250km Transmission of Frequency Multiplexed 64QAM Signals For Digital CATV Backbone Application

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64QAM is recognized as a standard for the digital television transmission method on cable plants. This is more robust than the traditional VSB-AM analog method in white noise and nonlinear distortion environment that is typical in the CATV environment. As it is a digital method, it can be regenerated as necessary. Therefore, it will be a better format for long distance transmission using optical fiber. In this paper, we propose an economical CATV backbone solution using a 64QAM transmission system. The system has one digital headend and several analog headends connected by optical fiber cable. The digital headend facility is shared by other headends. We conducted experiments to verify the concept of the digital 64QAM backbone. The experimental system has 250km fiber with 5 cascaded erbium doped optical fiber amplifiers (EDFA) and 11 channels of 64QAM signal or 60CW signals were transmitted as test signals. Such parameters as input/output of EDFAs and modulation depth of laser diode were intentionally changed to find the optimized value. We conclude that it is feasible to transmit 30 channels of 64QAM signals through 250km of optical fiber with EDFAs without regeneration.

QAM DIGITAL TRUNK SYSTEM

Network Architecture

We propose here the QAM digital trunk system. An image of this system is shown in Figure 1. There are some cable operators or cable plants made up of the HFC system with radial optical fibers. If the operator plans to serve digital services individually, he must invest in digital headend such as CS-IRDs, real-time encoders, scramblers, 64QAM modulators and management systems. Especially in the case of the contents provider, satellite operator and cable operator which are all independent. We propose that several operators share one digital headend and transmit digital signals to each operator's analog headend using optical fiber and EDFAs for long distance. This is clearly cost-efficient.

There are two methods of trunk transmission. One is the PCM/ATM method that uses time division multiplexing in the trunk line; at each local headend signals are

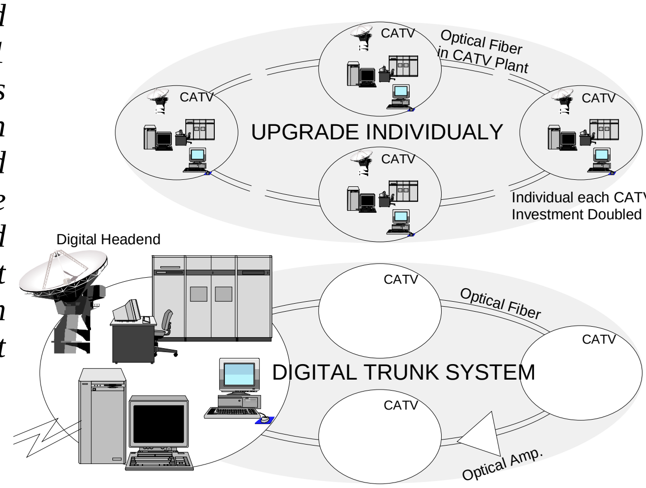


Fig.1 Image of digital services

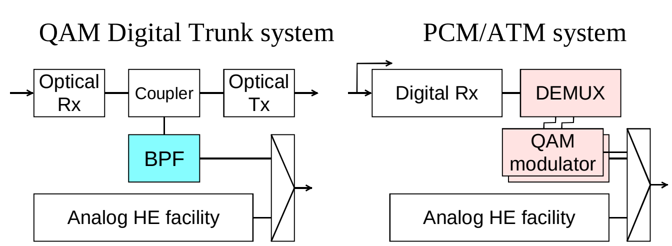


Fig.2a Example of local headend facility

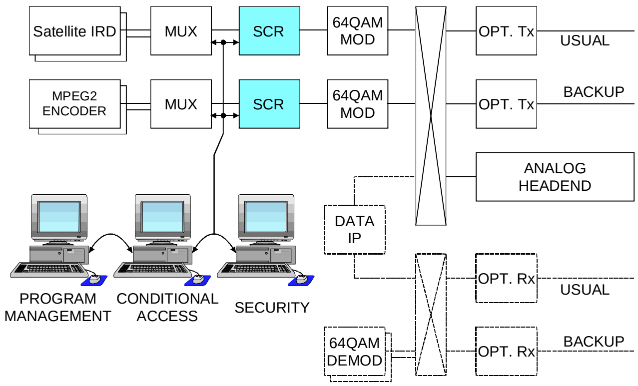


Fig.2b Example of digital headend facility

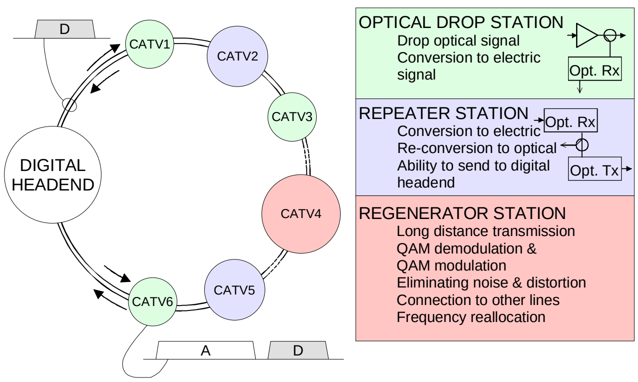


Fig.3 Function of local headends

de-multiplexed and converted to QAM format at every RF channel. An example of the local headend facility is shown in Figure 2a. The other is a method that transmits QAM signals in RF from the digital headend. In this method, each local headend consists of simple equipment including an optical receiver and band pass filter (BPF). The latter is a QAM digital trunk system, which is lower cost at each local headend than the former.

At the digital headend, received and/or served digital contents are transmitted. Figure 2b illustrates the configuration of the digital headend. It consists of satellite and terrestrial receivers, MPEG2 real-time encoders, multiplexers, conditional access equipment, QAM modulators, management system, mixers and optical transmission equipment. For higher reliability, the optical transmission line should be doubled. As the need arises, fast data transmission equipment, ultra capacity cash servers and fast Internet backbone can be connected.

Figure 3 illustrates the system image. The left ring shows that digital signals from the digital headend are transmitted in the trunk line via local headends (CATV1, CATV2,…, CATV6) clockwise and counterclockwise. At local headend, digital signals are combined with analog signals, and both signals are transmitted in the CATV plant. Each local headend is identified by its configuration and has the function shown on the right. The simplest configuration is called “Optical drop station”. It consists of an optical coupler, optical receiver and BPF. Digital signals from the digital headend are filtered to eliminate out-of-band noise and mixed with analog signals here. The next configuration called “Repeater station” consists of an optical receiver and optical transmitter. Optical signal is once converted to an electric signal and again converted to an optical signal. Therefore, if the transmission line is designed in a loop scheme, it is possible to transmit a signal to the digital headend from here. The third configuration is called “Regenerator station”. All QAM signals are demodulated to bit stream and modulated to QAM again. The purpose of regeneration is to remove noise and distortion integrated as long distance transmission. It is possible to add and delete a signal. It is also possible to change frequency allocation.

Here we show application examples using this system. An example in Figure 4 transmits the contents of local UHF broadcasting to other CATV plants. An operator in a local UHF area receives the signal and encodes it to MPEG2 format, then modulates it to QAM signal in R1 channel and transmits it to the digital headend. At the digital headend, the received signal in R1 channel is demodulated and multiplexed with other contents, and QAM modulated to D1 channel. Then subscribers in every CATV plant can enjoy UHF broadcasting by tuning to D1 channel at

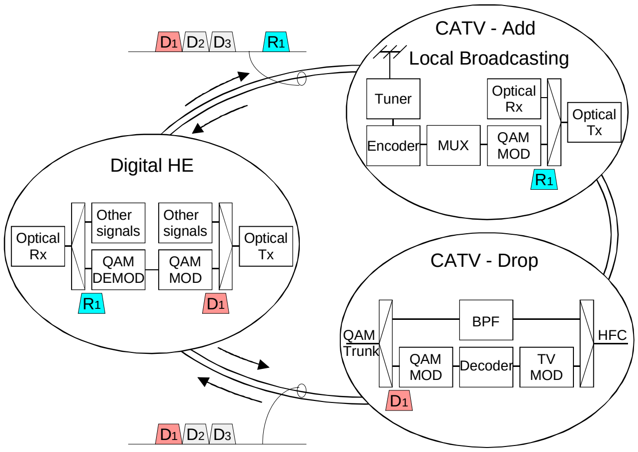


Fig.4 Application – Transmission of local broadcasting to every plants

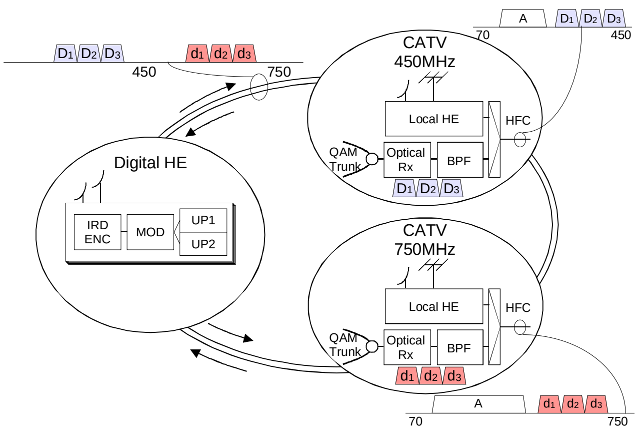


Fig.5 Application – Transmission to combination bandwidth of 450MHz and 750MHz

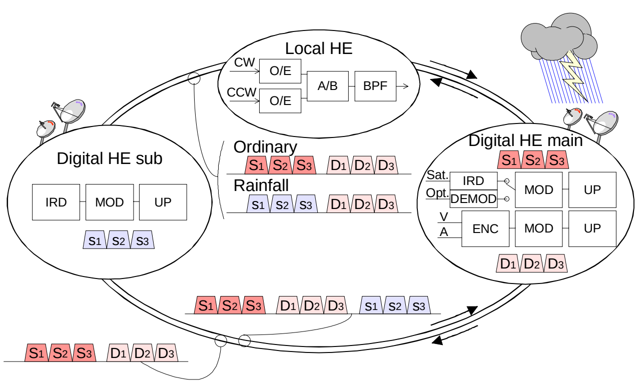


Fig.6 Application – Backup system for eliminating interruption from satellite

as high quality as in the broadcasting area. An example in Figure 5 is a combined system of 450MHz plants and 750MHz plants. In 450MHz plants, digital signals are usually located in higher range such as 300-450MHz. In 750MHz plants, they are usually 550-750MHz. In this case, digital signals are transmitted as simul-frequency from the digital headend. At the local headend of the 450MHz plant, signals for 450MHz plants are filtered and transmitted to the plant. Figure 6 is an example of a backup system in case signals via satellites are hindered by rain attenuation. There are two digital headends, separated enough distance to reduce the probability of co-hindrance. The main digital headend selects better signals from the satellite receivers or the signals that are received at the sub digital headend and transmitted through the trunk line. Then disturbed time will be shorter.

System Performance

In this system, QAM signals are transmitted from the digital headend to subscriber terminals via the optical trunk line, local headend, and CATV plant. On the other hand, analog signals are transmitted from the local headend to subscriber terminals. We assume here that C/N of analog signal (4MHz bandwidth) is 43dB. As C/N of 64QAM annex C needs more than 31dB per 4MHz, we distribute the system performance under the condition of 30dB C/N (averaged per Nyquist bandwidth) including margin. When QAM averaged power is NTSC signal –10dB, QAM C/N in CATV plant is 31.8dB. To obtain 30dB as total C/N, C/N in the trunk line should be more than 34.7dB. (Based on 4MHz carrier level, total C/N is 34.9dB, trunk line C/N is 39.6dB. Here expression of C/N means averaged value per Nyquist bandwidth without notice.)

250KM TRANSMISSION EXPERIMENT

Outline of Experiment

We conducted a transmission experiment to investigate the feasibility of a QAM digital trunk system and system design. Another

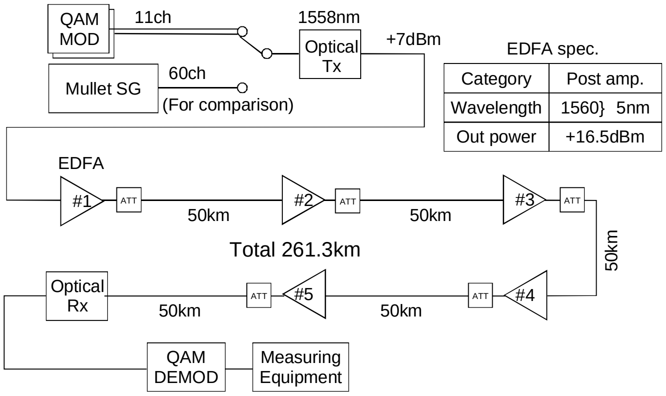


Fig.7 Block diagram of transmission experiment

Table 1 Parameters of the experiment

Symbol Rate	5.274 Msps
Interleave	I=12,J=17
RS FEC	(204,188)
Rolloff	0.13
Fiber zero dispersion	1551 nm
PRBS	2^{23}-1

purpose of the experiment is to obtain information on the number of optical modulation depth (OMD) we can set up, and the distance optical amplifiers can be separated. Figure 7 shows a block diagram of the experiment. Important parameters are listed in Table 1. Test signals are 11 channels of 64QAM or 60 channels of continuous wave (CW). CW is used for comparison. 64QAM signals are generated by our prototype modulators designed for ITU-T J83 annex C (Japan) system. 11 64QAM signals are located 222~288 MHz and 60 CWs are between 91.25MHz and 445.25MHz. We measured 64QAM characteristics at the center channel located at 252~258MHz. This channel modulator is connected to BER measuring equipment and other modulators self-generate PRBS signals individually. Optical transmission equipment uses DFB-LD direct modulation. All of the optical fiber is dispersion shift fiber. And optical bandpass filter is not attached in front of either EDFAs or optical receiver. EDFA is designed for the post amplifier with front and back pumping.

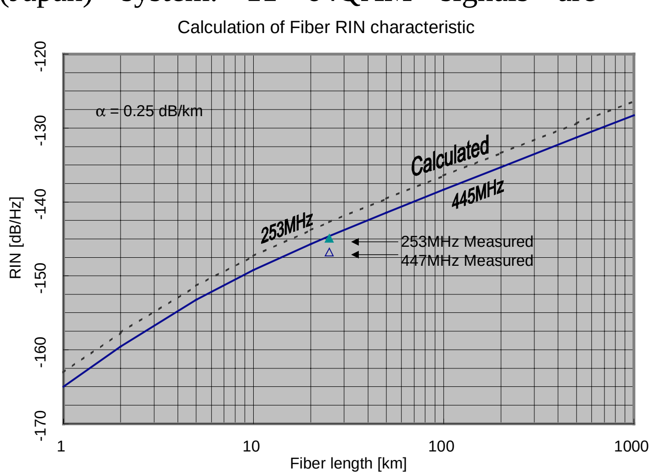


Fig.8 Fiber RIN used in experiment

Basic Performance

First we measured the fundamental performance of the optical equipment without optical fiber. The result under 60 CWs and optical modulation depth of each CW is 4% is C/N=54dB, CSO<-72dB, CTB<-74dB. Then we measured fiber RIN. Figure 8 shows fiber length vs. RIN. The dot is measured and the solid line is calculated using parameters of ordinary dispersion shift fiber. Fiber RIN appears to grow as length increases, as shown in the line in Figure 8. This means that fiber RIN influences transmission noise mainly in long distance while the receiver input power influences in short. Figure 9 shows the relationship between optical modulation depth per channel (OMD) and C/N when 11 QAM signals are transmitted. In the range, where OMD is several percent, C/N grows as OMD increases. In the range where OMD~10dB, C/N does not change as OMD changes. In this range, there may be three fundamental elements. The first element is the carrier level and noise level independent of the number of waves. Carrier level and C/N grow as OMD increases. Second is the third order distortion which grows as OMD increases. Since signals are QAM which spectrum is flat over the bandwidth except rolloff, third order distortion is observed as white noise. Third is the noise from other QAM modulators combined with. C/N is constant as OMD

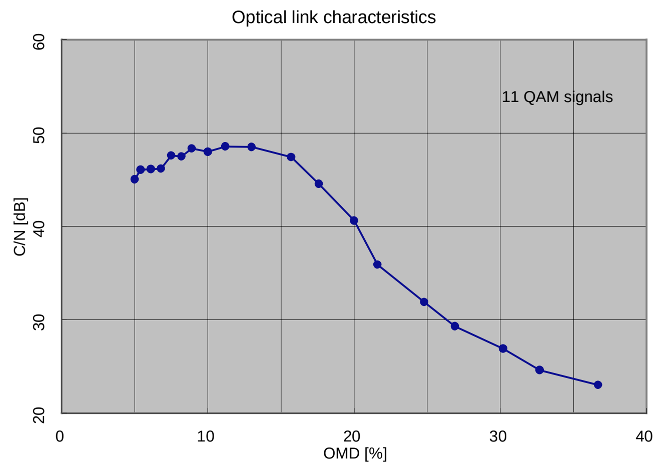


Fig.9 C/N of optical link equipment

changes. In the range where OMD exceeds 15%, C/N reduces as OMD increases. The effect of over-modulation such as distortion and laser clipping seems to cause this. Finally, BER performance of prototype QAM modulator and demodulator in this experiment is 10^{-4} when C/N=26.5dB without FEC.

Performance of EDFA

We outline C/N performance with cascaded EDFAs here. C/N of optical link without EDFA can be obtained from (1). We calculated C/N with cascaded EDFAs from (2) and (3) here. Variables and constants in formulas are as follows.

m: optical modulation depth per channel
Rs: receiver responsibility
P: received optical power
RIN: laser relative intensity noise
B: signal bandwidth
F: noise figure of the receiver preamp
T: temperature
k: Boltzmann constant
R: receiver equivalent resister
e: electron unit
Fi: noise figure of ith EDFA
Pi: input power of ith EDFA

But in actual conditions, because noise not only in the wavelength at the signal but in other wavelength is also amplified by wavelength characteristic of EDFA, noise in

$$C/N = \frac{\frac{1}{2}(mRsP)^2}{(RIN)B(RsP)^2 + 2eBRsP + \frac{4FkTB}{R}} \quad \ldots\ldots(1)$$

$$\frac{F_n}{P_n} = \frac{F_1}{P_1} + \frac{F_2}{P_2} + \cdots + \frac{F_N}{P_N} \quad \ldots\ldots(2)$$

$$C/N = \frac{\frac{1}{2}m^2(RsP)^2}{(RIN)B(RsP)^2 + \frac{2h\nu F_n}{P_n}B(RsP)^2 + \left(\frac{h\nu F_n}{P_n}\right)^2 BoB(RsP)^2 + 2eBRsP + \frac{4FkTB}{R}} \quad \ldots\ldots(3)$$

other wavelength affects C/N of received signal. Figure 10 shows optical spectra. Figure 10a is a transmitted spectrum through one EDFA. Figure 10b is through five EDFAs. Comparing these two figures, it appears that noise of 1560nm – 1565nm is amplified. This noise is called ASE (amplified spontaneous emission). The receiver will receive both the signal and ASE. As EDFA cascades, ASE is amplified and receiver C/N degrades. Figure 11 shows the relationship between input power of EDFA and C/N when an EDFA is in transmission. Here input power changes from –7dBm to +7dBm to keep C/N for QAM transmission. Solid lines are

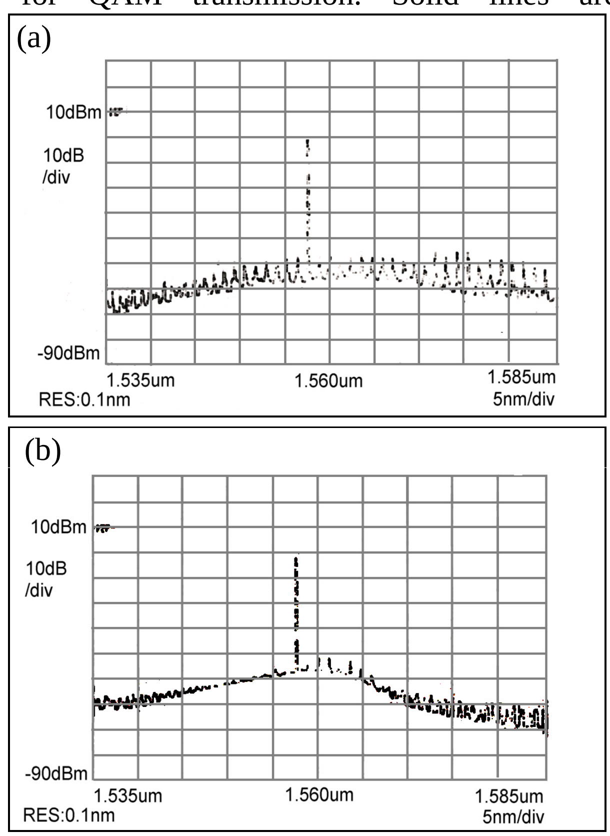
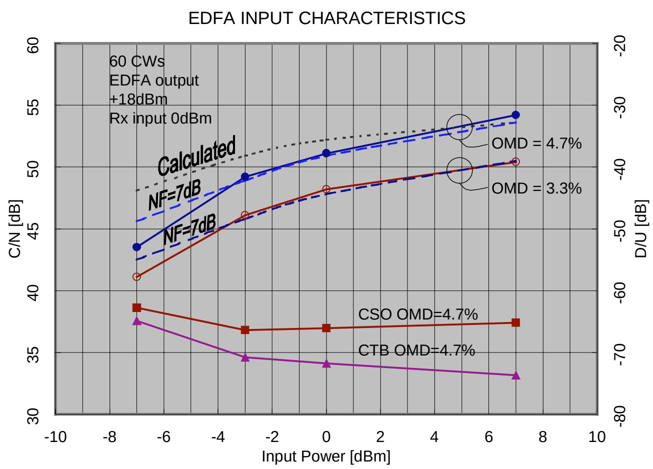
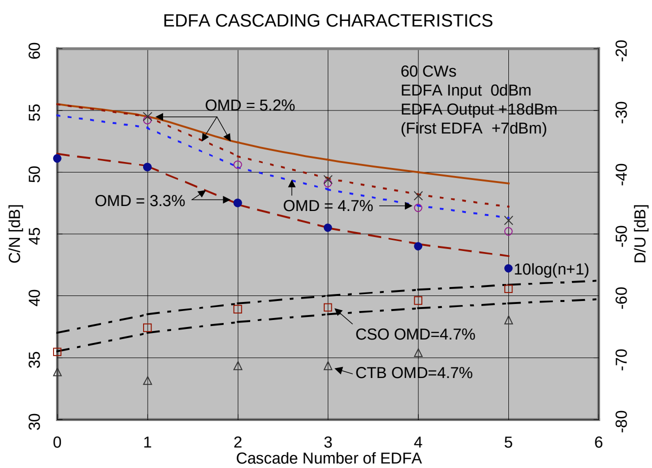


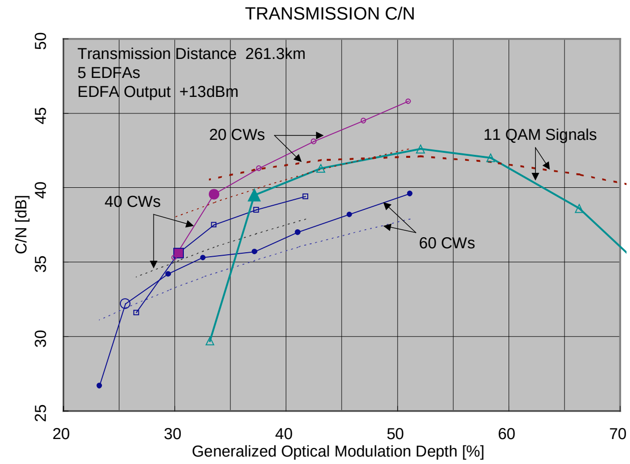
Fig.10 Optical spectrum
(a) 1 EDFA (b) 5 cascaded EDFAs

measured and

Fig.11 Input power characteristics







dotted lines are calculated. At high input range, the calculated line shows good approximation to measured data. However, as input power is lower, there is a difference between measured value and calculated value. This is because relative ASE power increases as lower input power. Noise figure (NF) of EDFA changes as input power; for example, NF is 7dB when input is +7dBm and NF is 4.5dB when input is 0dBm. Dotted line with caption “NF=7dB” in the graph assumes NF is 7dB constant. It seems to be good approximation over –3dBm input power. Figure 12 shows C/N, CSO and CTB as cascading EDFAs. In this graph, we measured using EDFAs and optical attenuators. As to C/N, the graph shows three cases of different OMD. In the case of OMD=5.2%, crosses of measured data degrade more than the solid calculated line. This also seems to be affected by ASE. Dotted lines in the graph are calculated assuming NF=7dB and show good approximation under four or five cascading. For more cascading, according to the condition of the growth of ASE, C/N seems to degrade much more than this approximation. In terms of distortion, CSO and CTB degrades as cascaded. One of the reasons is due to the wavelength characteristic of EDFA, i.e. optical gain is slightly different between the upper and lower edge wavelength of the optical signal. Dotted-solid lines fitted to distortion measured value are curves of 10log(n+1), where n is a cascade number of EDFA.

250km Transmission Characteristic

Now we will discuss the results of the 250km-transmission experiment. Figure 13 shows C/N vs. optical modulation depth where the number of waves is 11 QAM signals, 20 CWs, 40 CWs and 60 CWs. Output power of each EDFA is +13dBm. X axis is a generalized modulation depth calculated $M = m\sqrt{N}$ where m is OMD and N is the number of the wave. Usually, this number is 20% to 30% under normal HFC operation.

Fig.14 C/N and BER performance

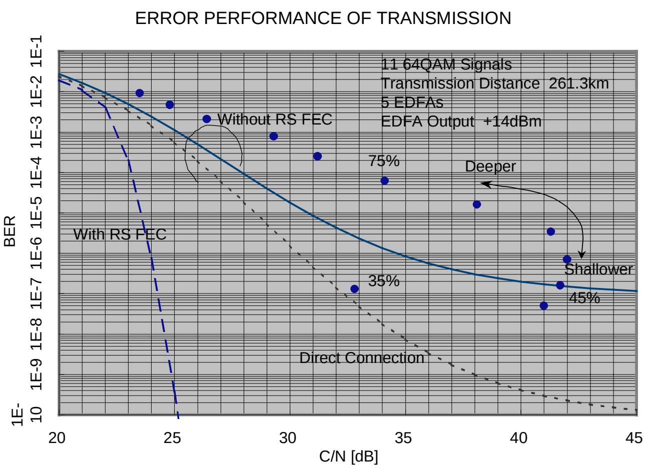


Fig.15 RS (188,204) ability

Fig.12 Cascading characteristics

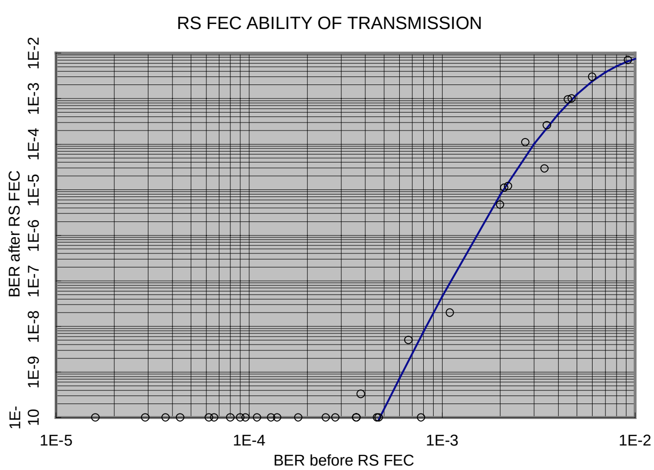


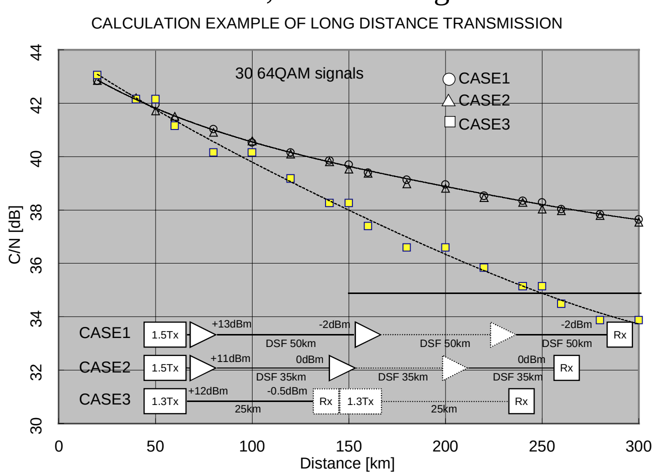
Fig.13 Modulation depth characteristics

At calculation of 11 QAM, the effect of modulator noise and CTB is considered. In the case of 20 CWs, C/N is larger as M is deeper. But this characteristic changes at M=33%. At the range of M<33%, the phenomenon that noise floor rises and distortion increases is observed. C/N degrades substantially. There is a similar phenomenon at M~30% of 40 CWs and at M~26% of 60 CWs. This phenomenon occurs at M~37% of 11 QAM signals as well. This point tends to be shallower as the number of wave increases. We consider that this point is the start of the effect of stimulated Brilloun scattering (SBS). At the shallower M range than this point, operation will be difficult. At the deeper M range, C/N degrades again because of distortion increasing. So we investigated a transmission performance at the range of 37%~M~50%. Figure 14 shows C/N and BER with/without RS FEC performance of long distance transmission. Dotted line in this graph indicates the performance of direct connection of 64QAM modulator and demodulator. Circular dots in this graph indicate C/N and BER as OMD changes. For example, at M=45%, 250km transmission C/N is 41.7dB and BER without FEC is $1.5x10^{-7}$. When M is changed, C/N and BER are changed to a deeper and shallower side in the graph. In the graph, two cases of M=35% and M=75% are shown with caption. The dot of M=35% is far away from other dots because this point seems to be observed under SBS condition. Solid line passing the point of M=45% means the calculation with the addition of white noise to observed value, i.e. this line indicates an estimation of BER performance at subscriber's terminal including transmission noise of CATV plants. To demonstrate this circumstance, we measured BER by adding white noise in front of the receiver, and obtained that BER performance is slightly better than this line. From this line, we can estimate that BER is about $2x10^{-5}$ when C/N is 30dB, and that C/N must be better than 28dB to obtain BER that is 10^{-4} or better. Figure 15 shows BER of transmission with RS vs. without RS. The solid line in this graph is calculated, and data on BER=10^{-10} means no error has occurred during measuring time. This graph, except for rare different data shows general theoretical performance. If BER before RS FEC is less than 10^{-4} then it will reduce to less than 10^{-10}.

Cascading of QAM signal

Fig.16 Calculation of long distance transmission

Here we consider very long distance transmission such as several hundred kilo meters or several times. As QAM is a digital transmission method, it can be regenerated as



necessary. The merit of regeneration; i.e. demodulation and modulation is that it eliminates transmission noise and distortion. Transmission noise from modulator, up-converter, optical equipment, optical fiber and coaxial equipment will be eliminated. However, symbol timing is very critical as it is integrated as cascading regeneration.

Figure 16 shows a calculation example for long distance transmission. It is assumed 30 QAM signals are transmitted. It is also assumed that 30 signals are allocated in one octave so that no second order distortion falls in signal frequency. We calculate three cases. Case 1 uses 1.5um LD and EDFA with –2dBm input and +13dBm output spanning 50km. Case 2 uses 1.5um LD and EDFA with 0dBm input and +11dBm output spanning 35km. In both cases, input power of PD is the same as that of EDFA. Case 3 uses 1.3um LD with +12dBm output and PD with –0.5dBm input spanning 25km and repeating. From this graph we can read that case1 and case 2 are very similar in characteristics, but that of case 3 deteriorates as distance lengthens. This difference is from the assumption that CTB increases by the summation of power in case 1 and case 2 and by summation of voltage in case 3. The former is from Figure 12 and in the latter it can be safely assumed that all fiber links have similar distortion characteristics. Case 1 and case 2 have different input and output power, but have similar curve. For this reason noise of fiber RIN is principal in long distance transmission and relatively small in that of input power or cascading. Note that the cascade number of case 1 may not be the same as case 2. For example, 4 EDFAs are cascaded to transmit 200km in case 1, but 5 in case 2. As EDFA cascades more than this experiment, according to the condition of ASE, C/N will degrade more. The effect of ASE is not considered in this calculation except for that described above. Under the condition that C/N from the digital headend to subscriber’s home is 30dB and C/N between the trunk line is 34.7dB, QAM signals will be transmitted 250km without regeneration.

CONCLUSION

We have proposed a QAM digital trunk system that has several analog headends and a shared digital headend connected by optical fiber. This system will reduce the cost of installing a digital headend facility. We conducted a 250km-transmission experiment with 5 cascaded EDFAs and obtained data. It includes that C/N is more than 40dB and BER without FEC is about 10^{-7} under 11 64QAM signals are transmitted and that calculated

C/N shows good approximation by substituting a constant value for EDFA noise figure. From the results of this experiment, we conclude it will be feasible to transmit 30 QAM signals over 250km with 5 EDFAs and several times via regeneration stations.

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