The effect of SRS on pilot-tone detection technique in DWDM system

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A math model that can describe the effect of stimulated Raman scattering (SRS) on pilot-tone detection technique is proposed. Through numerical simulation, it is shown that the effect of SRS could produce ghost-tones. The power of ghost-tones was larger for the channels separated further from the real-tone. The power ratio between real-tone and ghost-tones increases linearly with the increase of transmission length when propagation distance longer than 300 km.

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Optical performance monitoring is an import issue for the design, operation and maintenance of optical transport networks (OTN). In recent years, a lot of digital and analog monitoring techniques have been proposed and reported, such as bit error rate (BER) estimation, error block detection, optical power measurement, optical signal-to-noise ratio (SNR) evaluation with optical spectrum measurement, Q-factor monitoring, and pilot-tone detection [1−7]. Among them, pilot-tone-based monitoring technique is attractive because it is reliable, cost-effective and easy to realize. This technique adds small signal sinusoidal pilot-tones to optical signals for optical performance monitoring and channel identification. Optical path changing in wavelength division multiplexing (WDM) networks and optical switch failure in optical cross connection (OXC) could be easily supervised by the monitoring technique. Nevertheless the slow dynamic properties of erbium-doped fiber amplifier (EDFA) could produce ghost-tones[8], they degrades the performance of pilot-tone-based monitoring technique. These ghost-tones could not only mislead the network operators but also cause mistakes in the pilot-tone-based monitoring technique. There is an easy way to solve that problem by using high frequency (> 100 kHz) pilot-tones. However, stimulated Raman scattering (SRS) effect can also induce ghost-tones that could not be suppress only by increasing the tone frequency[9]. We analyzed the effects of SRS on pilot-tone-based WDM supervisory technique and gave the math model and showed the numerical simulation result.

The power of each WDM channel with pilot-tone can be described as

$$p_i(t)|_{z=0} = p_i + \Delta p_i \sin(\omega_i t + \theta_i), \tag{1}$$

where p_i is the average output power of the ith channel, Δp_i is the peak amplitude of the sinusoidal portion of the channel power, and ω_i is the angular modulation frequency of each pilot-tone.

Further, we assume that the interchannel frequency spacing Δf is equal (but arbitrary), the shortest wavelength channel as channel 1, the longest wavelength channel as channel N, and the Raman gain profile of silica fiber is a triangular function[10]. We can therefore write $g_{i,j} = g'(i-j)\Delta f/(2A)$, where $g_{i,j}$ is the Raman gain efficiency between channels i and j, A is effective area of optical fiber, and $g' = \mathrm{d}g/\mathrm{d}f$ is the slope of Raman gain profile. If $i < j$, it is shown that the power of channel i transfer to channel j through the effect of SRS. In Ref. [11] it is means that the SRS crosstalk will be higher for low pilot-tone frequency (< 400 MHz) because fiber dispersion is not significant and cannot cause walk-off between pilot-tones at different optical wavelength. So if the pilot-tone frequency was lower than 400 MHz, the fiber's dispersion could be neglected. After ignoring fiber's dispersion, we may formulate the differential equations, which govern the signal light propagation in the dense wavelength division multiplexing (DWDM) transmission system with N equally spaced channels, given as

$$\frac{\mathrm{d}p_i(z)}{\mathrm{d}z} + \alpha \cdot p_i(z) + G \cdot p_i(z) \sum_{j=1}^{N} (j-i) p_j(z) = 0, \tag{2}$$

$$p_i|_{z=0} = p_i(0), \quad i = 1, 2, 3, \cdots N, \tag{3}$$

$$G = \frac{g'\Delta f}{2A}. \tag{4}$$

In Eq. (2) $p_i(z)$ is the power of the nth channel as a function of propagation distance z and α is the fiber attenuation coefficient. $p_i(0)$ is input optical power of ith optical channel at $z = 0$.

With above differential equation, the following general solution can be gotten

$$p_i(z) = \frac{p_i(0) J_0 \exp(-\alpha z)}{\sum\limits_{j=1}^{N} p_j(0) \exp(G J_0 (j-1) L_{\mathrm{e}})} \times \exp(G J_0 (i-1) L_{\mathrm{e}}), \tag{5}$$

where $L_{\mathrm{e}} = \frac{1-\exp(-\alpha z)}{\alpha}$ is the nonlinear effective length.

If $p_i(0)$ is a function of t as Eq. (1), $p_i(z)$ can be expressed as

$$p_i(z) = \frac{(p_i + \Delta p_i \sin(\omega_i t + \theta_i)) J_0 \exp(-\alpha z)}{\sum\limits_{j=1}^{N} (p_j + \Delta p_j \sin(\omega_j t + \theta_i) \exp(G J_0 (j-1) L_{\mathrm{e}})} \times \exp(G J_0 (i-1) L_{\mathrm{e}}), \tag{6}$$

where $J_0 = \sum\limits_{i=1}^{N} (p_j + \Delta p_j \sin(\omega_i t + \theta_i))$. Expression (6)

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shows that the power of the ith channel contains the pilot-tone power of the other channels. The ghost-tones have been produced through the effect of SRS among optical channels. The amplitude of ghost-tones and pilot-tone can be obtained from the Fourier transform on Eq. (6). Then the influence of SRS effect on pilot-tone-based monitoring technique can be analyzed.

To evaluate the influence of SRS effect on pilot-tone-based monitoring technique, the numerical simulation with eight channels was made. Its parameters are shown in Table 1.

The Raman gain profile was given as

$$g(\Delta f) \approx k\Delta f, \quad (\Delta f \in [0,100]\ \mathrm{cm}^{-1}),$$
$$g(\Delta f) \approx k'\Delta f, \quad (\Delta f \in [0,500]\ \mathrm{cm}^{-1}),$$

where $k = 2.35 \times 10^{-16}$ m·cm/W, $k' = 1.8 \times 10^{-16}$ m·cm/W, Δf is frequency shift.

If plenty of the values $p_i(z,t)$ were gotten at the same distance z in different time t, using fast Fourier transform (FFT) to $p_i(z,t)$, the electrical spectrum of pilot-tones could be gotten. The power of ghost-tones and pilot-tone could be read from the radio frequency (RF) spectrum. In this paper 32768 values were calculated at every distance z with time interval $1/(3.2768 \times 10^7)$ second.

Figures 1 and 2 show the RF spectrum of 3rd channel and 6th channel at z km. There is not any ghost-tonesin each channel. The pilot-tone frequency of the 3rd channel is 100 kHz, and that of the 6th channel is 160 kHz.

After channels 3 and 6 were transmitted 40 and 80 km, respectively, the ghost-tones due to the effect of SRS appear. Figures 3 and 4 show the RF spectrum of channels 3 and 6 after transmitting 80 km.

The results show that the effect of SRS can product ghost-tones, the power of ghost-tones was larger for the channels separated further from the real-tone. It was agree with the experimental result in Ref. [9]. This result can be easily explained that the larger frequency shift of two channels, the larger Raman gain index. Figure 5 shows the powers of real-tone (frequency is 100 kHz) and ghost-tones as a function of transmission length in the 3rd channel.

Figure 6 shows the ratio between real-tone power and ghost-tones power in channel 3 (pilot-tone frequency is 100 kHz) as a function of transmission length, where real-tone frequency is 100 kHz; ghost-tones frequency is 60, 160, and 200 kHz. The ratio became larger and larger as the transmission length increases. The ratio almost kept constant when transmission length was longer than 20 km. The reason of this phenomenon is that the effective length of SRS is 20 km. The crosstalk due to the effect of SRS increases slowly when transmission length is longer than

Table 1. Numerical Simulation Parameters

Parameters	Value	Note
A_e	5×10^{-11} m^2	Fiber Effective Area
α	0.2 dB/km	Fiber Loss
Δf	200 GHz	Channel Frequency Space
N	8	Channel Number
λ_1	1547.7 nm	The Shortest Wavelength
λ_8	1559.0 nm	The Longest Wavelength
z	0 – 80 km	Transmission Length
ω_i *	$2n\pi$ kHz**	Pilot-Tones Angular Frequency
p_i *	1 mW	The Average Output Power of Each Laser
Δp_i *	0.2 mW	The Peak Amplitude of the Sinusoidal Portion of the Laser Power

* $i = 1, 2, 3, \cdots, 8$; ** $n = 60, 80, 100, 120, 140, 160, 180, 200$

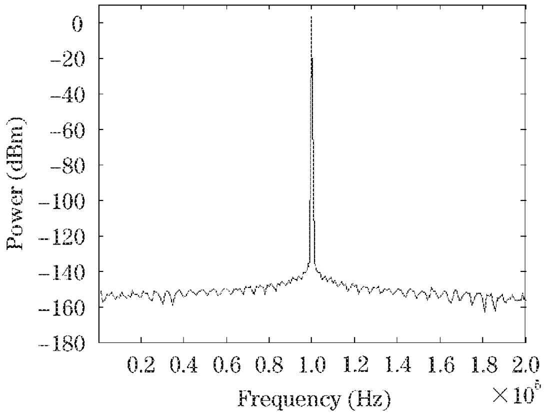

Fig. 1. RF spectrum of channel 3.

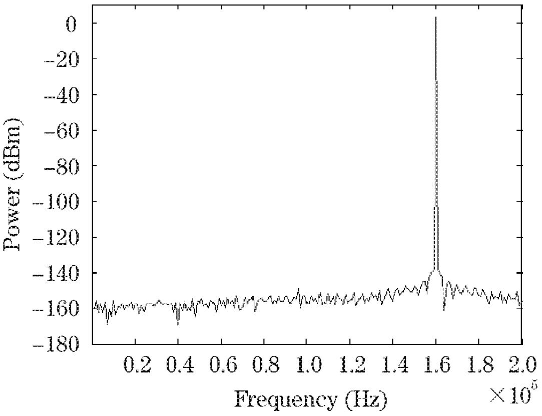

Fig. 2. RF spectrum of channel 6.

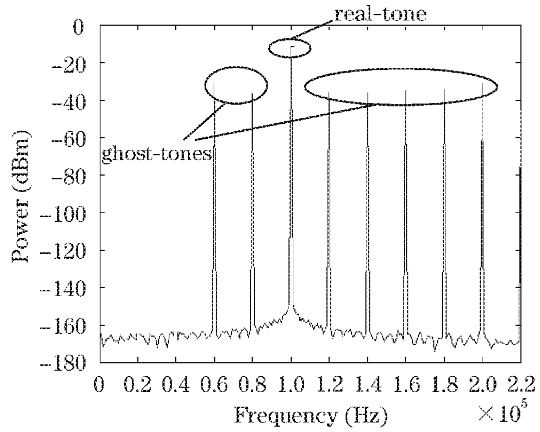

Fig. 3. Spectrum of 3rd channel (transmitted 80 km).

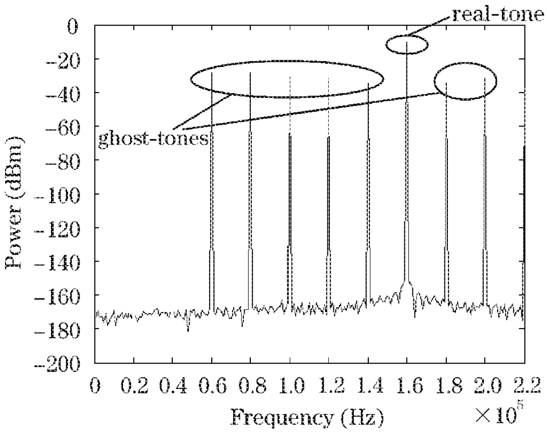

Fig. 4. Spectrum of 6th channel (transmitted 80 km).

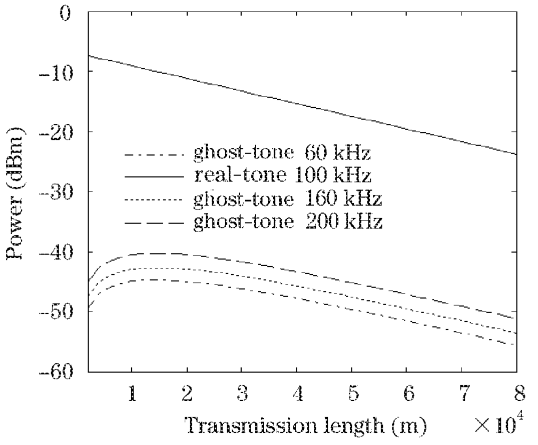

Fig. 5. Powers of real-tone and ghost-tones in the 3rd channel.

SRS effective length. The separation between the channel with 200 kHz pilot-tone and the channel with 100 kHz is the largest, so the ration between ghost tone (200 kHz) and real-tone (100 kHz) is the largest at the same transmission length. That is because the pilot-tone with frequency 200 kHz is the identification of the channel with the longest wavelength, the energy of shorter wavelengths' pilot-tone could transfer to it through SRS.

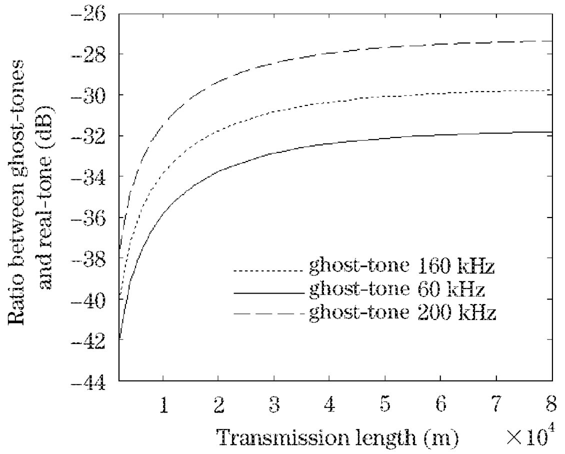

Fig. 6. Power ratio versus transmission length.

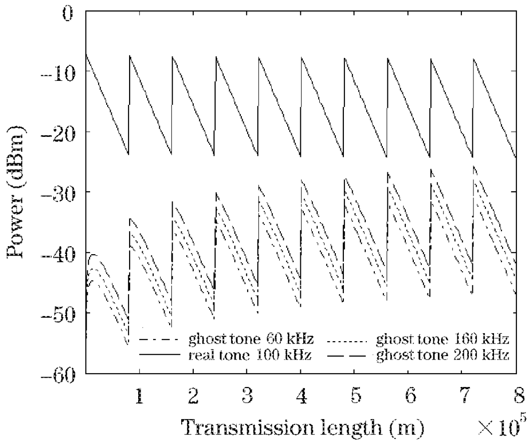

Fig. 7. Powers of real-tone and ghost-tones in the 3rd channel.

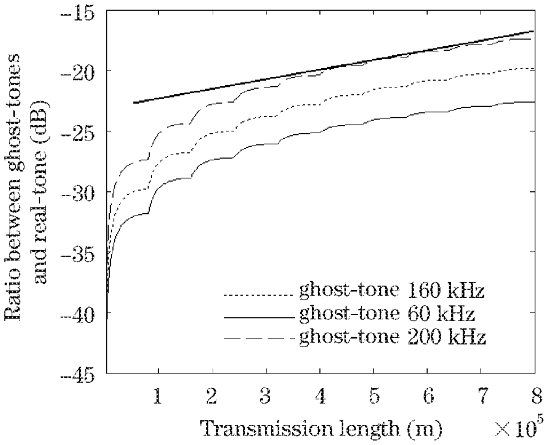

Fig. 8. Power ratio versus transmission length.

Figure 7 shows the real-tone and ghost-tones in the 3rd channel as a function of transmission. Figure 8 shows the power ratio between real-tone and ghost-tones as a function of transmission length, where transmission length is 800 km (each span is 80 km, the loss of 80-km-long single-mode fiber (SMF) can be compensated by EDFA completely), the frequency of real-tone is 100 kHz. We can see from Fig. 8 that the ratio increases linearly with the increase of transmission length when transmit distance longer than 300 km. The power ratio between real-tone and ghost-tones changes more slowly if the transmission length is longer than 300 km. This means that fore 300-km transmission has the dominant effect on the performance degradation of pilot detection.

In conclusion, the SRS causes an energy transfer from shorter to longer wavelengths. That will induce ghost-tones in pilot-tone-based monitoring technique. We proposed math model that can describe the effect of SRS on pilot-tone-based monitoring technique. Numerical simulation based on this model with eight equally spaced channels, and the pilot-tones ranging from 60 to 200 kHz was made. It was found that the amplitude of ghost-tones was larger for the channels separated further from the real-tone. The power ratio between real-tone and ghost-tones increases linearly with the increase of transmission length when transmit distance longer than 300 km. Fore 300-km transmission has the dominant effect on the performance degradation of pilot detection.

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