INTERNATIONAL TELECOMMUNICATION UNION

ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

J.186

(02/2002)

SERIES J: CABLE NETWORKS AND TRANSMISSION OF TELEVISION, SOUND PROGRAMME AND OTHER MULTIMEDIA SIGNALS

Miscellaneous

Transmission equipment for multi-channel television signals over optical access networks by sub-carrier multiplexing (SCM)

ITU-T Recommendation J.186

ITU-T J-SERIES RECOMMENDATIONS

CABLE NETWORKS AND TRANSMISSION OF TELEVISION, SOUND PROGRAMME AND OTHER MULTIMEDIA SIGNALS

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ITU-T Recommendation J.186

Transmission equipment for multi-channel television signals over optical access networks by sub-carrier multiplexing (SCM)

Summary

This Recommendation describes a transmission method for multi-channel television signals over optical access networks. J.186 transmission equipment is capable of transmitting multi-channel AV-VSB, QPSK and 64-/256-QAM video signals by using Sub-Carrier Multiplexing (SCM).

Source

ITU-T Recommendation J.186 was prepared by ITU-T Study Group 9 (2001-2004) and approved under the WTSA Resolution 1 procedure on 13 February 2002.

FOREWORD

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications. The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

In this Recommendation, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

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As of the date of approval of this Recommendation, ITU had not received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. However, implementors are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database.

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Transmission equipment for multi-channel television signals over optical access networks by sub-carrier multiplexing (SCM)

1 Background

For an undetermined period before digital transmission fully replaces analogue transmission, it will be necessary for optical access networks to carry both formats. Digital signals should be transmitted using Frequency-Division Multiplexing (FDM) in addition to analogue signals in order to assure an effective transition from analogue to digital transmission.

2 Scope

This Recommendation describes a method of transmitting multi-channel television signals over optical access networks through the use of Sub-Carrier Multiplexing (SCM).

In the SCM technique, the main carrier is the optical frequency signal carrier; the sub-carriers transfer the electrically multiplexed FDM video signals in the optical sideband. The format of the signals output by the Photo Detector (PD) of the Optical Network Unit (ONU) is the same as that of the signals input to the modulator of the optical transmitter. The SCM method is used in the trunk line of Hybrid Fibre-Coax (HFC) systems.

The system described in this Recommendation transmits FDM analogue AM-VSB and digital 64-QAM/256-QAM/QPSK television signals by SCM technology. The optical modulation format is Intensity Modulation (IM).

Optical amplifiers are used to compensate the losses of the optical transmission/splitters used to create the access network. Dispersion compensation fibres (DCF) are used to compensate the chromatic dispersion of access network fibres. DCF imposes the reverse chromatic dispersion in advance in order to offset the degradation due to CSO created by the transmission of 1.55 μm optical signals over 1.3 μm zero-dispersion access fibres.

SCM technology is simple, and is based on an electrical/optical (E/O) converter and optical amplifiers in the transmitter side, and an optical/electrical (O/E) converter in the receiver side. However, the allowable optical transmission/splitter loss is smaller than that in the FM converted system. Moreover, optical reflections in the transmission lines may degrade video quality.

The system can be integrated with the G.983.1 ATM-based optical access system by using G.983.3 WDM technology. This allows the system to offer broadcast services and also data and voice communication services over the same optical access network. By using a G.983.1 ATM-based optical access system, upstream signals, e.g. control functionality and data to indicate user requirements, can be transmitted as well.

3 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published.

3.1 Normative references

– ITU-T Recommendation J.83 (1997), *Digital multi-programme systems for television, sound and data services for cable distribution*.

– ITU-T Recommendation J.87 (2001), *Use of hybrid cable television links for the secondary distribution of television into the user's premises*.

3.2 Informative references

– ITU-T Recommendation G.983.1 (1998), *Broadband optical access systems based on Passive Optical Networks (PON)*.

– ITU-T Recommendation G.983.3 (2001), *A broadband optical access system with increased service capability by wavelength allocation*.

4 Abbreviations, symbols and conventions

4.1 Abbreviations

This Recommendation uses the following abbreviations.

AGC	Automatic Gain Controller
ALC	Automatic Level Controller
AM-VSB	Amplitude Modulation Vestigial Sideband
AMP/BRC-U	Amplifier and Branch Unit
A-RA	Receiver Amplifier for Analogue video transmission
A-TA	Transmitter Amplifier for Analogue video transmission
CNR	Carrier-to-Noise Ratio
CSO	Composite Second Order distortion
CTB	Composite Triple Beat distortion
D/U	Desired-to-Undesired distortion ratio
DCF	Dispersion Compensation Fibre
D-RA	Receiver Amplifier for Digital video transmission
D-TA	Transmitter Amplifier for Digital video transmission
E/O	Electrical to Optical
FDM	Frequency-Division Multiplexing
HE	Head End
IM	Intensity Modulation
O/E	Optical to Electrical
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RA	Receiver Amplifier
RIN	Relative Intensity Noise
SCM	Sub-Carrier Multiplexing

STB	Set-Top Box
TA	Transmitter Amplifier
TX	Transmitter
V-OLT	Optical Line Terminal for Video signals
V-ONT	Optical Network Terminal for Video signals
VSWR	Voltage Standing Wave Ratio
WDM	Wavelength-Division Multiplexing
XM	Cross Modulation distortion

4.2 Symbols

This Recommendation uses the following symbols:

N Total number of FDM carriers

m_j Intensity modulation index of the jth carrier

4.3 Conventions

If this Recommendation is implemented, the key words "MUST" and "SHALL" as well as "REQUIRED" are to be interpreted as indicating a mandatory aspect of this Recommendation.

The keywords indicating a certain level of significance of a particular requirements that are used throughout this Recommendation are summarized below.

"MUST"	This word or the adjective "REQUIRED" means that the item is an absolute requirement of this Recommendation.
"MUST NOT"	This phrase means that the item is an absolute prohibition of this Recommendation.
"SHOULD"	This word or the adjective "RECOMMENDED" means that there may exist valid reasons in particular circumstances to ignore this item, but the full implications should be understood and the case carefully weighed before choosing a different course.
"SHOULD NOT"	This phrase means that there may exist valid reasons in particular circumstances when the listed behavior is acceptable or even useful, but the full implications should be understood and the case carefully weighed before implementing any behavior described with this label.
"MAY"	This word or the adjective "OPTIONAL" means that this item is truly optional. One vendor may choose to include the item because a particular marketplace requires it or because it enhances the product, for example; another vendor may omit the same item.

5 System description

5.1 System configuration

Figure 1 is a block diagram of the equipment needed by the optical access network to transmit multi-channel television signals by using Sub-Carrier Multiplexing (SCM). To minimize the deterioration in video signal quality, this system was optimized in two steps: trunk line transmission and access network transmission. The trunk line transmission system consists of two transmitters and two receivers for separate analogue and digital video signal transmission. In the second step, all video signals (both analogue and digital modulation formats) are mixed in the V-OLT, and then transmitted from the V-OLT to the V-ONT across the access network.

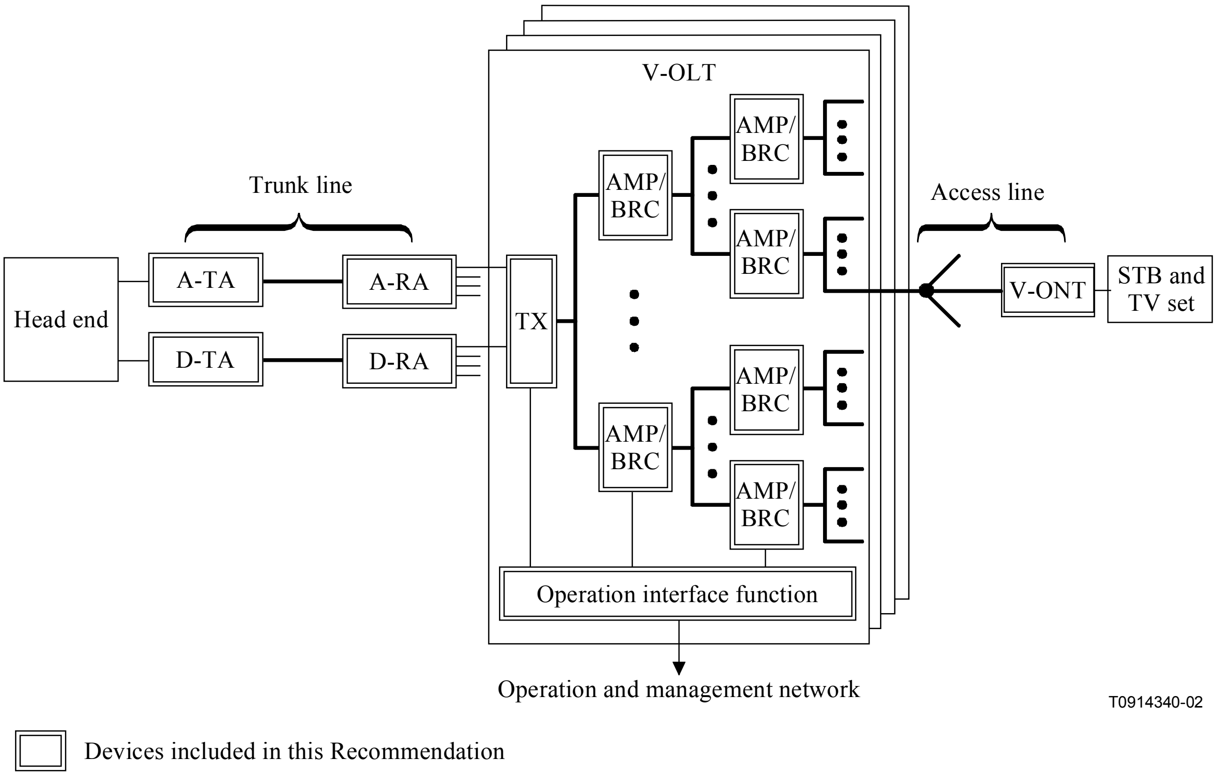

Figure 1/J.186 – Configuration of the SCM multi-channel video signal transmission system

V-OLT consists of TX and cascaded Amplifier/Branch-Units (AMP/BRC-U), which amplify and branch the optical signal output by the TX. AMP/BRC-U's can be cascaded in several stages up to the specified RIN deterioration permitted. The operation interface function collects alarms from the whole system and transmits them to operation and management network. Optical signals output from V-OLT are branched again by optical splitters and transmitted to V-ONT's through the optical access network.

V-ONT converts the optical input signal into FDM multi-channel electrical video signals, and then amplifies those signals. The output signals from V-ONT are input to the user's TV set.

The functions of each device are shown in Table 1.

Table 1/J.186 – Summary of functions of each device

Device	Function
A-TA/RA	Transmission of analogue AM-VSB video signals from HE to central office
D-TA/RA	Transmission of digital QAM or QPSK video signals from HE to central office
V-OLT (TX, AMP/BRC)	The V-OLT amplifies optical analogue AM-VSB and digital video signals transmitted from Head End. The V-OLT then branches them to V-ONTs.
V-ONT	The V-ONT converts received optical signal to electrical FDM video signals. The V-ONT outputs them to set-top box (STB) and TV monitor.

5.2 Main characteristics

Table 2 shows the main characteristics of the SCM multi-channel video signals transmission system.

Table 2/J.186 – Main characteristics of the SCM multi-channel video signals transmission system

Item and parameter	Limit	Condition and meaning
Frequency of transmitted FDM video signals, F_{tr}	Type 1: $47 \le F_{tr} \le 864$ MHz Type 2: $47 \le F_{tr} \le 2050$ MHz	Type 2 is used for transmission of QPSK signals.
Relative intensity noise degradation due to optical fibre transmission from TA to RA	≤ –153 dB/Hz	
Relative intensity noise degradation due to optical fibre transmission from V-OLT to V-ONT	≤ –153 dB/Hz	
NOTE – Frequency bands of transmitted FDM video signals, $47 \le F_{tr} \le 864$ MHz, include regional CATV bands of 54 to 864 MHz for North America, 47 to 862 MHz for Europe, and 90 to 770 MHz for Japan.		

5.3 Total number of FDM carriers and their intensity modulation indexes

The total number of carriers and their intensity modulation indexes must comply with the following formula.

$$\sqrt{\sum_{j}^{N} m_j^2} \le 0.30$$

where:

N Total number of FDM carriers

m_j Intensity modulation index of jth carrier

6 Transmitter amplifier (TA)

6.1 Configuration of TA

Figure 2 shows a block diagram of a typical TA. A-TA and D-TA, which are used for analogue and digital video signal transmission, respectively, consist of the same function blocks. FDM analogue and digital video signals from head-end equipment are put into the "RF IN" port. These signals are mixed with the pilot signal, and then the signal levels of these signals are adjusted to the appropriate amplitude in order to avoid generating clipping noise in electrical/optical (E/O) conversion. These electrical signals are then converted into an optical signal by the E/O converter. The optical signal output from the "OPT OUT" port is transmitted to RA.

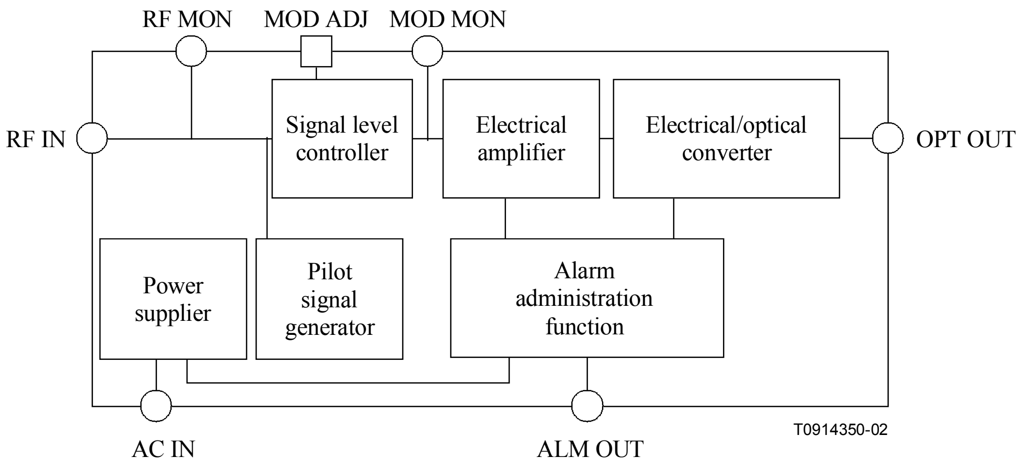

Figure 2/J.186 – Block diagram of TA

"MOD ADJ" controller enables the modulation index of the transmitted video signals to be adjusted.

"RF MON" port is the RF signal monitor port and is used for measuring the input RF signal quality and its level during system operation. The FDM video signals' quality and power levels are monitored. The input RF signal is divided with the appropriate splitting ratio in order to output the RF monitor signal from the "RF MON" port. The ratio is small so that the splitting does not influence RF signal input.

The alarm administration function collects the alarms, which are generated by each function. When an alarm is collected, it is transferred from "ALM OUT" port to the "ALM IN" port of the RA.

6.2 Main characteristics of TA

The main characteristics of TA are shown in Table 3.

Table 3/J.186 – Main characteristics of TA

Item		Limit	Meaning and condition
Electrical input	Reference level	85 dBμV/ch	Carrier level of AM-VSB signal
	Input impedance	75 Ω unbalanced	
Optical output	Output power	≥ +10 dBm	
	Wavelength	Not specified	
	Optical modulation index	5.2 ± 0.3 %/carrier	When electrical signal input level is 85 dBμV/ch
	Relative intensity noise, RIN	≤ –155 dB/Hz	RIN of optical output signal from TA
	Optical spectrum	Single longitudinal mode	
Pilot signal	Frequency accuracy	≤ 50 ppm	When no video modulation applied
	Amplitude	82 ± 0.5 dBμV	Converted value as a signal input level

6.3 Alarm administration items of TA

Alarm administration items to be observed by TA are shown in Table 4.

Table 4/J.186 – Alarm administration items of TA

Alarm administration item	Symbol	Alarm occurrence condition
Video transmission signal input alarm	S IN DWN	When input signal level is less than that of a single carrier
Optical signal output alarm	S OUT DWN	When an error is found in the E/O converter or the Pilot signal generator
Power supply alarm	PWR	When an error is found in the power supply
Fuse alarm	FUSE	When a TA fuse blows out
AC power input interruption	AC DWN	When an error is found in AC power input

7 Receiver amplifier (RA)

7.1 Configuration of RA

Figure 3 shows a block diagram of a typical RA. A-RA and D-RA are used for receiving analogue and digital video signals, respectively. They consist of the same function blocks. The optical/electrical (O/E) converter converts optical signal transmitted from TA into electrical FDM signals. The automatic level controller (ALC) adjusts the level of the electrical signals. ALC refers to the level of the pilot signal transmitted from TA. Adjusted electrical signals are amplified and then split. The split electrical signals are transmitted to the V-OLTs.

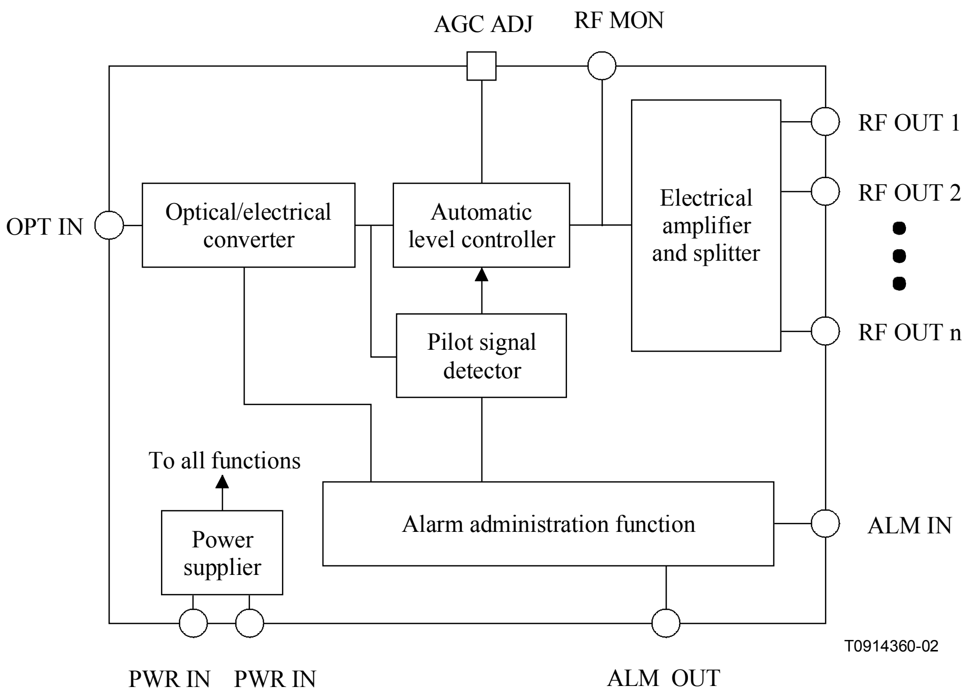

Figure 3/J.186 – Block diagram of RA

"AGC ADJ" controller enables the level of the RF signal output by "RF OUT" ports to be adjusted.

"RF MON" port is the RF signal monitor port. The "RF MON" port is used for measuring the input RF signal quality and power level during system operation. FDM video signal quality and power levels are monitored. The RF signal adjusted by AGC is divided with the appropriate splitting ratio in order to output the RF monitor signal from the "RF MON" port. The ratio is small so that the splitting does not influence RF signal performance.

The alarm administration function collects the alarms generated by each function, and then transmits the collected alarms to the operation interface function of the V-OLT. The alarms of TA, which are received via the "ALM IN" port, are also transferred via the alarm administration function of RA.

7.2 Main characteristics of RA

The main characteristics of A-RA and D-RA are shown in Table 5.

Table 5/J.186 – Main characteristics of RA

Item		Limit	Meaning and condition
Optical input	Power level	Not specified	
	Wavelength	Not specified	
	Reflectance of optical output connector	≤ –35 dB	
Electrical output	Output signal output level	85 ± 0.5 dBμV	When the input signal level of TA is 85 dBμV Output at each port
	VSWR	≤ 1.5	
	Impedance	75 Ω unbalanced	
	AGC control	Pilot signal should be used for reference.	
	Output power deviation between output ports	≤ ±0.5 dB	When RA has multiple ports

7.3 Alarm administration items of RA

Alarm administration items of RA are shown in Table 6.

Table 6/J.186 – Alarm administration items of RA

Alarm administration item	Symbol	Alarm occurrence condition
Optical signal input alarm	R IN DWN	When the input optical signal level is abnormal
Pilot signal alarm	PIL	When the received pilot signal level is abnormal The pilot signal is transmitted from TA
Modem alarm	MODEM	When the alarm signal transmission line from TA is disconnected
Fuse alarm	FUSE	When an RA fuse blows out
Power supply alarm	PWR ALM	When an error is found in power supply

8 Transmitter (TX)

8.1 Configuration of TX

Figure 4 shows a block diagram of a typical TX located in V-OLT. FDM analogue AM-VSB and digital video signals come from A-RA and D-RA are launched into A-FDM IN and D-FDM IN ports, respectively. These FDM signals are amplified and are mixed together with the pilot signal. These mixed FDM electrical signals are converted into an Intensity Modulated (IM) optical signal by the Electrical/Optical (E/O) converter. This optical signal is then optically amplified. The amplified optical signal is branched at the optical splitter. The output optical signals from TX OUT are transmitted to AMP/BRC-Us located in V-OLT.

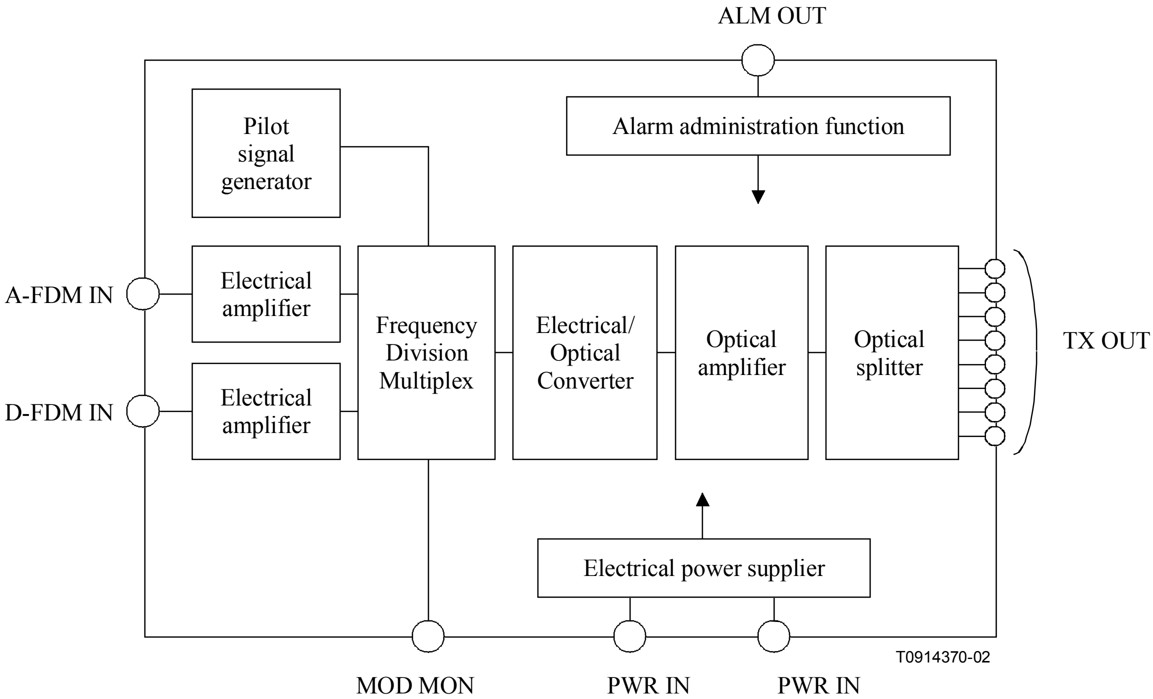

Figure 4/J.186 – Block diagram of TX

The pilot signal is used in order to make sure that the signal from TX is being transmitted to V-OLT and V-ONT successfully. Moreover, V-ONT refers to the pilot signal when adjusting the power levels of video signals output from V-ONT.

MOD MON port is the input FDM signal monitoring port; it is used for measuring the input FDM signal quality and level during system operation. The input FDM signals are divided with the appropriate splitting ratio in order to output the FDM monitor signals from the MOD MON port. The ratio is small so that the splitting does not degrade FDM signal transmission.

The alarm administration function collects the alarms generated by each function. When an alarm is generated, it is collected and transferred from ALM OUT to the operation interface function of the V-OLT.

8.2 Characteristics of TX

The main characteristics of TX are listed in Table 7.

Table 7/J.186 – Main characteristics of TX

Item and parameter		Limit	Condition
Electrical input	Reference level	85 dBμV/ch	Carrier level of AM-VSB signal
Optical output	Output power	≥ +6 dBm	
	Number of output ports	Not specified	
	Wavelength, λ	1555 ± 5 nm	
	Optical modulation index	5.0 ± 0.3 %/ch	When electrical signal input level is 85 dBμV/ch
	Relative intensity noise, RIN	≤ –153 dB/Hz	RIN of optical output signal from TX One port is open
	Optical spectrum	Single longitudinal mode	
Pilot signal	Frequency accuracy	≤ 50 ppm	
	Amplitude	82 ± 0.5 dBμV	Converted value as a signal input level

8.3 Alarm administration items of TX

Alarm administration items, which should be observed by TX, are shown in Table 8.

Table 8/J.186 – Alarm administration items of TX

Alarm administration item	Symbol	Alarm occurrence condition
Analog video signal input alarm	A REC	When the level of input analogue video signal is abnormal
Digital video signal input alarm	D REC	When the level of input digital video signal is abnormal
E/O output alarm	E/O OUT	When optical output power level is abnormal
Optical amplifier alarm	AMP OUT	When pump light power level is abnormal When optical input/output power level is abnormal
Pilot signal alarm	PIL	When pilot signal level is abnormal
Power supply alarm	PWR ALM	When an error is found in the power supply
Fuse alarm	FUSE	When TX FUSE blows out

9 Amplifier and branch unit (AMP/BRC)

9.1 Configuration of AMP/BRC

Figure 5 shows a block diagram of the typical optical amplifier and optical branch (AMP/BRC) unit.

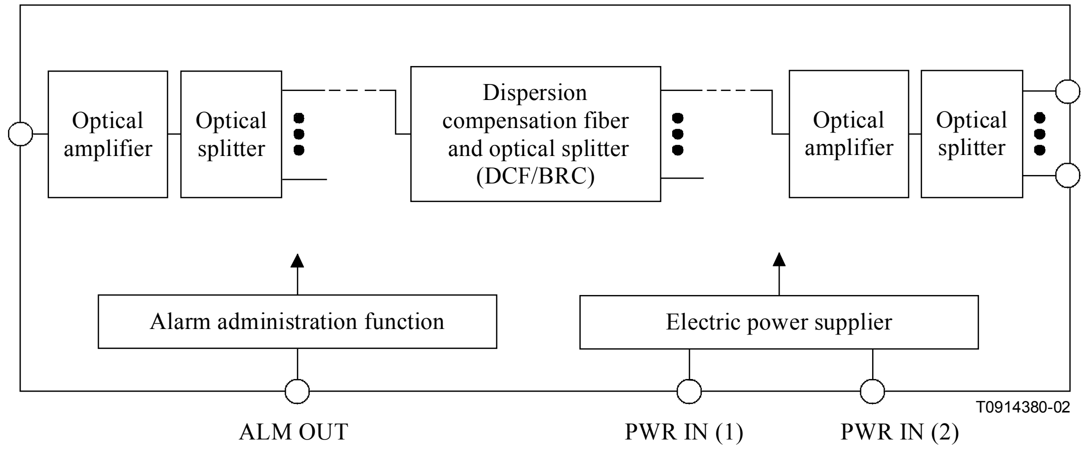

Figure 5/J.186 – Block diagram of AMP/BRC

The AMP/BRC unit consists of cascaded optical amplifiers and optical splitters. It amplifies and branches the optical signal output by TX.

When the E/O converter in TX consists of a directly modulated laser, the AMP/BRC unit should also have dispersion compensation fibre and the optical branching function (DCF/BRC). In this case, access lines are grouped according to their length, and each access line is connected to an appropriate DCF/BRC. Thus, the chromatic dispersion generated in each access lines is less than the specified limit.

If one or more optical outputs ports are not used for transmission, and the E/O converter in TX uses direct modulation, they must be optically terminated.

9.2 Main characteristics of AMP/BRC

The main characteristics of the amplifier and branching (AMP/BRC) unit are shown in Table 9.

Table 9/J.186 – Main characteristics of AMP/BRC unit

Item and parameter		Limit	Conditions
Optical amplifier	Input/output optical signal wavelength, λ	1555 ± 5 nm	
	Output power	≥ +16 dBm	Input power is +6 dBm.
	Relative intensity noise, RIN	≤ –150.4 dB/Hz	Input power is +6 dBm.
	Number of amplifier stages	Not specified	
	Number of output ports	Not specified	
DCF	Relative intensity noise, RIN	≤ –151.4 dB/Hz	
	Permissible chromatic dispersion	≤ 39.6 ps/nm	

9.3 Alarm administration items of AMP/BRC

Alarm administration items to be observed by TX are shown in Table 10.

Table 10/J.186 – Alarm administration items of AMP/BRC

Alarm administration item	Symbol	Alarm occurrence condition
Optical signal input alarm	REC	When optical input power level is abnormal
Optical amplifier alarm	OUT	When pump light power level is abnormal When optical output power level is abnormal
Power supply alarm	PWR ALM	When an error is found in the power supply
Fuse alarm	FUSE	When TX FUSE blows out

10 Optical network terminal for video signals (V-ONT)

10.1 Configuration of V-ONT

Figure 6 shows a typical function block of the V-ONT. The optical signal transmitted from the V-OLT is converted into electrical FDM signals by the optical/electrical (O/E) converter, and then amplified to the appropriate power level. In SCM systems, the carrier level of signals output from the O/E converter depends on received optical power; however, the carrier level of signals output from V-ONT should be constant. To compensate any decrease in amplitude, the gain of the electrical amplifier is automatically controlled by the Automatic Gain Controller (AGC), which refers to the pilot signal level. The alarm administration function also refers to this signal level. The alarm is output when the pilot signal level no longer meets the specified value. This alarm is used to judge whether transmission signal error has occurred.

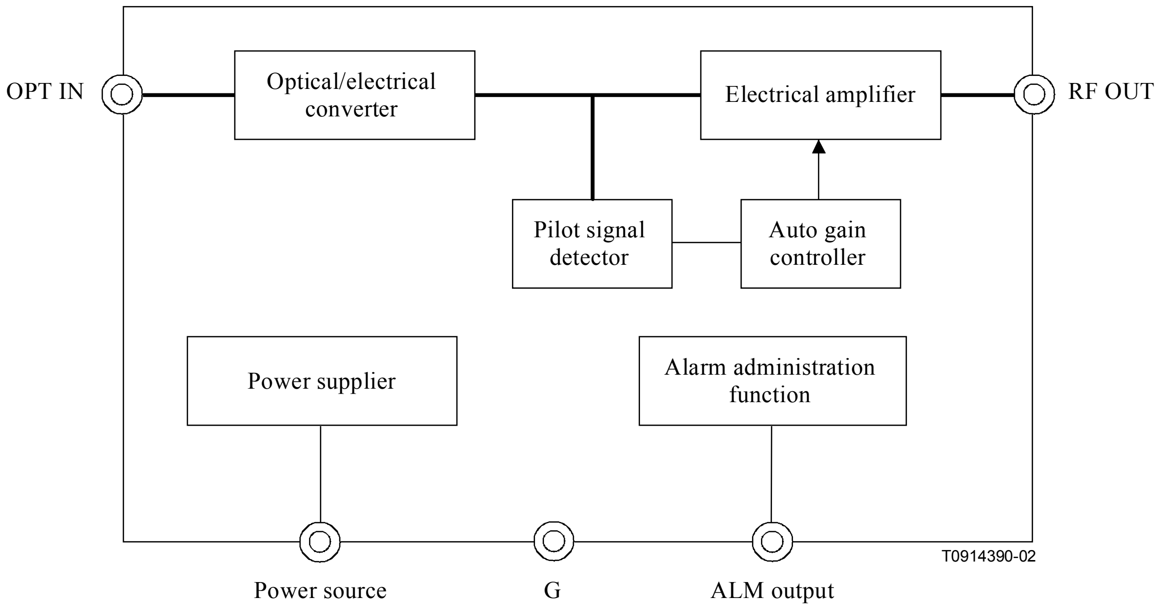

Figure 6/J.186 – Block diagram of V-ONT

10.2 Main characteristics of V-ONT

The main characteristics of V-ONT are listed in Table 11.

Table 11/J.186 – Main characteristics of V-ONT

Item		Limit	Conditions
Optical signal input	Minimum input power	Type 1: ≤ –11 dBm Type 2: ≤ –20 dBm	Type 2 is used for transmission of QPSK signals.
	Wavelength	1555 ± 5 nm	
Electrical signal output	VSWR	≤ 2.5	
	Impedance	75 Ω unbalanced	
AGC	Output level	≥ 75 dBμV/ch	When OMI of TX is 5 %/carrier

10.3 Alarm administration items of V-ONT

Alarm administration items to be observed by V-ONT are shown in Table 12.

Table 12/J.186 – Alarm administration items of V-ONT

Item of alarm administration	Symbol	Alarm occurrence conditions	Remark
Output alarm	OUT	When the power level of pilot signal is lower than the specified value	Pilot signal is measured at RF OUT port.

Annex A

Performance of analogue and/or digital video transmission system

A.1 Specified transmission quality for analogue video signal

Table A.1 shows specified transmission quality for the AM-VSB analogue video signal. The carrier power of the analogue video signal is measured as the peak envelope power.

Table A.1/J.186 – Specified transmission quality for analogue video signal

TV system	M-system NTSC	B, G-system PAL	L-system SECAM
Noise bandwidth	4.2 MHz	4.75 MHz	5.0 MHz
CNR	≥ 44 dB	≥ 44 dB	≥ 44 dB
CSO	≤ –55 dB	≤ –52 dB	≤ –52 dB
CTB	≤ –54 dB	≤ –52 dB	≤ –52 dB
XM	≤ –46 dB	≤ –46 dB	≤ –46 dB

A.2 Specified transmission quality for digital video signal

Table A.2 shows specified transmission quality for the digital video signal.

Table A.2/J.186 – Specified transmission quality for digital video signal

	QPSK signal	64-QAM signal			256-QAM signal
		Annex A/J.83	Annex B/J.83	Annex C/J.83	
Noise bandwidth	27.0 MHz	8.0 MHz	6.0 MHz	4.0 MHz	6.0 MHz
CNR	≥ 13.5 dB [a), b)]	≥ 27 dB [a), b)]	≥ 27 dB [a), b)]	≥ 31 dB [c)]	≥ 33 dB [a), b)]
Second-order D/U	Not specified	Not specified	Not specified	Under study [d)]	Not specified
Third-order D/U	Not specified	Not specified	Not specified	≤ –43 dB [e)]	Not specified

a) This value includes the simultaneous presence of all impairments in the 6-MHz channel bandwidth including composite distortion or other discrete interference.

b) The carrier power is measured as the average RMS signal power.

c) The carrier power is measured as the peak envelope power.

d) Refer to Annex A/J.87.

e) These undesired signals are caused by interference among AM-VSB channels.

Appendix I

Modulation index and minimum received optical power

When all carriers are modulated by the same format, the formula described in 5.3 can be changed to the formula shown below.

$$m_j \leq \frac{0.30}{\sqrt{N}} \qquad \text{(I-1)}$$

The required minimum received optical power, $P_{\min}$, is given by Equation (I-2).

$$P_{\min} = \frac{e + \sqrt{e^2 + \alpha \cdot \left(2eI_{do} + N_{th}{}^2\right)}}{\alpha \cdot R} \quad \text{[W]} \qquad \text{(I-2)}$$

Here, e is the charge of the electron, R is the quantum efficiency of photo detector in V-ONT, I_{do} is the dark current, N_{th} is the thermal noise. α is given by Equation (I-3).

$$\alpha = \frac{m_j{}^2}{2B_W \cdot CNR_{req}} - RIN \quad \text{[s]} \qquad \text{(I-3)}$$

Here, B_W is noise bandwidth, CNR_{req} is required CNR, and RIN is relative intensity noise of the optical signal launched into V-ONT. In Equation (I-3), the carrier power of CNR_{req} is measured as peak envelope power. The assumed values for all these parameters are the following:

RIN	–145.8 dB/Hz
I_{d0}	100 nA
N_{th}	10 pA/√Hz
R	0.8 A/W

The condition given in the following is assumed:

Modulation format of transmitted signal	64-QAM of Annex B/J.83
Number of carriers N	110

According to Equation (I-1), m_j of 0.0286 is the calculated maximum modulation index for the jth carrier. Required minimum received optical power, $P_{\min}$, is calculated to be –11.0 dBm.

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Printed in Switzerland
Geneva, 2002