Optical Signal Processing and Stealth Transmission for Privacy

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***Abstract*—Optical encryption, key generation, and optical stealth transmission techniques for protecting the privacy of communication in optical networks are proposed and summarized. The signal processing methods based on fiber components provide ways to encrypt data and generate encryption keys at the speed of data transmission in optical fibers. Private and confidential communication is achieved without compromising the capacity and bandwidth of the optical network. Optical stealth transmission can hide the signal in plain sight. Because an eavesdropper can neither read the data nor detect the existence of the transmitted signal, optical stealth transmission provides a higher level of privacy. A hybrid system which includes both the public channels and stealth channels can effectively provide anonymous communication and defend against traffic analysis.**

***Index Terms*—Optical encryption, key distribution, photonic neurons, optical steganography, amplified spontaneous emission, interference cancellation.**

I. Introduction

THE remarkable proliferation of broadband information technology requires that data be transmitted at high speeds and long distances over fiber optic networks. As with other communication media, fiber optics are subject to security and privacy threats, especially when the network spans large geographic domains encompassing different national interests. Even within the jurisdiction of a single country, treats from both internal and external security attacks are ever-present. Therefore, providing both confidentiality and privacy in today's fiber optic networks is a critical need.

Although confidentiality and privacy can be supported through conventional higher-layer services, these security objectives may be better supported in the physical or "optical layer" by using the unique and ultra-fast properties of optical signal processing [1], [2]. In particular, confidentiality can be supported by optically processing and encrypting the data in real time without generating an electromagnetic signature [1]. Similarly, privacy can be supported by using optical techniques to mask the existence of communications in the optical network, or by stealthily hiding optical signals using the natural physical characteristics of the optical channel.

Different approaches to optical signal processing with fiber-based techniques have been studied by the optics community. These approaches include optical XOR logic encryption [3]–[9], optical code division multiplexing (Optical CDMA) [10]–[16] and optical chaotic encryption [17]–[23]. Optical XOR logic can reach a real-time 20 Gb/s encryption speed. Optical CDMA techniques not only protect the transmitted data but also provide a multiplexing method that enables multiuser sharing of the optical network. Optical chaotic encryption encrypts the transmitted data as noise-like signals, so the eavesdropper cannot digitize the encrypted signal. Without decrypting the data when receiving the optical signal, the eavesdropper is unable to recover the data.

Previously proposed optical signal processing techniques can effectively protect the security and privacy of the data; however, they still have several disadvantages. For example, optical XOR logic encrypts the transmitted data with another data sequence by performing XOR logic of the two data sequences. Because the encrypted data signals remains in digital form [3]–[9], even if the eavesdropper cannot find the correct key, the data can be recorded and recovered using post-processing decryption. Chaos encryption effectively solves this problem, but it requires synchronization between the transmitter and receiver, and the synchronization parameters cannot be directly used as the key for the encryption process [17], [18]. Therefore, a technique having both analog noise encryption as well as parameters that can be used for the encryption key is required.

It is not only desirable to use analog noise-based optical encryption with a suitable key, but it is also necessary to generate and distribute the key. The security level of the system depends strongly on the length of the key and how frequently the key can be changed. Quantum key distribution has been widely studied for this purpose [24], [25], though the stability of quantum key distribution has not yet been demonstrated for practical applications.

In addition to encryption, an alternative for protecting the privacy of the optical network is stealth transmission. Encryption can prevent the data being read by an eavesdropper, while the existence of the signal is still exposed. In some cases, even the exposure of the encrypted data can enable a malicious attack on the system. To hide the existence of the signal, stealth transmission is needed.

Several optical signal processing techniques for privacy are presented in this review paper, including an optical encryption

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technique that protects the transmitted signal with analog noise, a key generation technique based on neuromorphic spike processing, and optical stealth transmission methods that can hide the existence of signals. Both the optical encryption and key generation techniques utilize all-optical signal processing, as discussed in Section II. The principles of optical stealth transmission are introduced in part A of Section III, and the use of optical stealth transmission to defend against traffic analysis is discussed in part B of Section III.

II. Optical Signal Processing

A. Analog Noise Protected Optical Encryption

Interference is undesirable when transmitting and receiving data. However, if the interference can be controlled, its noise-like signature can be used to effectively carry out encryption. In this section, we will introduce a technique for control and cancellation of interference and then discuss how it can be applied to optical encryption.

Interference cancellation techniques are especially important for wireless communication [26]–[28]. If a wireless router transmits and receives signals at the same time, the transmitting antenna generates unwanted interference for the receiving antenna. Because the transmitting antenna is much closer than the source of the signal of interest, the amplitude of interference is usually much larger than the amplitude of the signal. We have previously developed a technique to cancel the interference in which the transmitting antenna is connected internally though a fiber link with the receiving antenna. This is illustrated in Fig. 1, where the fiber link is shown within the dashed rectangle. The fiber link includes two channels with two lasers and converts the electric signals from both the transmitting antenna and receiving antenna into optical signals by intensity modulation [26]. The signal from the receiving antenna contains both the signal of interest and the interference, while the signal from the transmitting antenna only contains interference. The fiber link can invert the signal from the transmitting antenna using optical devices and sum the signals from the two antennas. Since the signal from the transmitting antenna is inverted, it can cancel the interference from the receiving antenna.

The benefit of using the fiber link for interference cancellation is not only that it achieves high speed and real-time processing, but also that it reaches a high cancellation ratio of 30 dB [26]. The challenge for this method is that the phases and amplitudes of the interference in the two channels have to be precisely matched in order to be canceled by each other [26]. If either phase or amplitude is not matched, the cancellation ratio will decrease significantly with the mismatch.

Both the benefit and challenge of this cancellation technique are actually benefits if this technique is applied as an encryption method [29], [30]. The interference noise can serve as analog noise accompanying the transmitted signal. The precise requirement of amplitude and phase matching can be used as the key for the encryption process [29]. The high-speed property of the fiber optic processing method satisfies the requirement of large bandwidth and real time processing of the signal encryption. In our experiment, we have achieved 10 Gb/s encrypted data transmission with real time encryption in a 25 km fiber link

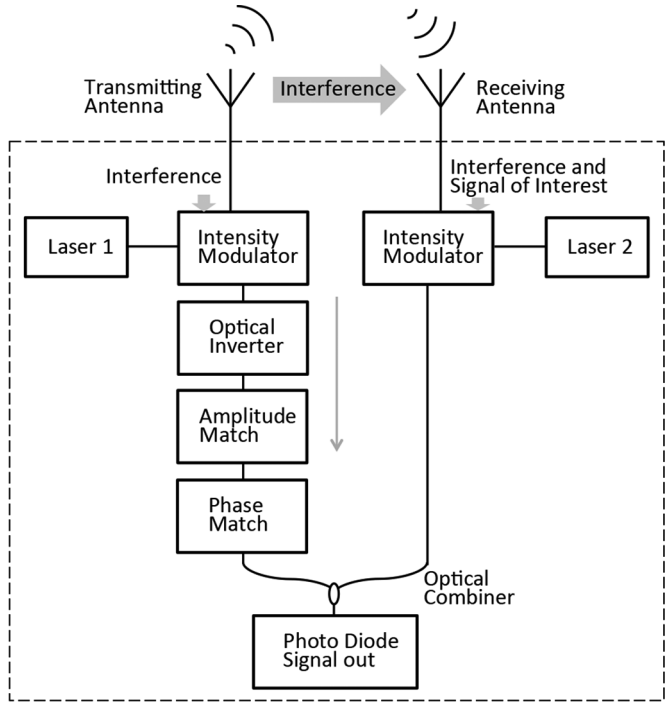

Fig. 1. Schematic diagram of interference cancellation.

[29]. The signal is disguised as natural analog noise, and only by matching both the amplitude and phase of the analog noise between transmitter and receiver can the receiver decrypt the signal. The analog noise shares the same frequency range with the signal, so that the noise cannot be removed by filters. If the eavesdropper cannot find the matching condition, the signal cannot be digitized. If the signal cannot be decrypted when being received, the data is lost and cannot be recovered by a post-processing technique.

The schematic diagram of the encryption system reveals that the transmitter is very similar to the interference cancellation system (Fig. 2). The only difference is that, in the interference cancellation system, the amplitude and phase are designed to be matched, while in the transmitter of the encryption system, the amplitude and phase differences are generated deliberately, so both of the parameters can be used as keys for encryption. The signals in Channel 1 (C_1) and Channel 2 (C_2) can be described as:

$$C_1 = S_1 + N_1. \tag{1}$$

$$C_2 = N_2. \tag{2}$$

where S_1 is the transmitted signal and N_1 is the interference noise in channel 1. N_2 is the cancellation noise in channel 2 [29]. To decrypt the signal, the amplitude and phase of N_1 and N_2 have to be matched at the receiver. Fig. 3 shows the measured eye diagrams of the encrypted signal [29]. When the interference is cancelled by the receiver, a clear eye diagram is received (Fig. 3(a)); when the interference is not cancelled, the signal is noisy and cannot be digitized (Fig. 3(b)).

This technique is also suitable for multi-user wavelength division multiplexing (WDM) systems. For a single user, the encryption system needs two channels with different wavelengths.

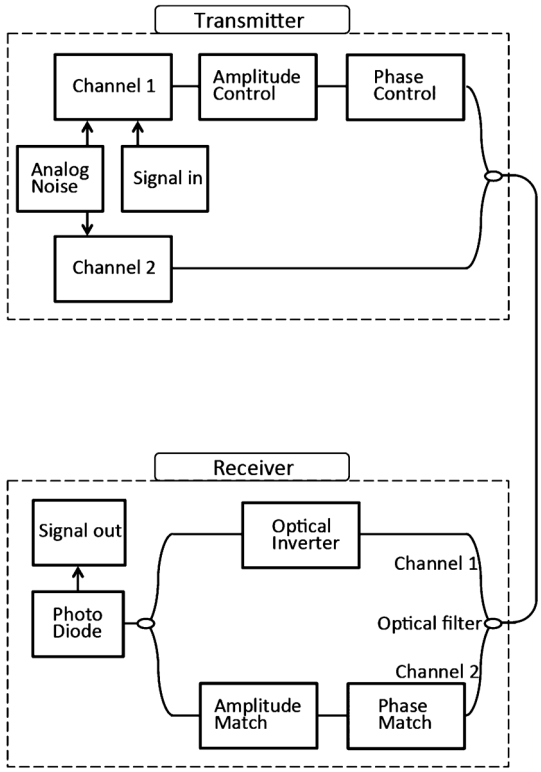

Fig. 2. Schematic diagram of analog noise encryption system.

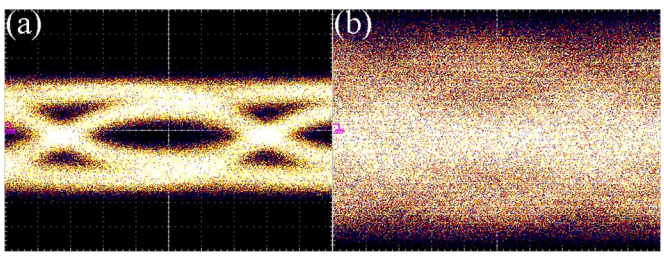

Fig. 3. (a) Eye diagrams of the encrypted signals with the interference cancelled (b) Eye diagrams of the encrypted signals without the interference cancelled. This figure is from [29].

In the case of a multi-user WDM system, the different users deploying multiple WDM channels can share the same channel for carrying the analog noise used for cancellation (Fig. 4). Different WDM channels can use different keys for the encryption, which means different amplitude and phase of the interference noise signal is applied.

The number of channels that share one cancellation channel is limited by the signal-to-noise ratio (SNR) of the cancellation channel, because the power of the cancellation channel is decreased by splitting into multiple users. The decreased power can be compensated by optical amplifiers; however, the SNR of the cancellation signal degrades after being amplified so that the interference in the signal cannot be effectively cancelled. Here we provide a simple model to calculate how many channels are supported. In this model, the input optical power of the cancellation channel is 1 mW and it has 5 dB loss after 25 km transmission. A receiver splits and receives part of the cancellation signal and then uses an EDFA to amplify the signal. To calculate the SNR of the cancellation signal after it is amplified

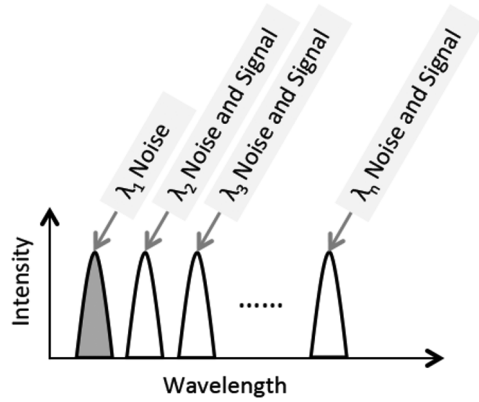

Fig. 4. Analog noise encryption in a wavelength division multiplexing (WDM) system.

by the EDFA, we assume that the noise is dominated by the beat noise between the signal and the ASE generated by the EDFA. In this case, the SNR can be calculated as [31]:

$$SNR = \frac{GP_{in}}{4S_{sp}\Delta f} \tag{3}$$

Where G is the gain the EDFA, P_{in} is the optical input power of the EDFA, Δf is the bandwidth of the receiver (which is 10 GHz in our experiment), and S_{sp} is the spectral density of the ASE noise from EDFA. S_{sp} can be written as:

$$S_{sp} = (G-1)n_{sp}hv \tag{4}$$

where n_{sp} is the population-inversion factor (which is close to 1 for an ideal amplifier) [31] and $h\nu$ is the photon energy. Substituting (4) into (3) and assume $\mathrm{G} \gg 1$, we get:

$$SNR = \frac{P_{in}}{4hv\Delta f} \tag{5}$$

The criterion for judging whether the SNR of the cancellation signal is adequate for decryption is that the noise cannot accumulate to a level that affects the amplitude matching between the interference signal and cancellation signal. The experimental measurement shows that the amplitude matching tolerance in terms of optical power is 0.53 dB as a full-width range, or 0.265 dB as a half width range [29]. This means the optical noise power cannot be higher than $(10^{0.0265}-1)\times 100 = 6\%$ of the optical signal power, or in other words, the SNR in (5) cannot be lower than $(100\%/6\%)^2 = 289 = 25$ dB. The square comes from the fact that the power of the electric current in a photo-diode is proportional to the square of the optical power when calculating SNR. Therefore, the input power of the EDFA in (5) can be calculated as $\mathrm{P_{in}} = 25\ \mu$W, which is the minimum input power of the EDFA at the receiver to achieve effective demodulation. Since the launched optical power of the cancellation signal is 1 mW, it is attenuated to 0.3 mW after 25 km transmission. The cancellation channel can support a maximum of 0.3 mW/25μ W $= 12$ channels. This theoretical analysis provides a direct understanding of which factors may affect the number of channels that can share a cancellation channel.

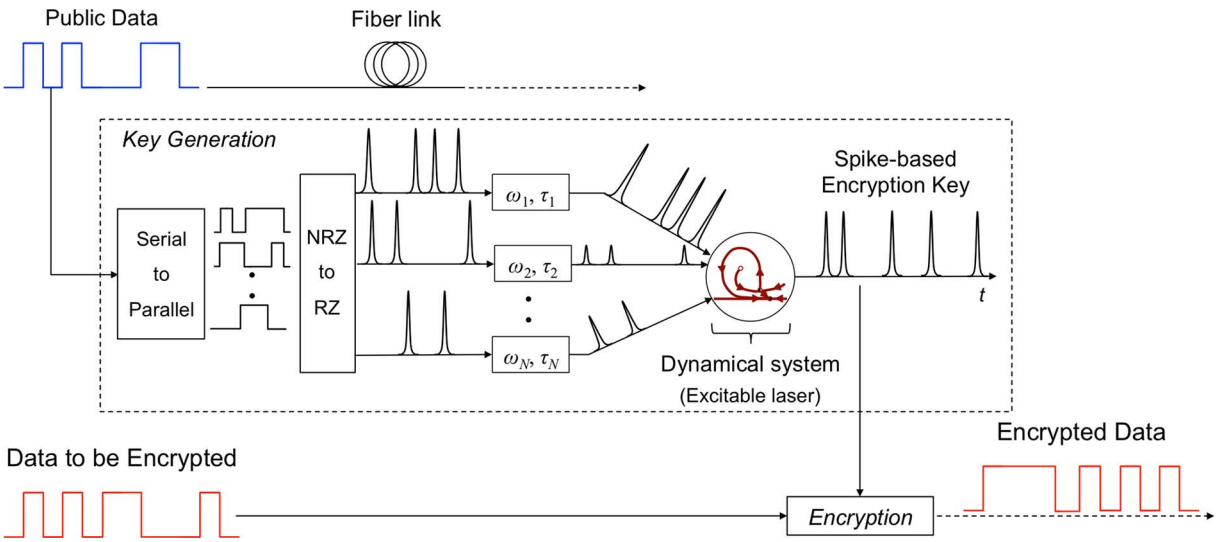

Fig. 5. Schematic diagram of key generation based on neuromorphic spike processing.

B. Key Generation Based on Neuromorphic Spike Processing

Neuromorphic spike processing—a hybrid analog and digital processing technique inspired by neuroscience—is a sparse-based coding scheme where information is encoded as events. It takes advantage of both the bandwidth efficiency of analog computation and the noise robustness of digital computation [32], making the spike-based approach attractive for information processing. Recently, there has been a significant interest in photonic bio-inspired computing [33]–[42] in which the biophysics of neural computation algorithms are exploited in the context of harnessing the high speed, high bandwidth, and low crosstalk available to photonic interconnects [40]–[43] to potentially grant the capacity for complex, ultrafast categorization and decision-making [35]. This could provide a wide range of computing and signal processing applications (e.g., adaptive control, real-time embedded system analysis, and cognitive RF processing).

Here we propose the simple idea of using photonic neuromorphic signal processing for key generation. More specifically, our scheme involves exploiting the public data to generate a dynamically changing spike-based key by employing a nonlinear dynamical excitable system. The generated key can be used for optical encryption. A system is said to be excitable if it is at an attracting equilibrium state, but can be triggered by a small perturbation to produce a large amplitude excursion, after which the system settles back to the attractor in what is called the refractory phase [44]. We recently discovered [45] a close analogy between the dynamics of lasers and those of spiking biological neurons, both of which can exhibit excitability.

In this scheme, the idea is to use the public channel to generate an encryption key that is spike-based (Fig. 5). This is done all-optically by first performing a serial to parallel conversion with a 1:N deserializer [46]. Next, the parallel non-return-to-zero (NRZ) bits are converted to their equivalent return-to-zero format (RZ) [47]. Each of these pulses is weighted and delayed to create spatiotemporal patterns before being spatially summed. The resulting pulse train is input to an excitable laser which performs temporal integration of nearby pulses with a time constant, firing a single spike when the integration state variable crosses a threshold. The resulting spike-based key is dynamically changing at the rate f_{data}/N; where f_{data} is the public date rate. This key can be used for encrypting secret data using either a temporal phase mask [48], [49] or XOR logic [3]–[9]. The data being encrypted would also need to have a bit rate of f_{data}/N. A simple phase-locked loop would be needed for phase synchronization between the spike key (used as a phase mask) and the data being encrypted. The encrypted data cannot be recovered by an eavesdropper without the a priori knowledge of the weights and delays utilized in the dynamical system at the transmitter. In this technique, the key does not need to be distributed on a secret channel. Since the key is generated by applying a nonlinear (non reversible) process using the public data, the public data itself can be used at the receiver to generate the key using a similar dynamical system to decrypt the secret data. Recent advances in photonic device fabrication has made it possible to build such excitable lasers that are very similar; furthermore, the inherent process variations can be compensated for by varying the pump currents to the lasers to obtain near identical dynamics (for a given set of input stimulation). Synchronization at the receiver is an issue, but can be addressed by using an initial training sequence consisting of the packet header for the secret data at the transmitter and receiver. Then the received training sequence can be matched to the public data in a way similar to that used for sync in a bit error rate tester receiver box.

This neuromorphic signal processing technique is aimed for generating and distributing keys for encryption. The public data used for generating keys is known to both the communicating pair and the adversary, however, the adversary does not how to generate the key from the public data. This key generation technique can work with any optical encryption method, such as optical chaotic encryption, temporal phase mask, or XOR logic. Taking optical chaotic encryption as an example, the keys for chaotic encryption technique are the parameters to synchronize the optical amplifier that generates chaos at the transmitter and receivers [17], [18]. These parameters can be generated by the neuromorphic signal processing technique.

The proposed all-optical processing scheme can potentially operate at data rates far in excess of what is capable with electronics and hence is attractive for fast encryption. In general, optical signal processing is also attractive because fiber-based devices neither generate an electromagnetic signature which can be observed from a distance nor can be jammed by external electromagnetic interference, hence posing less side-channel risk than their electrical counterparts.

III. Optical Stealth Transmission

A. Optical Steganography for Stealth Transmission

Privacy ensures individual control of what information may be received or collected and to whom the information may be disclosed [50]. Different from confidentiality, which assures that information is not readable to unauthorized individuals, privacy involves protecting contextual and personal information related to a communication and hiding the existence of the information from unauthorized users. Privacy requires a higher level of protection than confidentiality. Optical stealth transmission or in another words, optical steganography, is an effective way to protect privacy.

Optical steganography was first proposed in 2006 by Wu *et al.* [51]. The objective of optical steganography is to provide a stealth channel that is hidden in both the time domain and the frequency domain. Optical steganography is similar to multimedia watermarking techniques, where a stealth marker is embedded and hidden in the existing audio or image information. The methods to achieve this are different between optical steganography and watermarking. Watermarking techniques use a mathematical method to hide the marker in the public information, while optical steganography hides the stealth signal in the physically existing noise of the optical network [52]–[58].

There are two methods of hiding the stealth channel. The first method is to stretch the optical pulses by chromatic dispersion [52]. In this case, the stealth signals are return-to-zero intensity-modulated data. The stealth bits are carried by optical pulses from a mode locked laser (Fig. 6). The pulses have a narrow width in the time domain and wide spectral bandwidth in the frequency domain. The dispersion components stretch the pulses, so the amplitude of the pulse is low enough and merge into the noise (Figs. 7(a) and 7(b)). In the frequency domain, because the power of stealth channel is usually 15–20 dB lower than the public channel, and has much wider bandwidth, the spectrum of the stealth channel looks like the noise of the public channel (Fig. 7(c)).

The essence of the first method is to stretch the pulse and have the amplitude low enough to mimic the noise, while the second method is different: instead of mimicking the noise, this method directly uses the noise as a carrier [60], [61]. In fiber optic networks, optical amplifiers are widely used that compensate for attenuation but also introduce amplified spontaneous emission (ASE) noise. The ASE noise has randomized phase and degrades system performance by reducing its SNR. However, the property of randomized phase is actually a benefit for stealth transmission. Noise with random optical phase is

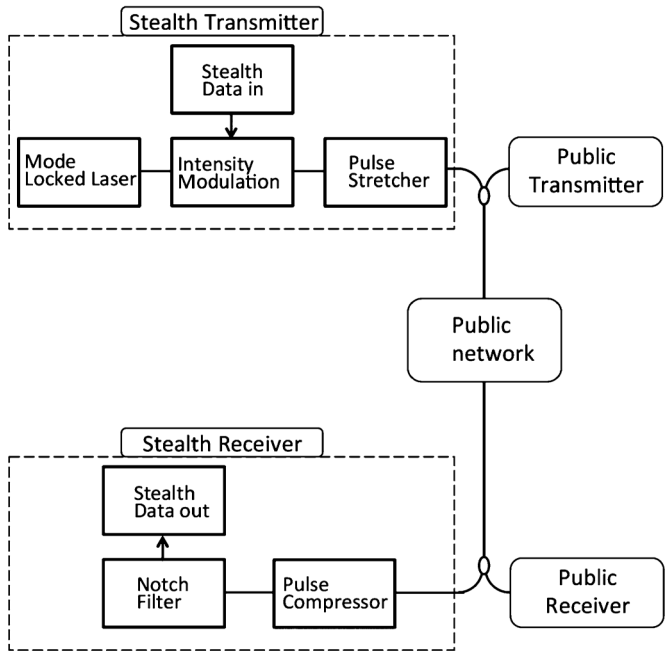

Fig. 6. Optical steganography based on pulse stretching.

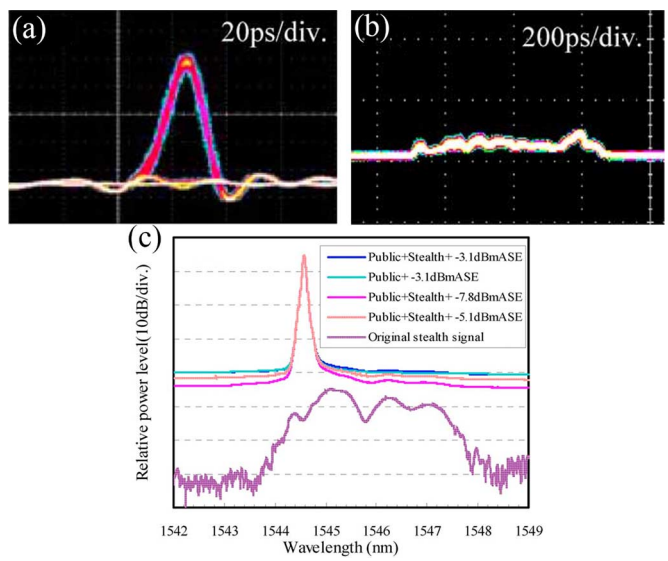

Fig. 7. (a) The stealth signal before being stretched (b) The stealth signal after being stretched (c) The spectra of the public channel and the stealth channel. This figure is from [59].

coherent only within a very short range [62]. In this scheme, the stealth transmitter and receiver form a fiber interferometer (Fig. 8) and the stealth signal is carried by phase-modulated ASE noise. If the optical delay does not match between the transmitter and receiver, constructive interference will not occur, and only ASE noise is received. Only by precisely matching the optical delay can the stealth signal, carried by ASE, interfere with itself and demodulate the data. Therefore, the random phase property of ASE noise effectively hides the signal in the time domain (Figs. 9(a) and (b)). In the frequency domain, the ASE noise covers the entire optical communication band, and the stealth channel carried by ASE has exactly the same spectrum as the original ASE (Fig. 9(c)). Therefore, the stealth channel is also undetectable in the frequency domain.

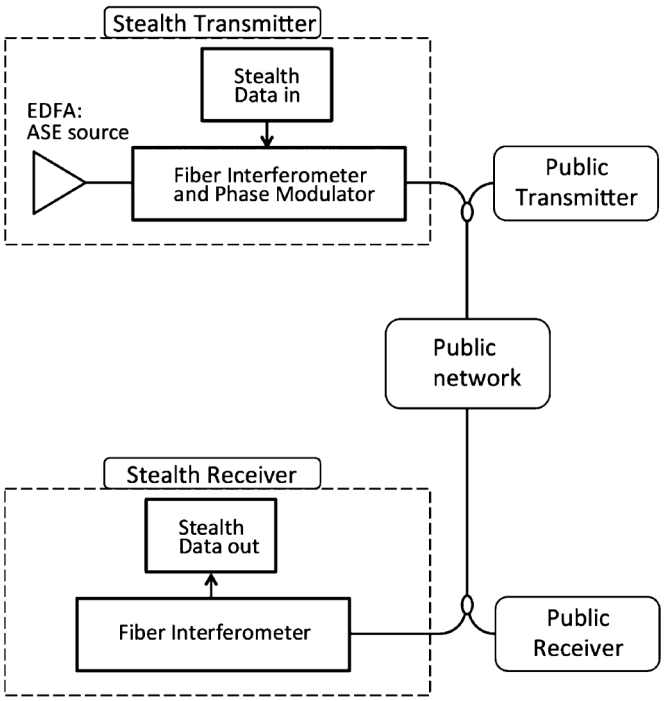

Fig. 8. Optical steganography based on ASE noise (EDFA: erbium doped fiber amplifier; ASE: amplified spontaneous emission).

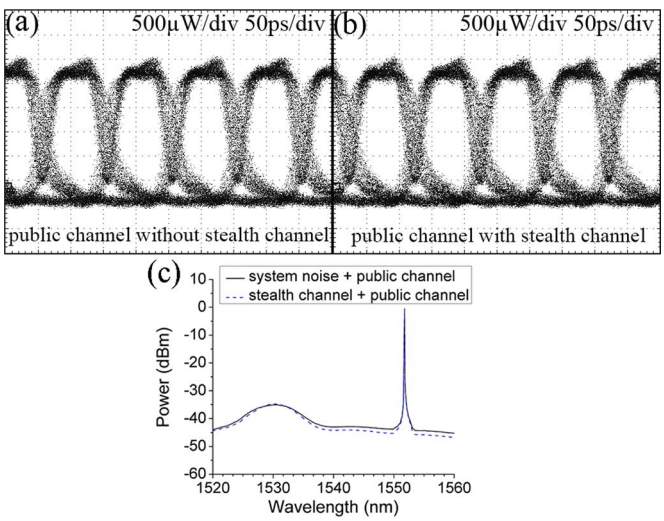

Fig. 9. (a) Eye diagram of public channel without stealth channel (b) Eye diagram of public channel with stealth channel (c) Spectrum of public channel with and without stealth channel. This figure is from [60].

ASE-based steganography uses spontaneous emission to transmit signals, which is fundamentally different from traditional fiber channels. Traditional fiber channels are carried by lasers and the SNR can be increased by increasing the power of the laser [63]. In the case of signals carried by ASE noise, the SNR saturates at a constant when optical beat noise dominates, since both the signal and the beat noise come from the ASE [64]. The constant does not depend on the power of the stealth channel and only depends on the ratio of the optical spectrum bandwidth to the electric bandwidth of the stealth channel, which is also the capacity of the stealth channel [64]–[67]. As a result, the capacity of the stealth channel is limited by the need to maintain the SNR and bit error rate below the forward error correction (FEC) limit.

To enable higher capacity of the stealth channel, wavelength-division multiplexing for the stealth channel has been studied [62]. Instead of the using the entire spectrum of the ASE noise to carry one channel, a band pass filter is used to carry the stealth signal on a portion of the ASE spectrum. The bandwidth of each stealth channel is 1.1 nm and multiple stealth channels can exist in parallel. Another benefit of having the filtered ASE spectrum as the signal carrier is that it adds another layer of security to the system. Before finding the right coherence length, the eavesdropper also needs to find the right spectral range that carries the stealth channel.

Another limitation for ASE-based optical steganography is the speed of changing the key at the transmitter. An optical delay-line can be employed as the key for hiding the stealth channel. Since the eavesdropper may use a scanning technique and find the matching condition; the optical delay length needs to be changed with time. The security level of the system is affected by the rate of change. Optical delays controlled by mechanical devices have dynamic time constants on the order of seconds. To provide a faster changing scheme, a temporal phase mask is applied [48], [49]. The phase mask is implemented with a phase modulator, which can be changed in every stealth bit. The rate of change can be in the order of nanoseconds, nine orders of magnitude faster the changing a mechanical optical delay.

Besides changing the key rapidly, the size of the key space also impacts the security level of a system. Both a phase mask and an optical delay can be used as the key for the stealth channel. The number of available phase mask codes depends on the ratio between the bandwidth of phase mask to the bandwidth of the stealth channel. The ratio is limited by the noise properties of the ASE. In the experiment, the ratio is 16 and the code space is 18,000 [48]. The key space of the optical delays does not have a limit. Because the phase of the ASE noise is completely random, there is no limit on the delay length difference. Besides phase masks and optical delays, dispersion can also be used as the key for hiding the stealth channel [68]. The dispersion can be generated by dispersion compensation fiber, photonic crystal fiber, or chirped fiber Bragg gratings [69], [70]. Since both dispersion and optical delay have to be matched between the transmitter and receiver, they are orthogonal and form a two-dimensional key space [68].

B. Stealth Transmission and Anonymous Communication

Optical steganography hides the signals in plain sight, and has significant potential to protect the privacy of user communications. One important application of optical steganography is to enable the design of anonymous communication systems.

Systems for anonymous communication aim to hide the sender identity from the recipients of the communication, as well as third parties in the network, such as Internet service providers (ISP). Users that desire anonymity include intelligence agencies, law enforcement, whistleblowers, political dissidents, journalists, businesses, and even ordinary Internet users wishing to avoid surveillance.

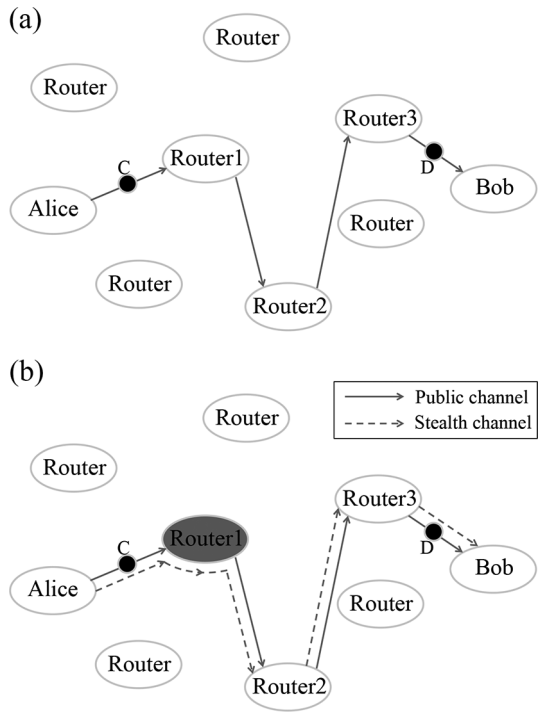

Fig. 10. Comparison of traditional Tor and Steganography assisted Tor (SAT).

We note that today's networks are easily susceptible to traffic analysis attacks that compromise user anonymity [71], [72]. For example, a network adversary, such as a malicious ISP or a router, can eavesdrop on user communications to infer the identity of communicating parties, thus violating user anonymity. Even the use of encryption techniques does not provide anonymity. Encryption only hides the contents of the communications, but does not protect the identity of the communicating parties.

The conventional approach for hiding the identities of the communicating parties is known as layered encryption, or in another words, the "Onion Router" (Tor) [73]–[75]. The Tor network is a deployed system for anonymous communication. If Alice wants to send a message to Bob, Alice chooses a path with routers/proxies (Fig. 10(a)). Layered encryption ensures that each router on the path learns the identity of only the previous router/node and the next router/node. Thus, no single router learns the identity of both the client and the destination. Even if one of the routers or links acts as an eavesdropper, user privacy is still preserved.

While the Tor network serves millions of users, its approach is not effective against traffic analysis. First, an attacker can perform traffic analysis of encrypted communications to learn the size and timings of the transmitted signals, since encryption does not hide the message size or timings. Second, if the eavesdropper can attack point C and D in the network of Fig. 10(b), the comparison and statistical analysis of message size and timing can reveal the correlation between the message flown through link C and link D. Thus, the message transmitter and receiver are exposed, breaking user anonymity.

The system can be effectively protected by optical steganography; in other words, steganography-assisted Tor (SAT). The function of optical steganography is to hide the very existence of signals. Either a certain link in the network can be hidden in the stealth channel or the stealth channel can pass through a router without being detected by the router. If the eavesdropper attacks point C and D, these two links can be hidden in the stealth channel. If the eavesdropper attacks router 1, the stealth channel can bypass router 1. Since the eavesdropper cannot detect the existence of the transmitted signal, he/she cannot do traffic analysis of the signal.

For efficiently deploying the stealth channel in the public network, the bandwidth of the stealth channel has to be considered. Because the capacity of the stealth channels is limited, it may be impractical to hide the entire data stream in the stealth channel. In this case, the stealth channel can hide a portion of messages in the data stream, while the remaining portion traverses the public channel. This approach perturbs the correlation function between the data streams at different links, and eavesdroppers are unable to de-anonymize users via traffic analysis. To qualitatively test the performance of an SAT system, the correlation function between data streams can be calculated as [75]:

$$r(d) = \frac{\sum_i ((x_i - \mu)(x'_{i+d} - \mu'))}{\sqrt{\sum_i (x_i - \mu)^2} \sqrt{\sum_i (x'_{i+d} - \mu')^2}} \tag{6}$$

where x_i is the data packet number measured in the i-th time window of a data stream, μ is the mean of $\{x_i\}$, x'_{i+d} is the packet number measured in the $i+d$-th time window of another data stream, μ' is the mean of $\{x'_{i+d}\}$, and d is the relative time delay between the two data streams. Future work is needed to optimize the scheme of choosing the packets for the stealth channel. The design of the scheme for a SAT network should aim to minimize the correlation function of two data streams in two connected links while consuming minimum capacity of the stealth channel.

IV. Conclusion

We proposed an optical encryption technique based on analog noise cancellation, a key generation method based on neuromorphic spike processing and optical stealth transmission techniques that hide the signals in the pre-existing noise. The proposed optical encryption technique protects signals with analog noise, which cannot be digitized, so without decrypting the signal when receiving the signals, the eavesdropper cannot recover the signal by post-processing techniques. Cancellation of the analog noise requires matching both the phase and the amplitude of the noise, which provides a two-dimensional key space for the encryption process. The optical key generation method generates encryption keys with a neuron spike processing system. The system converts public signals into the keys for encryption, with transmission of the public signals functioning as key distribution. Both optical encryption and key generation techniques process the lightwave signal in fiber-based components and thus do not emit any electromagnetic signature.

Optical stealth transmission enables signal transmission without detection, let alone decryption. Stealth transmission based on ASE noise uses amplifier noise to carry signals. Since this amplifier noise permeates most fiber optic networks, the eavesdropper cannot differentiate between stealth signals

and pure noise with either temporal or spectral domain analysis. In this way, optical stealth transmission (a.k.a. optical steganography) can effectively protect the privacy of optical data communication. Combined with layered encryption (Tor), optical steganography provides anonymous communication and defends the system against traffic analysis attacks.

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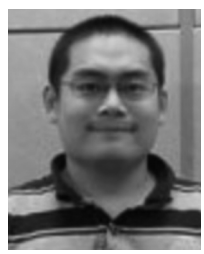

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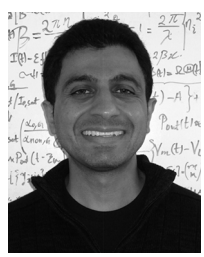

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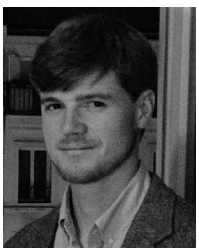

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