Sequence-Coded Coherent Laser Range-Finder with Hundreds of Photons Sensitivity

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Abstract: Coherent detection of a sequence coded laser range finder is demonstrated over fiber. The shot noise limited receiver sensitivity reaches 800 photons, and 0.002 photons per bit. Signals of 250 femto-Watt power are successfully compressed. © 2019 The Authors.

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1. Introduction

Measurements of distances to remote objects are among the most fundamental sensor objectives. Laser range finders are being employed towards that end for decades. Interest in laser range finders increased in recent years, as a basis for light detection and ranging (LIDAR) systems [1]. Such systems provide three-dimensional imaging, and are becoming the sensors of choice towards autonomous driving. The simplest implementation of laser ranging relies on the transmission of isolated, short and intense pulses, the collection of echoes reflected from targets, and measurements of the two-way time-of-flight [1]. However, the optical power of echoes received from long distance is typically very weak: Losses between transmission and reception may reach ten orders of magnitude and more. Isolated transmission pulses must therefore reach high instantaneous peak powers, which restrict the choice of sources, increase the probability of interception by an adversary, or become altogether impractical.

As an alternative to single-pulse transmission, the optical energy may be spread over an extended series of much weaker pulses [2]. Collected replicas of the transmitted sequence are compressed at the receiver into a short virtual pulse, through post-processing correlation with a proper reference waveform [2-4]. Sequence coding has been widely employed in microwave-frequency radars [2]. In recent years, our groups have carried over the concept towards laser range finders [5]. The transmitted signal was intensity-modulated by a carefully constructed unipolar sequence, and simple direct detection was used at the receiver end [3-5]. Measurements were demonstrated up to 1,100 meters distance. However, the performance of the system was limited by additive noise of thee photo-detectors.

In this work, we combine sequence coding with coherent detection of weak coded signals [6]. Interference with a local oscillator generates much larger current in detection of very weak signals, and overcomes additive noise. Sensitivity is limited only by the shot noise associated with the local oscillator power [7]. We experimentally demonstrate that successful sequence compression requires total signal energy that is equivalent to only several hundred photons. Performance is determined by the integrated signal enery, and it is independent of measurement duration. Compression was achieved even when the average collected energy per code symbol was only 0.002 of the photon energy. Compared with our previous work on sequence-coded range finder with incoherent, direct detection, sensitivity measurement durations are reduced by a factor of 50,000. The system can be used for ranging over tens of kilometers in free space, or in distributed optical fiber reflectometry at tens of kHz rates.

2. Principle of operation and sensitivity analysis

The instantaneous power of the transmitted signal is repeatedly modulated by a series of pulses of duration T:

$$P(t)=P_{in}\sum_{n}a_{n}\mathrm{rect}\left[\left(t-nT\right)/T\right]. \tag{1}$$

Here P_{in} represents constant power in Watts, t stands for time, $\mathrm{rect}(t)=1$ when $|t|\le 0.5$ and equals zero elsewhere, and a_n are the elements of a unipolar Legendre sequence L_N [4,5]. Legendre sequences are available at lengths $N=4k-1$, where k is an integer and N is a prime. Element a_n, $n=1\ldots N$ in the sequence equals 1 if an integer l exists such that $l^2 \bmod N = n \bmod N$. If no such integer exists, then $a_n=0$ instead [4,5]. The sequence is replayed every N bits. The Legendre sequence is compressed through cross-correlation with a bipolar representation $\tilde{L}_N$ of elements $\tilde{a}_n = 2a_n - 1$: $\tilde{a}_n = 1$ when $a_n = 1$, but $\tilde{a}_n = -1$ if $a_n = 0$. The periodic cross-correlation between L_N and $\tilde{L}_N$ is perfect, in the following sense: It assumes peak values of $(N+1)/2 \approx N/2$ at offsets that are integer multiples of N, with sidelobes of exactly zero everywhere else. Hence, in the absence of noise, compression of unipolar Legendre sequences in range-finder applications does not introduce false targets. However, noise in any real-world system would introduce non-zero ranging sidelobes.

Let us denote the temporally-averaged optical power of the collected signal at the receiver end as P_{S}, so that the instantaneous signal power equals $2P_{\mathrm{S}}$ when $a_n = 1$ and zero for $a_n = 0$. The receiver consists of four balanced detection modules, for phase and polarization diversity. The photo-current at the output of each module is proportional to the beating pattern between a single polarization and quadrature component of the received signal field, and the local oscillator field. Consider the in-phase quadrature component along one polarization first. We assume that shot noise associated with a sufficiently strong local oscillator is the dominant noise mechanism. The signal-to-noise ratio (SNR) in the detection of a single logical '1' bit is $(2\eta P_{\mathrm{S}})/(h\nu \cdot \Delta f) \times \cos^2\theta \cos^2\varphi$, where $h\nu$ is the photon energy, η denotes the internal efficiency of the detectors, and $\Delta f \approx 1/T$ is the measurement bandwidth. The term $\cos\theta$ is the projection between the normalized Jones vectors of signal and local oscillator fields, and φ is the optical phase difference between the two fields.

The signal is detected over an integer number M repetitions of the N bits-long sequence. Only half of the MN bits carry power, whereas noise accumulates over all of them. The SNR following cross-correlation is given by:

$$\mathrm{SNR}_{\mathrm{Corr}} = \frac{MN\eta P_{\mathrm{S}}}{2h\nu \cdot \Delta f}\cos^2\theta\cos^2\varphi \approx \frac{\eta P_{\mathrm{S}} MNT}{2h\nu}\cos^2\theta\cos^2\varphi = \frac{\eta P_{\mathrm{S}} T_{\mathrm{Meas}}}{2h\nu}\cos^2\theta\cos^2\varphi = \frac{\eta}{2} N_{\mathrm{Phot}}\cos^2\theta\cos^2\varphi . \tag{2}$$

Here $T_{\mathrm{Meas}} \equiv MNT$ is the ranging measurement duration, and $N_{\mathrm{Phot}} \equiv P_{\mathrm{S}} T_{\mathrm{Meas}}/h\nu$ is the energy of the collected signal in equivalent number of photons. Similar expressions can be reached for the quadrature-phase component, and for both phase components of the orthogonal polarization. Since polarization and phase are arbitrary, all four output ports of the coherent receiver must be examined simultaneously. We represent each peak in the compressed sequence by its maximum value among all four outputs. At the best case, in which the signal is fully aligned with one polarization and phase component, the SNR of the processed trace reaches a maximum of $\eta N_{\mathrm{Phot}}/2$. At the worst case, when the signal is equally split among the four terms, $\mathrm{SNR}_{\mathrm{Corr}}$ is four times lower.

The quality of the processed trace is expressed in terms of the peak-to-sidelobe ratio (PSLR): the power ratio between the compressed correlation peak and the highest noise-induced sidelobe. The PSLR depends on $\mathrm{SNR}_{\mathrm{Corr}}$ and on the code length N [5]. For sequences that are several thousand bits long, we found that the PSLR is lower than $\mathrm{SNR}_{\mathrm{Corr}}$ by approximately a factor of 15 [5]: $\eta N_{\mathrm{Phot}}/120 \le \mathrm{PSLR} \le \eta N_{\mathrm{Phot}}/30$. We arbitrarily set the criterion for successful compression as a PSLR of at least 10. This requirement corresponds to a minimum number of signal photons between 300 and 1,200, depending on the projections on polarization and phase components. Note that this integrated energy requirement does not vary with measurement duration. The necessary number of photons may be degraded by detector inefficiency and by excess losses in the receiver hardware.

3. Experimental setup and results

Coherent detection and compression of encoded sequences was demonstrated in a proof of concept experiment over fiber. Schematic illustration of the experimental setup is shown in Fig. 1(left). Light from a coherent fiber laser source at 1550 nm wavelength (NKT, 5 kHz linewidth) was split in a 90/10 fiber-optic coupler. The continuous wave at the 90% port of the coupler was used as the local oscillator and connected to the appropriate port of a Kylia COH-28 coherent receiver. Light at the 10% branch passed through an electro-optic amplitude modulator, driven by the output voltage of an arbitrary waveform generator. The instrument repeatedly generated a 4003 bit-long Legendre sequence with 1 ns symbol duration, which corresponds to 15 cm ranging resolution in fiber. The modulated waveform was connected to the input signal port of the coherent photo-receiver through a variable optical attenuator. The input signal power P_{S} was monitored for each acquisition using an optical power meter. The excess loss of the receiver was 1 dB, and the internal efficiency of the balanced detectors used was 90%. The outputs of the four detectors were sampled by a four-channel digitizing oscilloscopes over different durations T_{Meas}. The sampled traces were correlated with a bipolar Legendre reference sequence through off-line digital signal processing, and the PSLR was noted for each compressed trace.

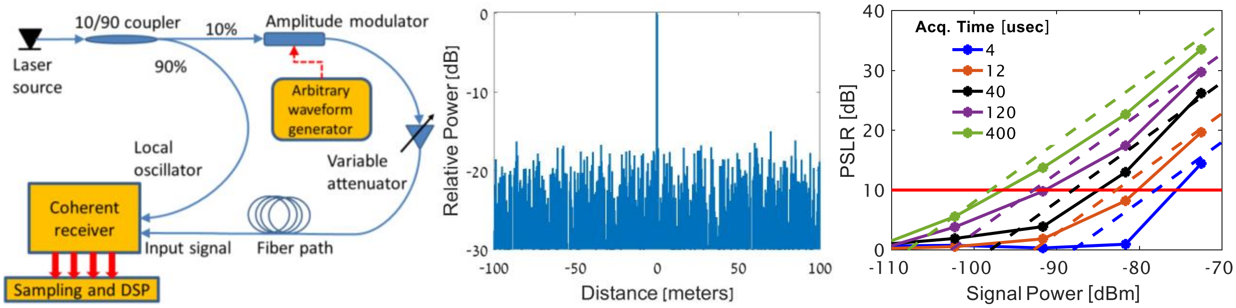

Figure 1. Left: Schematic illustration of the experimental setup. DSP: digital signal processing. Fiber paths are noted in blue, electrical cables in red. Center: An experimental signal trace modulated by a repeating 4,003 bits-long Legendre sequence, following coherent detection and post-processing compression. The average optical power of the collected signal was -92 dBm (630 femto-Watts), and the acquisition duration was 400 μs. A main peak represents the propagation delay between transmitter and receiver (presented arbitrarily as distance zero). The power ratio between the peak and the highest noise-induced sidelobe is 14 dB. Right: Calculated Peak-to-sidelobe ratios as a function of the collected signal power. Analytic predictions are shown in dashed lines. Experimental data is presented in solid lines, circular markers. Colors represent different acquisition durations (see legend). The threshold condition for successful compression is a peak-to-sidelobe ratio of 10 dB (horizontal red solid line).

Figure 1(center) shows a compressed waveform, detected with P_S = -92 dBm (630 femto-Watts) and T_{Meas} = 400 μs. A clear peak is observed (presented arbitrarily at distance zero). The width of the peak is 15 cm as expected. The PSLR of the processed signal is 14 dB, above the required minimum threshold. Figure 1(right) shows the calculated PSLR as a function of P_S. Results are shown for different durations T_{Meas} (see legend). Each combination of (P_S, T_{Meas}) is represented by the best PSLR among the four output ports of the receiver, as discussed above. The PSLR improves with signal power and acquisition duration as anticipated, and each level of PSLR is associated with constant collected signal energy $P_S T_{\text{Meas}}$. Analytic predictions for the optimistic upper bound $\theta = \varphi = 0$ are presented as well. The experiment is in very good agreement with the model. The measured sensitivity is 0.1 femto-Joule, or the equivalent to 780±100 signal photons. Considering the efficiency and losses of the receiver, the predicted best-case sensitivity corresponds to 430 photons. The 2.4 dB difference is well within the uncertainty associated with polarization and relative phase projections.

The average power of the weakest signal we could process with incoherent detection of the same sequence was 30 pico-Watts (-75 dBm). A measurement time of 0.2 seconds was necessary at that experiment. With coherent detection, a signal of the same power was successfully compressed with an acquisition duration of only 4 μs, or 50,000 times shorter. Moreover, signals as weak as 250 femto-Watts (-96 dBm) were compressed successfully with a 400 μs-long acquisition duration. In the latter trace, the average collected energy per code bit was equivalent to only 0.002 of the photon energy. The sequence cannot possibly be recovered with direct detection at these energy levels. Coherent receivers that are integrated on-chip are being rapidly developed towards data communications. Range finder applications can benefit from such progress. The proposed system is suitable for ranging over tens of km in free space. The high sensitivity is also useful for distributed optical time domain reflectometry over fibers, with high spatial resolution and fast acquisition, towards high-rate distributed acoustic sensors [8,9].

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