System Performance Measurement and Analysis of Optical Steganography Based on Noise

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***Abstract*— System performance of optical steganography is theoretically analyzed and experimentally demonstrated. The optical stealth channel is carried by amplified spontaneous emission noise, which hides the stealth data in both the time and frequency domain. Meanwhile, because the stealth channel uses noise as the signal carrier, the relation between signal-to-noise ratio (SNR) and carrier power is fundamentally different from the traditional optical channels carried by modulating lasers. To transmit and hide the stealth signal in the existing public network, the degradation principle of SNR of the stealth channel is studied. Such principle can guide the design of the stealth transmission system and optimize the carrier power of the stealth channel.**

***Index Terms*— Amplified spontaneous emission, optical fiber communication, optical steganography.**

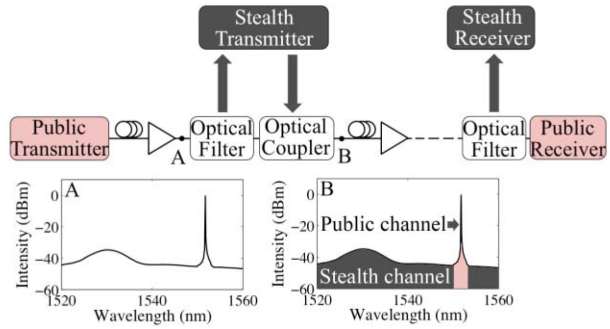

Fig. 1. System demonstration of hiding the stealth channel in the public network. The public channel is shown in light red and the stealth channel is shown in dark gray.

I. Introduction

OPITCAL steganography provides an effective way to hide a stealth channel in both the time domain and frequency domain of the public network [1]–[3]. Recently, an optical steganography method based on amplified spontaneous emission (ASE) noise has been proposed and experimentally demonstrated [4]–[7]. The stealth signal is carried by the ASE noise that comes from erbium doped fiber amplifiers (EDFAs) in the public optical network. The optical spectrum of the stealth data channel is exactly the same as the spectrum of the noise in the public channel. In the time domain, the stealth channel takes advantage of the short coherence length of the ASE noise. Since the stealth transmitter uses phase modulation, the delay length at receiver has to be exactly matched the delay length at the transmitter in order to recover the phase information and demodulate the data [4]. The requirement of the matching condition provides a large key space for the stealth channel, which makes it virtually impossible for an eavesdropper to detect the existence of the stealth channel [4], [5].

While optical steganography based on ASE noise can effectively hide the stealth channel, the system performance of the stealth channel is fundamentally different from the traditional optical channels that transmit data by modulating a laser source. One of the most important metrics of a communication system is the signal-to-noise ratio (SNR), which characterizes the power level of the signal and the accumulation of noise. In the case of the stealth signal which is carried by ASE noise, the SNR has both the numerator and denominator expressed as noise; this means that increasing the power of the signal carrier also increases the power of the noise. Moreover, studying the relation between SNR and the power level of the signal is especially important for the stealth channel. Since the stealth channel makes use of the existing ASE noise in the public channel, the power of the noise has to accumulate to a certain level before the stealth channel can be introduced into the network. Based on the SNR model of the stealth channel, a balance has to be made between the noise level that required to be accumulated in the public channel and the SNR of stealth channel that can be achieved by this amount of noise.

In this letter, we derive and analyze the relationship between SNR of the stealth channel and the power of the ASE carrier, and corroborate these findings experimentally. We find that the SNR saturates when the noise in the stealth channel is dominated by the beat noise. We also study the effect of transmitting a stealth signal in a long-haul system with multiple EDFAs. The results shows that the stealth signal carried by ASE noise can be amplified by EDFAs, which means that the stealth channel can seamlessly share the existing network with the public channel. The experiment results and analysis can guide the system designers for applying and hiding the stealth channel in the public network and also provide input for establishing power budgets.

II. Principle

A. Introducing Stealth Channel to the Public Network

As depicted in Fig. 1, a stealth channel can be introduced on an optical network after the public signal propagates through an EDFA and generates ASE noise. The spectrum on the right

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shows the spectrum in point A of the system diagram and the spectrum on the right shows the spectrum in point B. The peak in the spectrum is the public channel and the flat region the ASE noise. An optical filter can be used to separate the ASE noise from the public channel. After adding the stealth signal by modulating the ASE noise [6], [7], the stealth channel can be combined with the public channel and transmit through the public network. At the receiver, an optical filter can be used to separate the stealth channel and public channel.

B. SNR of the Stealth Channel

The SNR of the stealth channel is given by

$$SNR_{stealth} = \frac{\langle I \rangle^2}{\sigma^2_{thermal} + \sigma^2_{shot} + \sigma^2_{ASE-ASE}} \tag{1}$$

where $<I>$ is the average of receiver current, $\sigma^2_{thermal}$ is the thermal noise, σ^2_{shot} is the shot noise, and $\sigma^2_{ASE-ASE}$ is the beat noise.

The thermal, shot and beat noise can be expressed as [8], [9]

$$\begin{aligned} \sigma^2_{thermal} &= (4k_B T/R_L)F_n \Delta f \\ \sigma^2_{shot} &= 2qR(2S_{sp}\Delta\nu_{opt})\Delta f \\ \sigma^2_{sp-sp} &= 4R^2 S^2_{sp}\Delta\nu_{opt}\Delta f \end{aligned} \tag{2}$$

where k_B is boltzmann constant, T is room temperature, R_L is the load resistance of the photodiode, F_n is amplification ratio of the electric amplifier at the receiver, Δf is the electric bandwidth of the photodiode, q is the electron charge, R is the responsivity of the photodiode, S_{sp} is the spectral density of ASE noise, and $\Delta\nu_{opt}$ is the optical bandwidth of the ASE noise. The beat noise only comes from the ASE beating with itself. Note that the public channel will not beat with the stealth channel, because the public channel is filtered at the stealth receiver (Fig. 1).

The major difference in the SNR of the stealth channel and the traditional public channel is in the signal power term. Since the signal of the stealth channel is carried by ASE noise, the electrical signal power is proportional to the square of the spectral density of ASE noise:

$$\langle I \rangle^2 = (2RS_{sp}\Delta\nu_{opt})^2 \tag{3}$$

Meanwhile, the beat noise is also proportional to S^2_{sp}. Dividing both the numerator and denominator of the SNR by $(2RS_{sp})^2\Delta\nu_{opt}$, we find that the SNR does not always increase with the signal carrier power (S_{sp}); it saturates to $\Delta\nu_{opt}/\Delta f$ when S_{sp} is large enough and the beat noise dominates:

$$SNR_{stealth} = \frac{\Delta\nu_{opt}}{\Delta f\left(\frac{(4k_B T/R_L)F_n}{(2RS_{sp})^2\Delta\nu_{opt}} + \frac{q}{RS_{sp}} + 1\right)} \tag{4}$$

In the denominator of (4), the summation in the bracket are contributed by thermal noise, shot noise and beat noise. In the case when the beat noise dominates, (4) can be written as:

$$SNR_{stealth} = \frac{\Delta\nu_{opt}}{\Delta f} \tag{5}$$

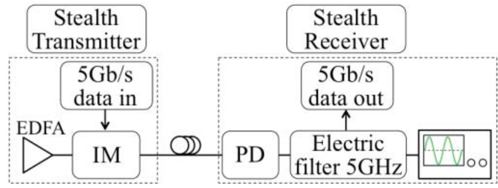

Fig. 2. Experiment setup for SNR analysis of optical stealth transmission (EDFA: erbium doped fiber amplifier, IM: intensity modulator, PD: photodiode)

The SNR of the stealth channel in this case is a constant and does not depend of the ASE power. As a conclusion of the theory, when the ASE power (S_{sp}) keeps increasing to a value that the ASE beat noise dominates, the SNR of the stealth channel saturates at a constant that only depends of the ratio of optical bandwidth to electric bandwidth.

III. Experiment and Discussion

A. Back to Back Transmission

The SNR of the stealth channel is measured with a pair of stealth transmitter and receiver with a data rate of 5Gb/s (Fig. 2). A low pass electric filter with 3dB cut off frequency Δf=5GHz is used at the receiver. The signal of the stealth channel is intensity modulated ASE that generated by an EDFA. Although the intensity-modulated signal can be directly received by a photodiode and thus cannot hide the signal in the time domain, the structure of an intensity modulator is similar to the stealth transmitter that uses phase modulation in [4] and both of them are Mach-Zehnder interferometers. The only difference is that in [4], one light path of the interferometer has additional optical delays, which hide the signal in the time domain and provide the key space. In term of SNR performance, the theory summarized based on intensity modulation can still be applied to analyze stealth system that use phase modulation.

The saturation effect described in the principle section is experimentally demonstrated in Fig. 3(a), which shows the SNR measurement of the stealth channel as a function of the ASE power. The experimental results (square markers) are in close agreement with the theoretical calculation (line) based on (1). The results show that when the received power is lower than −10dBm, the SNR is proportional to the square of the received power, which means the noise is dominated by thermal noise (4). When the received power is larger than −10dBm, the SNR saturates at around 24dB, which means the noise is dominated by the beat noise. In this case, both the noise and the signal is proportional to the square of the power of ASE carrying the stealth signal. In addition, the SNR does not depend on the power of the stealth signal and is equal to the ratio of optical bandwidth of ASE to the electric bandwidth of the receiver (5). In the experiment, the electric bandwidth of the receiver is 5GHz. The ASE power mainly comes from the spectral peak around 1530nm with a full width half maximum (FWHM) bandwidth of 10nm (Fig. 3(b)), corresponding to 1.28THz. The peak around 1530 with 10nm width contributes 71% of power in the entire ASE spectrum. The calculated ratio $\Delta\nu_{opt}/\Delta f \approx 24$dB is the same as the

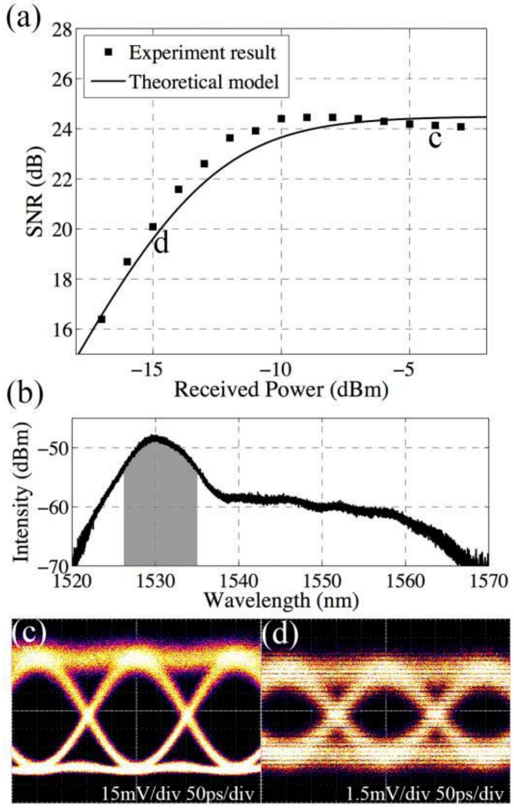

Fig. 3. (a) SNR at the receiver with different the received ASE power. (b) Spectrum of the ASE noise. (c) Eye diagram with beat noise dominating. (d) Eye diagram with thermal noise dominating.

measured saturation of the SNR in Fig. 3(a). Furthermore, the measured results show that when the ASE power increases above −10dBm, the SNR slightly decreases. This is because at higher output power, the peak of the ASE spectrum at 1530nm becomes narrower [10]; that is, a smaller Δv_{opt} corresponds to a smaller SNR. The eye diagrams of both cases further prove the above analysis. Fig. 3(c) corresponds to point "c" in Fig. 3(a). The high level is much noisier than the low level, which indicates that the beat noise dominates. Fig. 3(d) corresponds to point "d" in Fig. 3(a). The high level and low level have the same amount of noise, which indicates that the thermal noise dominates. The shot noise in this system is small compared with thermal noise and beat noise in both cases.

B. Long-Haul Transmission With Amplifiers

To transmit the stealth channel over long distances, we study the degradation of the SNR after the stealth channel passes through EDFAs (Fig. 4). Two optical attenuators with fixed attenuation of 20dB each are used to emulate the loss from 100km of standard single mode fiber. An EDFA is used after each attenuator to compensate for the loss. Low pass electric filter with 3dB cut off frequency at 5GHz is used at the receiver. The SNR of the stealth channel is measured at A, B and C points in Fig. 4.

The measured results show the stealth channel carried by ASE noise can be amplified by EDFA but with SNR degradation (Fig. 5(a)). The SNR at B (Fig. 4) is measured by setting the ASE power at A to be −10dBm and changing the

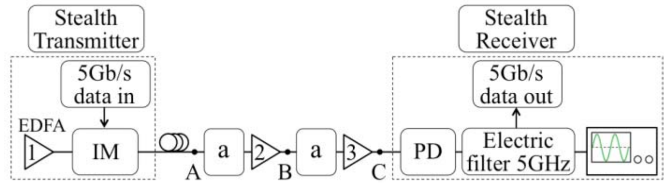

Fig. 4. Experiment setup for SNR analysis of optical stealth transmission for long distance transmission (EDFA: erbium doped fiber amplifier, IM: intensity modulator, a: optical attenuator, PD: photodiode)

gain of the first EDFA. Similarly, the SNR at C is measured by setting the ASE power at A to be −10dBm and the gain of the second EDFA to be 20dB and changing the gain of the third EDFA (Fig. 4).

The SNR of the stealth channel with the EDFA has the same saturation effect when the beat noise dominates (Fig. 5(a)). The saturated SNR value is smaller when more amplifiers are applied, because the EDFA not only amplifies the original ASE that carries the signals but also generates additional ASE noise. The amplified ASE is not coherent with newly generated ASE and the beating effect between them causes the degradation of SNR. In this case, (4) changes into

$$SNR_{stealth} = \frac{\Delta v_{opt}}{\Delta f\left(\frac{(4k_BT/R_L)F_n}{(2RS_{sp})^2\Delta v_{opt}} + \frac{q(S_{sp}+S'_{sp})}{RS_{sp}^2} + \left(1+\frac{S'_{sp}}{S_{sp}}\right)^2\right)} \quad (6)$$

where S_{sp} is the spectral density of ASE carrying the stealth signal after amplification and it is proportional to the gain G. S'_{sp} is the spectral density of the newly generated ASE from EDFA, which is given by

$$S'_{sp} = n_{sp}\, hv_0(G-1) \quad (7)$$

where n_{sp} is the spontaneous-emission factor of the amplifier and hv_0 is the photon energy. In this experiment since G (=10-2500) is large, $G - 1 \approx G$. Also, since both $S'sp$ and S_{sp} are proportional to the gain, the ratio S'_{sp}/S_{sp} is independent of G. The SNR of the stealth channel saturates at a value that depend on both $\Delta v_{opt}/\Delta f$ and S'_s/S_{sp} (6). After the first amplifier, the maximum value of SNR decreases to 21dB. After the second amplifier, the maximum value of SNR decrease to 19dB.

To study the stealth channel with more amplifiers, we theoretically calculate the SNR after the stealth signal passes through 10 amplifiers, each with $G = 20$dB to compensate 20dB loss from 100km fiber (Fig. 5(b)). The three curves in Fig. 5(b) depict different launch powers of the signals carried by ASE. When the launch power is −4dBm and −10dBm, the beat noise dominates, and they both have relatively the same SNR at 0 km; however, a smaller launch power leads to a faster degradation of the SNR with amplifiers. When the launch power is further decreased to −16dBm in Fig. 5(b), the initial SNR is much smaller because the thermal noise dominates in this case. For long-haul transmission with distance longer than 1000km, the −16dBm launched ASE power is not sufficient to carry the stealth signal.

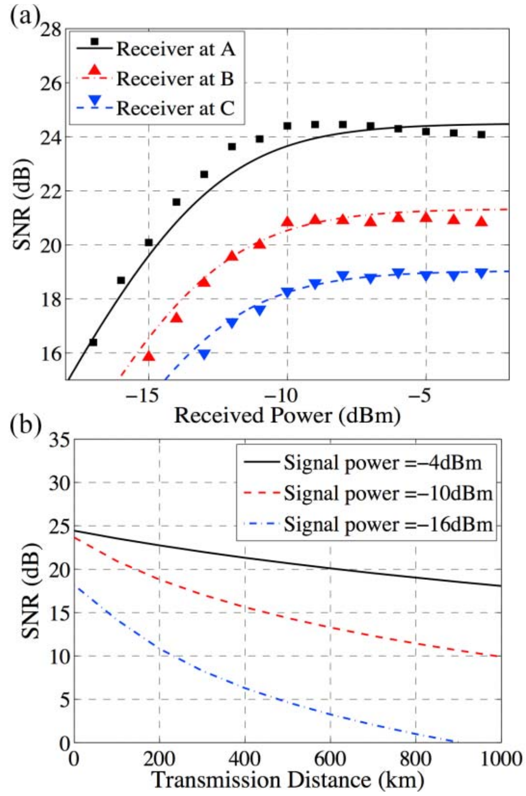

Fig. 5. (a) Dependence of SNR on the received power with different number of amplifiers. (b) Dependence of SNR on the transmission distance at different launch powers.

C. System Design and Analysis

The design of the stealth channel needs to find an optimum balance between the SNR and the required ASE power. Because the ASE power carrying stealth signal comes from the accumulation of noise from the public channel (Fig. 1), a lower ASE power level requires less noise in the public channel and thus provides more flexibility of applying the stealth channel in the public network. In the case of short distance communication without using amplifiers, the best operating point is when the SNR just saturates, which corresponds to −10dBm in Fig. 3(a). The SNR reaches a maximum value at −10dBm. The operating point depends on the amount of thermal noise of the receiver. In the case of long-haul transmission, where amplifiers are introduced, the initial ASE power needs to be increased further. Because the ratio of the initial ASE power and the newly generated ASE by the amplifier determines the degradation rate of SNR after the signal passes through other amplifiers, a larger initial power results in slower degradation of the SNR. The choice of operating point can be based on (6) considering the newly generated ASE for the required transmission distance. Besides signal attenuation and amplifier noise, the dispersion from the single mode fiber also affect the SNR of the stealth channel. In this case, dispersion compensation is needed. The experiment that use dispersion compensation fiber in the stealth channel has been demonstrated in [4] and the dispersion effect on the stealth channel has been analyzed in [5] and [6].

IV. Conclusion

We theoretically analyzed and experimentally proved the relation between the SNR of the stealth signal and the launched ASE power. Since the stealth channel is carried by ASE noise, which is fundamentally different from the public channel, the SNR does not always increase when the power of the signal carrier increases. The saturation effect of SNR is experimentally observed when the beat noise dominates. The operating point of the launched ASE power for short distance stealth transmission system is when it just saturates the SNR.

The experimental results also demonstrate that signals carried by ASE can be amplified by EDFAs. The SNR degradation of the amplified signal is studied in both theory and in experiment. The degradation depends on the ratio of the launched ASE power and the newly generated ASE by the EDFAs. To transmit the stealth channel over the long distances, the launched power should be higher than the power that just saturates the SNR.

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