Noise Accumulation in CATV Distribution Systems Employing 1550-nm Externally Modulated Transmitters

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Abstract
In this paper we present a method to determine the SNR and CNR performance of 1550-nm CATV distribution systems formed by optical amplifier-fiber cascades. The distribution of multiple AM CATV channels over long fiber spans is degraded by the presence of Rayleigh backscatter-induced low-frequency interferometric noise. When the laser source is modulated externally the low-frequency interferometric noise is mixed and translated around the AM carriers. The scattering-induced noise sets a limit on the link CNR as a function of fiber characteristics, fiber length, and source linewidth. Due to the narrow linewidth of solid-state and single-frequency semiconductor laser sources, the standard CNR measurement can give erroneous results because of the narrow-band translated noise. In this analysis we compared NCTA CNR and baseband video SNR performance of a CATV distribution system employed in a hub-ring architecture.

INTRODUCTION

With the advent of Erbium-Doped Fiber Amplifiers (EDFA's) employed as power and/or in-line amplifiers combined with externally-modulated 1550-nm transmitters, long fiber spans can be deployed to replace coax lines in the CATV network infrastructures. Furthermore, operation at the low fiber loss window at 1550 nm, the use of chirp-free external modulators, and the commercial availability of high output power EDFA's has made it possible to deploy longer fibers to broadcast CATV channels from the headend to the local service areas such as to hubs, fiber star feeders, and distribution nodes.

Performance of fiber-optic transmission systems can be seriously degraded by multiple reflections from discrete reflection points [1]-[5] and by Rayleigh backscattering within the fiber [5]-[11]. Although multiple reflections along the fiber can be suppressed by careful system design such as by using obliquely polished connectors, fusion splices and high return loss passive components, suppression of Rayleigh backscatter generated interferometric noise poses some fundamental limitations. In addition, employing in-line optical amplifiers at the hub sites to extend system reach could generate even more severe impairments when no isolators are used [8],[9],[11].

Noise is also inherent in an optically-amplified transmission system due to the spontaneous emission and amplification of photons in the active fiber of the amplifier. The signal-to-noise performance of the amplifier is characterized by its noise figure and is a function of a number of external parameters including amplifier gain, input signal power, and wavelength. The noise figure can be quantified in the optical domain by measurement of output signal power and amplified spontaneous emission (ASE) spectral power and density. The amplifier noise figure is also measured in the electrical domain, and this method is probably more applicable for AM CATV applications. In addition to ASE noise, interferometric noise can be generated due to reflections within the optical amplifier. The noise mechanism is the same as for discrete reflections and Rayleigh double-backscatter in the fiber link except that doubly-reflected signals in the amplifier may be amplified in each direction by the gain medium. Thus, it is particularly important to minimize the reflection of signals within and through the amplifier [11]. In this paper we present a method to determine the CNR and SNR performance of a CATV distribution network employing optical amplifier-fiber cascades in a counter rotating ring architecture [12].

NOISE FIGURE MODEL OF AMPLIFIER-FIBER CASCADE AM SYSTEM

Figure 1 shows a schematic of a CATV distribution system employing N optical amplifiers in an amplifier-fiber cascade. The CATV system noise factor can be expressed as follows:

$$F(f)=F_a+F_{sh}+F_{rin}+F_{th}+F_b(f) \qquad (1)$$

where F_a, F_{sh}, F_{rin}, F_{th}, and F_b are the noise factor of the accumulated optical amplifier noise, shot noise, laser relative intensity noise (RIN), receiver thermal noise and accumulated fiber

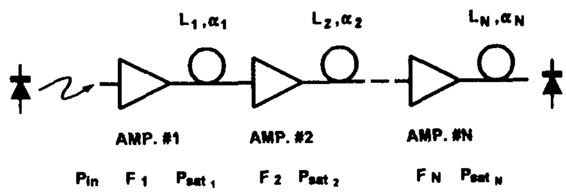

Fig. 1. Block diagram of N optical amplifier-fiber cascades.

Rayleigh double-backscatter noise, respectively. The total noise factor of N cascaded optical amplifiers is defined as

$$F_a=F_1+Pin\cdot\sum_{k=2}^{N}\frac{F_k}{\alpha_{k-1}\cdot Psat_{k-1}} \qquad (2)$$

where Pin is the input optical power at the first optical amplifier, F_k is the noise factor of the k^{th} amplifier, $Psat_k$ is the saturated output power of the k^{th} amplifier and α_k is the fiber and splitting loss after the k^{th} amplifier. The shot noise factor is given by

$$F_{sh}=\frac{Pin}{\alpha_N\cdot Psat_N}\cdot\frac{1}{\eta} \qquad (3)$$

where η is the photodetector quantum efficiency. The thermal noise factor is given by

$$F_{th}=\left(\frac{1}{\alpha_N\cdot Psat_N}\right)^2\cdot\frac{<i_{th}^2>}{\left(\frac{\eta\cdot q}{h\cdot\nu}\right)^2}\cdot\frac{Pin}{2\cdot h\cdot\nu} \approx\left(\frac{1}{\alpha_N\cdot Psat_N}\right)^2<i_{th}^2>\cdot\frac{Pin}{2\cdot h\cdot\nu} \qquad (4)$$

where $<i_{th}^2>$ is the receiver equivalent current noise density. The laser RIN noise factor is expressed as

$$F_{rin}=RIN\cdot\frac{Pin}{2\cdot h\cdot\nu} \qquad (5)$$

where h is Planck's constant and ν is the optical frequency of laser emission. The total fiber Rayleigh backscatter noise factor is defined as

$$F_b(f)=RIN_b(f)\cdot\frac{Pin}{2\cdot h\cdot\nu} \qquad (6)$$

where $RIN_b(f)$ is the fiber Rayleigh double-backscatter relative intensity noise (including the low-frequency and translated interferometric noise). The Rayleigh double-backscatter RIN is expressed as

$$RIN_b(f)=\kappa\frac{4}{\pi}\left(\frac{\alpha_s S}{2\alpha_t}\right)^2\left[2\alpha_t\sum_{k=1}^{N}L_k-N+\sum_{k=1}^{N}e^{-2\alpha_t L_k}\right]\left(\frac{\Delta f}{\Delta f^2+f^2}+\frac{m^2}{2}\sum_{j=1}^{N_c}\frac{\Delta f}{\Delta f^2+(f-f_j)^2}\right) \qquad (7)$$

where κ is the depolarization factor, α_s is the Rayleigh backscatter coefficient, S is the fiber capture factor, α_t is the fiber absorption coefficient, m is the optical modulation index and N_c is the total number of channels. Inspection of expression (7) indicates that Rayleigh double-backscatter RIN has a non-flat noise floor, and therefore, a non-flat noise factor.

AM-VSB VIDEO CNR AND SNR DEFINITION

The AM-VSB CATV fiber optic distribution system employing optical amplifiers is deteriorated by shot noise, thermal noise, laser relative intensity noise (RIN), amplifier spontaneous noise and Rayleigh signal-backscatter beat noise. The video signal quality due to broadband noise is defined by NCTA RF CNR [13] and baseband video SNR measurements [14]-[16]. Assuming all the noise terms except the signal-backscatter noise term have flat power spectral densities the theoretical NCTA CNR at channel f_j is defined as

$$CNR=\frac{Pin}{2h\nu}\cdot\frac{m^2}{2}\cdot\frac{1}{F(f_j)\cdot B_n} \tag{8}$$

where $B_n=4$ MHz is the NCTA noise bandwidth (we have assumed a brick-wall shape bandpass filter). Note that F(f) (the non-flat noise factor due to Rayleigh backscatter RIN) in the CNR definition of expression (8) is determined with the carrier at frequency f_j turned-off (i.e., m=0 at f_j). The baseband video filter used in SNR measurements consists of cascaded 10 kHz high-pass, 4.2 MHz bandwidth low-pass, and unified weighting filters. The theoretical baseband video SNR is defined as

$$SNR=\frac{Pin}{2h\nu}\cdot\frac{(m\cdot A_m)^2}{4}\cdot\frac{1}{\int_{f_l}^{f_c}\left(V(f+f_j)+V(-f+f_j)\right)|H_c(f)|^2} \tag{9}$$

where A_m is the blanking-to-peak white video signal level in percentage, $V(f)=F(f)\cdot H_v(f)$ is the total noise factor filtered (weighted) by the vestigial sideband demodulator, $H_v(f)$ is the vestigial sideband demodulator filter transfer function, $H_c(f)$ is the CCIR 567 baseband unified weighting filter transfer function, and $f_l=10$ kHz and $f_c=4.2$ MHz are the video low-pass filter lower and upper frequency limit, respectively. Theoretical SNR calculation with unified video weighting filter yields a 0.6 dB improvement over CNR calculation when the noise power spectral density within the channel bandwidth is flat. Our experimental measurements yielded 0.4 dB to 0.8 dB improvement of SNR over CNR (with minimal translated noise around the AM carrier) which is consistent with the theoretical 0.6 dB improvement. If the noise power spectral density (PSD) is not flat, theoretical CNR and SNR calculations will yield different results, indicating that RF CNR measurements can not be faithfully employed.

1550 nm EXPERIMENTAL CATV DISTRIBUTION SYSTEM

Figure 2 shows the experimental set-up [17] used to measure the NCTA RF CNR and baseband video SNR of our 78 channel AM-VSB CATV distribution system. Inspection of Fig. 2 reveals that the transmitter consists of a laser source, a

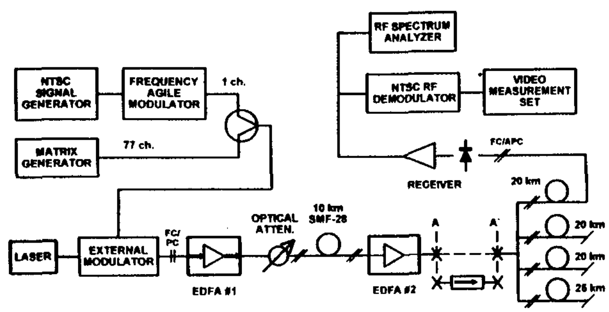

Fig. 2. Experimental set-up of a 78 channel AM-VSB CATV distribution system. Section A-A' denotes the position of the in-line amplifier output isolator.

linearized external modulator and an EDFA (with internal input and output isolators) used as a power amplifier. The laser source is a 1554 nm wavelength 700 kHz linewidth SL-MQW DFB laser chip packaged in an internally isolated module. We used a single channel agile AM carrier modulated by a NTSC video signal (luminance) combined with 77 unmodulated AM-VSB channels using a RF directional coupler. The power amplifier has a saturated output power of about $P_{o1}=13$ dBm at $P_{i1}=2.8$ dBm and a noise figure of about 5.5 dB. The saturated output power of the in-line amplifier is about $P_{o2}=12$ dBm at $P_{i2}=3$ dBm and has a noise figure of about 4.4 dB (measured with the output optical isolator placed in section A-A' in Fig. 2). The optical attenuator at the transmitter output is adjusted to maintain the in-line amplifier input power from -3 to 3 dBm. The received optical power after 20 km of single-mode fiber from port 1 is kept at about -0.9 dBm. The optical receiver equivalent input current noise density is less than 8 pA/√Hz with an optical return loss greater than 51 dB. The agile carrier is tuned either to channel 2 or to channel 29 for CNR and SNR measurements. For NCTA CNR measurements, the NTSC video signal at the transmitter is turned-off (only the unmodulated carrier is transmitted through the system) and the RF output from the receiver is connected to a RF spectrum analyzer. The AM carrier peak power level is first measured and then the channel under test is turned-off to measure the spot frequency noise power level [13]. This noise power measurement procedure is adopted to minimize ambiguities in measuring the non-flat translated noise spectra. For baseband video SNR measurements, the NTSC video signal at the transmitter is turned-on and the RF output connected to a Tektronics 1450-1 television demodulator operating in the synchronous detection mode. The baseband signal from the demodulator is sent to a Tektronics VM 700-A video measurement set (video analyzer). Within the video analyzer the baseband signal and noise pass through a 10 kHz high-pass filter, 4.2 MHz bandwidth low-pass filter and unified weighting filter. Finally, the noise at the filter output is integrated and compared to a nominal 100 IRE unit video signal (luminance) level.

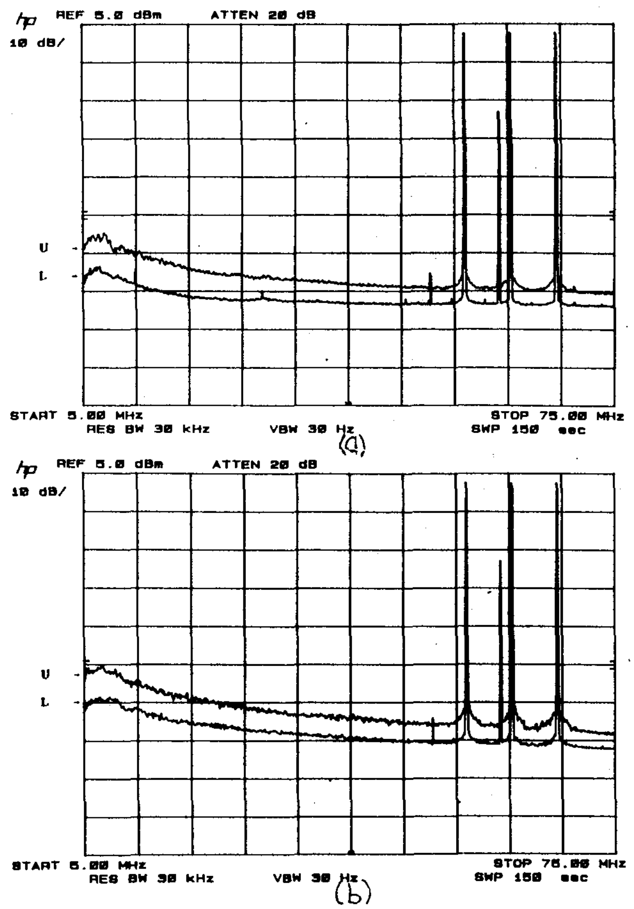

Fig. 3. RF spectrum of low-end channels:(a) with; and (b) without isolators. Upper (U) and lower (L) traces indicate the spectra at P_{i2}=-3 dBm and 3 dBm, respectively.

Figures 3(a) and 3(b) show the low frequency and translated RF spectra of the low end channels with and without an in-line amplifier output isolator, respectively. Inspection of Fig. 3 indicates that the low frequency noise spectral density is suppressed as much as 7 dB when input power is increased from -3 dBm to 3 dBm. When an in-line amplifier output isolator is employed the signal-backscatter spectral density is suppressed by about 5 dB as compared to the spectral density without output isolator. The audio carrier which is about 20 dB lower in magnitude and 4.5 MHz away from channel 2, is generated by the agile modulator (shown in Figs. 3(a) and 3(b)). Without an output isolator both the SNR and the CNR are degraded due to doubly amplified signal-backscatter beat noise; note that the lower frequency channels are the most degraded by the tail of the low-frequency and by the translated noise spectral density. The spot frequency noise spectral density for the CNR measurement is determined with the carrier turned-off. The SNR and CNR without output isolator is 44.1 dB and 44.8 dB at P_{i2}=3 dBm, respectively. At P_{i2}=-3 dBm the SNR and CNR is measured to be 39.7 dB and 40.5 dB. With an output isolator in place the SNR measurement is about 0.3 dB lower than the CNR measurements indicating that 0.9 dB degradation is due to

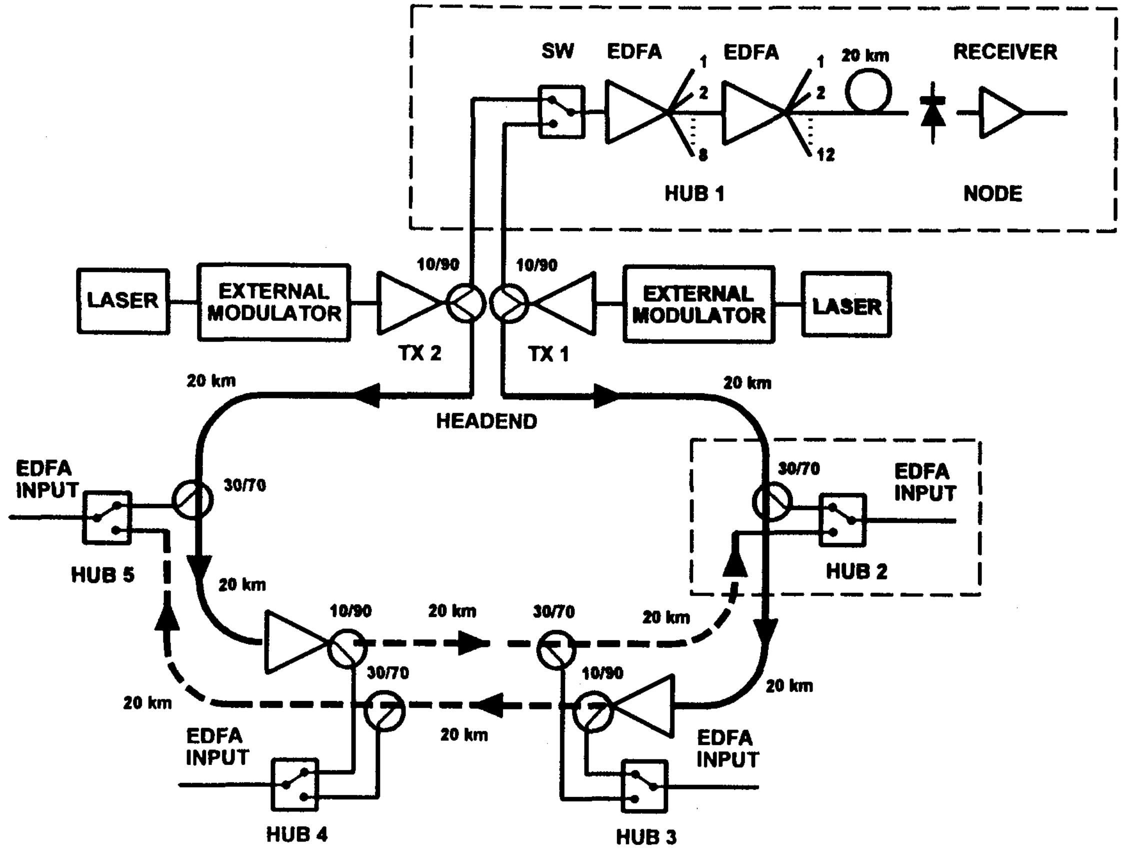

Fig. 4. Counter rotating CATV hub-ring optical network. Solid line indicates primary and dotted line indicates redundant fiber transmission path.

translated noise (with flat noise the SNR is about 0.6 dB higher than CNR). The SNR at $P_{i2}=3$ dBm is 49 dB and at $P_{i2}=-3$ dBm is 44.6 dB. Finally, we measured the Composite Second-Order (CSO) and Composite Triple-Beat (CTB) distortion of our AM-VSB CATV distribution system. For input powers ranging from -3 dBm to 3 dBm the CTB at 307.25 MHz is better than 60.5 dB; no CTB degradation is seen without the output isolator. The CSO at 55.25 MHz is greater than 64 dB and 65 dB with and without the output isolator, respectively. The CSO at 547.25 MHz is measured to be about 1 dB worse than the CSO measured at the low-end channel.

1550 nm CATV HUB-RING NETWORK PERFORMANCE ANALYSIS

Figure 4 shows a schematic of a counter rotating five-hub ring optical network. The optical ring network consists of one headend and five hub sites (one hub site is co-located with the headend). The headend consists of two externally modulated optically amplified transmitters. The input power at the transmitter power amplifier is about 6 dBm. The saturated output power of the power and in-line EDFAs are assumed to be 16 dBm with a noise figure of 4 dB. To ensure network survivability, the AM-VSB CATV channels from the headend are routed clockwise through hub 2 to hub 5 and counter-clockwise through hub 5 to hub 2 by transmitter 1 and 2, respectively. The distance between hub sites is 20 km, therefore, total distance from the headend transmitter 1 (or transmitter 2) to hub 5 (or to hub 2) is 80 km. In our analysis broadcast channels are distributed and trunked by two cascaded in-line amplifiers (see Fig. 4) to 96

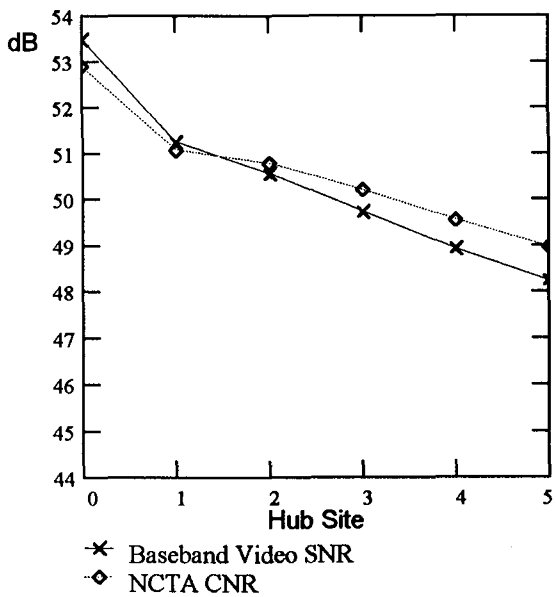

Fig. 5. NCTA CNR and baseband video SNR at channel 2 of the CATV distribution ring network for 100 kHz laser linewidth.

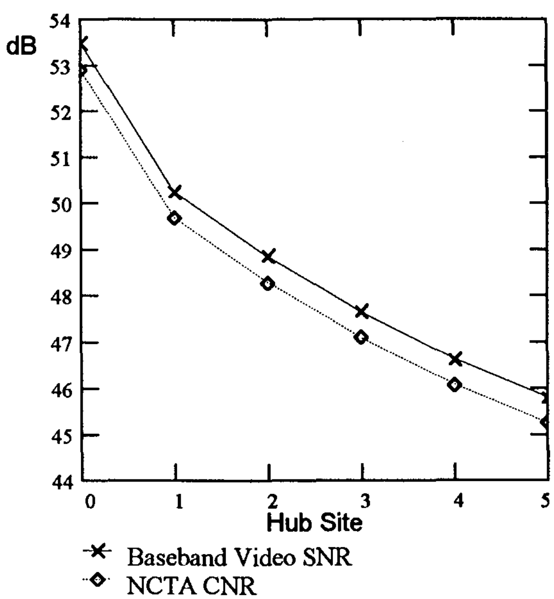

Fig. 6. NCTA CNR and baseband video SNR at channel 2 of the ring network for 5 MHz laser linewidth.

nodes (8X12) which are 20 km away from the hub sites. Our model assumes a 78 AM-VSB channel transmission with a 3 % optical modulation depth per channel.

Using expression (1) in (8) and (9) we compared the NCTA CNR and baseband video SNR at channel 2 for 100 kHz and 5 MHz laser linewidths. Figures 5 and 6 show the baseband video SNR and NCTA CNR at 100 kHz and 5 MHz laser linewidth, respectively. The SNR and CNR at hub site 0 in Figs. 5 and 6 are determined at the output of the headend (output of transmitter 1 and 2). The received optical power at hub sites 1, 2, 3, 4 and 5 for AM carriers transmitted by transmitter 1 (rotating clockwise on the hub-ring optical network) is 6 dBm, 5.3 dBm, 6 dBm, 5.3 dBm and 4 dBm. The SNR and CNR at the headend output is 53.5 dB and 52.9 dB, respectively. At the node of hub site 1 the SNR and CNR is 51.3 dB and 51.1 dB for 100 kHz linewidth, and 50.3 dB and 49.7 dB for 5 MHz linewidth, respectively. At the node of hub site 5 the SNR and CNR is 48.2 dB and 49 dB for 100 kHz linewidth, and 45.8 dB and 45.2 dB for 5 MHz linewidth, respectively. Further inspection of Fig. 5 and 6 reveal that the system performance at 100 kHz laser linewidth is degraded mostly by translated noise and at 5 MHz laser linewidth the system is degraded by the low-frequency interferometric noise.

CONCLUSIONS

An experimental 78 channel AM-VSB CATV distribution system is constructed employing two EDFA's simulating headend and hub sites and we compared NCTA CNR and baseband video SNR measurements using a 700 kHz linewidth externally modulated 1550 nm DFB transmitter. With no output isolators within the in-line amplifier we experimentally and theoretically determined that even for laser linewidths as low as 700 kHz (100 kHz with our theoretical calculations) the CNR and SNR performance is degraded by Rayleigh backscatter induced low-frequency and translated noise. Therefore, both input and output isolators are essential within in-line amplifiers employed for AM-VSB distribution. We presented a simplified method to determine the SNR and CNR performance of 1550 nm CATV distribution systems formed by

N number of amplifier-fiber cascades. Using our expression we evaluated the performance of a counter rotating CATV hub-ring optical network [12].

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