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Performance Analysis of Fiber-Optic Millimeter-Wave Band Radio Subscriber Loop

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SUMMARY This paper proposes a new subscriber distribution method called FTTA (Fiber To The Area), which uses millimeter-wave radio band to connect subscribers with base station and optical fiber to connect base station with control station in order to obtain broad-band transmission. Usually two main causes of signal degradation, i.e., rainfall attenuation on radio channel and intermodulation distortion on optical channel are considered in this system. Taking into considerations of these two factors, we analyze the available capacity of FTTA system for various 2^{2n}QAM modulation levels. The analysis clarifies that there exists an optimum modulation level that can maxize the available capacity, and AGC circuit in the base station is useful to compensate the rainfall attenuation. It is shown that 18.0 Gbps is available under the optimum modulation method of the 64 QAM with AGC and 12.0 Gbps under the 16 QAM without AGC when 20 carriers are used.

key words: *optimum modulation, available capacity, rainfall attenuation, AGC, millimeter-wave band radio subscriber loop*

1. Introduction

Recently, in advanced information-oriented society, there has been increasing demands for multi-media communication including voice, data, and picture. To satisfy the demands, we need to realize broad-band transmission, and the optical fiber system is one of the solutions. However it is difficult to connect every subscriber by optical fiber because of its vast investment in time and money [1]-[3].

To solve this problem, in many countries, it has been actively studied to make use of millimeter-wave radio channel for not only access networks but also subscriber networks [4]-[6], since it is possible to realize very high capacity transmission using millimeter-wave radio band. Radio communication system with millimeter-wave, furthermore, is quite efficient in spectrum utilization, since it can cover small service zone with line-of-sight transmission and little co-channel interference [4]. And this radio transmission system is flexible for changing number of subscribers and it is easy to apply for high capacity mobile communications [5].

In this paper we propose a new subscriber distribution method called FTTA (Fiber To The Area) system [7]-[9], which uses millimeter-wave radio band to connect subscribers with a base station and simultaneously uses optical fiber to connect base stations with a control station. Thus introducing a millimeter-wave radio system for subscriber link, we will be able to solve troublesome problems in all fiber optic system.

On this proposed system there are two main causes of signal degradations: one is rainfall attenuation due to using millimeter-wave on radio channel, the other is intermodulation distortion due to using subcarrier modulation on optical channel. Therefore the system performance has to be analyzed taking these two degradations into consideration. In addition, the rainfall attenuation may be removed using AGC (Automatic Gain Control) circuit in the base station, by which the available capacity is expected to increase. Hence the system performance of FTTA should be analyzed with or without AGC.

In this paper, firstly, we describe the concept of FTTA system, then we introduce the available capacities on radio and optical channels, respectively. When AGC circuit is installed in the base station, the available capacity on optical channel is calculated. Finally, considering performances on both channels, we calculate overall available capacity of FTTA system. Furthermore, the optimum modulation level that maximizes the available capacity is clarified.

2. System Model

Concept of FTTA system is illustrated in Fig. 1. We assume that each zone radius on FTTA is 300 m in order to enhance the spectrum utilization efficiency and to reduce transmitter power of both subscribers and base stations. And 2^{2n}QAM will be assumed as modulation method of this system.

On radio channel between subscriber and base station, information signal is transmitted by using 50 GHz as carrier frequency-band. It is assumed that this bandwidth per carrier is 150 MHz to transmit future broad band signals such as 150 or 600 Mbps. Base station receives RF signals from subscribers, converts RF signals into optical signal by means of SCM (Subscriber multiplexing) on fiber and transmits to control station through optical fiber. Control station

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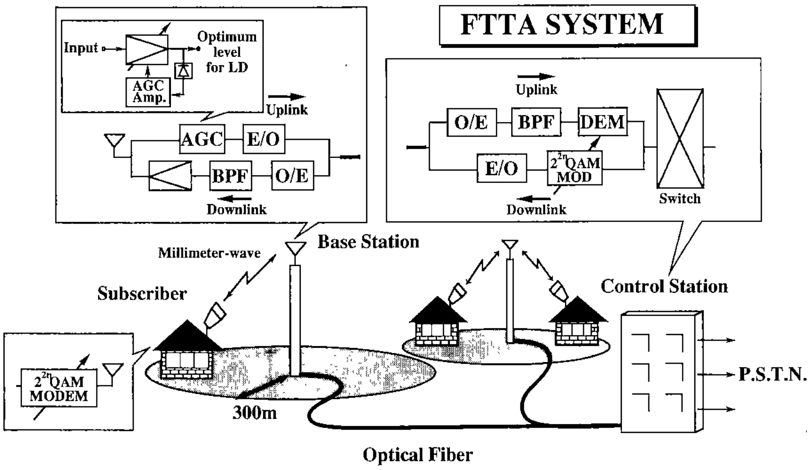

Fig. 1 Concept of FTTA.

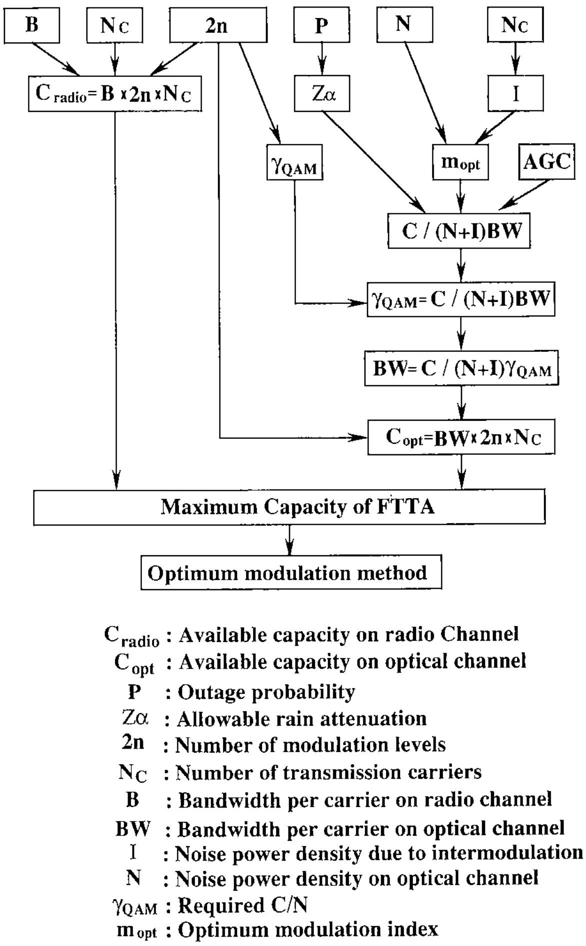

Fig. 2 Procedure of analysis.

receives optical signal from base station, converts optical signal into RF signals, demodulates these signals, assigns each signal to channel and connects it to public switched networks.

In radio channel, as the number of modulation levels increases, channel capacity increases as long as subscribers can transmit enough signal power to base station. However, to use millimeter-wave band, if signal power becomes beyond a threshold level due to rainfall, outage occurs on radio channel. On optical channel, the signals, which will be transmitted from base station, are affected by several types of noise on optical link, such as relative intensity noise, shot noise, thermal noise and intermodulation distortion caused by nonlinearity of Laser Diode. As the number of modulation levels increases, the required carrier to noise power ratio (CNR) to obtain sufficient quality increases. And as the number of carriers increases, intermodulation distortion increases. So maximum capacity per carrier should be decreased as the number of modulation levels increases, because the bandwidth of modulated signal should be narrowed to maintain the required CNR.

Since signals are transmitted through both radio and optical channels in FTTA system, available capacity of the FTTA system is restricted by the smaller one of the radio or the optical channel capacity. Thus it is expected that there exists an optimum number of modulation level that can maximize the available capacity on both channels.

In this paper we will analyze the available capacities on both channels for various numbers of modulation levels, and then clarify an optimum number of modulation levels that can maximize the available capacity. The calculation procedure of optimum modulation method is shown in Fig. 2, and the detail is mentioned in the following sections.

3. Available Capacity of Radio Channel

3.1 Outage Probability by Rainfall Attenuation

To use millimeter-wave band, if signal power decreases to a threshold level due to rainfall, outage occurs on radio channel. The permissible attenuation due to rainfall, Z_α(dB), is given as follows [10];

$$Z_\alpha = P_T + G_R + G_T - L_f - KTBF - \gamma_{QAM} \tag{1}$$

where

P_T	: Transmission power from subscriber
G_R	: antenna gain of a subscriber
G_T	: antenna gain of base station
L_f	: free-space loss
$KTBF$	: noise on receiver
K	: boltzman constant
T	: absolute temperature
B	: bandwidth
F	: noise figure
γ_{QAM}	: the required CNR.

γ_{QAM} is the required carrier to noise power ratio (CNR) to transmit signal of 2^{2n}QAM and given as follows [11];

$$\gamma_{QAM} = \frac{1}{3}(2^{2n}-1)\,\gamma_{QPSK} \tag{2}$$

where γ_{QPSK} is the required CNR when QPSK is used. In this paper γ_{QAM} guarantees that bit error rate is 10^{-6}, for example γ_{QPSK} is 13.8 dB [10].

In this system, it is assumed that subscribers use horn antenna directing to the base station. The antenna gain of subscribers, G_R, is calculated as follows [10];

$$G_R = \left(\frac{4\pi ab}{\lambda^2}\right)\eta_r \tag{3}$$

where a and b are length and width of horn antenna, respectively, η_r is aperture efficiency and λ is wavelength given by carrier frequency.

For base station, it is assumed that the cell is constructed by the sector zone to cover the all area. Sector zone angle is represented by θ_1, that is the width beamwidth of each horn antenna, and it determines antenna gain. If we denote it as G_T, it is obtained as follows [12];

$$G_T = \frac{3.2\times10^4}{\theta_1\theta_2} \tag{4}$$

where θ_1 and θ_2 are half-power beamwidths of width and length, respectively.

Free-space loss L_f is calculated as follows [10];

$$L_f = \left(\frac{4\pi r}{\lambda}\right)^2 \tag{5}$$

where r is distance between subscriber and base station. From the above, the relation of transmission power P_T and permissible attenuation due to rainfall, Z_α, is indicated in Fig. 3 with parameters shown in Table 1. For example, when 16 QAM as modulation method and 10 dBm as P_T are used, Z_α is 8.3 dB.

Probability distribution function of rain attenuation Z is approximated by gamma function [10], [13].

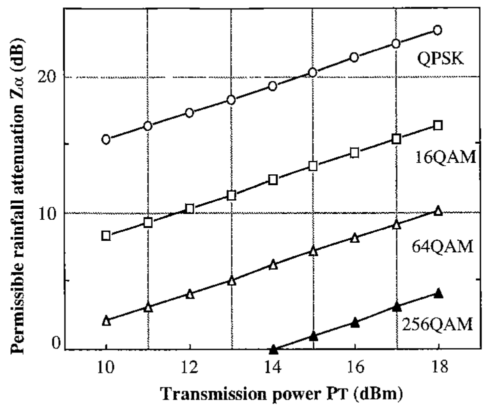

Fig. 3 Relation between P_T and Z_α.

Table 1 Parameters in Fig. 3.

antenna gain (subscriber) GR length a width b aperture efficiency ηr	37.4 dB 15cm 15cm 70%
antenna gain (base station) GT half-power beamwidth width θ1 length θ2	15.5 dB 30 degree 30 degree
boltzman constant K	1.38×10^{-23}J・K
absolute temperature T	290K
bandwidth B	150MHz
noise figure F	10dB
cell radius r	300m
transmission power PT	10~18dBm

$$f(Z) = \frac{\beta_z^{\nu_z}}{\Gamma(\nu_z)} Z^{\nu_z-1}\exp(-\beta_z Z) \tag{6}$$

where β_z, ν_z are distribution parameters and are given as follows [10];

$$\nu_z = E(d)\times\nu_y,\quad \beta_z = \frac{E(d)}{\gamma\times d}\beta_y \tag{7}$$

$$E(d) = \frac{(0.25d)^2}{4[d+2(d+12\sqrt{d}+48)\times e^{-0.25\sqrt{d}}-96]} \tag{8}$$

where d is distance between subscriber and base station, γ is constant and it is 18.4 in case of using 50 GHz [13], and ν_y and β_y are given as follows [10];

$$\nu_y = \frac{[g(1)]^2}{g(2)-[g(1)]^2},\quad \beta_y = \frac{\nu_y}{g(1)}\beta^n,$$

$$g(i) = \frac{\Gamma(\nu+i\times n)}{\Gamma(\nu)}, \tag{9}$$

where ν and β are parameters of one-minute rain rate distribution and n is constant. In case of using 50 GHz as carrier frequency-band and 300 m as cell radius, ν, β and n are 0.0075, 2.18 and 0.843 respectively [13].

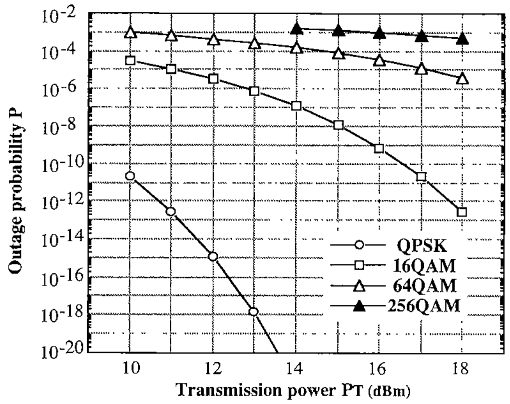

Fig. 4 Relation between P_T and P.

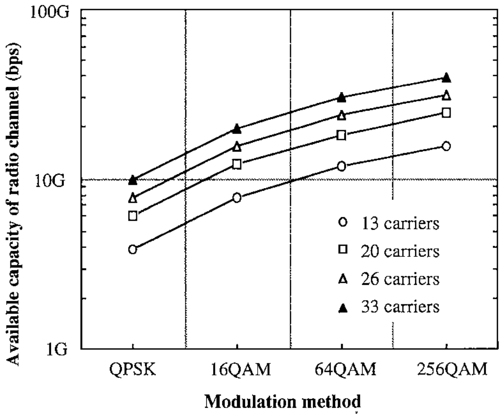

Fig. 5 Relation between modulation method and C_{radio}.

Outage probability P is the probability which the amount of rainfall attenuation exceeds the permissible value Z_a.

$$P=\int_{Z_a}^{\infty} f(Z)\,dZ$$

$$\cong \frac{1}{\Gamma(\nu_z)} \cdot \cfrac{\exp(-t)\cdot t^{\nu_z}}{t+\cfrac{1-\nu_z}{1+\cfrac{1}{t+\cfrac{2-\nu_z}{1+\cfrac{2}{t+\cdots}}}}} \qquad (10)$$

where $t=\beta_z Z_a$ [9]. The above equation is estimated from the data in three months from July to September. So the outage probability throughout a year is $P/4$. Applying Eq.(1) to Eq.(10), the relation of transmission power P_T and outage probability P is shown in Fig. 4. Figure 4 shows that outage probability P increases when P_T is fixed and modulation level increases, for the required CNR γ_{QAM} increases.

3.2 Available Capacity of Radio Channel

On radio channel it is assumed that subscribers transmit signals to a base station by enough transmission power, namely it is assumed that signal bandwidth transmitted from subscribers transmit to a base station perfectly. Therefore we can select various example as system parameter. In this analysis, following system parameters are assumed for one example. Carrier frequency is 50 GHz and bandwidth per carrier is 150 MHz to realize future broad band signal transmission, for example 150 or 600 Mbps of ATM (Asynchronous Transfer Mode) transmission. The number of transmission carriers is calculated from bandwidth assigned on radio channel and 150 MHz as bandwidth per carrier. In the case of using 2, 3, 4, 5 GHz as all bandwidth assigned on radio channel, the relation of bandwidth on radio channel and the number of transmission carriers is shown in Table 2. Using the above parameters, the available capacity on radio channel between subscriber and base station, called C_{radio}, is calculated by

Table 2 The number of carriers on radio channel.

all radio bandwidths	2GHz	3GHz	4GHz	5GHz
number of carriers	13	20	26	33

$$C_{radio}=BW\times 2n\times N_c \qquad (11)$$

where BW is bandwidth per carrier, $2n$ is the number of bits per unit bandwidth and N_c is the number of transmission carriers. The relation of number of modulation levels and C_{radio} is indicated in Fig. 5 when bandwidth on radio channel is used as parameter.

In Fig. 5, when 16 QAM is used as modulation method, the C_{radio} is 12 Gbps by using 3 GHz of bandwidth (20 carriers) and is 20 Gbps by using 5 GHz of bandwidth (33 carriers). And when 3 GHz of bandwidth are used, the C_{radio} is 6 Gbps by using QPSK as modulation method and is 24 Gbps by using 256 QAM. Obviously the available capacity on radio channel increases as the number of modulation levels and carriers increase.

4. Available Capacity of Optical Channel

4.1 Available Capacity without AGC

RF signal transmitted from subscriber is converted into optical signal by using intensity modulation of Laser Diode (LD) in base station. In this case modulation index m is given as follows [14];

$$m=\frac{\sqrt{2P_{in}/R_{LD}}}{I_b-I_{th}} \qquad (12)$$

where P_{in} is the LD input carrier intensity, R_{LD} is the LD input impedance, and I_b and I_{th} are the LD bias and threshold current, respectively. Eq.(12) indicates that modulation index is in proportion to $\sqrt{P_{in}}$. When P_{in} is attenuated by the amount of rainfall attenuation Z and the AGC (Automatic Gain Control) circuit is not installed before the LD, modulation index is $1/\sqrt{Z}$ times of the usual modulation index.

The optical signal transmitted from base station is transmitted to control station. In control station the optical signal is converted into RF signals by PIN-PD with sensitivity η and demodulate these signals. When the number of input signals to LD is plural, intermodulation distortion (IMD), D, occurs by the combinations of input signals [15]. Therefore, in control station, the received carrier to noise power ratio $C/(N+D)$ is given as follows [14];

$$\left(\frac{C}{N+D}\right) = \frac{\frac{1}{2}m^2 I_{ph}^2}{\{RIN \cdot I_{ph}^2 + 2 \cdot e \cdot I_{ph} + \langle Ith^2 \rangle\} \cdot BW + D} \tag{13}$$

where

BW : bandwidth per carrier
e : electron charge
RIN : the relative intensity noise for the LD
I_{ph} : average current received in control station
$\langle Ith \rangle$: equivalent input noise current density in optical receiver
D : intermodulation distortion power (IMD).

In Eq. (13) I_{ph} is given as follows [14];

$$I_{ph} = \eta \cdot \frac{P_o}{F_{\text{loss}}} \tag{14}$$

where η is PD sensitivity, P_o is output power of LD and F_{loss} is fiber loss including connector loss.

As the number of carriers increases, the influence of IMD becomes large. Particularly third-order intermodulation distortion (IM3) have a great influence on signal power as interference. There are two types of IM3: one is two-tone type which occurs by combinations of two RF signals and the other is three-tone type which occurs by combinations of three RF signals. In this analysis, it is assumed that n carriers are arranged at equal interval on frequency axis. The number of two-tone type IM3, called $D_2(n, r)$, and that of three-tone type IM3, called $D_3(n, r)$, influenced on rth carrier of n carriers, are given as follows [16];

$$D_2(n, r) = \frac{1}{2}\left[n - 2 - \frac{1}{2}\{1 - (-1)^n\}(-1)^r\right] \tag{15}$$

$$D_3(n, r) = \frac{r}{2}(n - r + 1) + \frac{1}{4}\{(n-3)^2 - 5\} - \frac{1}{8}\{1 - (-1)^n\}(-1)^{n+r}. \tag{16}$$

And when frequencies and modulation indexes of n uniformly spaced carriers are given as $\omega_1, \omega_2, \cdots, \omega_n$ and $m_1, m_2, \cdots, m_n$, respectively, the input signal to LD is given by

$$v = m_1 \cos \omega_1 + m_2 \cos \omega_2 + m_3 \cos \omega_3 + \cdots + m_n \cos \omega_n. \tag{17}$$

The signal given by Eq. (17) enters LD, where LD have the following input-output characteristic;

$$P = P_o[1 + a_1 v + a_2 v^2 + a_3 v^3 + \cdots] \tag{18}$$

where P_o is output power of LD, v is input signal intensity, and a_i is ith-order coefficient.

When it is assumed that modulation indexes are equal constant value of m respectively, amplitude of two-tone type IM3 and three-tone type IM3 is given as follows [16];

$\frac{3}{4}a_3 m^3$: Two-Tone Type

$\frac{3}{2}a_3 m^3$: Three-Tone Type

Therefore the amount of IM3 in rth carrier of n carriers is given as

$$D = \frac{1}{2}\left(\frac{3}{4}a_3 m^3 D_2(n, r) + \frac{3}{2}a_3 m^3 D_3(n, r)\right)^2 I_{ph}^2. \tag{19}$$

Since the center carrier of n carriers has the largest IMD, the $C/(N+D)$ of center carrier is the worst, compared with the other carriers [15]. As a result, in this analysis, we consider $C/(N+D)$ of center carrier.

It is also assumed that we usually use modulation index m which will maximize Eq. (13), that is, from $d/dm(C/(N+D)) = 0$:

$$m = \left(\frac{N' \cdot BW}{S'^2 \cdot I_{ph}^2}\right)^{\frac{1}{6}} \tag{20}$$

where S' and N' is

$$S' = \frac{3}{4}a_3 D_2(n, r) + \frac{3}{2}a_3 D_3(n, r)$$

$$N' = RIN \cdot I_{ph}^2 + 2 \cdot e \cdot I_{ph} + \langle Ith^2 \rangle$$

respectively. When the amount of rainfall attenuation Z is permissible attenuation level, Z_a, on radio channel, modulation index becomes $m/\sqrt{Z_a}$, and the received $C/(N+D)$ is minimized in control station. From Eqs. (13) and (20), minimum received $C/(N+D)$ is given as

$$\left(\frac{C}{N+D}\right)_{\min} = \frac{Z_a^2}{2Z_a^3 + 1}\left(\frac{I_{ph}^4}{(N' \cdot BW)^2 \cdot S'^2}\right)^{\frac{1}{3}}. \tag{21}$$

In the optical link, BW should be narrowed to maintain obtainable CNR is the required CNR γ_{QAM}. The available bandwidth $BW_{\max}$ on optical channel is maximized when minimum $C/(N+D)$ shown in Eq. (21) is equal to the required CNR γ_{QAM}, that is, from $C/(N+D)_{\min}=\gamma_{QAM}$:

$$BW_{\max}=\left\{\frac{Z_a^6 I_{ph}^4}{((2Z_a^3+1)\gamma_{QAM})^3 N'^2 \cdot S'^2}\right\}^{\frac{1}{2}}. \quad (22)$$

Thus, the available maximum capacity on optical channel without AGC is obtained by

$$C_{opt}=BW_{\max}\times 2n\times N_c. \quad (23)$$

4.2 Available Capacity with AGC

Rainfall on radio channel attenuates signals all over the bandwidth equally. So rainfall attenuation can be removed when AGC circuit is installed before the LD. Therefore modulation index is constant value of m. From Eqs. (13) and (20), the received $C/(N+D)$ with AGC is described by

$$\left(\frac{C}{N+D}\right)_{AGC}=\frac{1}{3}\left(\frac{I_{ph}^4}{(N'\cdot BW)^2\cdot S'^2}\right)^{\frac{1}{3}}. \quad (24)$$

To compare Eq. (21) to (24), the received $C/(N+D)$ with AGC is $(2Z_a^3+1)/(3Z_a^2)$ times of that without AGC. For example, when permissible outage probability is 0.01%, where Z_a is 6.8 dB, the received $C/(N+D)$ with AGC is 3 times of that without AGC. By the same procedure given in Eq. (22), the maximum available bandwidth can be obtained as follows;

$$BW_{\max/AGC}=\left\{\frac{I_{ph}^4}{(3\gamma_{QAM})^3 N'^2\cdot S'^2}\right\}^{\frac{1}{2}}. \quad (25)$$

Therefore when AGC is used in base station, the maximum available capacity $C_{opt/AGC}$ on optical channel is described as

$$C_{opt/AGC}=BW_{\max/AGC}\times 2n\times N_c. \quad (26)$$

When the number of carriers is used as parameter, the relation of the number of modulation levels and the available capacity C_{opt} and $C_{opt/AGC}$ is shown in Fig. 6 with parameters indicated in Table 3. The figure indicates that as the number of carriers and modulation levels increase, the available capacity decreases, because the IMD increases as the number of carriers increases, and the required CNR, γ_{QAM}, also increases as the number of modulation levels increases. And it is obvious that the available capacity with AGC is larger than that without AGC. For example when 20 carriers is transmitted and 64 QAM with AGC is used, the available capacity is 37.5 Gbps, and it is 6.5 Gbps in the case of without AGC, and the available capacity improvement of 5.8 times can be achieved.

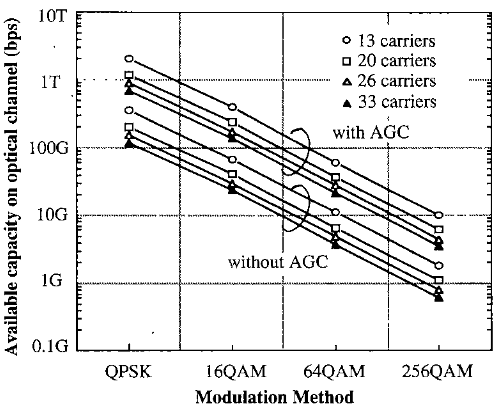

Fig. 6 Relation between modulation method and C_{opt}.

Table 3 Parameters used in Fig. 6.

the number of carriers	Nc	13,20,26,33
outage probability	P	0.01%
permissive atteuation level	Zα	6.8dB
output power of LD	Po	-3dBm
fiber loss with connector	Floss	5dB
PD sensitivity	η	0.8 A/W
electron charge	e	1.6×10^{-19} c
equivalent input noise current density	$\langle Ith^2\rangle$	4.0×10^{-22} W/Hz
the relative intensity noise for LD	RIN	-152 dB/Hz
3th-order coefficient for input-output characteristics of LD	a3	0.01

5. Optimum Number of Modulation Levels

As the capacity transmitted on both radio and optical channels simultaneously is the available capacity in FTTA system, it is restricted by the smaller capacity of radio and optical channel capacities.

Figure 7 shows the relation of the number of modulation levels and the available capacity on both radio and optical channel. As the number of modulation levels increases, it increases on radio channel, and decreases on optical channel reversely.

Therefore in FTTA system there is an optimum

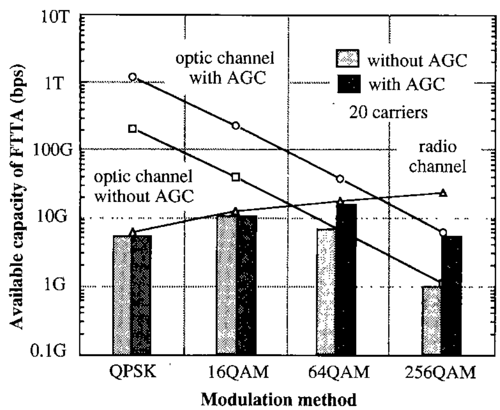

Fig. 7 Optimum modulation method.

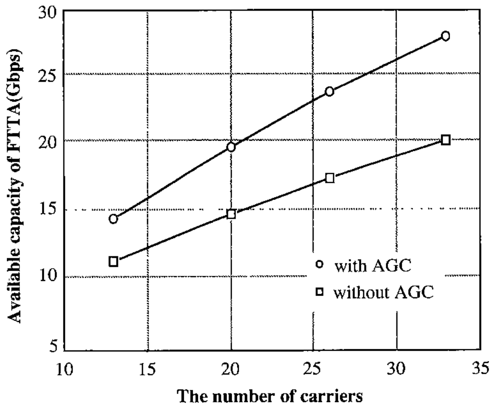

Fig. 8 Available capacity of FTTA.

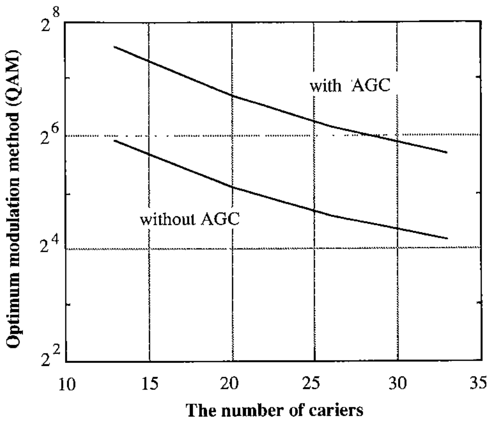

Fig. 9 Optimum modulation method of FTTA.

modulation method that can maximize the available capacity. Figure 7 shows that, if it is assumed that modulation method is 2^{2n}QAM, the maximum capacity of 12.0 Gbps can be available when the 16 QAM of 20 carriers are used and AGC is not used. 18.0 Gbps is available when the 64 QAM and AGC are used. It is 6.0 Gbps lager than that without AGC.

In Fig. 7 the maximum available capacity is calculated in the case of 20 carriers. When the number of carriers is changed and various numbers of modulation levels are used, the maximum available capacity and optimum modulation levels are different from the results in Fig. 7. So we have calculated the maximum available capacity and optimum modulation levels taking carrier numbers change into consideration. Figures 8 and 9 illustrates the calculated results, and it show that the available capacity increases and optimum modulation level decrease, when the number of carriers is increased.

6. Conclusions

In this paper, we proposed FTTA as a subscriber distribution system, and analyzed the available transmission capacity taking both rainfall attenuation on the radio channel and intermodulation distortion on the optical channel into consideration. In the analysis we also dealt with the case using AGC circuit, that can remove the flat attenuation due to the rainfall. As a result, the followings were obtained.

1. On the radio channel with radio bandwidth limitation, as the number of modulation levels and carriers increase, the maximum capacity per carrier increases.
2. On the optical channel, as the number of modulation levels increases, the required carrier to noise power ratio increases, and as the number of carriers increases, the intermodulation distortion increases. Thus the maximum capacity per carrier decreases as the number of modulation levels increases.
3. In FTTA, since signals are transmitted through both radio and optical channels, the available capacity is restricted by the smaller one of the radio or optical channel capacity. Thus it is expected that there exists an optimum number of modulation level that can maximize the available capacity on both channels. For instance, in the case of 20 carriers, the available capacity is 12.0 Gbps by 16 QAM in FTTA without AGC.
4. When AGC is installed in the base station in order to remove rainfall attenuation, the input signals to LD can be optimized to maximize the optical channel CNR. Therefore the available transmission capacity on the optical channel increases, e.g., in the case of 20 carriers, the available capacity is 18.0 Gbps under the optimum modulation of 64 QAM.
5. When AGC is installed in the base station, the amount of available maximum capacity is larger than that in FTTA without AGC. For example, in the case of 20 carriers in FTTA with AGC, the available capacity is 6.0 Gbps larger than that in FTTA without AGC.

In this analysis, we have not considered limitation of transmission power and the co-channel interferences among cells. Those effects should be further studied.

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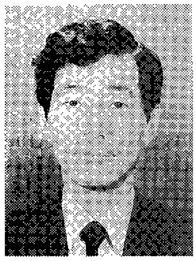

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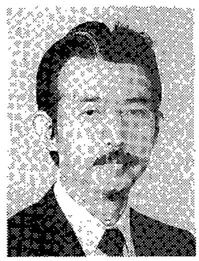

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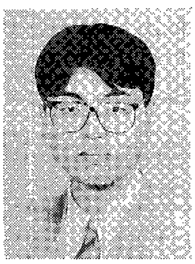

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