1. Introduction

Fiber-to-the-home (FTTH) has recently come into full-scale use. Over 40% of cable television (CATV) operators have already shifted to FTTH. A passive optical network (PON) system, a form of FTTH, has been popular in communication access networks. Now, a 10-Gbps-class PON system is expected to be put into practical use.

The sub-carrier multiplexing (SCM) and frequency modulation (FM) conversion methods have already been standardized as applicable to transmitting broadcast signals over FTTH. They use the 1550-nm wavelength in optical fiber exclusively for broadcasting and are applied to both analog (VSB-AM) and digital (OFDM, QAM) signals. In addition, conventional set top boxes (STBs) can be applied to these methods. Such compatibility has affected the growth and development of these methods. These two methods are referred to as the frequency division multiplexing (FDM) methods.

Ultra high definition television (UHDTV), which has 4 or 16 times the number of pixels of HDTV, was proposed and approved as a standard by the ITU. In terms of the distribution of UHDTV programs to homes, we can expect an increase in the demand for a higher transmission bandwidth with lower cost.

Considering the adaptation to such a new broadcast system, progress on replacing metal cables with optical fibers even in homes, and the expiration of analog transmission by March 2015 in Japan, it is now possible to apply time-division multiplexing of baseband digital broadcasting signals for distribution to homes. We previously proposed such a time-division multiplexing (TDM) method (hereafter, "the TDM method").

The TDM method transmits baseband digital broadcasting signals with a modified transport stream multiplexing frame (TSMF) as a dedicated frame structure. It has a higher multiplexing efficiency compared with conventional TDM methods in order to distribute broadcast signals over an optical network, a TV trunk network that connects broadcasting stations based on asynchronous transfer mode (ATM) technology, and Internet Protocol television (IPTV), which has been recently developed.

Furthermore, compared with conventional FDM methods, the requirements of transmission system components are substantially mitigated because the...
digital signal of the TDM method has the same noise tolerance as communication signals. This is expected to result in cost-effective transmission system implementation. We estimated the transmission equipment cost of the TDM method as 20 - 25% that of the FDM methods\textsuperscript{18). However, the TDM method may require a measure that enables simple migration from the conventional FDM CATV system to baseband TDM transmission and an additional method\textsuperscript{19} compatible with metal cables and conventional STBs.

With regard to the conventional CATV system over FTTH, the preferred performance of the system components and network design examples have been made public\textsuperscript{20,21}. For IPTV, various technologies and network configurations concerned with PON, as a service infrastructure of IPTV that has recently become popular, have been extensively studied\textsuperscript{22}. Specifying the preferable performance of system components with the TDM method may be required in the future. The preferable performance must be evaluated with a network configuration by considering coexistence with communication services in view of the growth of triple-play services delivering video, voice, and Internet access.

For this study, we quantitatively evaluated the economic efficiency of the TDM method by investigating the signal quality of it and conventional FDM methods and by comparing the network configuration of each method in consideration of coexistence with the communication services. We discuss the most economically suitable performance allocation approach for system components. This paper is intended as a resource for providing an efficient guideline to specify the performance allocation and preferable performance for system components for the TDM method.

We first discuss the construction of an optical network configuration in Chapter 2. In Chapter 3, we first overview the proposed TDM method, and then, we impose conditions on signals and equipment and derive the permitted power loss in each section of the network with the TDM and FDM methods. In Chapter 4, we define a simple distribution network model. In Chapter 5, we derive and compare the number of optical amplifiers \( S \), number of subscribers \( N \), and distribution area followed by an analysis and discussion of the differences.

2. Network Configuration

2.1 Definition of Network Configuration
An example of a CATV configuration over FTTH is shown in Fig. 1\textsuperscript{20}. An optical signal from a headend is divided and amplified repeatedly and delivered to subscribers.

A distribution network consists of two parts. One part is an access network, which has the same configuration as a PON with 32 branches and a transmission distance of at most 20 km in consideration of coexistence with the communication services by wavelength division multiplexing (WDM). The other part is a backbone network comprised of a headend and multiple connections to different access networks.

In Fig. 1, the transmission distance and the number of branches in each section generally differ according to various conditions such as geographical conditions and population density. This results in a difference of the received signal power at each subscriber. Therefore there may be some subscribers which receive extra signal power, because the distribution network is designed so that the subscriber under the worst condition such as the longest transmission distance and the maximum stages of amplification stages can receive the signal. The purpose of this paper is to compare the maximum number of optical amplifiers, the maximum number of subscribers and the maximum distribution area for the TDM and FDM methods. Considering this purpose, the network configuration including subscribers which receive extra signal power brings difficulty for the exact comparison. Therefore, to simplify the following discussions, we assume the transmission distance and the number of branches are the same in each section so that the received signal power becomes the same in all subscribers.

From an above-mentioned assumption, when \( m_j \) is the number of branches of the \( j \)-th section \( (j = 1...J) \) in a network, the number of access networks accommodated by a headend is equal to the product of \( m_1 \times m_2 \times ... \times m_J \).

Then, considering the 32 branches in each access network, when \( N \) is the number of subscribers
accommodated by a headend, \( N \) is expressed as

\[
N = 32 \prod_{j=1}^{J} m_j .
\]  

In Fig. 1, when the number of optical amplifiers of the section nearest a headend, i.e., the number of optical amplifiers of the \( J-1 \)-th section, is defined as \( s_{J-1} \), \( s_{J-1} \) is equal to the number of branches of the \( J \)-th section \( m_J \). The number of optical amplifiers of the \( J-2 \)-th section \( s_{J-2} \) is equal to the product of \( m_J \times m_{J-1} \). Then the number of optical amplifiers of the \( k \)-th section \( s_k \) is expressed as

\[
s_k = \prod_{j=1}^{J} m_j ,
\] 

and then, the total number of amplifiers in a network \( S \) is expressed as

\[
S = \sum_{k=1}^{J} s_k = \frac{N}{32} \left( \frac{1}{m_1} + \frac{1}{m_1 m_2} + \cdots + \frac{1}{m_1 \cdots m_{J-1}} \right).
\]  

### 2.2 Definition of Permitted Power Loss

There are two parameters that represent the required signal quality at an optical receiver: the required power \( (P) \), which is affected by the output power of an optical transmitter \( (T) \) and the power loss of the branches and optical fiber at each section, and the required relative intensity noise \( (RIN_{RX}) \), which is affected by the RIN of a laser at an optical transmitter \( (RIN_{TX}) \), a noise figure \( (NF) \) and the quantity of amplification of an optical amplifier, and the number of amplification stages. The isolation of the WDM filter in Fig. 1 is assumed to be sufficient enough to ignore the effect of crosstalk\(^{11} \) so that the WDM does not affect \( RIN_{RX} \).

To maintain these parameter values at certain levels, the power loss at each section in Fig. 1 must be suppressed at a certain level value. The permitted power loss of the \( j \)-th section \( U_j \) is expressed as

\[
U_j = \begin{cases} 
E_{out} - L - P & (j = 1) \\
E_{out} - E_m & (j = 2 \cdots J - 1) \\
T - E_m & (j = J) 
\end{cases}
\] 

The symbols introduced in this chapter are listed as shown in Table 1.

| \( N \) | Number of subscribers accommodated by a headend |
| \( S \) | Number of optical amplifiers in a distribution network |
| \( m_j \) | Number of optical amplifiers of the \( j \)-th section |
| \( T \) | Output power of an optical transmitter |
| \( RIN_{TX} \) | RIN of a laser at an optical transmitter |
| \( P \) | Required power at an optical receiver |
| \( RIN_{RX} \) | Required RIN at an optical receiver |
| \( NF \) | Noise figure of an optical amplifier |
| \( E_m \) | Input power of an optical amplifier |
| \( E_{out} \) | Output power of an optical amplifier |
| \( L \) | Power loss for an access network |
| \( U_j \) | Permitted power loss of the \( j \)-th section |

### 3. Required Signal Quality

In this section, we first overview the proposed TDM method, and then, we derive \( U_j \) by setting the signal format and parameters for the equipment used to configure the transmission system with the TDM and FDM methods.

#### 3.1 TDM Transmission Method

Fig. 2 (a) shows the TDM transmission system\(^{12} \). At the headend, multiple programs of transport streams (TSs) are multiplexed into a modified TSMF after bit-rate conversion for synchronous multiplexing, and error correcting codes are added as a forward error correction (FEC). Then, they are optically intensity-modulated. At subscribers’ premises, an optically de-modulated baseband signal is de-multiplexed into TS packets after frame synchronization. A physical layer (PHY) block can be made to be compatible with communication standards.

![Fig.2 TDM transmission method.](attachment:fig2.png)
that use the 1550-nm wavelength, e.g. 1000BASE-ZX\(^{23}\) and 10GBASE-ER\(^{24}\). 8B/10B or 64B/66B encoding are used for clock data recovery as well as the communication standards mentioned above. WDM with communication signals can be applied as well as the FDM methods.

Fig. 2 (b) shows the structure of the modified TSMF. The number of data slots (X) can be taken to be 222 at a maximum when the number of TSs is limited up to 15, which results in a less than 1% header overhead.

The TDM method achieves stable, jitter-free transmission and low transmission latency due to synchronous transmission, whereas IPTV over PON needs a measure against jitter, and IPTV over PON has a certain latency due to buffers in routers and receivers, even though the same multiplexing method (TDM).

A network configuration as shown in Fig. 1 is also applied for the TDM method. As for an access network, PON architecture, a form of communication access network, is decided considering required signal power at ONU and OLT, characteristics of various services, and bidirectional bandwidth allocation for each subscriber. Meanwhile, a broadcasting network simply considers satisfying the required bit-error rate for the signal and transmitting the required number of channels. However, when the signal format and bit rate of the TDM method are set to be same as PON, a common architecture is applied as an access network for PON and the TDM method.

### 3.2 Signal Format and Parameters

The \(P\) and \(RIN_{\text{RX}}\) at an optical receiver, e.g. V-ONU in Fig. 1 or O/E in Fig. 2 (a), are determined by the transmission method, signal format, and required bit-error rate (BER) of the digital broadcasting signals. We assume \(BER = 10^{-4}\)\(^{25}\) by considering the RS (204, 188) error correcting codes typically used in existent digital broadcasts. RS (204, 188) makes the post-FEC bit-error rate be under 10\(^{-12}\) at BER = 10\(^{-4}\).

When \(CH\) is the number of channels to be transmitted, the signal formats and the bit rates derived from \(CH\) values are listed in Table 2.

The signal format of the FDM method is a 64-QAM signal compliant with ITU-T J.83 Annex C, which is generally used in Japanese CATV. The information bit rate including FEC is 31.644 Mbps per channel. It is equal to the physical bit rate.

Considering multi-channel services, the numbers of channels are set to be 30, 100, and 300. The total bit rates are approximately 0.95, 3.16, and 9.49 Gbps, respectively.

The signal format of the TDM method is non-return-to-zero (NRZ), and the duty ratio is 0.5. For fair comparison with the FDM method, the information bit rates including FEC are set to be 1, 3.2, and 10 Gbps, which reach 1 - 5% above the corresponding bit rates of the FDM method. The physical bit rates are 1.25, 3.2, and 10.3125 Gbps, considering the 8B/10B or 64B/66B encoding as shown in parentheses in Table 2. We set these parameters so that a part of the PHY of the TDM method is assumed to comply with GE-PON\(^{26}\), IEEE1394b\(^{27}\), and 10GE-PON\(^{3}\).

Table 3 lists the parameters of transmission equipment. \(M\) is the optical modulation index of the optical signal, \(\Delta F\) is the FM frequency deviation at a carrier frequency of 450 MHz, \(C/N_{\text{mod}}\) is the ratio of the carrier to noise power per unit frequency, \(B\) is the noise bandwidth, \(R\) is the quantum efficiency of the photoelectric conversion.

\[\text{Table 2 Transmission signal formats and number of channels (CH)}\]

<table>
<thead>
<tr>
<th>Signal format</th>
<th>TDM</th>
<th>FDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRZ, duty ratio:0.5</td>
<td></td>
<td>ITU-T J.83 Annex C 64QAM (31.644 Mbps/career)</td>
</tr>
<tr>
<td>800 ps (c1), 250 ps (c2), 97 ps (c3)</td>
<td></td>
<td>30 ps (c1), 100 ps (c2), 200 ps (c3)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bit rate (Gbps)</th>
<th>Condition 1 (c1)</th>
<th>Condition 2 (c2)</th>
<th>Condition 3 (c3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH – 30</td>
<td>CH – 100</td>
<td>CH – 300</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3.2</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>(1.25 with 8B/10B)</td>
<td>(4 with 8B/10B)</td>
<td>(10.3125 with 64B/66B)</td>
<td></td>
</tr>
<tr>
<td>0.94932</td>
<td>3.1644</td>
<td>9.4932</td>
<td></td>
</tr>
</tbody>
</table>

\[\text{Table 3 Equipment parameters.}\]

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>TDM</th>
<th>SCM</th>
<th>FM</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIN(_{\text{tx}}) (dB/Hz)</td>
<td>-120</td>
<td>-158.1</td>
<td>-140</td>
</tr>
<tr>
<td>(M) [%]</td>
<td>80</td>
<td>28.3</td>
<td>70</td>
</tr>
<tr>
<td>(\Delta F) (MHz/ch)</td>
<td>-</td>
<td>-</td>
<td>154.8 at c1, 69.6 at c2</td>
</tr>
<tr>
<td>(C/N_{\text{mod}}) (1/Hz)</td>
<td>-</td>
<td>-</td>
<td>2.4 x 10(^3)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Receiver</th>
<th>TDM</th>
<th>SCM</th>
<th>FM</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B) (MHz)</td>
<td>937.5 at c1, 3,000 at c2, 7,734 at c3</td>
<td>5.3/ch</td>
<td>5.3/ch</td>
</tr>
<tr>
<td>(R) (A/W)</td>
<td>0.9</td>
<td>0.84</td>
<td>0.8</td>
</tr>
<tr>
<td>(I_{\text{ph}}) (nA)</td>
<td>2</td>
<td>1.3</td>
<td>100</td>
</tr>
<tr>
<td>(I_{\text{eq}}) (pA/\sqrt{Hz})</td>
<td>10</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>
detector, \( I_{d0} \) is the dark current, and \( I_{eq} \) is the equivalent noise current.

The parameter values of the FDM methods and \( NF \) of an optical amplifier are set to be common in conventional equipment\(^{28}\). Condition 3 (c3) of the FM conversion method was excluded from consideration because no study has been undertaken to evaluate the appropriate parameters for so many channels. The parameter values of the TDM method are set as typical values of optical transceivers applied in communication networks\(^{18,29-31}\). The \( M \) of the TDM method is converted from the extinction ratio.

The differences of the parameter values in Table 3 are caused by the differences of the requirements for the equipment performance. For example, \( M \) of the SCM method is limited up to just a few percent per channel even with a high-linearity optical laser in order to suppress inter-carrier distortion. Therefore, for comparison in this paper, the parameters of equipment in practical use are used as a reference. These parameters may improve along with the development of various device technologies in the future.

### 3.3 Relation between \( P \) and \( RIN_{RX} \)

In the optical transmission system, the factors to determine the ratio of the signal power to the noise power (SNR) are the optical power of video signal, the noise of optical transmission line, and the noise at an optical receiver consists of the shot noise, the dark current and the thermal noise. SNR calculating formulas of the SCM method and the FM conversion method are given by the JCTEA technical report\(^{21}\). Considering the SNR of the TDM method is specified for the whole signal, not for the signal per sub-carrier of the FDM methods, the SNR calculating formula of the TDM method is represented as

\[
SNR = \frac{1}{B} \cdot \frac{(M \cdot R \cdot P)^2}{RIN_{RX} (R \cdot P)^2 + 2e(I_{d0} + R \cdot P) + I_{eq}^2}, \quad (5)
\]

where \( e \) is the electron charge.

The relation between BER and SNR for the NRZ baseband signal of duty ratio 0.5 is represented as

\[
BER = \frac{1}{2} \text{erfc} \left( \frac{\sqrt{2} \cdot SNR}{\sqrt{2}} \right). \quad (6)
\]

Then the relation between \( P \) and \( RIN_{RX} \) for the TDM method is derived by Eqs. (5) and (6).

The \( P \) and \( RIN_{RX} \) satisfying \( BER = 10^{-4} \) for conditions c1 - 3 in Table 2 and the parameters in Table 3 are shown in Fig. 3. We find that there is a trade-off within a certain definite range of \( P \) and \( RIN_{RX} \) values, and there is a mitigation of the required limit for one parameter even if the requirement for the other parameter is highly strict.

### 3.4 Discussion for Cost Effective Configuration

In this section, we discuss an approach to determining the appropriate pairs of \( P \) and \( RIN_{RX} \).

From an economical aspect, it is preferable that one headend accommodates more subscribers or a larger area. In other words, it is preferable that \( m_i \) in Fig. 1 be as large as possible or the distance of each section in the distribution network in Fig. 1 be as long as possible. To meet this demand, it is effective for \( U_j \) to be as large as possible at each section. \( U_1 \) increases as \( P \) decreases when \( E_{out} \) and \( L \) are constant, as shown in Eq. (4). Therefore the mitigation of \( P \), i.e., setting a low \( P \) value, increases \( U_1 \). This results in larger \( m_1 \) and longer distance of the section nearest the access networks. Meanwhile, the mitigation of \( RIN_{RX} \), i.e., setting a high \( RIN_{RX} \) value, can decrease \( E_{in} \) even when there is the same number of amplification stages\(^{21}\). This increases \( U_2 \ldots U_J \), resulting in a larger \( m_2 \ldots m_J \) and longer distance at the corresponding section. However, there is a trade-off between \( P \) and \( RIN_{RX} \), as mentioned in the preceding section; therefore, we have to consider the priority of these two parameters.

In various pieces of equipment used to configure a distribution network, the optical fiber length, number of splitters, number of branches of each splitter, and \( S \) vary depending on the allocation of \( m_1 \ldots m_J \) values even for the same \( N \) and same distribution area. An optical amplifier is an active device and relatively expensive. Therefore, it is assumed to be effective at reducing the capital expenditure (CAPEX) and operating expenditure (OPEX) of a transmission system to reduce the number of optical amplifiers.
We therefore consider an approach to allocating \( m_1 \ldots m_J \) values to minimize \( S \). From Eq. (2), the sum of \( s_{k-1} \) and \( s_{k-2} \) is expressed as

\[
s_{k-1} + s_{k-2} = s_k \left( m_k + m_{k-1} \right) .
\]

(7)

where \( 3 \leq k \leq J \).

The values of \( m_k \) and \( m_{k-1} \) can be determined under the condition that the product of \( m_k \times m_{k-1} \) is constant.

Although this condition maintains a constant \( N \), \( S \) can vary.

From Eq. (7), the sum of \( s_{k-1} + s_{k-2} \) will decrease when choosing a greater \( m_{k-1} \) and a smaller \( m_k \) when the above condition holds. Hence, \( S \) can be minimized when the number of branches at the section nearest the access networks \((k = 1)\) is first maximized, followed by maximizing the number of branches at the subsequent \((k > 1)\) branching section. With this approach, one can determine the distribution network with the fewest optical amplifiers.

Consequently, this results in a cost-effective implementation to mitigate the requirement for \( P \) so that \( U_i \) increases and to set a strict requirement for \( RIN_{RX} \).

In Section 2.1, we assume the transmission distance and the number of branches are the same in each section in Fig. 1. The above-mentioned discussion is valid for the network which has different transmission distance and number of branches in each section, because the discussion is about a certain section and a neighboring section in Fig. 1, and does not assume the same transmission distance and the same number of branches in each section.

3.5 Permitted Power Loss Values

In this section, the appropriate pairs of \( P \) and \( RIN_{RX} \) are determined, and \( U_j \) is derived for the TDM and FDM methods on the basis of the preceding discussion.

We determined \( P \) and \( RIN_{RX} \) satisfying \( BER = 10^{-4} \) as listed in Table 4. We assume a use of an optical amplifier of constant output power and variable input power. In this case, \( E_{out} \) is constant and \( E_{in} \) is affected by \( RIN_{RX} \) and the number of amplification stages. In addition, to keep \( NF \) constant, \( E_{in} \) must be greater than a certain value. We determined \( E_{in} \) satisfying \( RIN_{RX} \) as listed in Table 4. The minimum \( E_{in} \) is set at \(-30 \) dBm. \( E_{out} \) and \( T \) are set to be common in conventional optical amplifiers and transmitters. The \( L \) is set at 25.6 dB, which is calculated from the power-loss values of transmission system components, as shown in Table 5, where \( L_T \) is the transmission loss per km, \( L_{dis} \) is the branching loss of an \( m_i \)-branch splitter, and \( L_w \) is the insertion loss of a WDM filter. Transmission distance is set at 20 km and the number of branches is set at 32 in any access networks for simplicity. We assume 2 WDM filters in any access networks. Finally, we derived \( U_1 \ldots U_J \) as listed in Table 4 by using Eq. (4) and \( P \), \( E_{in} \), \( E_{out} \), \( T \), and \( L \) values.

Compared in the same \( CH \), the \( U_1 \) and \( U_2 \ldots U_J \) of the TDM method are 5.6 - 9.1 dB and 10.8 - 23.4 dB more than the FM conversion method and the SCM method, respectively. Therefore, the TDM method is expected to accommodate more subscribers or a larger area than are the FDM methods.

4. Network Model

In this chapter, we define a simple optical distribution network model to evaluate the effect of the permitted power loss values derived in the previous chapter on network configuration.

4.1 Backbone Network

A broadcasting backbone network as shown in Fig. 1 is simply built up by considering the condition to satisfy the required bit-error rate and to transmit the required number of channels, although a communication

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**Table 4** Permitted power-loss values.

<table>
<thead>
<tr>
<th></th>
<th>TDM</th>
<th>SCM</th>
<th>FM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P ) [dBm]</td>
<td>-27.8</td>
<td>-25.3</td>
<td>-22.9</td>
</tr>
<tr>
<td>( RIN_{in} ) [dB/Hz]</td>
<td>-115</td>
<td>-110</td>
<td>-100</td>
</tr>
</tbody>
</table>

**Amplifier**

- 1 stage: -20.5 dB
- 2 stages: -19.4 dB
- 3 stages: -18.3 dB
- 4 stages: -17.2 dB

**Access network**

- \( L_i \) [dB]: 25.6
- Permitted power loss

<table>
<thead>
<tr>
<th>( U_i )</th>
<th>24.2</th>
<th>21.7</th>
<th>19.3</th>
<th>15.4</th>
<th>12.7</th>
<th>10.2</th>
<th>8.6</th>
<th>6.9</th>
<th>5.2</th>
<th>3.5</th>
<th>2.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_i-U_{in} ) [dB]</td>
<td>40.5</td>
<td>39.8</td>
<td>39.5</td>
<td>39.2</td>
<td>38.9</td>
<td>38.6</td>
<td>38.3</td>
<td>38.0</td>
<td>37.7</td>
<td>37.4</td>
<td>37.1</td>
</tr>
<tr>
<td>( L_i ) [dB]</td>
<td>27.0</td>
<td>23.2</td>
<td>19.4</td>
<td>15.7</td>
<td>12.0</td>
<td>9.3</td>
<td>6.6</td>
<td>4.0</td>
<td>1.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 5** Power loss values for different components of access network.

<table>
<thead>
<tr>
<th>Component</th>
<th>Power loss [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical fiber (1 km)</td>
<td>( L_T )</td>
</tr>
<tr>
<td>( m_i )-branch splitter</td>
<td>( L_{dis} )</td>
</tr>
<tr>
<td>WDM filter</td>
<td>( L_w )</td>
</tr>
<tr>
<td>Access network</td>
<td>( 2L_T + L_{dis} + 2L_w )</td>
</tr>
</tbody>
</table>

**Note:**

- \( L_T = 25.6 \) dB
- \( L_{dis} \) and \( L_w \) depend on the access network configuration.
backbone network is configured by considering the characteristics of various services and bidirectional bandwidth allocation for each subscriber. In view of these circumstances, a broadcasting backbone network and a communication backbone network are assumed to be configured independently from each other. We do not consider a configuration of a communication backbone network in the following discussion.

The specific broadcasting backbone network model is defined as shown in Fig. 4, where each amplification and branching stage is represented as a sequence of layers\(^{17}\). Each layer including an access network is depicted as a circle. The area of each layer is equal to the sum of the areas of the networks on the layer beneath; the gaps between the circles are ignored. An optical amplifier and splitter are located at each node of the networks. Optical fibers connecting the equipment are laid in linear fashion. The network on the first layer, which has radius \(A_1\), connects multiple access networks, which have radius \(A_0\). We use the crystallized snow model\(^{32}\) as a reference to determine the radius in each layer. Radius \(A_j\) of the network on the \(j\)-th layer is defined as

\[
A_j = \frac{A_{j-1}}{4m_j - 1}. 
\]

where \(1 \leq j \leq J\). In Eq. (8), \(m_j\) is the number of branches of a network on the \(j\)-th layer. When the radius of an access network \(A_0\) is given, \(A_1 \ldots A_J\) are sequentially determined by Eq. (8) with given \(m_1 \ldots m_J\). In Eq. (8), \(A_j\) is smaller than the product of \(2 \times A_{j-1}\) when \(m_j \leq 3\). Considering this condition, we define the maximum transmission distance \(D_j\) of the network on the \(j\)-th layer as

\[
D_j = \begin{cases} 
A_j - A_{j-1} & (A_j \geq 2A_{j-1}) \\
A_{j-1} & (A_j < 2A_{j-1}) 
\end{cases} 
\]

so that \(D_j\) keeps a certain level of value.

### 4.2 Calculation Flow of Network Configuration

The sum of the transmission power loss and branching power loss must not exceed the permitted power loss at each layer. Therefore, the relation between \(D_j\) and \(m_j\) is represented as

\[
D_j = \frac{U_j}{L_{div}(m_j)} L_j. 
\]

Fig. 5 shows the relation between \(m_j\) and \(D_j\) by using the values of \(L_f\) and \(L_{div}(m_j)\) in Table 5. The solid lines represent \(D_j\) as calculated by using Eq. (10). The dashed lines indicate \(D_j\) as calculated by using Eqs. (8) and (9) for a given \(A_{j-1}\). The \(m_j\) and \(D_j\) values must be chosen at points on the dashed line specified by the given \(A_{j-1}\) below the intersection point with the solid line corresponding to the given \(U_j\).

As mentioned in Section 3.4, \(S\) can be minimized by setting the maximum permitted number of branches \(m_j\) from \(j = 1\) to \(j = J\), as shown in Fig. 6. First, \(U_1 \ldots U_J\) and \(A_0\) are given. Then, the maximum permitted \(m_j\) can be obtained, as shown in Fig. 5, and \(A_j\) can be determined by using Eq. (8). Finally, \(S\) and \(N\) are numerated from \(m_1 \ldots m_J\), and the distribution area having radius \(A_J\) is derived.
A distribution network is actually configured by deciding the deployment of an optical fiber, optical amplifiers and splitters by given initial and prospective \( N \) and geographical conditions including area size\(^{21}\). In this case, there may be some subscribers which receive extra signal power as mentioned in Section 2.1. The purpose of this paper is to compare the maximum values of \( S, N \) and the maximum area size for the TDM and FDM methods with a simple network model. We note the flow chart as shown in Fig. 6 is just a procedure to achieve our purpose and Fig. 6 does not necessarily mean a procedure to configure an actual distribution network.

5. Calculation Results

In this chapter, we quantitatively derive the values of \( S, N \), and the distribution area for the TDM and FDM methods by using the distribution network model described in the previous chapter.

5.1 Differences among Three Methods

The relationship between \( S \) and \( N \) was calculated as shown in Figs. 7 (a) - 9 (a) when \( CH = 30, 100, \) and \( 300. \) Figs. 7 (b) - 9 (b) show the relationship between \( S/N \), e.g., the number of optical amplifiers per subscriber, and \( N \) when \( CH = 30, 100, \) and \( 300. \) The values in parentheses are subscribers per km\(^2\), i.e., the density of subscribers \( \rho \), which is represented as

\[
\rho = \frac{32}{\pi \lambda^2}.
\]

When \( N \) was less than the maximum number that one optical amplifier can accommodate, \( S \) was equal to 1, independent of \( N \). Therefore, \( S/N \) decreased as \( N \) increased.

When \( N \) was more than the maximum number that one optical amplifier can accommodate, \( S \) increased as \( N \) increased, and \( S/N \) was approximately constant and independent of \( N \), as shown in Table 6, in all conditions for \( CH \) and \( \rho \).

When \( N \) exceeded a certain value and when the distribution area exceeded a certain size, the transmission power loss itself exceeded the permitted power loss at the upper layer in Fig. 4. It corresponds to the non-existence of an intersection point between the solid line and the dashed line in Fig. 5. In this case, a distribution network is not configured under such a condition for \( N \) and \( \rho \). More specifically, there is a limit for \( N \) and the distribution area accommodated by one headend. For example, in Fig. 9, the lines of the SCM
method ended mid-course. This was caused by such a limitation.

From Table 6, compared with the TDM method in the same $\rho$, the $S/N$ of the SCM and FM conversion methods were 5.2 - 6.2 and 2.7 - 3.8 times higher, respectively. If $\rho$ and $N$ are the same, the distribution area is the same. Hence, Table 6 also shows the differences in $S$ when $N$ and the distribution area were the same for all methods.

Next, $N$ was evaluated for when $S$ and the distribution area were the same for all methods.

**Figs. 10 - 12** show $N$ accommodated by a given distribution area at $S = 2$ and 10 when $CH = 30, 100$, and 300. Compared with the SCM and FM conversion methods for the same $S$, the $N$ of the TDM method was 5.5 - 6.1 and 2.9 - 3.7 times higher, respectively.

Figs. 10 - 12 also show that the distribution area of the TDM method expanded compared with the FDM methods when $S$ and $N$ were the same. For example, when $CH = 30$ and $N = 6000$, the distribution area of the TDM method at $S = 2$ was 32 km$^2$, and the distribution area of the SCM method at $S = 10$ was 6 km$^2$. The distribution area of the TDM method was over 5 times larger than that of the SCM method even when the $S$ of the TDM method was one-fifth that of the SCM method.
5.2 Analysis of Differences among Three Methods

In this section, we analyze the differences discussed in the previous section.

The relations between the ratio of the optical amplifiers on the layer nearest the access networks $s_1$ to the $S$ and $N$ were derived, as shown in Figs. 13 - 15, when $CH = 30, 100, \text{and} 300$, respectively. When $N$ was less than the maximum number that the network with one stage amplification could accommodate, the ratio naturally kept at 100%. Otherwise, the ratio became less than 100%. Then, as $N$ increased and the area expanded, $S$ increased, and the ratio fluctuated at lower than 100%.

The ratios were generally high, more than 85.7 - 94.4%, for all methods. This suggests that $S$ is highly dependent on $s_1$ and is of little relevance to $s_2$-$s_{J-1}$.

From Eqs. (1) and (2), $N$ is equal to the product of $32 \times m_1 \times s_1$. Therefore, $s_1$ decreases as $m_1$ increases as long as $N$ is constant. As mentioned in Section 3.4, $m_1$ increases as $U_1$ increases. Consequently, a larger $U_1$ in the TDM method significantly contributes to making $S$ smaller.

Also, $N$ increases as $m_1$-$m_J$, particularly $m_1$, increases, as long as $S$ is constant, as seen from Eq. (3). We also find that a larger $m_1$, i.e., $U_1$, contributes to the significant increase in $N$.

5.3 Analysis of Differences in Each Method

In this section, we analyze the differences in each method.

The $S$ increased as $CH$ increased when $N$ and the distribution area were the same, as shown in Table 6, for all methods. The $N$ decreased as $CH$ increased when $S$ and the distribution area were the same, as shown in Figs. 10 - 12, for all methods. This is because the requirement for both $P$ and $RIN_{RX}$ became strict, as shown in Fig. 3, and then, $U_1$-$U_J$, i.e., $m_1$-$m_J$, decreased, as shown in Table 4.

The distribution area and $S$ increased as $\rho$ decreased when $N$ was the same, as shown in Table 6, for all methods. The $N$, accommodated by a given $S$, decreased as the distribution area increased when $S$ was the same, as shown in Figs. 10 - 12, for all methods. This is because the total transmission distance became longer; thus, all the $m_1$-$m_J$ became smaller.

6. Conclusions

We compared an optical distribution network configuration that uses the TDM method with conventional FDM methods. We found that

1) there is a trade-off within a certain definite range of $P$ and $RIN_{RX}$ values at an optical receiver for the TDM and FDM methods. This is valid for a cost-effective configuration to mitigate the requirement for $P$ and to set a strict requirement for $RIN_{RX}$.

In a star-type topology network common in FTTH CATV systems,

2) even with an optical laser of inferior RIN performance compared with the FDM methods, the TDM method

(a) decreased $S$ up to 16.1 - 19.2% and 26.3 - 37.0% compared with the SCM and FM conversion methods, respectively, with the same $N$ and distribution area,

(b) increased $N$ 5.5 - 6.1 times and 2.9 - 3.7 times
more than the SCM and FM conversion methods, respectively, with the same S and distribution area, and
(c) expanded the distribution area substantially with the same S and N. In one instance, the area of the TDM method expanded over 5 times that of the SCM method; even the S of the TDM method was one-fifth that of the SCM method.

(3) The required S increases or N decreases when CH increases or the distribution area increases for all methods.

For future work, we will compare the quantitative transmission equipment cost of the TDM method with the conventional FDM methods by considering the latest cost trend for a network including a common backbone network with communication services. We intend to specify a preferable performance for transmission system components for the TDM method.

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