An Adaptive Data Rate Controller (ADRC) for the Through Cloud, Undersea Laser Communications Channel
Roger Stokes, Mark Bermal, Chris Griffith, Randall Blair, EJ Marttila & Greg Mooradian
QinetiQ North America, 7545 Metropolitan Dr, San Diego 92108 USA.

The decades-old VLF radio system used to communicate with submerged submarines is limited to a few 10’s of bits per second, and the submarine must surface to respond. If radio cannot be used for reasons of covertness, the submarine is silenced.

QinetiQ North America (QNA) is developing for DARPA an Adaptive Data Rate Controller (ADRC) for a Submarine Laser Communications (SLC) system utilizing wavelengths in the blue-green window of seawater. This SLC system (Figure 1) can link a submarine at speed and depth with an aircraft above the clouds at data rates up to megabits per second during both day and night. The high peak power and monochromaticity of a laser, along with a very narrow-band optical filter, significantly improves rejection of solar background, and thus maximizes communication depth.

The optical characteristics of clouds and seawater were investigated in the 1980’s by Mooradian et al, finding that multiple scattering in optically thick clouds is the dominant pulse broadening effect by several orders of magnitude.

The data rate depends on the degree to which optical pulses are broadened: (1) Optically thick cloud increases the received pulse width, the maximum data rate that can be encoded must decrease (depending upon the chosen modulation format) as the laser transmitter pulse repetition frequency (PRF) decreases. (2) During the day, optically thick clouds broaden the received pulse, requiring a longer integration time to collect all of the received signal (i.e., reducing the received signal-to-noise ratio (SNR) by “pulse stretching” as well as “attenuation”) To close the link with the required SNR, the laser transmitter PRF is going to have to be reduced to achieve the required increase in energy/pulse. This, in turn, reduces the SLC data rate. In practice (and counter intuitive), factor (2) can cause a much larger reduction in achievable data rate than factor (1).

Absorption of the optical pulse is caused almost entirely by the turbidity of seawater. Photons scattered out of the beam in water, even at very small angles, are almost all absorbed rather than being re-scattered back into the beam. So long as the beam intensity is sufficient, data rates of gigabits per second are possible at ranges of 10’s of meters.

There is almost no absorption in clouds. The reduction in solar background under cloud cover (typically less than 10 dB even in thick clouds) is almost entirely due to multiple scattering leaking out from the top of the cloud layer. Photons in the cloud can be scattered many hundreds of times, leading to significant broadening of the optical pulse.

The impulse response due to cloud broadening can be represented as a modified gamma function
\[ y(t) = C t e^{-kt} \]
where \( k = 2.45/\text{Pulse Width (FWHM)} \) and \( C \) is a constant. The amount of pulse stretching is a function of \( \tau \) (the optical depth of the cloud) and \( T \) (the physical thickness of the cloud). Typical values of \( \tau \) in the marine environment vary between 0 for no cloud cover to 30 for heavy overcast. The amount of pulse stretching is less than 250 ns for \( \tau < 6 \) and \( T = 200 \text{ m} \), rising to > 10 \( \mu\text{s} \) for \( \tau = 30 \) and \( T = 1 \text{ km} \).

In an SLC system, information is encoded using pulse position modulation (PPM). The frame time is the inverse of the average laser pulse repetition frequency (PRF), and is divided into \( 2^m \) slots of equal width, where \( m \) is the number of bits per PPM symbol. For example, by placing the laser pulse in one of 32 slots within a frame, \( m = 5 \), so each laser pulse can transmit 5 bits of information.

A sequence of PPM frames are transmitted, each encoding one PPM symbol. PPM symbols are grouped into blocks for forward error correction (FEC), with all PPM symbols in a block having the same frame time and \( m \) value.

PPM data rates in kilobits per second (kbps) are shown in Table 1 for PPM frames with \( m \) between 4 and 10. A fiber-based laser with a variable PRF and a fixed \( m \) occupies a column in this table, whereas a Q-switched crystal laser with a fixed PRF and a variable \( m \) occupies a row.

Typical deployed SLC systems will have 2 laser modules for redundancy. When the maximum energy per pulse is required (e.g., daytime with thick clouds), they will be triggered simultaneously (e.g.,
the 5-bit column in Table 1. If SNR permits, they can be triggered sequentially, reducing \( m \) by one, doubling PRF for the same amount of cloud broadening, and greatly increasing the achievable data rates (e.g., the 4-bit column in Table 1).

| PRF (kHz) | Bits per PPM symbol \( m \) |
|----------|---------------------------|
| 0.125    | 4                         |
| 0.25     | 6                         |
| 0.5      | 7                         |
| 1        | 8                         |
| 2        | 9                         |
| 4        | 10                        |
| 8        | 11                        |
| 16       | 12                        |
| 32       | 13                        |
| 64       | 14                        |
| 128      | 15                        |
| 256      | 16                        |
| 512      | 17                        |

Table 1  PPM data rates in kbps

Averaging the SNR estimates for 100-200 PPM frames gives an SNR accurate to around 0.5 dB, which is used as an input to the ADRC algorithm.

Figure 2 Transmitted and Received Pulses

Figure 2 shows the received PPM pulse for a PRF of 4 kHz with \( m = 5 \) (a slot width of 7.8 \( \mu \)s) and cloud broadening of 5 \( \mu \)s. The received pulse is the convolution of the transmitted pulse and the cloud broadening impulse response. To avoid inter-slot interference (ISI) the transmitted pulse is always less than or equal to half a slot in duration.

After passing through the optical filter, the received pulse is detected by an optical detector and digitized for processing by the PPM demodulator. The received PPM pulse may be nearly optimally demodulated with a triangular matched filter (e.g., by two cascaded CIC filters with equal delays).

The slot with the largest magnitude \( s \) determines the returned symbol value, and the variance \( \sigma^2 \) of the other slot values \( x_i \) (which have no signal) determine the noise, to give the SNR:

\[
\text{SNR} = \frac{s^2}{\sigma^2} = \frac{s^2}{[\text{mean}(x_i^2) - [\text{mean}(x_i)]^2]}
\]

Figure 3  Symbol Error Rate (SER) prior to FEC

As shown in Figure 4, Ethernet frames undergo Reed-Solomon FEC to reduce the BER of the link to \( 10^{-6} \) or better, allowing network protocols to operate efficiently. Each Reed-Solomon block also carries a side-channel for exchanging link control information from one end of the link to the other.

The ADRC controller operates on the principle of maximizing the data rate while maintaining a safe link margin, using the SNR estimates from a set of matched filters and the symbol error rate from the Reed-Solomon decoder to determine the changes to PRF and \( m \) required from the far-end ADRC controller, which updates them for transmission at the next Reed-Solomon block boundary. In this way, as cloud conditions and submarine depth change, the achievable data rate increases or decreases to match.