Communication Channel Optimization

The Electromagnetic Concepts Crew (EMC2) has pioneered work in high-speed free-space optical communication (FSOC) without the need for correction for atmosphere induced wavefront distortion (atmospheric scintillation). In that process, we have developed and demonstrated a novel and disruptive receiver technology. This advancement benefits all FSOC (a rapidly growing multi-billion-dollar market) in the ground, air, underwater, and space domains for both government and commercial applications. While the key advantages of the approach have been proven, the overall multiparameter performance optimization has not been addressed. A mathematical optimization and simulation across relevant parameters are sought under this request.

Mathematical description of the problem

The block diagram of the communication channel that uses Binary Phase-shift keying (BPSK) and the novel Raytheon receiver is depicted in Figure 1. The channel comprises Transmitter, Demodulator, and Detectors & Decoder. The Signal is a pseudo-random sequence of zeros and ones.

The goal of the task is to optimize an Encoder, optical-resonator-based Demodulator, and decoding algorithm of the QPSK Free Space Optical channel to achieve required Bit Error Rate (BER) with the lowest possible transmitter power. Higher order protocols (n-PSK, QPSK, etc.) should be studied next.

The elements that are subject to optimization are highlighted in yellow in Fig. 1. A semi-analytical solution for BER given the noise levels and the parameters of the Demodulator and Encoder exists. However, in itself, the existing model is not enough for optimization of the communication channel without expanding enormous amounts of computational resources. The system is non-linear and bandwidths of the transmitter and the receiver, as well as the parameters of the Encoder such as the rate of the phase change play a pivotal role in the channel optimization.

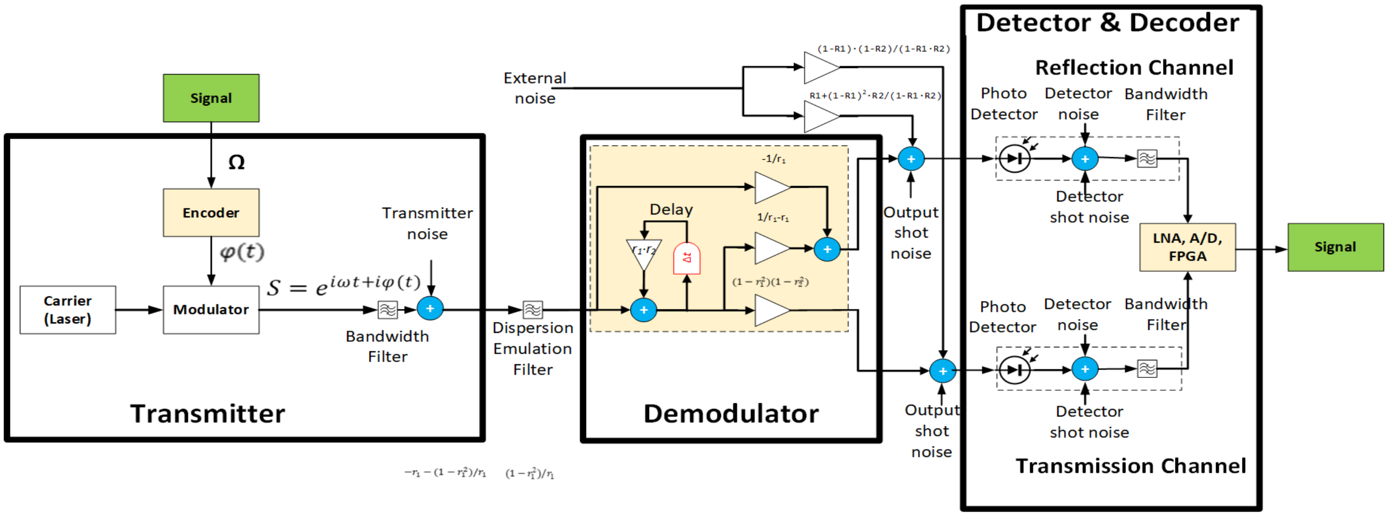


Figure 1. Block diagram of the communication channel. To simplify notation R1= r_1^2 and R2= r_2^2 where $r_1, and\ r_2$ are parameters of the demodulator.

Transmitter comprises Encoder, Carrier Generator, and Modulator. A Bandwidth filter is added to account for finite bandwidth of both Encoder and Modulator. Carrier generator (laser) produces a pure tone $Ae^{i\omega t}$. The Encoder coverts the Signal into phase values $\varphi(t)$ that are used by the modulator; the nominal baud rate is Ω. The modulator convers pure carrier tone into a phase modulated signal

$$S(t) = A \cdot e^{i\omega t + i\varphi(t)}$$

Since the modulator is not ideal, a bandwidth filter and noise sources are added to the block diagram. The algorithm for converting Signal into $\varphi(t)$ (within BPSK domain) requires optimization.

Demodulator is a physical device[1]; its parameters are defined in Figure 2. There are three parameters that define the Demodulator: $\Delta t, r_1, and\ r_2$. Most of the time $r_1 \cong r_2 = 0.7 \pm 0.2$. Demodulator comprises one delay line (Δt) and four gain modules with different gain values related to $r_1, and\ r_2$. The value of Δt is not synchronized with the baud rate[2]: $\Omega \cdot \Delta t < 1$. Typically, the best results are achieved around: $\Omega \cdot \Delta t = 0.7$. Demodulator is often "tuned", meaning that $\omega \cdot \Delta t/2\pi$ is integer. Both $\omega \cdot \Delta t$ and $\Omega \cdot \Delta t$ may vary in time. The value of $\omega \cdot \Delta t/2\pi$ may deviate from the "tuned" state by as much as 10%, meaning $|\{\omega \cdot \Delta t/2\pi\}| < 0.1$. The bandwidth of the demodulator elements is nearly infinite[3].

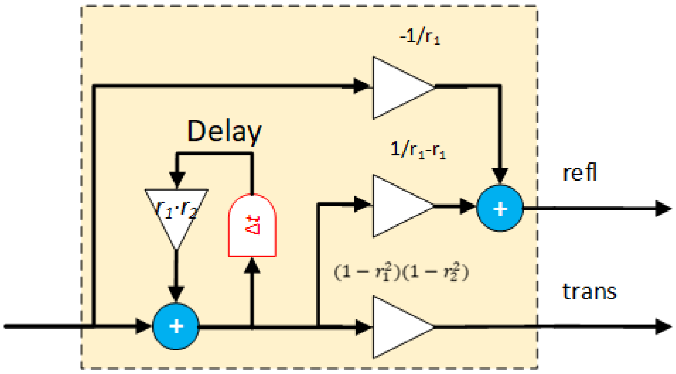
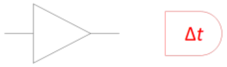


Figure 2. Block diagram of the demodulator. Demodulator has one input and 2 outputs. The latter are labeled transmission and reflection.

Gain and time delay elements:



The two outputs of the Demodulator are labeled as Reflection and Transmission channel. They can be used separately or together to decode the transmitted signal.

An element "Dispersion Emulation Filter" is placed between Transmitter and Demodulator. This filter simulates the "atmospheric scintillations", i.e., the fact that fractions of the transmitted signal are delayed with respect to each other when they reach the Demodulator. It turned out that the proposed Demodulator is insensitive to typically observed scintillations; the "Dispersion Emulation Filter" block is left for completeness.

---

[1] Raytheon owns more than 60 patents covering the structure and the applications of this device. It is an optical resonator, typically, an etalon.

[2] A resonator that satisfies both $\{\omega \cdot \Delta t/2\pi\}| \cong 0$ and $\Omega \cdot \Delta t \cong 1$ works but it is very sensitive to scintillation. The case $\Omega \cdot \Delta t > 1$ has not been studied.

[3] The demodulator operates in optical domain; its bandwidth is in hundreds of THz; communications are in the GHz domain.

Decoder comprises two detectors (labeled photodiodes) that detect square of the absolute value of the signal amplitude[4] as well as two bandwidth filters, one for each channel. Detector output is segregated by a threshold detector and assigned a value of one or zero. An algorithm within a block labeled FPGA produces the recovered signal.

---

[4] Unlike electrical detectors that detect signal value, photodetectors detect square of the amplitude and ignore the phase.