

# In-band optical frequency domain reflectometry in PONs

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**Abstract:** We present the novel concept of using data patterns as the driving signal for optical frequency domain reflectometry in PONs. Algorithms that generate the data patterns are developed, and the technique is confirmed through simulation.

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## 1. Introduction

Passive optical networks are rapidly becoming the dominant mode of truly broadband access around the world. Part of the attractiveness of PON systems is their easy maintenance, due to the presence of active electronics at both ends of the fiber. The electronics offer the chance to instrument the network with a variety of performance monitoring and fault detection systems. This allows the network operator to preemptively diagnose and repair troubles, potentially even before the user notices the problem.

In the case of a fiber fault, it is very useful to have an estimation of the location of the trouble. The classical solution is to use an optical time domain reflectometer (OTDR). It is desirable to build this capability into the optical line equipment, so that the OTDR function is available without manual intervention. This saves labor costs, and it offers the possibility of performing the OTDR test as a part of normal preventative maintenance. However, classical equipment approaches have proved to be too costly for such integration.

The idea of reusing the data transmitter as the OTDR source has been promoted recently [1]. In the upstream direction of a PON, the naturally bursty transmissions of the optical network units (ONUs) are easily adaptable as OTDR pulse or edge excitation [2]. In contrast, the downstream transmission of the optical line terminal (OLT) is continuous, and precludes the simple application of OTDR techniques. Prior work has studied the use of a low level and low frequency sinusoidal modulation superimposed on the downstream data signal. These signals are then used to implement an optical frequency domain reflectometry (OFDR) measurement.

While the superimposed sinusoidal signal scheme preserves the line format sufficiently to support existing receivers, it suffers from several drawbacks. First, the transmitter driver is no longer a digital circuit, but must become analog in nature, with the concomitant problems that arise from this. Second, the OFDR signal must be small in amplitude relative to the data signal, typically only 10% of the optical amplitude. Third, the frequency of the modulation must remain below the low-frequency cutoff of the receiver circuits, or the digital signal will be impaired. So, for all these reasons, a better alternative is desirable.

## 2. Measurement concept

The basic idea is to use data patterns themselves to create the desired sinusoidal excitation signals. A similar concept was introduced as a means to shape the digital spectrum to avoid Raman impairments in PON systems [3]. In the present application, a data pattern can be designed such that most of its energy is concentrated in a particular electronic frequency. The simplest example of this is the digital pattern 101010, which has its energy centered at one half of the bit rate. The synthesis of suitable patterns is described in the next section, but in this section we will illustrate how such patterns can be used to produce an OTDR measurement.

Fundamentally, what we wish to measure is the reflectance of the PON as a function of distance away from the OLT. The apparatus of the system is shown in Fig. 1. The OLT transmitter is under the control of the PON media access control (MAC) device. This device is responsible for forming the PON line format and encapsulating the downstream user data into this format. During a measurement, the MAC device applies the special data pattern to the transmitter, while queuing whatever user data arrives for transmission after the pattern is finished. The OLT transmitter launches its signal into the PON, which will then reflect some part of this signal back to the OLT, where it is captured by a receiver. This signal is then processed using a heterodyne electronic detector circuit, which uses synthetic sinusoids generated by the MAC device as its local oscillator signals.

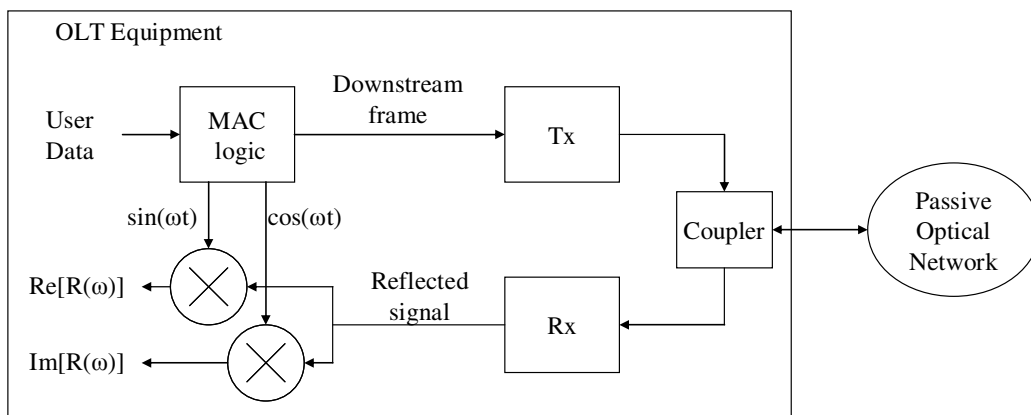


Fig. 1. OFDR implementation

The outputs of the detector circuit then give us the in-phase and quadrature RF components of the reflected signal. These components are related directly to the real and imaginary components of the Fourier transform of the PON reflectance function. The transform is measured at each frequency in turn. The sampled frequency-domain function can then be Fourier transformed into the desired reflectance as a function of distance.

The strength of the reflected signal is typically very small, and this is often not helped by the fact that the reflection receiver is not optimally coupled to the fiber (for reasons of cost, a 10% passive optical coupler is often used). Therefore, some way of increasing the signal-to-noise ratio is required. Because this OFDR scheme uses a heterodyne detector, the effective bandwidth of the measurement can be made quite narrow, limited only by the duration of the measurement. This reduces the effective noise power. And, of course, the stimulus signal is very nearly 100% of the available transmitter power. Beyond that, multiple observations of the same reflection frequency can be averaged numerically.

### 3. Data pattern generation and simulation

The data pattern choice is the key issue with this technique. Simple long-period square wave patterns are not suitable, because a) they don't concentrate energy all in one frequency, and b) they would cause the transmission system to fail. Generating the best pattern can be understood in a step-by-step design pattern. First, the basic desired sine wave is approximated using a delta-sigma technique, where each transmitted bit is set based on the current function augmented by the error from the previous bit. The error from the current bit is then passed on to the following bit. This is illustrated in Fig. 2a. Second, we must maintain the consecutive identical digit (CID) requirement of the line protocol, by forcing bit transitions when necessary. These forced bits introduce additional errors in the delta-sigma process, but that algorithm works to resolve them as quickly as possible. This improved pattern is shown in Fig. 2b.

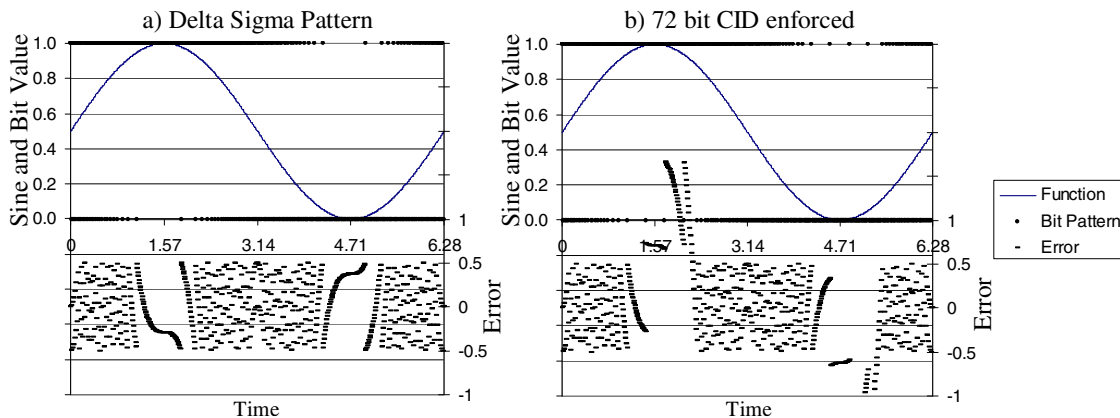


Fig. 2a-b. Data patterns that approximate a sine wave, with residual error functions

The pattern can be improved further, by enforcing the line framing rules. For example, in G-PON, the GEM frame has a maximum length, so a GEM header must be inserted every 4096 bytes to produce a valid stream. Finally, in G-PON every 125  $\mu$ s a G-PON TC-layer physical control block (PCB) pattern must be sent. Each of these additional forced patterns introduces some error in the approximation of the sine wave, but the total power fraction of the errors is quite small ( $<0.1\%$ ).

The total measurement system has been simulated numerically, the results shown in Fig. 3. These graphs show a typical OTDR trace expected from a fiber that is well behaved and exhibiting only Rayleigh scattering. The deviation from the theoretical curve is quite small, and the impairment due to the enforcement of line system requirements (CID maximums and protocol structures) is quite modest. This demonstrates that the use of special data patterns for OFDR stimulus is quite feasible, and has distinct advantages over the prior art.

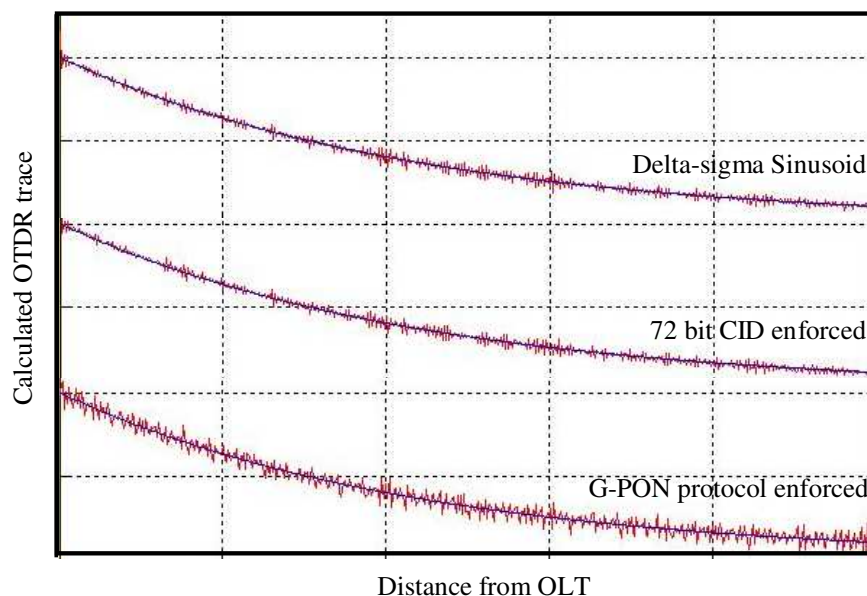


Fig. 3. Numerically simulated OTDR traces using a range of stimulus patterns

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