I Z I z

— ^beat-1 T ^MAI + ^th + ^1-sh

(16)

where abeat-i is the variance of the beat noise, which can be expressed as



o-Lat-i = 2rnCP|.

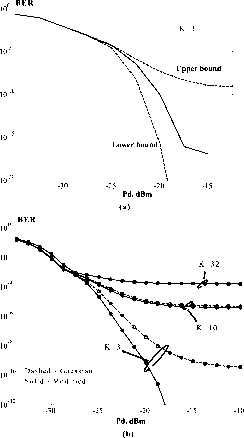


Fig. 3. BER performance evaluation using different noise pdfs (optimum threshold level D applied). (a) Upper and lower bound of the BER curve for K = 3. Upper bound: Gaussian pdf. Lower bound: Modified Gaussian pdf. Middle curve: Calculated using (12)-(14). (b) Upper and lower bounds of the BER performance for different!".

We can then calculate Pe(0|l)(m) using (10b) by replacing ^i-in with ai-co\* According to the central limit theorem, we can expect this approximation to be valid when m is large enough.

When the m value is low, as the pdf of each interferer beat term is two-pronged and bounded within we apply an­

other approximation to modify the Gaussian pdf by bounding the beat noise pdf within 2my^^Pd and replacing it by that without beat noise. The modified Gaussian distribution with variance (Ti-m is

^2

^l-r.

^1-co — ^Lat-1 +^MAI

^ +^t\ + <^Ush.

^1-in —^MAI + ^th +^l-sh5

ifP>:

(17a)

Thus, the error probability Pe(0|l)(m) can be calculated using this modified Gaussian distribution and expressed as

Pe(0|l)(m)=- erfc

Pd(l-hm^-j

- erfc

2m^/^Pd

— erfc

2my/lPd

ifP > 1

Pe(0|l)(m)=-erfc

Pd{^ + “

others. (17b)



The noise pdfs calculated from these three expressions with different values of m are plotted in Fig. 2. The variations be-

others

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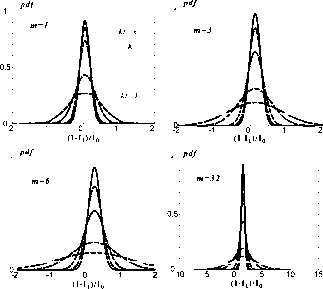


Fig. 4. Noise pdf with different values of kt for variou^i^.

tween them are quite remarkable when m is low, but as m in­creases, the profiles become identical.

We also evaluated the BER performance using these pdf ex­pressions fox K = 3 [Fig. 3(a)]. The Gaussian pdf gives the upper bound of the system BER, while the modified Gaussian pdf gives the l^^er bound. Fig. 3(b) compares the results of the two approximations with different values of iT. If iT is large enough, the deviations between the approximations are negli­gible, but if iF < 5, the difference is quite large. (In all these cal­culations, an optimal D value is applied to minimize the BER.)

C. Partially Coherent Regime {kt > 1)

Generally, the average received signal in the partially co­herent regime is given also by (9). P(l|0)(m) should also be the same as (10a) for the reasons given in case B.

The noise pdf with chip mark "1” can be derived from (5), as follows:

oo

pdf(a:, m) = F [Mp{w)] = ^ j exp(-j

tU)

(18)

where

exp [iTO(,f+ V^)Pda; . (19)

xexp

aW

Here, \\_kt\ gives the integer part of number kt. The error prob­ability Pe(0|l)(m) can be obtained from (15). We can easily

prove that when kt = 1, (19) becomes the same as (14); when kt oo, (18) turns out to be a Gaussian distribution.

The noise distributions with different values of kt and a dif­ferent number of interference signals m are plotted in Fig. 4. With the increase of kt, the noise pdf changes from the coherent limit {kt — 1) io the incoherent limit {kt oo). This shows how the beat noise is eliminated from a system through an in­crease in the coherent ratio kt.

IV. Performance Limitations Due to the Beat Noise and THE Means of Beat Noise Suppression

The effects of different noise sources on the BER perfor­mance of a TS-OCDMA system are illustrated in Fig. 5 (solid lines). In this example, iT = 32, the lowest solid curve in the figure is with receiver noise only, the middle one is that of an incoherent network with receiver noise plus MAI noise, and the highest one is that of coherent TS-OCDMA with beat noise. We can see that the MAI noise is the dominant noise source in inco­herent TS-OCDMA, while the beat noise dominates in coherent TS-OCDMA and thus is the main limit on system performance.

The dashed curves in Fig. 5 clearly show the relationship be­tween the BER performance and the coherent ratio kt of the system. The impact of the beat noise in a TS-OCDMA network is highly dependent on the coherent ratio kt: from the coherent limit {kt = 1), which is beat noise dominated, to the incoherent limit {kt oo), which is MAI-noise dominated, the impact of beat noise is gradually eliminated with increasing kt.

Fig. 6(a) shows the power penalty (at BER = 1 x 10“^) of the TS-OCDMA system with (coherent) and without (incoherent) beat noise versus K using 127-chip Gold code. Fig. 6(b) shows

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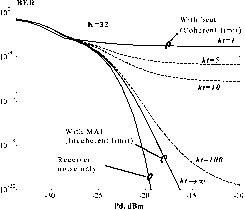
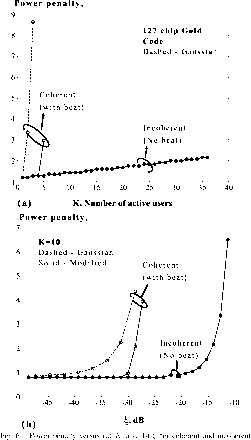


Fig. 5. Influence of the different noise sources and the coherent rati^t on the BER performance of a TS-OCDMA network with 32 active users.

the power penalty versus the crosstalk level ^ for K — 10. The base line is that with the receiver noise only. The results of using two BER approximations are also plotted to show the upper and lower bounds. Fig. 6(a) shows that because of beat noise the coherent TS-OCDMA using 127-chip Gold code can only support hve active users for error-free (10“^) transmission, whereas, without beat noise, it can accommodate more than 40. Fig. 6(b) shows that to support ten active users for error-free transmission, ^ must be about — 30 dB, which means the code length should be about 1000. That will be prohibitively large for practical encoder/decoder devices.

Three points need to be noted regarding these results. One is that in the above calculations, optimal threshold values Dopt are applied. The differences between the BER performance with Dopt and that using a hxed D = 0.5 can be seen in Fig. 7. The value of Dopt is determined by solving the equation <9(BER)/9D = 0 numerically (the curve with circles in the figure). The second point concerns the chip-rate detection in our model. In practice, chip-rate detection may not be available as the photodetector is not fast enough. The use of a PD with a narrower bandwidth B will result in a longer integration time in the model, thus degrading BER performance. Fig. 7 also shows the BER performance for different PD bandwidths. The third point is that in a 2-D OCDMA scheme with a coherent laser source, as in each wavelength, the signal is coherent time-spread, so it could be regarded as a partially coherent TS-OCDMA scheme with kt = Ps. Here, Ps is the weight of the encoded signal. In a symmetric 2-D OCDMA system Pg — pj^ (pj^ is the number of available wavelengths) [[18](#bookmark1)]-[[25](#bookmark1)], [[29](#bookmark1)]. Therefore, we can expect the degradation due to beat noise to also be eliminated if a large number of wavelengths are used.

As the beat noise critically limits system performance in co­herent and partially coherent TS-OCDMA networks, a way to alleviate its impact is crucial in OCDMA networks. In Table I, we classify the means to suppress beat noise into three mecha­nisms and summarize several possible methods. The first mech­anism is to reduce the crosstalk level (^). The use of longer code



time-spreading OCDMA networks.

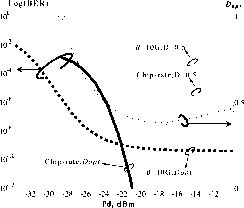


Fig. 7. BER performance with optimal (black line) and fixed (gray line^7, and under-chip-rate detection.

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TABLE I

Means of Suppressing Beat Noise in an OCDMA-PON

|  |  |  |  |
| --- | --- | --- | --- |
| Mechanism | Method | Notes | |
|  |  | Partially coherent OCDMA | Coherent OCDMA |
| Reduce  crosstalk | Using longer code | The code is too sparse, low power & bandwidth efficiency | Increased hardware cost & limited transmission data rate |
| Synchronized  OCDMA | 1. Need control of optical path within chip-length (mm) order (for precise synch.)  2. Lowers the bandwidth efficiency (rough synch.) | |
| Polarization  state | Polarization scrambling or modulation | Not effective for PON environment | |
| Low-coherence  source | LED, ASE, chirped DEB, modulation, etc. | Effective because of increased kt | Not effective for the coherence required in a chip duration (7c\*B ~1) |

is the most effective way to do this. This will lead to an increase of hardware cost and lower bandwidth efficiency. However, the progress made in SSFBG fabrication techniques has made it possible to produce ultralong optical codes with a very high chip rate [[35](#bookmark1)]. Another way is to use a synchronized scheme. With a precisely synchronized scheme, ^ can be reduced to a reasonably low level. However, the system synchronization re­quirement is too strict to be realized in practical network en­vironments. A roughly synchronized scheme can mitigate this problem by allowing the crosstalk from different users to offset each other, but this will lead to lower bandwidth efficiency.

The second mechanism is to control the polarization state of the crosstalk from each user through polarization scrambling or modulation. This is effective if the polarization state is known a priori and controllable but cannot work in the PON environ­ment.

The third mechanism is to lower the coherence of the light source. This is effective for partially coherent systems because kt is increased. This method cannot be used for coherent sys­tems, however, because the coherent coding operation requires that Tc ^ B ^ l[kt ~ 1).

V. Conclusion

Generally, TS-OCDMA systems can be classified according to the coherent ratio kt into incoherent {kt oo), coherent {kt — 1), and partially coherent {kt > 1) systems, kt reflects the coherent property of the light during the chip duration. The coherent scheme that works with bipolar codes is more efficient and enables better system performance than the partially co­herent and incoherent schemes that work with unipolar codes. In a coherent system, however, the beat noise is the dominant

noise source and main limit on system performance. In partially coherent systems, the effect of beat noise is gradually eliminated as kt rises. An incoherent system is free of beat noise and MAI noise is the dominant noise source.

There are several ways to overcome the beat noise in a co­herent or a partially coherent TS-OCDMA network. Using a low-coherence light source is effective in partially coherent sys­tems since this increases kt. In coherent systems, the use of longer codes and some kind of synchronization scheme can lower crosstalk, thus mitigating the impairment of beat noise.

For the coherent TS-OCDMA PON, beat noise is a serious issue since it is the major limitation in network design. The re­cent progress made in SSFBG techniques shows that it is pos­sible to eventually suppress the beat noise to an acceptable level in a coherent TS OCDMA network with an SSFBG encoder/de­coder.

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