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A New Frequency Switching/IM3 Reduction Method in Fiber-Optic Microcellular System

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SUMMARY Fiber-optic microcellular system has been studied actively as an excellent system for solving the equipment cost problems in microcellular systems. However, the occurrence of intermodulation distortion (IMD) arising from the nonlinearity of the laser diode used for E/O conversion which degrades the transmission quality is a serious problem in this system. In this paper, we propose a new frequency switching/IM3 reduction method, which dynamically reassigns the carrier frequencies to minimize the carrier to IMD power ratio under the hostile environment with time-varying received carrier strength, and analyze the performance improvements by the proposed method. The improvements obtained both for the worst value of the overall CNR and for the overall CNR in a specific user are numerically made clear. It is also shown that if the interval between frequency reassignings is set less than one second, a sufficient improvement in the overall CNR is achievable.

key words: *microcell, radio communication, optical communication, intermodulation, frequency switching*

1. Introduction

Recently, the demands for public mobile communications and a new personal communication system have been rapidly increased. Though microcellular system is considered to be a most useful candidate for satisfying them, it has the disadvantage in equipment cost. Fiber-optic microcellular system which is a joint system of radio and optical ones has been studied energetically to solve the problem [1]–[6].

Fiber-optic microcellular system is attractive because of its own advantages. It uses frequency resources effectively and can accommodate a large mass of subscribers since its cell size is very small. Furthermore, equipment of its base station is very simple and channel control becomes easy compared with conventional mobile communication system.

Fiber-optic microcellular system, on the other hand, has some disadvantages. In this system where optical fiber is used for transmission between base stations and control station, frequency division multiplexed (FDM) RF signals are converted into optical signal (E/O) by driving the input current of laser diode in proportion to RF signal strength. This technique has been called *subcarrier multiplexing* (SCM) onto the fiber [7]. Since laser diode (LD) used for E/O conversion has generally *nonlinear* characteristic between input current and output optical intensity, unnecessary interference components occur in RF band as a result of interactions among RF signals with different frequencies. This interference components are called *intermodulation distortion* (IMD), and particularly third order intermodulation distortion (IM3) causes serious degradation of the system transmission quality.

In usual mobile communications, we have to consider the amplitude fluctuation of received RF signal arising from *fading*, *shadowing* and *far-near* problem. In the up-link transmission from base station to control station, LD is driven by RF signals with time-varying strength, therefore the transmission quality time-varies too. Hence, useful strategies to compensate the transmission quality should be considered.

There may be countermeasures for compensating time-varying RF signal strength such as automatic power control (APC) at mobile terminal, automatic level control (ALC) at base station, IMD pre-distorter which is introduced before E/O conversion and frequency modulation of frequency multiplexed RF signal. We propose, in this paper, a new frequency switching/IM3 reduction method as a countermeasure that differs entirely from the aboves and consider the compensation effect when it is applied to the fiber-optic microcellular system.

In Sect. 2, the mechanism of IMD occurence and the influence of time-varying received signal strength to IMD are clarified. In Sect. 3, a new IMD compensation method is proposed. In Sect. 4, the performance improvement by the proposed method is numerically investigated.

2. Transmission Characteristic

2.1 Intermodulation Distortion

Figure 1 shows the block diagram of fiber-optic microcellular system. As previously indicated, intermodulation distortion (IMD) is produced at E/O conversion when SCM onto the fiber is used for signal transmission between base stations and control station. Though IMD consist of second, third and higher order prod-

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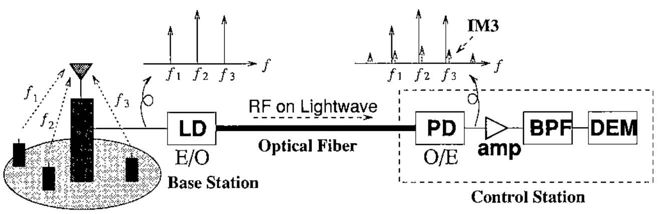
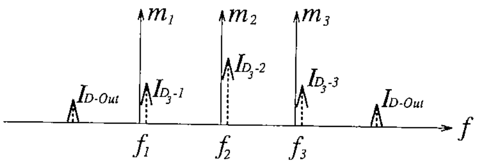
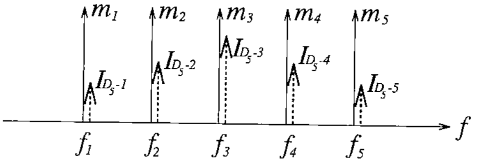


Fig. 1 Block diagram of the fiber-optic microcellular system.



(a) 3 carriers



(b) 5 carriers

Fig. 2 The power spectrum of IM3. (The components out of RF band are omitted for 5 carriers.)

ucts, it is enough to give attention to only third order intermodulation modulation (IM3) since the even order products occur out of RF band and more than fifth order of odd order products is much smaller than third order products [8].

There are two types of IM3, one is the *two-tone* type IM3 that is produced by two signals interactions and the other is the *three-tone* type IM3 that is produced by three signals interactions. The average power of three-tone IM3 is 6 dB bigger than that of two-tone IM3. And it is known that the number of three-tone IM3 is largest at the center frequency [9].

Suppose that three carriers which are arranged at same intervals in the RF band are modulated into optical signal. If input signal is expressed as

$$s_i(t) = m_1 \cos 2\pi f_1 t + m_2 \cos 2\pi f_2 t + m_3 \cos 2\pi f_3 t, \qquad (1)$$

LD output intensity P is given as

$$\begin{aligned} P = P_o\, [1 &+ (m_1 \cos 2\pi f_1 t + m_2 \cos 2\pi f_2 t \\ &+ m_3 \cos 2\pi f_3 t) \\ &+ a_2 (m_1 \cos 2\pi f_1 t + m_2 \cos 2\pi f_2 t \\ &+ m_3 \cos 2\pi f_3 t)^2 \\ &+ a_3 (m_1 \cos 2\pi f_1 t + m_2 \cos 2\pi f_2 t \\ &+ m_3 \cos 2\pi f_3 t)^3 + \cdots], \end{aligned} \qquad (2)$$

where P_o is average output optical intensity of LD, a_k $(k = 1, 2, 3, \cdots)$ is k-th order parameter of non-linearity and m_i $(i = 1, 2, 3)$ is optical modulation index(OMI) corresponding to carrier with frequency f_i $(i = 1, 2, 3)$. IM3 power is derived by expanding the third order term of Eq. (2). Let the received *dc* current of photo diode (PD) at the control station I_{ph}, IM3 power after O/E conversion $D_{3-1}, D_{3-2}, D_{3-3}$ which occurs at frequency f_1, f_2, f_3 can be expressed as

$$f_1 \cdots D_{3-1} = \frac{1}{2}\left(\frac{3}{4} a_3 m_2^2 m_3\right)^2 I_{ph}^2, \qquad (3)$$

$$f_2 \cdots D_{3-2} = \frac{1}{2}\left(\frac{3}{2} a_3 m_1 m_2 m_3\right)^2 I_{ph}^2, \qquad (4)$$

$$f_3 \cdots D_{3-3} = \frac{1}{2}\left(\frac{3}{4} a_3 m_1 m_2^2\right)^2 I_{ph}^2. \qquad (5)$$

D_{3-1} and D_{3-3} have one two-tone type IM3 and no three-tone type IM3. On the other hand, D_{3-2} has no two-tone type IM3 and one three-tone IM3.

Though each IM3 power has only one type in above example, generally, the IM3 power D_{n-i} that occurs at i-th frequency for n carriers FDM is expressed as

$$D_{n-i} = \frac{1}{2}\left(\frac{3}{4} a_3 \sum_{p,q} m_p^2 m_q + \frac{3}{2} a_3 \sum_{r,s,t} m_r m_s m_t\right)^2 I_{ph}^2.$$
$$(1 \leq p, q, r, s, t \leq n, \quad 2p - q = r + s - t = i) \qquad (6)$$

For instance, the IM3 power that occurs third frequency f_3 of five carriers is

$$\begin{aligned} D_{5-3} = \frac{1}{2}\bigg\{&\frac{3}{4} a_3 \left(m_2^2 m_1 + m_4^2 m_5\right) \\ &+ \frac{3}{2} a_3 \left(m_1 m_3 m_5 + m_2 m_4 m_5\right)\bigg\}^2. \end{aligned} \qquad (7)$$

Figure 2 shows the power spectrum of IM3 when all OMIs are identical for three and five carriers FDM respectively. For both (a) and (b), it is shown that IM3 power of inner frequency becomes big suffering the influence of tree-tone IM3 strongly. From Eq. (6) and Fig. 2, the fact that quality difference exists among carriers can be found. That is, intermodulation distortion does not only degrade the transmission quality but also make quality difference among users.

2.2 The Time-Varying Received Strength

In terrestrial mobile communications, even if the transmission power of mobile terminal is kept constant, received strength at the base station time-varies in the radio channel under the hostile environment of multipath propagation, terrain features and man-made obstacles. Hence, when we analyze the IM3, the received carrier strength and OMI should be taken into consideration.

Suppose that CDR means the carrier to intermodulation distortion power ratio, it is derived from Eq. (6)

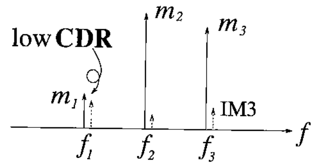


Fig. 3 The effect of time-varying received carrier strength.

for carrier with frequency f_i among n carriers and is given as following equation.

$$\frac{C}{D}=\frac{\frac{1}{2}m_i^2 I_{ph}^2}{D_{n-i}}, \tag{8}$$

where the numerator of the right side denotes the power of carrier with frequency f_i and the denominator denotes the power of IM3 component which occurs at frequency f_i. For example, CDR for $n = 1$ and $i = 1$ is

$$\frac{C}{D}=\frac{\frac{1}{2}m_1^2 I_{ph}^2}{\frac{1}{2}\left(\frac{3}{4}a_3 m_2^2 m_3\right)^2 I_{ph}^2}. \tag{9}$$

If OMIs m_1, m_2 and m_3 are random variables in this example, CDR of frequency f_1 becomes worse when m_1 is small and m_2 and m_3 are big (Fig. 3). Hence, it is necessary to compensate CDR under such condition.

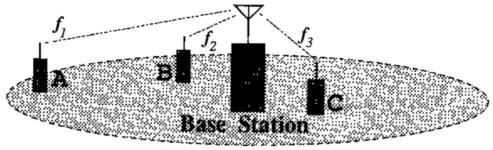
In the following section, a new countermeasure for CDR degradation is proposed and its performance is analyzed.

3. Frequency Switching / IM3 Reduction

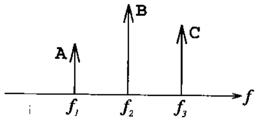
As a countermeasure for CDR degradation under the environment with time-varying received strengths, we propose a frequency switching/IM3 reduction method that differs from APC, ALC, and so on.

From Eqs. (3)–(5), it is noticed that IM3 power which occurs at a specific frequency depends on strengths of all received carriers. Assuming that each carrier strength is mutually independent of the other carrier strengths, frequency reassignment brings on changes in IM3 strengths and, reasonably, CDRs. Frequency switching/IM3 reduction is a method to maximize the CDR by means of the frequency assigning according to the suitable algorism.

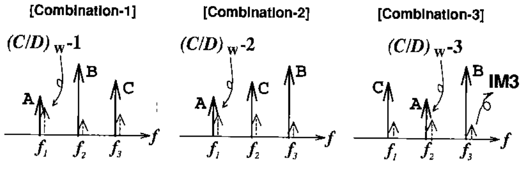
In practice, the frequency assignment that produces no IM3 is already reported. And the method that uses not channels with interference but those in good condition is sometimes adopted [10]. However these methods can't use frequency resources efficiently because they need frequencies that have no channels and can't transmit no information. This is against the primary purpose of microcellular system, that is, accommodating a large mass of subscribers. A frequency switching/IM3 reduction method does not need such useless frequencies so it is obviously advantageous concerning frequency efficiency.



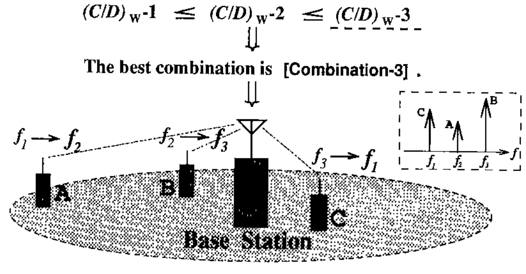
(a) Frequencies before switching.



(b) Operation i.



(c) Operation ii. (Symmetries are considered)



(d) Operation iii.

Fig. 4 Proposed switching algorism.

As frequency reassignment algorisms, the following are investigated. First, the aims of the switching algorism are

- To maximize the average value of CDRs.
- To maximize the worst value of CDR of all CDRs at all frequencies.

second, switching intervals are

- Periodic switching at constant intervals.
- Intermittent switching only when CDR of any carrier falls bellow the required value.

In this paper, from the reason why we need to improve CDR degradation, and why we want to examine the capability of the proposed method, we determined the use of the following algorism (Fig. 4),

i. Observe received strengths of all carriers.

ii. Calculate all CDRs when it is assumed that frequencies are reassigned and get the worst value of CDR as $(C/D)_{\mathrm{w}}$ for every combination of frequencies.

iii. Find the combination that maximizes $(C/D)_{\mathrm{w}}$ among all combinations of frequencies and switch frequencies actually according to that combination.

iv. Repeat the operation i–iii periodically at constant intervals.

If the proposed switching method was applied, it is expected that outage probability, which means the time rate that the CNR including intermodulation distortion is below the specified value, can be made small. And since the frequency of a specific user changes continuously, the qualities of all users are averaged. Furthermore, since whole procedures can be managed at control station, base stations don't need additional equipments and keep up the advantage of small and simple. (Even though control station must have large computer power.) Then, it is convenient that the frequency switching of mobile terminal is made by the existing frequency selection mechanism.

4. Performance Improvement by the Proposed Method

4.1 Definition of Overall Transmission Quality

After this, as the measure of overall transmission quality, we use carrier to total noise power ratio CNDR. This CNDR means the CNR including intermodulation distortion D after O/E conversion at control station and is represented as

$$\frac{C}{N+D} = \frac{\frac{1}{2}m^2 I_{ph}^2}{\{RIN \cdot I_{ph}^2 + 2 \cdot e \cdot I_{ph} + \langle I_{th}^2 \rangle\} \cdot BW + D_{n-i}}, \tag{10}$$

where each parameter means that

m_i : optical modulation index (OMI),
I_{ph} : received *dc* photo current,
RIN : relative intensity noise of LD,
e : charge of electron,
$\langle I_{th}^2 \rangle$: equivalent input noise power spectral density of receiver,
BW : carrier bandwidth,
D_{n-i} : intermodulation distortion power.

In the following, we study the CNDR improvement by the proposed method in the way of computer simulation.

Table 1 Parameters used in this calculation.

I_{ph}	-5.97 [dBm]
RIN	-152 [dB/H$_z$]
$\langle I_{th}^2 \rangle$	4.0×10^{-22} [A^2/H$_z$]
BW	300 [kH$_z$]
M	-17 [dB] (3*carriers*) -22 [dB] (5*carriers*)
σ	6.0 [dB]
α	0.11

4.2 Analysis Model

Suppose that three and five carriers are frequency division multiplexed in a base station, each carrier is unmodulated sinusoidal wave and they are arranged in the frequency domain at same intervals.

On the propagation path, transmitted signals suffer the rapid fluctuation called *fading*, and also suffer the slower variation of the short-term median strength of the received carrier called *shadowing*. It is known that shadowing strength is log-normal distributed and so called *log-normal shadowing*. It is difficult to reassign frequencies according to the fast fading, so it is reasonable that only the log-normal shadowing is taken into consideration. Assuming that m [dB] means OMI that is proportional to received strength under the log-normal shadowing, the probability density function $p(m)$ is represented as

$$p(m) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(m-M)^2}{2\sigma^2}\right], \tag{11}$$

where M [dB] is long-term average strength of received carrier and σ [dB] is standard deviation. And suppose that the strength of each carrier (or OMI) is statistical independent and the autocorrelation function is approximated to as

$$R(\tau) = \exp(-\alpha\tau), \tag{12}$$

where α is a parameter determined by the velocity of the mobile terminal and the frequency of the RF carrier [11]. And in this analysis, we assume that, probably impossible in practice, control stations can measure RF strengths precisely.

The parameters used in simulation actually are shown in Table 1 [11]–[14].

4.3 Improvement Obtained by Precise Switching Operation

Figure 5 shows the relationship between switching interval T_s and time-averaged $(C/N{+}D)_{\mathrm{w}}$. This $(C/N{+}D)_{\mathrm{w}}$ means the worst value of CNDR when the precise operation that is proposed in Sect. 3 was applied. It doesn't

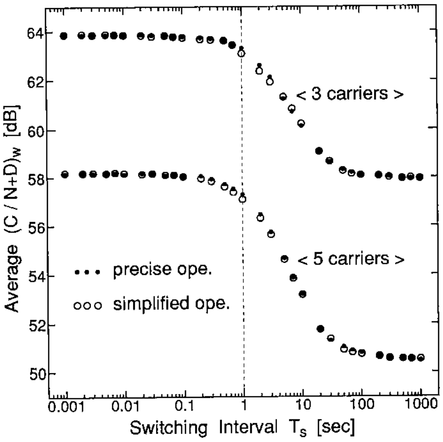


Fig. 5 The characteristic of switching interval vs. worst value of CNDR.

indicate the actual improvement in transmission quality of a specific user. However, it shows the maximum improvement by the proposed method. When T_s is sufficiently short compared with the log-normal shadowing, the improvements in $(C / N+D)_{\mathrm{w}}$ are about 6 dB for three carriers or about 8 dB for five carriers compared with that of no switching case referred to as the $(C / N+D)_{\mathrm{w}}$ with T_s over 10^3 seconds. It is known that outage probability decreases to one tenth as CNDR increases by 10 dB [14]. So assuming that distribution of instantaneous carrier strengths around the short-term median value, it is guessed that such improvement can reduce the outage probability or the BER. The figure also shows that a sufficient improvement is obtained when T_s is less than about one second. This is caused by the fact that the autocorrelation function $R(\tau)$ has the characteristic shown in Fig. 6. When $\tau \leqq 1$[sec], $R(\tau)$ is larger than 0.9 and high correlation exists between the post switching carriers and the preceding switching carriers. So, if switching operation was done with interval less than one second, received carrier strengths can be assumed as quasi static. Hence, Fig. 5 and Fig. 6 show the similar characteristic.

4.4 Improvement Obtained by Simplified Switching Operation

In the previous section, performances of the precise switching operation are investigated, and it is shown that good performances can be obtained by that operation. However, when the number of carriers is increased, the calculation of every $(C / N+D)_{\mathrm{w}}$ becomes elaborate. If the number of carriers is N, the burden of calculation increases in proportion to $N!$. The upper solid line of Fig. 7 shows this. So it is necessary to simplify the control algorism and we propose the simplified switching operation as following.

The simplified operation does not take the algorism of selecting the best frequency combination from all probables but switches carrier frequencies to satisfy each OMI the condition as

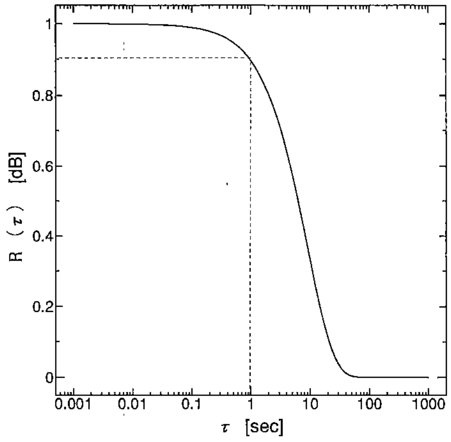


Fig. 6 The autocorrelation function.

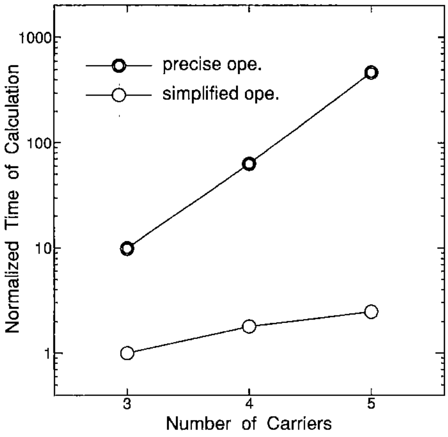


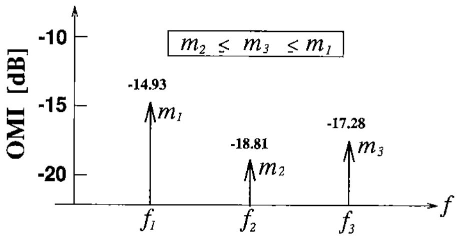
Fig. 7 The characteristic of calculation time.

3 carriers : $m_2 \leqq m_3 \leqq m_1$,
5 carriers : $m_4 \leqq m_2 \leqq m_3 \leqq m_5 \leqq m_1$.

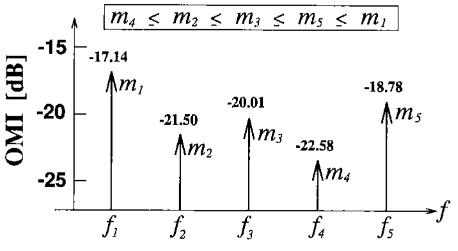
These combinations are determined from the OMI histogram that maximize $(C / N+D)_{\mathrm{w}}$ obtained from the precise switching operation (Fig. 8).

Figure 7 is the comparison of the calculation times of both operations. Each time in the figure is normalized by the time of three carriers and the simplified operation. From the figure, it is known that the precise operation needs from ten to hundreds times as much calculation time as the simplified operation and the difference between both operations becomes large as number of FDM carriers.

The improvement by the simplified operation are shown in Fig. 5. The figure shows that there is no difference between the improvement by the precise operation and one by the simplified operation. The reason is that the strength variation of shadowing is slow and the variance is small, so it is assumed that extreme OMIs which strays off the best combination by the simplified



(a) 3 carriers



(b) 5 carriers

Fig. 8 The histogram obtained by the precise operation.

operation hardly occur. From this result, it is evident that the simplified operation is superior to the precise operation as for the calculation time for switching, and does not degrade transmission quality.

4.5 Performance Improvement for a Specific User

As an important measure to design the system, we should know the improvement in a specific user's time-averaged CNR. The term of specific user does not mean that it is in some special condition but is used as one user who continues communications changing his frequency. Figure 9 shows the relationship between the switching interval T_s and the time-averaged CNDR (overall CNR) of a specific user. There are characteristics similar to Fig. 5 and Fig. 6 in this figure. Since the switching algorism is aimed to improve worst value of CNDR in return for the deterioration of good value of CNDR, the improvement decreases compared with that obtained for worst CNDR. However, the improvement more than 2 dB for three carriers or 2.5 dB for five carriers can be obtained. Hence, it is expected that the transmitting power can be reduced.

5. Conclusions

A frequency switching/IM3 reduction method was newly proposed to compensate the intermodulation distortion arising from the laser diode nonlinearity, and the improvement effect on CNDR was analysed.

Obtained results were as follows :

1) For the worst value of CNDR, the improvement of about 6–8 dB is obtained, which is expected to reduce the outage probability.

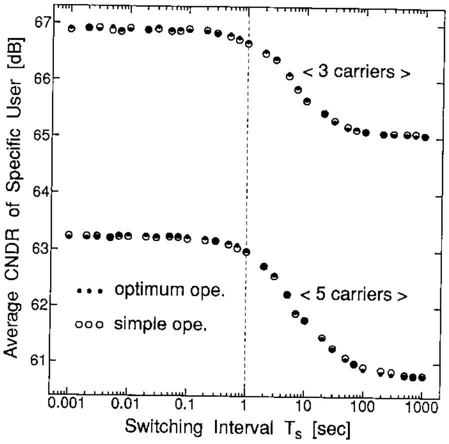


Fig. 9 The characteristic of switching interval vs. CNDR of a specific user.

2) For the CNDR of a specific user, about 2–2.5 dB improvement is obtained, which is about 4 dB lower compared with that for the worst value of CNDR mentioned above.

3) If the switching interval is set less than on 1 second, a sufficient improvement is achievable.

4) The simplified switching operation is superior to the precise operation as for the calculation time, and there is no performance degradation by using this simplified operation.

For further system evaluation, the following subjects need to be analyzed.

- BER performance or outage probability considering rapid fluctuation of carrier strength (*fading*).
- An influence of measurement error on the system performance improvement.
- The rule of order for more than five carriers.
- The improvement in the condition with frequencies out of use.
- The absolute calculation time for reassignment.

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Appendix: Deriving the IM3 Power

IM3 power for three carriers FDM is derived by expanding the third order term of Eq. (2).

$$\begin{aligned}
&(m_1 \cos 2\pi f_1 t + m_2 \cos 2\pi f_2 t + m_3 \cos 2\pi f_3 t)^3 \\
&= m_1^3 \cos^3 2\pi f_1 t + \frac{3}{2} m_1 (m_2^2 + m_3^2) \cos 2\pi f_1 t \\
&\quad + m_2^3 \cos^3 2\pi f_2 t + \frac{3}{2} m_2 (m_3^2 + m_1^2) \cos 2\pi f_2 t \\
&\quad + m_3^3 \cos^3 2\pi f_3 t + \frac{3}{2} m_3 (m_1^2 + m_2^2) \cos 2\pi f_3 t \\
&\quad + \frac{3}{4} m_1^2 m_2 \{\cos 2\pi(2f_1 + f_2)t + \cos 2\pi(2f_1 - f_2)t\} \\
&\quad + \frac{3}{4} m_1^2 m_3 \{\cos 2\pi(2f_1 + f_3)t + \cos 2\pi(2f_1 - f_3)t\} \\
&\quad + \frac{3}{4} m_2^2 m_3 \{\cos 2\pi(2f_2 + f_3)t + \underbrace{\cos 2\pi(2f_2 - f_3)t}_{(a)}\} \\
&\quad + \frac{3}{4} m_2^2 m_1 \{\cos 2\pi(2f_2 + f_1)t + \underbrace{\cos 2\pi(2f_2 - f_1)t}_{(b)}\} \\
&\quad + \frac{3}{4} m_3^2 m_1 \{\cos 2\pi(2f_3 + f_1)t + \cos 2\pi(2f_3 - f_1)t\} \\
&\quad + \frac{3}{4} m_3^2 m_2 \{\cos 2\pi(2f_3 + f_2)t + \cos 2\pi(2f_3 - f_2)t\} \\
&\quad + \frac{3}{2} m_1 m_2 m_3 \{\cos 2\pi(f_1 + f_2 + f_3)t \\
&\quad + \cos 2\pi(f_1 + f_2 - f_3)t + \underbrace{\cos 2\pi(f_1 - f_2 + f_3)t}_{(c)} \\
&\quad + \cos 2\pi(f_1 - f_2 - f_3)t\}. \qquad (\mathrm{A}\cdot 1)
\end{aligned}$$

If three carriers with frequencies f_1, f_2, f_3 are arranged at same intervals in the RF band as $f_2 = f_1 + \Delta f$ and $f_3 = f_1 + 2\Delta f$, the frequency $2f_2 - f_3$ of the term (a) becomes equal to f_1. The received photo current of PD at the control station corresponding to the term (a) is represented as

$$I_{(a)} = \frac{3}{4} a_3 m_2^2 m_3 \cos 2\pi(2f_2 - f_3)t \cdot I_{ph}, \qquad (\mathrm{A}\cdot 2)$$

and the IM3 power that occurs at frequency f_1, that is, D_{3-1} of Eq. (3) is obtained as

$$D_{3-1} = \frac{1}{2}\left(\frac{3}{4} a_3 m_2^2 m_3\right)^2 I_{ph}^2. \qquad (\mathrm{A}\cdot 3)$$

Similarly, the frequency of the term (b) is equal to f_3 and one of the term (c) is equal to f_2, so D_{3-2} and D_{3-3} of Eqs. (4) and (5) are derived as

$$D_{3-2} = \frac{1}{2}\left(\frac{3}{2} a_3 m_1 m_2 m_3\right)^2 I_{ph}^2, \qquad (\mathrm{A}\cdot 4)$$

$$D_{3-3} = \frac{1}{2}\left(\frac{3}{4} a_3 m_1 m_2^2\right)^2 I_{ph}^2. \qquad (\mathrm{A}\cdot 5)$$

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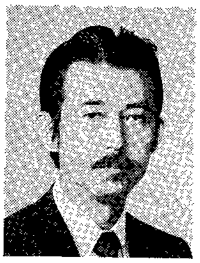

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