Hybrid Coding Technique for Pulse Detection in an Optical Time Domain Reflectometer

S. SHEIKH MUHAMMAD [1], Haleema MEHMOOD [2], Anwar NASEEM [2], Aun ABBAS [2]

[1] National University of Computer and Emerging Sciences (FAST-NU), Lahore, Pakistan
[2] Lahore University of Management Sciences, Sector U, DHA, Lahore Cantt, 54792, Pakistan

sm.sajid@nu.edu.pk, haleema.mehmood@lums.edu.pk, anwar.naseem@lums.edu.pk, aun@lums.edu.pk

Abstract. *The paper introduces a novel hybrid coding technique for improved pulse detection in an optical time domain reflectometer. The hybrid schemes combines Simplex codes with signal averaging to articulate a very sophisticated coding technique that considerably reduces the processing time to extract specified coding gains in comparison to the existing techniques.*

The paper quantifies the coding gain of the hybrid scheme mathematically and provides simulative results in direct agreement with the theoretical performance. Furthermore, the hybrid scheme has been tested on our self-developed OTDR.

Keywords

Optical Time Domain Reflectometer (OTDR), Signal averging (N), Golay Codes (L), Simplex Codes (M), Pulse detection, Composite Coding Scheme.

1. Introduction

Optical Time domain reflectometer (OTDR) uses a light pulse to probe the optical fiber and characterize it along its length. The OTDR works on the measurement of time delayed response of backward Rayleigh scattered signal and its applications range from fiber cut detection to line interrogation and distributed sensing. Faults and reflections alongside the propagation characteristics of the fiber under test (FUT) can be determined by the analysis of the backscattered signal.

Various coding techniques have been suggested to overcome the technical bottleneck of the dynamic range and the spatial resolution tradeoff [1]. Principally, coded sequences of unit short optical pulse are used to obtain a higher trace level and better Signal-to-Noise ratio (SNR) from the increased effective probe power or pulse width. The final OTDR trace with improved SNR can be restored through appropriate decoding.

A portion of this paper (Section 3.4) was presented at ConTEL 2011 in Graz, Austria .

The research in the coding techniques for the OTDR has revolved around ways of improving dynamic range and the SNR of the detected signal while trying to retain the spatial resolution. Increasing the pulse width of the probe pulse improves the SNR and thus the dynamic range but degrades the spatial resolution of the OTDR. Use of correlation techniques, similar to those used in wireless radars employing pseudorandom bit sequences (PRBS) have been suggested [2] but found unsuitable for practical applications owing to the periodic features of the PRBS which lead to receiver saturation [3]. The complementary correlation OTDR found reasonable success [4] and was followed by the simplex codes based design [1]. The simplex codes were later experimentally tested and a coding gain of up to 9.2 dB by the application of a 255-bit simplex code was demonstrated [5].

The emerging optical technologies on the access network are in the dire need of methods to provide inline testing. Real time in service fault localization is important in the WDM-PON and GPON networks since service interruptions cause large amount of data loss to the subscribers. Inline tests require that the injected power into the fiber under test is kept as low as possible. If OTDRs are employed for such testing, hybrid coding and signal processing can be utilized to keep the injected pulse power at a minimum level.

In our view, the analysis of the backscattered probe pulse requires techniques to improve SNR of the trace and also algorithms to improve the accuracy of cut detection. In this paper, we discuss both the SNR enhancement techniques and the cut detection algorithms. We are also proposing a novel hybrid structure which combines well known methods like signal averaging and S coding to extract an overall higher SNR improvement for the OTDR system. The novelty of the work lies in hybridized structures used for improved pulse detection.

2. Comparison of Existing Coding Techniques

A well designed OTDR has high dynamic range and spatial resolution. Work has been going on for improving the distance resolution capability of the OTDR for years which has used many different SNR enhancement techniques, including signal averaging, Golay code based correlation, Bi-orthogonal codes and Simplex codes based correlation. A set of coded pulse sequences can be used instead of a conventional isolated pulse to effectively increase the total probe pulse power and retain the spatial resolution provided by the isolated pulsewidth, thus enhancing the SNR. Increased SNR in an OTDR measurement can in turn be utilized for increasing the dynamic range in a given measurement time or a reduction in the number of averages required to obtain specified accuracy.

The correlation techniques primarily spread the signal in time domain and reconstruct the fiber impulse response by correlating the detected signal with the probe signal. Codes with good correlation properties are sought with the prime idea to increase the energy of the injected pulse without affecting spatial resolution. Therefore the code used must be such that its correlation looks the same as that of a single pulse and has no side-lobes. However, no codes with zero side-lobes exist.

To overcome this problem, sets of codes have been suggested with complementary correlation properties. Complementary correlation means that the side-lobes of one codeword are the complement of the side-lobes of the other codeword, and by adding the two correlated outputs, the side-lobes cancel each other while the main lobe gets doubled as depicted in Fig. 1. The prime examples of complementary correlated codes are the Golay [4] and the Complementary correlated Promethus ortho-normal sequences (CCPONS) [6], both of which are bipolar codes and must be reduced to unipolar form for transmission over an optical channel. Golay codes realize the full advantage of correlation by probing and correlating with pairs of probe signals that have complementary autocorrelation properties.

Simplex codes promised a slight SNR improvement over the OTDRs employing Golay codes at short code lengths [7]. Bi-orthogonal codes and Moore-Penrose generalized inverses were experimentally tested to produce an overall SNR improvement of up to 9 dB over a conventional OTDR [8]. The Bi-orthogonal code set is known to yield minimum least square errors in the estimation of linearly transformed objects. The use of aperiodic Barker codes has also been suggested in connection with a coherent OTDR [9].

The coding gains in the OTDR pulse detection scenario are generally measured relative to the gain of signal averaging of an equal number of simple single pulse traces. Golay coding with a pulse sequence of L bits requires 4 traces to provide a noise amplitude reduction by a factor of $1/L$. If the noise at the receiver is considered as an uncorrelated zero mean random process with variance σ^2, the relative noise power reduction is

$$\xi_{Golay} = \sqrt{\frac{4\sigma^2}{L}} \ . \qquad (1)$$

The noise power reduction for S-codes calculates as

$$\xi_S = \sqrt{\frac{4M\sigma^2}{(M+1)^2}} \ . \qquad (2)$$

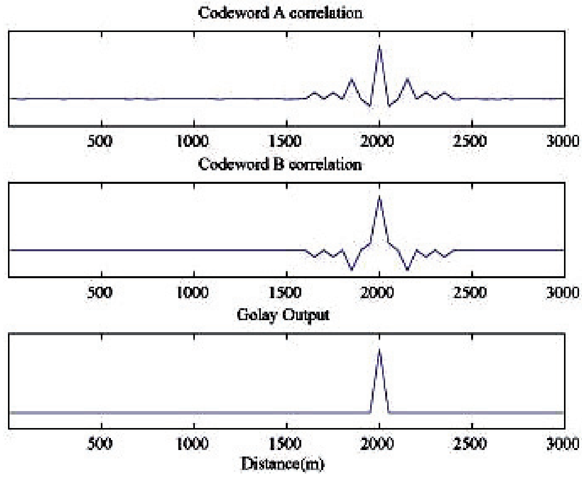

Fig. 1. Correlation properties of Golay codes.

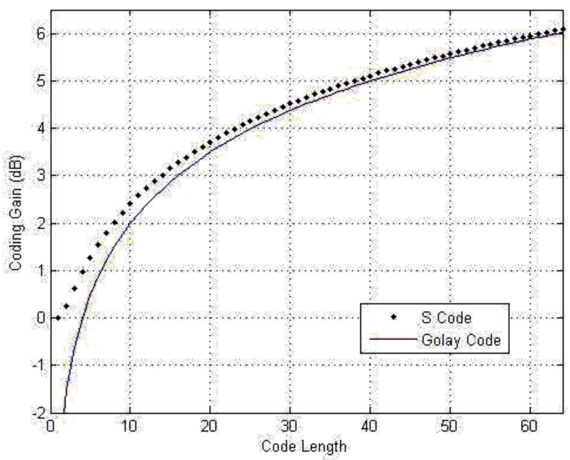

Fig. 2. Relative gain comparison.

Fig. 2 plots the relative gains in terms of noise amplitude reduction of Golay and S codes as a function of code length. The S codes are superior to Golay codes for small code length but for large code length the noise reduction becomes similar. Coding gain comparison at short code lengths is valuable as short codes are less likely to exceed the receiver linear dynamic range.

3. Hybrid Coding Techniques

In this paper, hybrid implementation structures that incorporate gains from multiple techniques have been proposed. The prime idea is to maximize the performance of the system. Moreover, we have studied and analyzed the OTDR pulse detection as a joint detection/coding problem. Our approach involves reducing the noise floor in order to decrease the probability of missed detection.

3.1 Signal Averaging

Signal averaging reduces the influence of noise by numerical filtration of the backscattered signal. In OTDR, the reflectivity $R(z)$ is the measured reflected power by the injection of a single optical pulse into the fiber. The power is converted into electrical current or voltages by subsequent processing. The resulting measurements can be averaged to reduce the noise variance [10].

Signal averaging in OTDRs sums repetition of measurement shots using an accurate time reference for synchronization. A single shot measurement $r_i(t)$ can be represented as a sum of the signal part $s(t)$ and the uncorrelated noise element $n_i(t)$

$$r_i(t) = s(t) + n_i(t)\,. \tag{3}$$

The sum $r_{avg}(t)$ of N repetitive measurements is

$$r_{avg}(t) = \frac{1}{N}\sum_{i=1}^{N} r_i(t) = s(t) + \frac{1}{N}\sum_{i=1}^{N} n_i(t)\,. \tag{4}$$

The rms noise level (or standard deviation) σ_i of $n_i(t)$ sums up as

$$\sigma_\Sigma = \sqrt{E\left[\frac{1}{N}\sum_{i=1}^{N} n_i(t)\right]^2} = \frac{1}{N}\sqrt{N.E[n_i^{\,2}(t)]} \tag{5}$$

where E is the expected value. Substituting σ_i yields

$$\sigma_\Sigma = \frac{1}{N}\sqrt{N.\sigma_i^{\,2}} = \frac{\sigma_i}{\sqrt{N}}\,. \tag{6}$$

The signal-to-noise ratio of the averaged signal thus improves as $\sqrt{N}$. The above analysis assumes zero mean uncorrelated noise.

Fig. 3 shows the improvement of the noise floor due to averaging process for a specific case of $N = 16$ by plotting the averaged trace (lower trace in the figure) and the non-averaged noise (the upper trace). Clearly, the standard deviation of noise has been reduced. This trace has been acquired through our self-developed experimental OTDR setup discussed in detail in section 4 of this article.

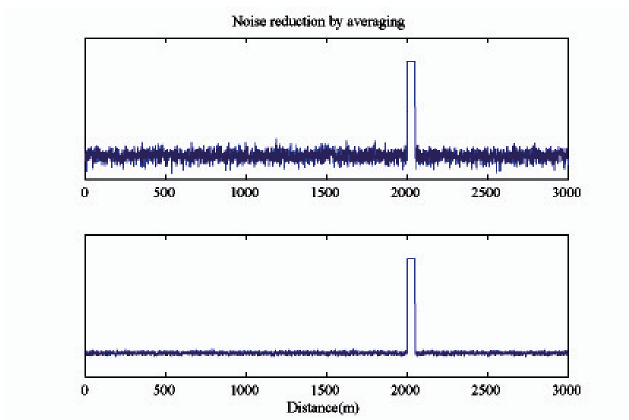

Fig. 3. Noise reduction in averaged pulse detection trace.

3.2 Complementary Correlation Codes

A set of 2 codewords, each L bits long, are said to be complementary if the sum of the autocorrelations of all the codewords is zero for all non- zero shifts [3]. Consider the simple case of two complementary codewords A and B. Then

$$A * A + B * B = 2L\delta_k \tag{7}$$

where δ_k is the delta function. Such a complementary code pair is known as a Golay pair. Golay codes of lengths that are any power of 2 can be easily constructed iteratively from a basic 2 element pair. Such complementary correlation codewords are bipolar and have to be converted to unipolar form because of the unipolar characteristics of an optical system. This is done by introducing a bias to the codeword set, making it suitable for use with an optical system but at the same time doubling the size of the set. For the above Golay pair, the corresponding unipolar codeword set is found by

$$A_1 = \frac{1+A}{2}, A_2 = \frac{1-A}{2}, B_1 = \frac{1+B}{2}, B_2 = \frac{1-B}{2}\,. \tag{8}$$

An OTDR employing Golay coding injects the 4 probe signals into the fiber one by one and stores the response for each. The response for codeword A2 is subtracted from that of A1 and that of B2 from B1. The two subtracted traces are correlated with A and B respectively. The correlated traces have complementary correlation sidelobes which cancel each other when added. This added trace is the final output which has the same distance resolution as a single-pulse correlated trace but reduced noise power. The reduction in noise power depends upon the code length and is equal to L. Since it takes four traces to achieve that gain, the relative optical gain per trace is

$$G_C = \sqrt{\frac{L}{4}}\,. \tag{9}$$

This means that for any $L > 4$, the gain per trace will be greater than that for simple averaging.

3.3 S Codes

Signal Simplex codes use set of "S-codes" to improve signal to noise ratio (SNR) [1] in the OTDR pulse detection. The S-codes are the rows of an $M * M$ matrix S, called the S-Matrix, and are obtained from the normalized Hadamard matrix of order M+1 by omitting the first row with columns and substituting 0 for -1's [5].The S-matrices may be constructed using methods involving quadratic residues, maximal length shift-register sequences and twin primes. Using these methods, S-matrices of order $4p+3$, 2^{p-1} and p^2+2p (where p, $p+2$ are primes) may be found. A series of optical pulses corresponding to each member of a set of S-codes is launched into the fiber under test and the backscatter is measured as a function of delay. This may be expressed as

$$\boldsymbol{\eta}(t) = \mathbf{S} * \mathbf{R}(z) + \boldsymbol{\varepsilon} \quad (10)$$

where $\boldsymbol{\eta}(t)$, $\mathbf{R}(z)$ and $\boldsymbol{\varepsilon}$ are column vectors representing measured backscattered power, reflectivity at each location, and amplitude noise in each measurement respectively. **S** is the $M * M$ matrix whose rows are the S-codes. The quantities of interest represented by $\mathbf{R}(z)$ are found by multiplying $\boldsymbol{\eta}$ by $\mathbf{S}^{-1}$. Additionally, M values for each $\mathbf{R}(z)$ will be obtained and these may then be averaged. The S-code decoded trace looks exactly like a single pulse trace but with reduced noise power as shown in Fig. 4. Fig. 4 shows the 3*3 S-code and its decoded output. The noise power in the decoded trace is reduced by a factor of 1/4 as compared to the original trace.

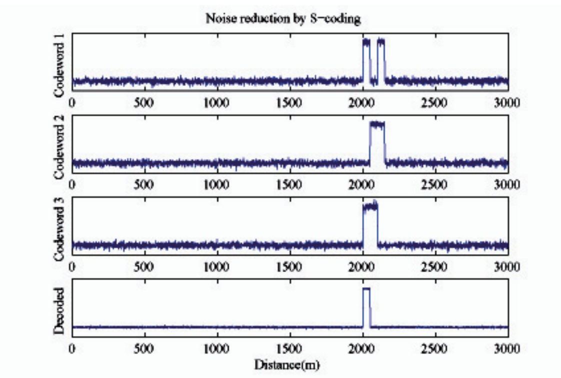

Fig. 4. 3-bit simplex code.

Noise reduction for $M = 3$ bit S sode $= \dfrac{\sigma^2}{4}$

Noise reduction for $N = 3$ averaging $= \dfrac{\sigma^2}{3}$

So, the SNR improvement of the 3-bit S code compared to $N = 3$ averages is

$$\sqrt{\sigma^2/_3 \div \sigma^2/_4} = \sqrt{\frac{4}{3}} = \frac{2}{\sqrt{3}}. \quad (11)$$

The above discussion can easily be extended for a generic code length M and the coding gain for a general S-code of length M has been calculated as $\sqrt{\dfrac{M+1}{2\sqrt{M}}}$ [7].

3.4 Composite Coding Scheme

Composite Coding Scheme [12] is based on a combination of Simplex codes and Golay codes enabling much higher relative gains than achieved by either of the techniques individually. S code of size M requires the acquisition of M traces while a Golay code of length L requires 4 trace acquisitions. For complementary correlated codeword sets of other sizes, the minimum no. of traces needed is fixed, e.g. 8 traces for a set of 4 codewords. Unlike simplex codes, the number of traces needed for complementary correlation codes, does not increase as the targeted gain increases. The size of the code used, however, is limited by the length of the fiber, receiver linearity constraints and receiver saturation limitations. The composite structure uses Simplex code as the inner code and a Complementary Correlation code as the outer code. Consider the case where $M = 3$ and $L = 8$, where M is the size of the S code and L is the size of the Golay code. Each of the outer (Golay) codewords is used as an input to the S-coder as shown in Fig. 5.

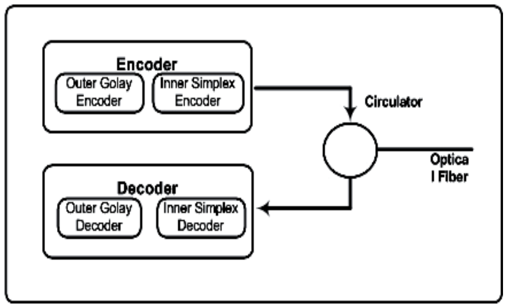

Fig. 5. Composite coding architecture.

The S-coder then produces an S-code which uses the Golay input as its basic pulse, i.e. uses this codeword in place of every 1 bit. In this manner, each of the 4 Golay sequences produces a 3 bit S-code. The final combined codeword set consists of 4 * M = 12 codewords. The fiber is probed with each of the combined codewords, acquiring 4 M traces. Let the noise power in each trace be σ^2. These traces are passed as input to the S-decoder in groups of M traces. The S-decoder performs 4 decoding operations; one on each set of the Golay coded Simplex traces. The output of the S-decoder is 4 traces, each of which corresponds to an L bit Golay trace and with a reduced noise variance of σ^2/G_S^2. The 4 Golay traces are then presented as input to the Golay decoder which gives a single output trace. This final output trace has a noise variance of

$$\sigma_f^{\ 2} = \frac{\sigma^2}{G_S^{\ 2} G_C^{\ 2}}. \quad (12)$$

3.4.1 Simulative Results of the Composite Coding Scheme

Fig. 6 shows the gain associated with composite code with different values of Golay length (L) in conjunction with S-codes of different sizes. The composite code achieves a total noise amplitude reduction of an L bit Golay code and an M bit S-code in only 4 * M traces. As long as $L > 4$ we achieve relative gain greater than any other coding technique employing the same number of traces. This optical gain of the composite scheme is given by

$$Gc = \frac{(M+1)\sqrt{L}}{4\sqrt{M}}. \quad (13)$$

The combined technique gives 1.5 dB more gain for each doubling of the size of Golay code. This is apparent from the square root dependence of gain on the size of the Golay code. For a particular S code length of 128, the Composite coding with Golay length (L) 32 will give

4.51 dB more gain compared to Simplex Code as shown in Fig. 6.

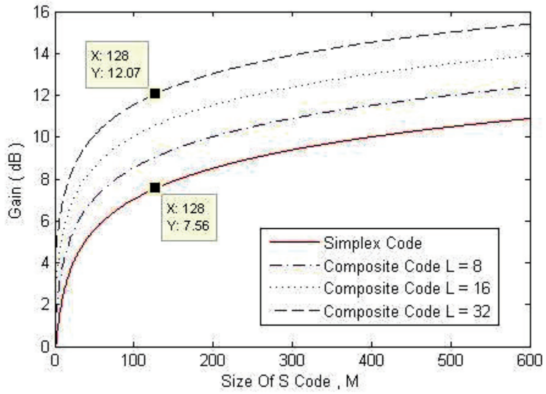

Fig. 6. SNR improvement via composite coding.

3.5 Hybrid Technique

Both averaging and S codes are strong methods for SNR enhancement in OTDR pulse detection. We propose hybrid structures (Fig. 7 and Fig. 8) that incorporate gains from multiple techniques and have combined S codes, averaging and optimized detection to maximize the system performance. Structure 1 (Fig. 7) gives the same performance as hybrid structure 2 (Fig. 8) and reversing the order of S coding and signal averaging has no effect. We have used structure 1 and experimental test-bed is explained in section 4.

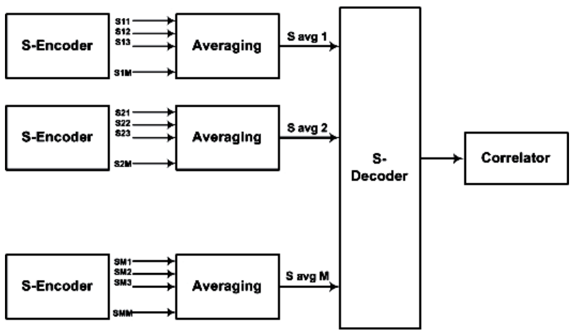

Fig. 7. Hybrid implementation structure 1.

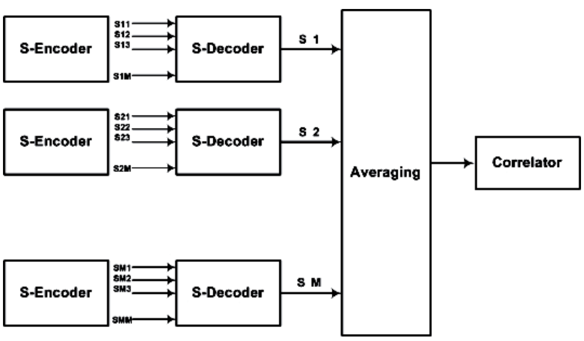

Fig. 8. Hybrid implementation structure 2.

Once an averaged and S-decoded OTDR trace is acquired, the next step is to detect the location and nature of different events along the fiber. The focus is on measuring reflective events, specifically any cut or break in the fiber that cause a strong reflection of the incident light. This appears as a pulse on the OTDR trace whose location needs to be determined. For a pulse of a known shape, the optimum detection technique is through a matched filter or correlator. The noise reduction possible through the use of the correlator is illustrated in Fig. 9.

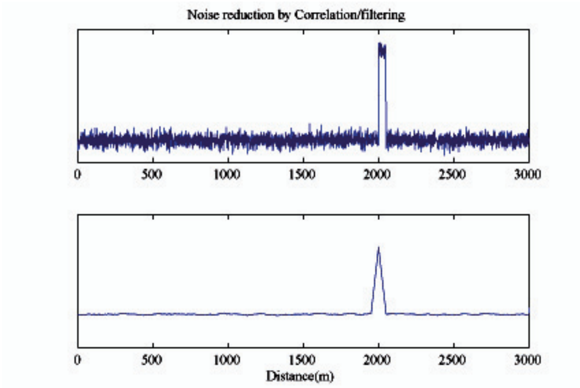

Fig. 9. Noise reduction through correlator.

There is a correlation peak at the location of the pulse which can be detected by standard signal processing techniques. The peak gives the exact position of the pulse in case of good SNR whereas for poor SNR the peak could be off by a few samples. Peak detection can be done using a threshold whose value can be set according to the noise on the trace. A mid-level threshold reduces the probability of false alarm while at the same time decreasing the probability of missing the pulse. Additional checks can be used on the width, height and even on the particular shape of the correlated pulse in order to decrease the probability of error.

3.5.1 Mathematical Analysis of the Hybrid Coding Technique

Hybrid Coding technique combines the gains from S codes and averaging to provide an overall SNR enhancement for pulse detection in the OTDR. For an M bit long S-code along with N averages, the joint gain is given by

$$\xi_h = \sqrt{\frac{4\sigma^2}{N(M+1)^2}}. \tag{14}$$

The combination of averaging and S codes allows keeping the number of averages and the length of the S-codes within reasonable limits allowing reduction in acquisition and processing time. Hybrid technique requires lesser computational times than averaging or S-coding alone in order to achieve similar gains.

3.5.2 Simulative Results of the Hybrid Coding Technique

In investigating the pulse detection in an OTDR, the main parameters of interest are the probability of error and the probability of false detection. In Fig. 10, we provide a comparison of the probability of error (in simpler terms, the probability of missing a reflected pulse) for a simple trace without using any signal enhancement technique with an averaged trace and a hybrid trace.

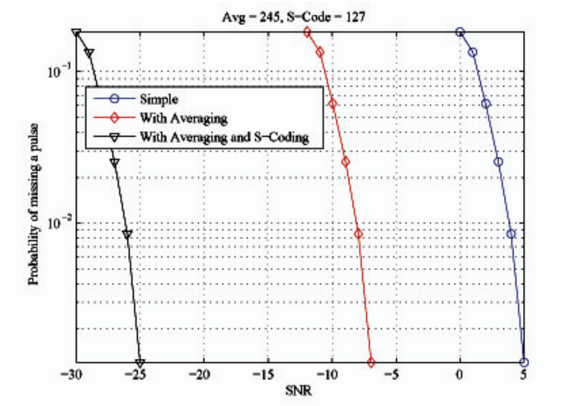

Fig. 10. Probability of error analysis.

The hybrid trace utilizes an averaging with N of 245 and the S-codes with an M of 127. Clearly the hybrid performs much better than the other two techniques. In Fig. 11, a comparison of the probability of false detection (meaning recording of a reflected pulse where it had not existed) between a simple, averaged and hybrid trace is provided to establish the superior performance of the hybrid technique.

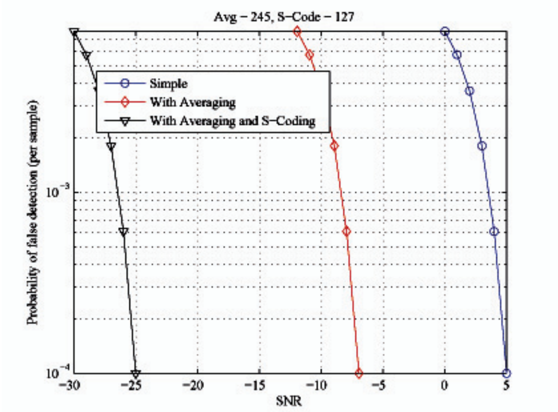

Fig. 11. Probability of false detection analysis.

4. Experimental Testbed

To experimentally verify our hybrid coding scheme, an in-house OTDR board was developed. A pigtailed pulsed-type laser diode (200 mW, 1550 nm) and an InGaAs PIN photodiode receiver (Spectral Range: 1300/1550 nm, Responsivity: 0.9 A/W) were used for the optical source and detector, respectively. The laser power was coupled into the fiber under test using a fiber directional coupler. The received current corresponding to the optical power incident on the photodiode receiver was converted into voltage by the transimpedance amplifier (TIA). ADC sampled the incoming voltages at 20 Mbps with a 12 bit resolution, offering ample dynamic range to detect the optical events. This whole assembly was implemented as an Integrated AFE/Optical Interface Daughter Board as shown in Fig. 12.

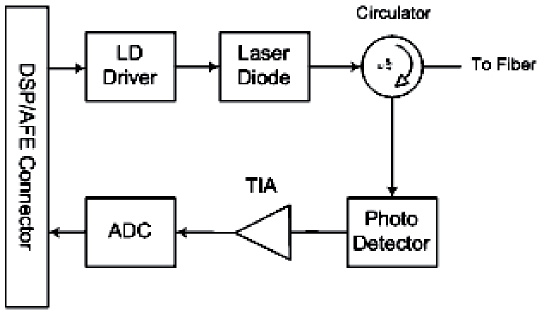

Fig. 12. AFE/optical interface daughter board.

The DSP/AFE connector was used to connect this daughter board to the Signal Processing Board. The Signal Processing Board contained the DSP, FPGA, and associated memories required for storing and processing OTDR traces. The on board Analog Devices Blackfin BF532 DSP was used to perform control, decoding and post signal processing functions. In addition, it had the capability to provide the output in compliance with standard BellCore format. The Xilinx Spartan III FPGA was responsible for laser diode triggering, capturing received optical signals and averaging (Fig. 13).

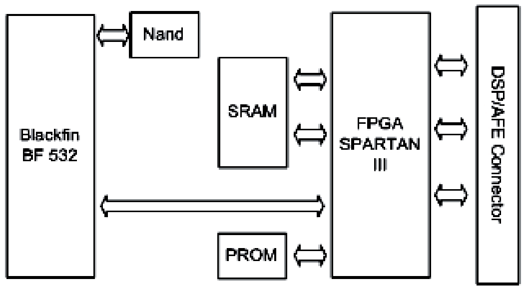

Fig. 13. Signal processing board.

Control signal from ADSP was provided to FPGA to initiate the acquisition process. Real time measurement of optical power trace involved firing a controlled width pulse coded sequence of the laser into the optical fiber and capturing the received power trace for a specified period of time. The captured trace was written into the SRAM. The process was repeated based on the number of averaged traces (N) and the length of the S code (M). Once the capturing process was completed, then the decoding and post processing algorithm was run to extract various parameters of interest, including the location of cut, splices or bends.

The complete self-developed OTDR is shown in Fig. 14. A practical trace acquired through our self developed OTDR for a cut 50 km down a single mode fiber is shown in Fig. 15, which signifies the fact that the trace is able to capture the loss profile for the fiber under test as well as pinpoint any splices or cuts in the fiber structure.

The result for a test performed by implementation of the hybrid coding scheme with S code of length M of 3 and number of averages N of 16 over a 10 km single mode fiber is shown in Fig. 17. To compare, Fig. 16 illustrates the OTDR trace in conventional mode, directly obtained from the simple average of 16 single-pulsed traces. As is evident from the comparison of Fig. 16 and 17, the hybrid technique has performed excellently well on our self developed OTDR; the reflection from the fiber terminator has high SNR and is very clearly visible. The noise floor in the case of the hybrid coding is much below that for the simple averaging case, hence confirming the enhanced performance of the hybrid coding scheme.

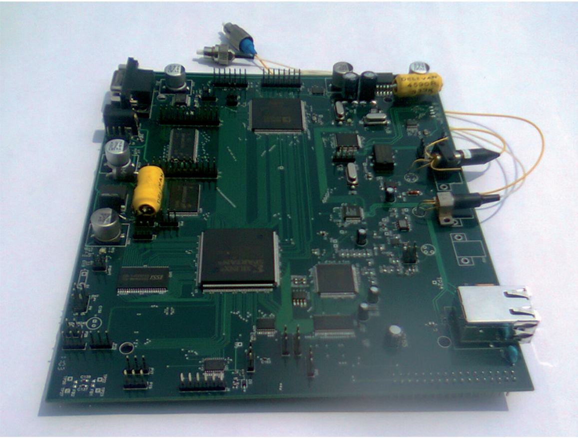

Fig. 14. Self-developed OTDR board.

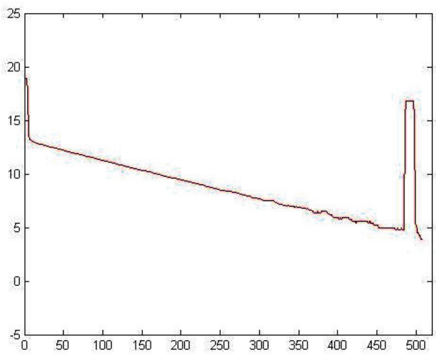

Fig. 15. Self developed OTDR trace for a cut 50 km down a single mode fiber.

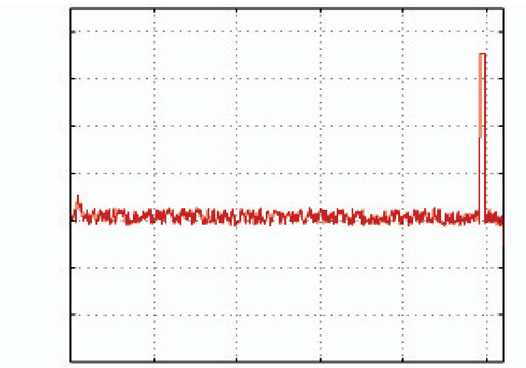

Fig. 16. Trace using only N=16 over a 10 km single mode fiber OTDR board.

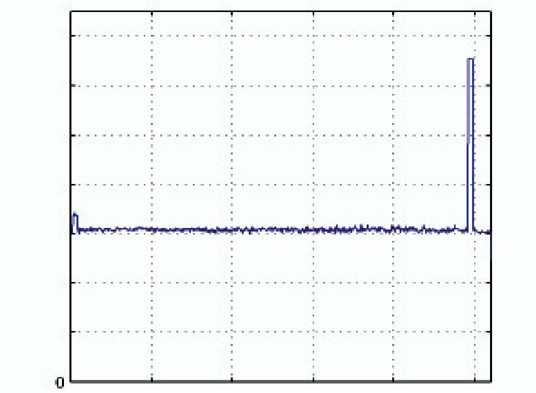

Fig. 17. Hybrid coding trace for M=3, N=16 over a 10 km single mode fiber.

5. Conclusion

Hybrid coding techniques has been proposed for improved pulse detection in an optical time domain reflectometer which considerably reduces the processing time, computational load and system complexity required to extract any specified coding gain as compared to the existing techniques. The combination of S codes and averaging in the hybrid scheme allows keeping the size of the S-code within reasonable limits and extracting higher gains by relatively lesser number of averages.

For Composite Coding scheme, an intelligent combination of Complementary Correlation Codes and Simplex Codes provides SNR enhancement. Moreover, this composite scheme gives valuable reduction in time for similar gain when compared with the existing methods. The additional coding gain provided by the hybrid scheme or composite coding scheme can be utilized for pulse detection at larger distances or refined features extraction for the fiber under test.

Hence, the proposed hybrid coding technique ensures time effective pulse detection in optical time domain reflectometer with greater accuracy without compromising the spatial resolution.

Acknowledgements

This work was supported by a research grant from the National Information Communication Technologies (ICT) Research and Development Fund of Pakistan.

References

[1] JONES, M. D. Using Simplex codes to improve OTDR sensitivity. *IEEE Photonics Technology Letters*, 1993, vol. 15, no. 7.

[2] OKADA, K., HASHIMOTO, K. et al. Optical cable fault detection using correlation technique. *Electronics Letters*, 1980, vol. 16, no. 16.

[3] HEALEY, P. Review of long wavelength single-mode optical fiber reflectometry techniques. *Journal of Lightwave Technology*, 1985, vol. LT-3, no. 4.

[4] NAZARATHY, M., NEWTON, S. A., et al. Real time long range complementary correlation optical time domain reflectometer. *Journal of Lightwave Technology*, 1989, vol. 7, no. 1.

[5] LEE, D., YOON, H. et al. Optimization of SNR improvement in the noncoherent OTDR based on Simplex codes. *Journal of Lightwave Technology*, 2006, vol. 24, no. 1.

[6] SAHU, P. K., GOWRE, S. C. et al. Optical Time Domain Reflectometer performance improvement using complementary correlated Prometheus orthonormal sequence. *IET Optoelectronics*, 2008, vol. 2, no.3.

[7] PARK, N., LEE, J. et al. Coded Optical Time Domain Reflectometry: principle and applications. *Proceedings of SPIE*, 2007, vol. 6781.

[8] LEE, D., YOON, H. et al. SNR enhancement of OTDR using biorthogonal codes and generalized inverses. *IEEE Photonics Technology Letters*, 2005, vol. 17, no. 1.

[9] KING, J. P., SMITH, D. F. et al. Development of a coherent OTDR instrument. *Journal of Lightwave Technology*, 1987, vol. LT-5.

[10] BELLER, J. A high performance signal processing system for the HP8146A Optical Time Domain Reflectometer. Hewlett-Packard Journal, 1993, vol. 44, no. 1.

[11] HEALEY, P. Complementary code sets for OTDR. *Electronics Letters,* 1989, vol. 25, no. 11.

[12] NASEEM, A., MEHMOOD, H. et al. Composite coding scheme for OTDR SNR enhancement. In *Proceedings of the 11th International Conference on Telecommunication ConTEL*. Graz (Austria), 2011, p. 321 - 324.

About Authors ...

S. SHEIKH MUHAMMAD received the Bachelors and Masters degrees in Electrical Engineering from the University of Engineering and Technology, Lahore, Pakistan in 2001 and 2003 respectively. He completed his PhD in Electrical Engineering with Excellence from the Graz University of Technology, Austria in 2007. He is widely known for his research in the system design aspects of Free Space Optical Communications and has authored or co-authored around 15 journal and 30 conference proceedings. He organized the First and the Second Colloquiums on Optical Wireless Communications in Graz and New Castle at the IEEE conferences CSNDSP 2008 and 2010, respectively. Dr. Sajid was nominated as the Guest Editor for the Journal of Communications' Special Issue on Optical Wireless Communications in September 2009, and has been invited as a Guest Researcher through the ASEA-UniNET program in 2010. He is working as Associate Professor of Electrical Engineering with the National University of Computer and Emerging Sciences (FAST-NU) where he lectures regularly on Communication System Design, Optical Communications and Coding Theory.

Haleema MEHMOOD received her Bachelors in Electrical Engineering from the University of Engineering and Technology, Lahore, Pakistan in 2006 and her Masters degree from Stanford University, CA, USA in 2009. From 2009 to 2011, she worked at the Lahore University of Management Sciences on injection seeded WDM-PON systems and OTDR control and post-processing algorithms. She is currently pursuing her PhD at Stanford University where she is part of the Dynamic Spectrum Management Group. Her research focuses on the rate of adaptation and convergence behavior of DSL lines in the presence of time-varying noise and interference.

Anwar NASEEM received the Bachelors and Masters degrees in Electrical Engineering from the University of Engineering and Technology, Lahore, Pakistan in 2008 and 2012 respectively. Anwar has over 4 years of experience in Design and Development of Embedded Systems, especially in safety critical applications involving dual processor architecture with RENESAS M16C/62P. He also holds proficiency in using SCIOPTA – Real Time Kernel as RTOS. From 2008 to 2011, he had worked as Research Associate on the design and development of an in-house OTDR board in the School of Science and Engineering at Lahore University of Management Sciences. His research interests lie in Sensor Networks, Network Security and Optical Communication Systems.

Aun ABBAS received his Bachelors in Electrical Engineering in 1988 from the University of Engineering and Technology, Lahore, Pakistan and the Masters and PhD degrees in Electrical Engineering from the Carleton University, Ottawa, Canada in 1993 and 1997 respectively. He has been involved both in industry and academia including many years at Nortel, Centillium, UET Lahore, LUMS and now LG-Ericsson. He has contributed significantly to the broadband access standards and has been a regular participant in ITU-T SG 15, IEEE 802, ANSI T1E1.4 and ATM and DSL Forum. He cofounded the Teleware Systems (private) Limited which later became Palmchip Pakistan and continues to provide services to clients around the globe and has spawned a number of sister companies. Currently he is the CEO of National Information Communication Technologies (ICT) Research and Development Fund of Pakistan.