***Impulse Response Characterization and
Space-Time Equalization Requirements for Fixed
Broadband Wireless Systems at 29.5 GHz***

by

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the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of*

Master of Science in Information and System Science

Department of Systems and Computer Engineering

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Abstract

Recently, telecommunications service providers have shown heightened interest in providing broadband wireless access to fixed networks via millimeter wave radio transmission. The large amount of untapped bandwidth at millimeter wave frequencies has prompted advances in technologies such as LMDS, which are geared to operate in such high frequency bands.

Channels typically exhibit multipath propagation and tend to be frequency selective in nature causing different frequency components of the input signal to be attenuated and phase-shifted differently. This distortion of the transmitted signal leads to intersymbol interference (ISI) and causes bit errors at the receiver. Equalization compensates for ISI created by multipath.

The present study investigates the system performance benefits of employing decision feedback equalization and diversity combining through an analysis of the data recorded during a propagation measurement campaign in Parkwood Hills in Ottawa. The results will explore the space-time equalizer requirement for LMDS in a residential environment.

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Chapter 1: Introduction

1.1 Background

The increased demand for interactive multimedia communication services is the motivation for recent advances in broadband wireless technology. Up until the early 1990s, much of the broadband wireless spectrum remained untapped because the technology did not yet exist to carry traffic efficiently over high bandwidth frequencies. With state-of-the-art advances in microwave and millimeter wave technology, industry has recognized the potential for deployment of services in a band of frequencies that promises to be the means of providing fixed broadband wireless services to residential and commercial customers.

Local Multipoint Distribution Service (LMDS) is a fixed broadband wireless point to multipoint communication system that provides reliable digital two-way voice, data and Internet services in the 28 GHz band of the spectrum. The implementation of such systems has been sparse due to the limitations associated with channel characteristics at such high frequencies as well as the recent economic downturn in the telecommunications industry.

Physical impairments/obstacles limit the achievable transmission rates over high frequency channels. The frequency selective nature of the channels causes different frequency components of the input signal to be attenuated and phase-shifted differently causing the impulse response to span several symbol intervals resulting in distortion and

interference between successive transmitted input symbols. This phenomenon is known as intersymbol interference (ISI).

Equalization techniques attempt to counteract the effects of ISI to ensure reliable symbol detection at the receiver. Improvements in equalization techniques can potentially enable increasing data rates to be transmitted at frequencies perceived for LMDS services.

1.2 Objective and Motivation

As the demand for higher data rate applications increases, so does the need to develop increasingly sophisticated receiver structures to properly handle and interpret received signals. Due to effects such as fading and ISI, wireless communication systems require signal processing techniques that improve the link performance of the radio channel.

Decision feedback equalization is a commonly used method to counteract the detrimental effects of the transmission channel. The use of diversity techniques in addition to decision feedback equalization to improve system performance is proposed.

A propagation measurement campaign was previously conducted in the Parkwood Hills area of Ottawa in order to characterize the wireless channel (i.e. estimate the channel impulse response). A two-antenna array was set up at the receiver/base station to enable space diversity measurements. The current study investigates the challenges associated with the physical channel with respect to high frequency broadband signals through an analysis of the recorded data. The results will explore the space-time equalizer requirement for LMDS in a residential environment.

1.3 Contributions

At frequencies intended for LMDS services, high bandwidth signals generally undergo time-smearing due to the distortive filtering associated with the multipath channel. In order to counteract the detrimental effects of the channel, decision feedback equalization is employed in an attempt to reshape the system transfer function to one that meets Nyquist's first criterion. Nonlinear decision feedback equalization is preferred over linear transversal equalization due to its ability compensate for amplitude distortion with less noise enhancement.

The present study consisted of an analysis of previously recorded data and compared various decision feedback equalizer (DFE) configurations in an attempt to characterize a suitable DFE structure. T-spaced and T/2-spaced DFEs were investigated for performance comparison purposes. Over similar time spans, DFEs with more closely spaced feedforward filter taps can achieve higher levels of performance than DFEs with more sparsely spaced feedforward filter taps.

Combinations of up to 10 feedforward and 10 feedback taps were considered to investigate achievable DFE performance levels for two different symbol rates: 10Msps and 40Msps. These are typical symbol rates intended for an LMDS configuration. The simulation results show how equalization requirements vary with transmission rates. As expected, increasing symbol rates demand increasing equalization capabilities to ensure similar performance levels.

An antenna array at the receiver is employed to enable the investigation of the benefits of space diversity. In the event that one of the two channels experiences severe degradation, it is beneficial that a source of diversity be available. It is highly unlikely that both channels will experience severe degradation at the same time. A diversity combining technique is implemented to successfully show that system performance benefits from space diversity exceed those associated with feedforward filter tap spacing.

1.4 Organization

This report is conveniently divided into 6 distinct chapters. The current chapter provides a brief introduction to the content of the present investigation. Chapter two introduces the general concepts associated with LMDS, the motivation for this study. System configuration, benefits of LMDS, channel propagation issues and perceived applications are discussed. Chapter three is a broad overview of some of the relevant literature pertinent to any discussion relating to broadband wireless transmission over dispersive channels. Some particular areas include: channel characteristics, equalization in particular decision feedback equalization, T-spaced versus T/2-spaced DFE configurations, system performance measures, and diversity considerations. Chapter four provides a description of the propagation measurement campaign conducted in the Parkwood Hills area of Ottawa and a look at typical channel behavior derived from the field survey. Chapter five delves into a detailed analysis of system performance as a result of various DFE configurations. The effect of multipath on system performance as well as the performance enhancement associated with combinations of up to 10 feedforward and 10 feedback taps is considered for T- and T/2-spaced DFEs and for

symbol rates of 10 and 40 Msps is discussed. Furthermore, the benefit of space diversity is demonstrated. Chapter six summarizes the main results of this investigation/analysis.

Chapter 2: Local Multipoint Distribution Service

The expanding use of the Internet and other computer networks has got service providers racing to provide high-speed digital communications to business and residential subscribers. Telecommunication service providers have expressed interest in multipoint communications system technology to provide wide access to clients for delivery of a full range of data, video, and telephony services. This burgeoning interest in new technology led to the introduction of Local Multipoint Distribution Service (LMDS). In Canada, it is referred to as Local Multipoint Communication Service (LMCS). Unfortunately, this interest has since taken a nosedive due to such severe detrimental environmental conditions as rain and non-line-of-sight.

LMDS/LMCS is a terrestrial broadband wireless bi-directional point-to-multipoint communication distribution technology operating in the millimeter wave frequency band. Industry Canada has designated the band 25.35 – 28.35 GHz for the development of LMCS in Canada and has allowed the implementation of LMCS in 66 urban areas throughout Canada. Figure 2.1 shows the authorized zones in Eastern Ontario and Western Quebec [1]. The U.S. FCC has allocated 1.3 GHz of bandwidth for LMDS as follows: 27.5 - 28.35 GHz, 29.1 - 29.25 GHz, 31.075 - 31.225 GHz, 31 - 31.075 GHz, and 31.225 - 31.3 GHz [2].

Figure 2.1: Southeast Ontario and Southwest Quebec LMCS Service Areas

Current widespread communication technologies focus their attention lower in the RF spectrum because low frequency signals with enough power can be sent long distances and penetrate buildings. LMDS uses low powered, high frequency signals transmitted over a short distance [3].

2.1 Configuration

The typical LMDS setup consists of a central network management facility with fiber-linked PSTN and Internet connections. The central facility relays a signal via point-to-point microwave links to hubs located on rooftops or as stand-alone towers for transport to the subscriber premises. The downstream channel is a point-to-multipoint broadcast channel from the hub to the subscriber. The upstream channel, from the subscriber to the hub, is a multipoint-to-point link.

LMDS uses a cellular architecture and attempts to reuse the entire frequency band in each cell. Each cell in the coverage area is equipped with a hub transceiver that communicates via point-to-multipoint radio links with subscribers at fixed locations throughout the service area. Cells with omnidirectional hub antennas are nominally circularly shaped and transmit orthogonal linear polarizations in adjacent cells. However, in an attempt to optimize frequency reuse, the cell site microwave equipment is more commonly configured with multiple sectored antennas, transmitters, and receivers. A typical configuration is a four-sector cell site using 90-degree beamwidth antennas to provide services to the subscriber environment. The resulting cell shape is circular. Each of these sectored antennas can support the full bandwidth of the allocated spectrum. Horizontal and vertical polarization is generally employed throughout the system in an alternating pattern between the sectors. Maximizing the isolation between the adjacent cells/sectors through orthogonal polarization significantly reduces cochannel interference and enables more efficient frequency reuse [4]. Furthermore, more elaborate hub sectorization planning will increase capacity. For example, twelve 30-degree sectors can potentially triple capacity over four 90-degree sectors if adjacent sectors are adequately isolated from cross-polarization. Cross-polarization isolation is reduced by multipath reflections from obstacles in the transmission channel. Minimization of cross-polarization due to multipath is achieved by using highly directional antennas. Figure 2.2 shows a typical LMDS system layout with 4-sector cells and alternating horizontal and vertical polarization in neighboring sectors.

Figure 2.2: Typical LMDS Structure

The upstream and downstream air interface formats may differ due to the nature of the digital traffic in either direction. The customer premises equipment may communicate with the network using time-division multiple access (TDMA), frequency-division multiple access (FDMA), or code division multiple access (CDMA). In the downstream direction, TDMA is the preferred digital transmission scheme [5].

The FDMA scheme, which assigns a dedicated segment of spectrum to a user, on the uplink is well suited for a transmission of constant fixed bandwidth or a bandwidth varying slowly over time. When the upstream traffic is light or variable, TDMA, which

share the spectrum among several users through the use of time slots, is preferable [5].

Code division multiple access (CDMA) supports a significantly smaller number of users than TDMA in high frequency reuse scenarios.

The current investigation deals with the upstream signal sent from the subscriber location to the base station with an antenna array.

2.2 Benefits

LMDS technology offers service providers a method of providing high-capacity local access that is less capital-intensive than a wireline solution. Due to the relatively minimal infrastructure (i.e. no underground cables or fibers) for this wireless last-mile solution, deployment costs are greatly reduced. The reduction in physical infrastructure allows systems to be deployed rapidly and easily with minimal disruption to the environment [6].

For LMDS, cell sites must be established early on. Once the infrastructure is complete, new costs are incurred only as additional customers sign on. By contrast, the majority of the cost associated with wireline networks is incurred before the first paying customer signs on. As such, LMDS can thrive with a low penetration rate. Furthermore, since much of the cost of the LMDS is not incurred until the customer premises equipment is installed, the network service operator can time capital expenditures to coincide with the signing of new customers (demand-based buildout) [6].

LMDS is a broadband infrastructure. Therefore, even with an initial deployment of only telephony service over LMDS, any service provider can expand to provide other broadband services with minimal additional infrastructure cost. Much of the LMDS equipment at both the network and customer sides can be reused.

LMDS is extremely fast compared to dial-up modems, cable modems, DSL, T-1 lines, Frame Relay, and ISDN communications [7]. Only a fiberoptic link has greater capacity than LMDS. However, deployment of a fiberoptic network is relatively costly and slow. Initial tests by Hewlett Packard indicate that, at peak capacity, each LMDS subscriber could possibly expect data rates of at least 7 Mbps downstream and 1 Mbps upstream [5]. In addition, on average, LMDS is expected to support downstream transmissions of 35 to 58 Mbps and 51.84 to 155.52 Mbps for residential and commercial subscribers respectively.

2.3 Propagation Issues

Bit rates generally ranging from 10 to 50 Mbps are anticipated for LMDS services. Such high data rates make signal transmission highly susceptible to intersymbol interference as a result of the distortive effects of the channel. A channel that exhibits delay spread causes distortion as time-delayed signals are combined at the receiver. LMDS installations attempt to reduce the detrimental effects of delay spread (or multipath) through the use of highly directional antennas and line-of-sight transmission. Equalization and/or diversity techniques can further reduce ISI. Equalization and diversity are investigated in the present study.

As with any radio system, the system performance is limited by the ability to provide sufficient signal strength and bandwidth over individual radio links. The high data rate applications perceived for LMDS require the use of highly efficient modulation techniques for acceptable system performance.

Several modulation methods can be used. Low-density modulation allows greater distance at a given power but sacrifices data throughput rates. Increasing the number of signals in the modulating signal constellation will allow more bits to be transmitted in a hertz of spectrum. The price for more bits per hertz is the need for a much cleaner signal at the receiving site. With a limit on the radiated power, this means reduced range. Thus the tradeoff becomes either lots of data-carrying capacity or longer range.

Modulation schemes intended for LMDS are QPSK, 16-QAM, and 64-QAM. The higher order constellation modulations can be utilized since LMDS systems are predominantly line-of-sight and there is a minimal amount of multipath interference. The drawback to the higher order modulations is the larger C/I ratio and the required receiver sensitivity. As the modulation order increases, larger values of E_b/N_0 , C/I, and receiver power are needed to sustain a given BER. Therefore, QPSK will always have a greater range than the other two LMDS modulations for a given transmitter power. Similarly, the coverage area of 16-QAM will always be larger than that of 64-QAM [8]. The modulation schemes available differ primarily in how efficient they are at using available spectrum. Quadrature Phase Shift Keying (QPSK) provides 1.5 bps/Hz. For 16-QAM and 64-QAM modulation, the spectral efficiency is 3.5 and 5 bps/Hz, respectively. Higher bandwidth

efficiencies require correspondingly higher carrier-to-interference (C/I) ratios, which mean smaller cell sizes [9].

There are a number of channel propagation issues that threaten to hinder the performance of LMDS systems. During the cell-site planning phase, it is necessary to consider a variety of factors that may affect the area/distance that the cell site can support with reliability. Modulation considerations have been described above. Transmission path obstructions, height of the transmit/receive antennas, degree of overlap in adjacent cells, rainfall rates, and line-of-sight are some of the critical items to consider.

The most evident source of attenuation in this survey is foliage that often obstructed the transmission path. Scattering from vegetation causes depolarization of transmitted signals [10]. As such, wind-induced motion of foliage can cause significant fluctuations in received signal levels. In [11], it was noted that the attenuation due a single tree has been observed to be on the order of 30 dB and the attenuation due to building blockage has been observed to be in excess of 60 dB. Attenuation from foliage can be quite large but overlapping cells and roof mounted antennas generally overcome the problem.

LMDS systems have customer antennas generally located on rooftops. In addition to the highly directional nature of LMDS antennas, the height of the customer-premises antenna plays a large role in reducing multipath effects. With increased height of the transmitter and/or receiver antenna, it is expected that fewer obstacles will be present in the transmission path to impair the received signal.

It is not uncommon that many locations within a cell will not receive a clear signal from the base station as a result of inadequate line-of-sight. Hewlett-Packard found a single transmitter would reach only slightly more than 60% of the homes in a cell. With overlapping cells, however, that number jumped to almost 85% of homes [3].

Rain fade is the attenuation of the signal caused by raindrops scattering and absorbing the millimeter waves. The LMDS systems at 28 GHz are most susceptible to rain effects causing a reduction in the signal level. Also, at millimeter wave frequencies, rain induced signal depolarization is produced by differential attenuation caused by non-spherical raindrops, leading to decreased signal level and decreased interference isolation between adjacent sectors and adjacent cell sites [2, 10].

LMDS requires line of sight between a transmitter and receiver. In built-up environments, it is often difficult to provide a line-of-sight path from the hub to each subscriber due to obstacles in the transmission channel. Careful planning is required and may demand a repeater to retransmit the signal over obstacles such as a building or a hilltop. Or, reflectors can be used to bounce strong signals into shadowed areas. Without the use of these remedies, shadowed areas will not receive LMDS services. Since LMDS is line-of-sight-dependent, shadowing and diffraction are not prevalent phenomena as compared to systems operating at lower frequencies.

To investigate the effects of the propagation environment, a measurement campaign was previously conducted in Parkwood Hills in Ottawa. Relevant details are described in

Chapter 4. Data from this campaign is used in our investigation of space-time receiver processing for LMDS.

2.4 Applications

LMDS is slated to provide an attractive solution to the last-mile problem of connecting consumers to broadband communication services. The services can range from one-way broadcast video to fully-interactive multimedia applications. LMDS can offer a variety of broadband applications to both residential and commercial subscribers.

The advent of LMDS was initially driven by digital TV applications. However, given the idea of basically limitless bandwidth, a plethora of other applications emerged as possible candidates for implementation via LMDS.

For residential subscribers, LMDS can offer digital broadcast video, high speed internet access, voice over IP telephony, video conferencing, Web TV, backhaul for personal communications services, and interactive entertainment such as video on demand, home shopping, and interactive video games [4].

The commercial subscriber can seek value in LMDS via corporate video broadcasting, distance learning, e-commerce, electronic delivery services, internet/intranet access, monitoring/surveillance, and voice over IP telephony. However, one of the most important applications for LMDS will be to connect LANs, intranets and PBXs of companies with distributed offices.

Chapter 3: Literature Review

Digital communications involves the transmission of information in digital form from a source that generates the information to one or more destinations. The design goal for a digital communication system is to transmit this information and receive it with as little error as possible.

Figure 3.1 depicts a simple model of a digital communication system. The modulator/transmitter block translates an input bit stream into a bandlimited analog signal and upconverts it into a frequency band suitable for transmission. The propagation channel filters the transmitted signal sometimes causing the signal to be delayed, attenuated, and distorted at the receiver. The receiver/demodulator block is generally a sophisticated signal processor that attempts to recover the original transmitted bit stream from the received signal which has been corrupted by the channel and includes the effects of additive noise and possibly interference from other signals.

Figure 3.1: Digital Communication System

One area of particular importance in the analysis and design of communication systems is the characteristics of the physical channels through which information is transmitted.

3.1 Physical Channel

The transmission path between the transmitter and the receiver can vary from simple line-of-sight to one that is severely obstructed by natural terrain features and manmade objects. When an RF wave bounces off such obstructions as it travels between two points, a duplicate of the original signal is generated. The distance traveled by the duplicate signals is different causing them to arrive at their destination at different times. This time differential causes the signals to overlap and merge into a single distorted signal at the receiving end. The interaction between the multiple copies of the signal causes multipath interference.

Multipath propagation causes amplitude and phase fluctuations and time delay in the received signals. Amplitude and phase fluctuations are the result of multiple reflected out-of-phase copies of a signal that add up either constructively or destructively at the receiver at the same time. These combined signal waves are known as Rayleigh fading waves. The random phase and amplitudes of the different multipath components cause fluctuations in signal strength. Typically, the fading envelope shows variation over time, with large attenuation occurring periodically. This phenomenon makes the received signals much more susceptible to noise and causes significant degradation in signal characteristics [12].

The reflected waves are also subject to time delay. The combined signal at the receiver contains signals with different amounts of propagation delay. When signals arrive over different paths, they interfere with each other and cause a significant degradation in the received signals.

The effect of the channel on the transmitted signal is related to the bandwidth of the signal relative to the coherence bandwidth of the channel. The signal bandwidth is the reciprocal of the symbol duration. The coherence bandwidth of the channel is the range of frequencies over which two frequency components have a strong potential for amplitude correlation [13].

Depending on the multipath structure of the transmission channel, the signal can undergo either flat or frequency selective fading. If the channel has a constant gain and linear phase response over a bandwidth that is greater than the bandwidth of the transmitted signal, then the received signal will undergo flat fading and is considered a narrowband signal. In flat fading, the spectral characteristics of the transmitted signal are preserved at the receiver. However, the strength of the received signal changes with time due to fluctuations in the gain of the channel caused by multipath [13]. For the data rates under consideration for LMCS/LMDS configurations, it is more likely that signals will rather undergo frequency selective fading.

Frequency selective fading occurs when the channel possesses a constant-gain and linear phase response over a bandwidth that is smaller than the bandwidth of the transmitted

signal. The signal is therefore considered wideband. Under such conditions, the channel affects frequency components separated by more than the coherence bandwidth differently, giving some frequency components in the received signal spectrum greater gains than others. The impulse response of a frequency-selective channel has a multipath delay spread which is greater than the symbol duration (reciprocal bandwidth) of the transmitted waveform. When this occurs, the received signal includes multiple versions of the transmitted waveform that are attenuated and delayed in time, and hence the received signal is distorted [13].

Due to the time-dispersive nature of the multipath transmission channel, high data rate signals typically experience a phenomenon called intersymbol interference, ISI, at the receiver. Because multiple reflections of the transmitted signal may arrive at the receiver at different times, the receiver attempts to resolve a symbol that may be a combination of multiple symbols that are dispersed in time.

Because of multipath reflections, the impulse response of a wireless channel looks like a series of pulses. These pulses are used to define the power delay profile of the transmission channel. The delay profile is the expected power per unit of time received with a certain excess delay. It is generally obtained by averaging a large set of impulse responses [14]. Many multipath channel parameters, used to quantitatively describe a channel, can be derived from the power delay profile of the channel. The RMS delay spread is a commonly used measure of the extent of time dispersion introduced by multipath channels. For a reliable communication, without using adaptive equalization or

other anti-multipath techniques, the transmitted symbol rate should be much smaller than the inverse of the RMS delay spread [15].

The RMS delay spread is the square root of the second central moment of the power delay profile and mathematically defined as [13]:

$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\overline{\tau})^2} \quad (3.1)$$

where,

$$\overline{\tau^2} = \frac{\sum_k a_k^2 \tau_k^2}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k) \tau_k^2}{\sum_k P(\tau_k)}$$

$$\overline{\tau} = \frac{\sum_k a_k^2 \tau_k}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k) \tau_k}{\sum_k P(\tau_k)}$$

The delays , τ , are measured relative to the first detectable signal arriving at the receiver.

The above equations do not rely on the absolute power level of $P(t)$ but only on the relative amplitudes of the multipath components.

In order to properly compensate for the wireless channel's deleterious effects on the transmitted waveform, equalization techniques have evolved over the years. Standard modeling assumes that the propagation path from the transmitting antenna to the receiver can be approximated by a linear filter. Research by Bello concluded that it is feasible to model a propagation channel as a finite impulse response filter, with taps chosen at the signal's sampling interval and complex-valued coefficients chosen to accurately model the channel's impulse response [16].

3.2 Equalization

Equalization attempts to compensate for the channel's dispersiveness. By operating on the output of the channel, the equalizer attempts to reshape the received signal spectrum into one that exhibits a constant gain and linear phase over the entire received signal spectrum. A signal with such spectral characteristics sampled at least as fast as the symbol rate satisfies the Nyquist criterion [17]. This is a necessary condition to ensure no ISI.

Nyquist laid the foundation for pulse transmission over band-limited channels by solving the problem of overcoming ISI. Nyquist determined that the effect of ISI could be completely nullified if the overall response of the communication system is designed so that at every sampling instant at the receiver, the response due to all symbols except the current symbol is equal to zero [13]. The Nyquist sampling theorem states that, for a band-limited signal, sampling must occur with a frequency of at least twice the signal's maximum frequency component (bandwidth) in order to be able to uniquely reconstruct the signal without aliasing [18].

Two basic equalizer structures are employed in practice: linear and nonlinear. The linear (transversal) equalizer lies in cascade between the propagation channel and the decision device. In a linear equalizer, the current and past values of the received signal are linearly weighted by the filter coefficients and summed to produce the output. The coefficients of a linear transversal equalizer are selected to force the combined channel

and equalizer impulse response to approximate a unit pulse [19] that satisfies Nyquist's criterion. See Figure 3.2 for a graphical representation of a linear equalizer.

Figure 3.2: Typical Linear Equalizer

Nonlinear equalizers are used in applications where the channel distortion is too severe for a linear equalizer to handle. Linear equalizers do not perform well on channels that have deep spectral nulls in the passband. In an attempt to compensate for the distortion, the linear equalizer places too much gain in the vicinity of the spectral null, thereby enhancing the noise present in those frequencies [19].

There are several nonlinear equalizer structures. The decision feedback equalizer (DFE) is the structure of interest for the present study and will be discussed in detail herein.

3.3 Decision Feedback Equalization

Once an information symbol has been detected and decided upon, the ISI that it induces on future symbols can be estimated and subtracted out before detection of subsequent symbols. The typical DFE consists of a feedforward filter (FFF), which operates on the receiver signal, and a feedback filter (FBF), that operates on the reconstructed data at the output of the decision device [20]. Figure 3.3 shows a decision feedback equalizer in the context of a baseband communication system.

Figure 3.3: Typical Decision Feedback Equalizer

The output of the receiver filter can be described by the following equation:

$$z(t) = \sum_n d_n g(t - nT) + \eta'(t) \quad (3.2)$$

In the current investigation, the sequence of symbols $\{d_n\}$ are transmitted using a QPSK modulation scheme. The symbols can take on four possible values $\frac{1}{\sqrt{2}}(\pm 1 \pm j)$. The function $g(t)$ is the combined impulse response of the transmitter, channel, and receive filter. The function $\eta'(t)$ is the noise. It is generally assumed that the transmitted symbols are independent with zero mean and unit variance.

The output of the FFF and FBF filters can be described mathematically as follows:

$$FFF_{out} = \sum_{j=0}^{K_1} f_j^* z(nT - jT' - \tau_0) \quad (3.3)$$

$$FBF_{out} = \sum_{j=1}^{K_2} b_j^* d(n - j - D) \quad (3.4)$$

The complex-valued feedforward and feedback tap coefficients are $\{f_j\}$ and $\{b_j\}$ respectively. $K_1 + 1$ and K_2 are the number of feedforward and feedback taps respectively. τ_0 is the sampling delay and D is the delay of the system. The feedforward filter taps are T' -spaced. The input signal is sampled every T' seconds where $T' = T/S$ and S is the number of samples per symbol period T . The feedforward filter can be T -spaced or fractionally spaced (FS-DFE). For a T -spaced DFE, the input signal is sampled once per symbol interval (i.e. $S=1$) such that $T'=T$. A FS-DFE has closer feedforward tap spacing and the input signal is sampled every T' seconds.

The FBF is driven by decisions on the output of the decision device and its coefficients can be adjusted to cancel the ISI on the current symbol from past-detected symbols [17,

21]. This ability of the feedback filter to cancel ISI due to previous symbols allows more freedom in the choice of coefficients in the FFF. Therefore, the FFF need not approximate the inverse of the channel characteristics thus avoiding excessive noise enhancement and sensitivity to sampler phase [19, 21].

The analysis and design considerations associated with the DFE assume that past decisions are error-free in order to simplify the mathematical solution. When the receiver makes an error, the erroneous decision is used in the FBF resulting in a higher likelihood of subsequent decision errors. The possibility of error propagation is more severe if the FBF tap coefficients happen to be large in magnitude and number [21].

In [20], the author examines a DFE structure and determined that, in the absence of decision errors, the feedback receiver has been shown to be superior to the nonfeedback receiver.

3.4 Symbol-Spaced vs. Fractionally-Spaced

As previously indicated, the feedforward filter of a decision feedback equalizer can be symbol-spaced or fractionally-spaced. Our investigation will examine T-spaced and T/2-spaced DFEs. The feedback filter is a symbol-spaced linear transversal filter.

Early demodulators used T-spaced equalizers where the input signal was sampled once per symbol interval. The timing of the sampling clock was adjusted so that the samples were taken at the point in the symbol interval corresponding to the highest energy (i.e. the

optimum sampling phase to be discussed in the next chapter). These samples then entered the equalizer's tapped delay line filter or feedforward filter (FFF). Symbol rate sampling at the input to a T-spaced equalizer causes spectral overlap or aliasing [19].

Practical design of high-speed modems has deviated from T-spaced equalizers in preference of fractionally spaced equalizers [16]. As such, the input to the feedforward filter of the equalizer is sampled faster than the symbol rate. For the same feedforward filter time span, the fractionally-spaced equalizer will consume more computational resources than its T-spaced counterpart since the fractionally spaced equalizer will consist of more taps in the FFF. An FS-DFE, by virtue of its sampling rate, can more accurately approximate the inverse of the channel characteristics within the constraints of its length and delay than a T-spaced equalizer of the same length thus enabling an improvement in the ability to effectively compensate for more severe delay distortion with less noise enhancement [19].

The principal reason for employing a FSE is that even though the pulses arrive at the symbol rate, the actual bandwidth of the signal is typically 10 to 40 percent higher [16] resulting in aliasing when employing symbol rate sampling. Therefore, sampling the input at exactly the symbol rate is not sufficient to satisfy the Nyquist sampling theorem. The sampling rate of an FSE is selected to ensure that aliasing does not occur. The most common choice is to sample the input at twice the symbol rate, making the filter tap spacing equal to $T/2$ [16].

3.5 System Performance

In digital communications the most meaningful metric to measure performance of a system is the overall probability of error. This is the probability that any bit will be guessed in error by the receiver.

Significant research has been performed on the theory of optimum non-linear receiver structures under various optimality criteria related to probability of error. The zero-forcing condition and mean-square measures have been favored in relation to the optimum design because they simplify the mathematical problem of determining the optimum FFF and FBF tap coefficient [22]. Considerably more numerical effort is required if the probability of error is selected as the optimality criterion due the nonlinearity of the associated solution.

In the present research study, the minimum mean-square error is the selected optimality criteria. The mean-square error is based on the evaluation of an error signal. The error signal is the difference between the output of the equalizer (input to the decision device) and the true value of the symbol represented by the input to the decision device [23].

During each symbol interval, a new error signal is computed. An updating algorithm uses the error signal to estimate the optimum set of equalizer FFF and FBF tap coefficients that will result in a reduced cost function (i.e. MSE). The mean-square error is a quadratic function of the coefficients. The MSE can be envisioned as an N-dimensional paraboloid (punch bowl) with a bottom or minimum. The adjustment to each tap gain is in a direction opposite to an estimate of the gradient of the MSE with

respect to that tap gain. The idea is to move the set of equalizer coefficients closer to the unique optimum set corresponding to the minimum MSE (MMSE) [19]. In the current investigation, the spectral factorization technique developed by Weiner is used to determine the set of optimum coefficients for a DFE based on a minimum mean-square error performance criterion [24]. This method is outlined in Appendix A [25].

For the present study, the signal-to-noise ratio at the output of the DFE is considered.

The SNR at the output of the DFE is related to the MMSE as follows [17]:

$$\text{SNR} = \frac{1 - \text{MMSE}}{\text{MMSE}} \cong \frac{1}{\text{MMSE}} \quad (3.5)$$

assuming the data symbols are normalized such that $E(|d_n|^2) = 1$.

3.6 Diversity

In addition to channel equalization, diversity techniques can be used to improve system performance. Diversity exploits the random nature of radio propagation by finding (virtually) independent signal paths. This allows the receiver to have more than one look at the received symbol reducing the probability of erroneous symbol decisions. In a fading environment, it is reasonable to expect that two independent diversity paths will not experience simultaneous fading. As such, if one channel fades, a reliable signal can be expected from the other diversity path [26]. A number of diversity techniques can be used. Some of these are: frequency diversity, time diversity and space diversity.

Frequency diversity involves sending the signal energy in more than one frequency band.

The signal energy is shared among multiple frequency bands. This increases the

likelihood of correct symbol decisions since the probability that all frequency bands are heavily faded is less than the probability that a single frequency band is experiencing fading. Time diversity involves sending the signal energy at multiple points in time thus benefiting from the changing channel characteristics. The likelihood that the same signal sent at two different times will experience fading during the reception of the same symbol is low. The drawback of frequency diversity is that more bandwidth is required to transmit the same amount of information. Time diversity is less favorable due to both an increase in delay and a decrease in the achievable bit rate for a given channel.

Space diversity involves the use of an antenna array (i.e. more than one antenna.) Antennas are positioned with sufficient distance to ensure decorrelation of signals at each antenna. Other than the physical space implications, there are no drawbacks to employing space diversity as a means of improving system performance. Space diversity, space permitting, is the preferred diversity scheme to combat signal fading. The use of multiple receive antennas (i.e. space diversity) is investigated in the present study.

Appendix B provides an adaptation of the Weiner spectral factorization technique described in Appendix A. The adaptation considers the use of a two-antenna space diversity configuration at the receiver.

In this investigation, the input to the decision device consists of the output of two distinct feedforward filters and the feedback filter.

Chapter 4: Radio Propagation Measurement Campaign

A radio propagation measurement campaign was conducted in the Parkwood Hills area of Ottawa in the summer and fall of 1999. The results of the campaign were analyzed to characterize the outdoor radio channel in the band of frequencies allocated for LMCS/LMDS. The experiment quasi-simultaneously measured signals received at two antennas located side by side. The received signal samples were used to estimate the radio channel impulse response in each of the two radio channels. The main purpose of the measurement campaign was to study and compare the impulse responses of an LMCS type system as seen from the base station then subsequently determine the receiver equalization requirements to make the system suitable for LMDS services. A complementary study of space-time processing is available in [27].

4.1 Setting

Parkwood Hills is a suburban area mainly consisting of one- and two-storey homes and a few high rise apartment buildings. The streets are generally lined with mature deciduous and coniferous trees. The area is mostly flat, with small ground depressions.

The base station, which houses the receiver, was located on the roof of an apartment building. This location towers above all others within approximately a 2 km radius except for a few similar buildings located to the north. A high rooftop was sought for the experiment as the probability of line-of-sight with subscriber units for LMDS is increased as the height of the base station increases.

The receiver was connected to 2 antennas that provide space diversity measurements of the signal sent from the transmitter. No rooftop location had a perfect view of the entire circular cell at the same time. Therefore the pair of antennas was moved to either the east position or west position depending on which location provided a view, in the direction of the transmitter, that was unobstructed by walls/chimney on the rooftop. In other words, the east position was used to measure signals sent from the east half of the cell while the west position was used to measure signals sent from the west half of the cell. The east base station was located at 140.7 m above sea level while the west base station was at 144.8 m.

The transmitter was set in a trailer with the transmit antenna mounted on a mast. The transmit antenna was located at 4.9 m above ground level. The transmitter trailer was moved to 219 different locations within a 2 km radius of the receiver. At each randomly selected measurement location, the antenna was re-leveled and, using a compass, aimed in the direction of the base station. At each location, a probing signal was sent every second for a period of 200 seconds and measured at each of the receiver antennas quasi-simultaneously. From these measurements, the impulse response of the reference and secondary radio channels could be estimated every second for a period of 200 seconds. In other words, each of the 200 sets of measurements enabled a separate estimation of the reference and secondary channel impulse responses.

The radio channel was sampled for 9 or 10 different antenna separations: 10λ , 15λ , 20λ , 30λ , 40λ , 50λ , 100λ , 250λ , 500λ , and 750λ . For every separation, the signal at both

antennas was sampled as described above. The reference antenna was fixed for all measurements from a particular location. The secondary antenna was displaced relative to the reference antenna for each of the antenna separations.

Measurements were attempted from 219 transmitter locations. Most locations failed due to insufficient signal power at the receiver. Only 69 sites resulted in suitable data for analysis as trees or houses almost always blocked the view of the base station. Due to the high-rise buildings to the north, no measurements were successful from that direction. The signal was too weak.

4.2 Setup

The transmitter equipment was designed to enable the estimation of the impulse response of a radio channel centered at 29.5 GHz with a bandwidth of 80 MHz. The output power at the transmitter was 21.2dBm. The transmitter used a vertically polarized directional antenna (27.56dBi) with a 3 dB beamwidth of ± 4 degrees. A BPSK signal with carrier frequency 29.5GHz was modulated by a reference signal. The reference signal consisted of a 511-bit pseudo random binary sequence (PRBS) generated at 40Mchips/s. The BPSK signal was transmitted and received at the base station by two distinct antennas.

The two receiver antennas were omnidirectional biconical with slanted polarization and a 2dBi gain. The receiver employed coherent quadrature demodulation to obtain the in-phase and quadrature components of the received signal. The demodulated quadrature

signals were sampled at a rate of 160MHz. This sampled complex envelope was subsequently used in the estimation of the channel impulse response.

The BPSK reference signal was recorded in back-to-back configuration in order to obtain its unfiltered in-phase and quadrature components for use in estimation of channel impulse responses.

4.3 Impulse Response Estimation

The estimation was obtained by correlation of the sampled complex envelope of the received signal with the sampled unfiltered quadrature samples of the BPSK/QPSK reference signal. Based on the sampling frequency of the quantities used in the estimation of the impulse response, the discrete samples of the channel impulse response are spaced $0.00625\mu\text{s}$ (i.e. 160MHz) in time.

The upper diagram in Figure 4.1 shows a typical result of the cross-correlation procedure. Noise is a non-trivial component of the received signal. As such, a thresholding technique is employed in order to determine which components of the impulse response estimate are true impulse response echoes. For the purposes of noise thresholding, it is assumed that the background thermal noise is Gaussian with Rayleigh-distributed amplitudes. For the present research effort, interference from man-made noise is assumed non-existent.

Figure 4.1: Typical Estimated Impulse Response

An investigation by Sousa [28] revealed that it is reasonable to assume that valid impulse response echoes are found in less than 5% of the samples. This assumption is considered valid for the present investigation due to the similarity of the propagation environment.

The noise variance, σ_N^2 , used in the calculation of the threshold was evaluated based on the median of the samples of the impulse response estimate since the average of the samples is grossly distorted by the few large samples corresponding to the valid impulse response echoes. The probability that the amplitude exceeds some level ς is given by:

$$P = \exp\left(-\frac{\varsigma^2}{2\sigma_N^2}\right) \quad (4.1)$$

The estimated median level σ_m can be found by setting ζ to σ_m and equating P with 0.5, so that:

$$\sigma_N = \sigma_m / \sqrt{\ln 4} = 0.85 \sigma_m \quad (4.2)$$

The thermal noise standard deviation is therefore 1.4 dB below the median in the absence of interference. The threshold for each of the impulse response estimates is set to achieve a constant false alarm rate (CFAR) independently of the signal-to-noise ratio. To accomplish this, the threshold is set to:

$$\zeta = \eta \sigma_N \quad (4.3)$$

The probability that the noise exceeds the threshold in any given sample without the echo is given by:

$$P_f = \exp(-\eta^2 / 2) \quad (4.4)$$

In this investigation, a false alarm probability, P_f , of 5×10^{-6} was used. From (4.2), η is determined to be approximately 4.94 (i.e. 13.87 dB). Therefore, the threshold is set at 4.94 times the estimated noise level σ_N (i.e. 13.87 dB above σ_N or 12.47 dB above the median signal level, σ_m) as shown in the upper plot of Figure 4.1.

Due to the filtering at the transmitter, each estimated impulse response appears to consist of pulses that are spread in time with a central peak (see the upper plot of Figure 4.1). A

true channel impulse response is expected to consist of a series of dirac delta pulses of varying magnitude and phase. As such, the impulse response estimates were massaged to remove the time width associated with each peak extending above the threshold. For each such peak, all surrounding components were removed (set to zero) in order to more accurately estimate the impulse response. This refined impulse response estimate is depicted in the lower plot of Figure 4.1.

The present investigation is slated to consider two data rates, 10Msps and 40Msps. At each data rate, the equalization requirements for a T-spaced and a T/2-spaced decision feedback equalizer will be evaluated.

In the system model used for the evaluation of equalization requirements, the transmitter and receiver filters were implemented as square root raised cosine filters. As such, their combined response has raised cosine spectral characteristics, which satisfies the Nyquist criterion. The transfer function of a raised cosine filter is given by [13]:

$$H_{RC}(f) = \begin{cases} 1 & 0 \leq |f| \leq (1-\alpha)/2T_s \\ \frac{1}{2} \left[1 + \cos \left(\frac{\pi[(2T_s|f|)-1+\alpha]}{2\alpha} \right) \right] & (1-\alpha)/2T_s < |f| \leq (1+\alpha)/2T_s \\ 0 & |f| > (1+\alpha)/2T_s \end{cases} \quad (4.5)$$

where α is the rolloff factor and T_s is the sampling interval.

The Fourier transform of the above transfer function is the impulse response of a raised cosine filter given by [13]:

$$h_{RC}(t) = \left(\frac{\sin(\pi t / T_s)}{\pi t} \right) \left(\frac{\cos(\pi \alpha t / T_s)}{1 - (4\alpha t / (2T_s))^2} \right) \quad (4.6)$$

A sampled raised cosine pulse with rolloff factor of 0.25 was used to simulate a joint transmit and receive filter that meets Nyquist's first criterion. To generate the required sampled input to the DFE, each impulse response estimate was convolved with a sampled raised cosine pulse generated to simulate the appropriate data rate. The product of the convolution operation was subsequently downsampled to ensure the sampling frequency (one and two samples per symbol for T-spaced and T/2-spaced DFE respectively) required to properly implement the DFE. In addition, the optimum sampling phase was sought out in the process of generating the input to the DFE. System performance related to variations in sampling phase is discussed in the next section.

4.4 Sampling Phase

The input to the DFE consists of a sampled version of the filtered transmitted signal.

This signal can be described as follows:

$$z(t) = h_t(t) \otimes h_c(t) \otimes h_r(t)$$

where $h_t(t)$ is the impulse response of the transmitter

$h_c(t)$ is the impulse response of the channel

$h_r(t)$ is the impulse response of the receiver front end

The sampling rate of the above function depends on the tap spacing of the FFF of the DFE. A T-spaced and a T/2-spaced DFE require one and two equally spaced samples per

symbol interval respectively. The performance of the system will depend on the timing of the sampling (or sampling phase). Consider the data obtained from a reference channel measurement at 50 St-Clair Street.

Figures 4.2 and 4.3 show the dependence of system performance on sampling phase for a T-spaced DFE at data rates of 10 and 40MSPS respectively. The performance is highly sensitive to even small departures from the optimum sampling phase regardless of data rate. For the remainder of this document, the notation (a,b) in reference to DFE configuration signifies “a” feedforward taps and “b” feedback taps. The two curves in Figure 4.2 were generated assuming DFE configurations of (1,0) and (1,1). In both cases, the optimum sampling phase is $4T/16$. The two curves in Figure 4.3 were generated assuming DFE configurations of (3,0) and (3,1). In both cases, the optimum sampling phase is 0. It is expected that the optimum sampling phase will remain constant and any sampling phase error will degrade performance regardless of the DFE configuration.

Figure 4.2: Equalizer Output SNR versus Sampling Phase (T-Spaced, 10MSPS)

Figure 4.3: Equalizer Output SNR versus Sampling Phase (T-Spaced, 40Msps)

Figures 4.4 and 4.5 show the dependence of system performance on sampling phase for a T/2-spaced DFE at data rates of 10 and 40Msps respectively. The performance is insensitive to sampling phase. The two curves in Figure 4.4 were generated assuming DFE configurations of (2,0) and (2,1). The two curves in Figure 4.5 were generated assuming DFE configurations of (6,0) and (6,1). In both Figures, the performance levels are identical for practical purposes and show no dependence on sampling phase. The same behavior is expected regardless of the particular DFE configuration.

Figure 4.4: Equalizer Output SNR versus Sampling Phase (T/2-Spaced, 10Msps)

Figure 4.5: Equalizer Output SNR versus Sampling Phase ($T/2$ -Spaced, 40Msps)

Chapter 5: Results and Discussion

This chapter presents and discusses the results of the channel propagation investigation.

The channel characteristics as well as the equalization requirements based on these channel characteristics are analyzed. The Parkwood Hills measurement campaign that produced the results that will be discussed herein was presented in Chapter 4. The main purpose of this analysis is to investigate the performance of spatial-temporal equalization for LMDS systems in a residential area. It is anticipated that the conclusions drawn from this investigation will be applicable to other similar propagation environments.

Channel characteristics are independent of the data rate that travels through the channel. However, the equalization requirements will vary with the data rate. The optimum equalization requirements were investigated for two different data rates: 10Msps and 40Msps. These are typical data rates intended for an LMDS/LMCS configuration.

For each antenna separation at each transmitter location, the reference signal was sent two hundred times resulting in sufficient data to estimate 200 instantaneous impulse responses. Due to the overwhelming amount of data, it was decided to select a single estimation of the impulse response for each location/antenna separation pair and perform analysis based on that impulse response only. As this investigation is intended to produce results for a fixed broadband wireless system with (likely) line-of-sight path, the impulse response of any individual communication channel is not expected to vary drastically with time. Therefore, it was deemed acceptable to limit the investigation to a

single impulse response. The impulse response that exhibited the highest RMS delay spread was selected for the channel model.

It was observed that the 200 sets of measurements for each location/antenna separation pair yielded similar impulse response estimates. Due to the computational effort involved in analyzing all the recorded data for each location/antenna separation pair and to the similarity observed between all estimates, it was decided to simply consider a small subset of the data in determining the highest RMS delay spread impulse response. For every location/antenna separation pair, twenty distinct impulse response estimates were selected and their RMS delay spread calculated to find the worst-case impulse response.

Let us take a closer look at particular data from Parkwood Hills.

Propagation measurements were attempted at 219 sites within a 2 km radius of the base station. Only 69 sites resulted in successful measurements. The signals sent from the ‘unsuccessful’ sites were not received with enough power to distinguish signal from noise likely due to obstacles in the LOS path between the transmitter and receiver. Each successful location was tested for 9 or 10 different antenna separations: 10λ , 15λ , 20λ , 30λ , 40λ , 50λ , 100λ , 250λ , 500λ , and 750λ . For every antenna separation, the signals from both receiver antennas were sampled every second for a period of 200 seconds.

It is known that at high data rates such as those perceived for LMCS/LMDS applications, multipath delay spread is a major transmission problem leading to ISI. Also, the delay

spread varies with the environment and the characteristics of the transmitter and receiver antennas. Since, for the present set of measurements, a very narrow beamwidth transmitter antennas was used, the multipath delay spread of the received signal is expected to be relatively small.

The receiver/basestation was set up with 2 antennas forming an antenna array. The received signal was recorded at each antenna for a number of different antenna separations. The reference antenna remained fixed whereas the secondary antenna was displaced relative to the reference antenna by an integer number of wavelengths. It was anticipated that the results of this study would shed some light on:

- the effect of multipath on system performance when using decision feedback equalization
- the benefit of spatial diversity
- the effect of antenna separation distance.

The received signal at each antenna was used to determine the channel impulse response for the two channels (between the transmitter and each of the receiver antennas). Each of these pairs of channels typically have differing channel characteristics. These characteristics are a function of the channel impairments encountered between the transmitter and the respective receiver antenna. We investigated how particular channel characteristics can affect the SNR at the output of an equalizer. The output SNR was determined for each antenna individually. In addition, in order to investigate the benefit

of two diversity paths, we considered the output SNR of the equalizer when the input signals from both antennas have been combined.

For the remainder of this document, the wireless channel between the transmitter and the reference antenna will be referred to as the reference channel. Similarly, the wireless channel between the transmitter and the secondary antenna will be referred to as the secondary channel.

Due to the overwhelming amount of data collected during the measurement campaign, it was decided that the analysis of only a portion of the data would be sufficient to draw the desired conclusions. As such, the results for merely three different antenna separations were considered: 10λ , 20λ , and 500λ .

In the following sections, we will discuss in detail the results for one particular location only. In general, the conclusions drawn for this particular site are relevant for all measurement locations. Let's consider the results associated with the 50 St-Clair Street transmitter location. This particular location presents channel characteristics ranging from non-dispersive to highly-dispersive in nature and offers opportunity to compare system performance related to the extent of channel dispersion.

During the measurement campaign, the field crew indicated the presence of trees/leaves in the LOS path between the transmitter and the receiver. First, let's investigate the case where the antenna separation is at a minimum: 10λ .

5.1 “50 St-Clair Street”, 10λ

Figures 5.1 and 5.2 illustrate the estimated impulse responses of the reference and secondary channels respectively, after noise thresholding. Of the 20 instantaneous impulse responses estimated for each of these channels, those depicted exhibited the highest RMS delay spread. The greater the RMS delay spread, the more likely channel equalization will be required. Therefore, the impulse response with the highest RMS delay spread is a good candidate for analysis of equalization requirements.

Figure 5.1: Estimated Impulse Response of the Reference Channel (50 St-Clair Street, 10λ)

Figure 5.2: Estimated Impulse Response of the Secondary Channel (50 St-Clair Street, 10λ)

Of the 20 impulse response estimates obtained for the reference channel, none exhibited multipath delay spread. As such, the RMS delay spread is zero and the impulse response of the reference channel at this location consisted of a single component as depicted in Figure 5.1. This ideal channel exhibited a signal-to-noise ratio of 27.9 dB. Since there is no multipath, ISI is not a factor and will not contribute to signal degradation. The secondary channel exhibited some multipath however. Of the 20 impulse response estimates obtained for the secondary channel, only one exhibited multipath delay spread (see Figure 5.2). This non-ideal channel exhibited a signal-to-noise ratio of 26.4 dB. The impulse response span is 37.5ns and the RMS delay spread is 9.2ns (see table C7). The low RMS delay spread can be attributed to the proximity and/or relative small size of the

delayed multipath component as compared to the main component. In this case, the channel acts as a filter that causes two copies of the same signal to be ‘read’ by the receiver at different times. The copies will have traveled along two different paths to reach the receiver. Each path differs in length causing the copies of a signal to arrive at different delays. Furthermore, each copy will be received with a different signal strength (or power) depending on the attenuation factors encountered between the transmitter and the receiver.

The calculated impulse response span and RMS delay spread associated with each location/selected antenna separation pairs are tabulated in Appendix C. The File Name provides an indication of the location and antenna separation corresponding to the associated calculated values. The “File Name” values follows the convention “a_b” where “a” represents the location of the transmitter and “b” indicates the antenna separation associated with the measured data that resulted in the tabulated channel characteristics. A1, A3, and A9 represent antenna separations of 10, 20, and 500 wavelengths respectively.

Several measurement locations are characterized by long impulse response spans. These spans are either the result of valid distant impulse response echoes or noise components that did not get eliminated by thresholding. Figure 4.1 is a good example of a lengthy impulse response span where the distant echo is likely the result of noise.

Typical values of RMS delay spread for mobile radio channels are on the order of microseconds [13]. However, the highly directional nature of the transmit antenna used in this campaign significantly reduces multipath reflections which is generally reflected in the RMS delay spread values encountered in the present investigation.

5.1.1 Symbol Rate: 10Msps

For a symbol rate of 10Msps, the symbol duration is 100ns. Compared to the symbol duration, the impulse response span for both channels is small at worst. As the reference channel is an ideal one, any data rate up to approximately 40 – 80 Msps, the resolution limit for these measurements, can be pumped through the channel and the signal will remain undistorted. The secondary channel however is not ideal at this location. The estimated channel impulse response consists of two components, as shown in Figure 5.2, which will cause some distortion.

The system model was implemented with a decision feedback equalizer at the receiver to investigate the possible performance improvement that may be expected.

The simulation was conducted assuming an average input SNR of 20 dB into the DFE.

To accomplish this, the sample noise variance, σ_N^2 , was set to a level such that:

$$\frac{SP}{\sigma_N^2} = 100 \quad (5.1)$$

where SP is the received signal power obtained as follows:

$$SP = \frac{1}{T} \sum_i |h_t(i\Delta t) \otimes h_c(i\Delta t) \otimes h_r(i\Delta t)|^2 \Delta t$$

where $h_t(t)$ is the impulse response of the transmitter

$h_c(t)$ is the impulse response of the channel

$h_r(t)$ is the impulse response of the receiver front end

Δt is the sampling period = 160 MHz

$T = (\# \text{ of samples per symbol}) \Delta t$

The combined impulse response of the transmitter and receiver front end is a sampled raised cosine function with a rolloff factor of 0.25. The value 100 in equation (5.1) is the linear representation of 20dB. This value of SNR was selected in order to investigate the effects of ISI when the signal power, as compared to the noise power, is of reasonable strength.

The first simulation, considering the data obtained at 50 St-Clair Street, assumed a symbol-spaced DFE. Initially, the performance capabilities were investigated for each diversity channel individually as discussed below.

The output SNR associated with the reference channel remained constant at 20.04 dB regardless of the number of feedforward and feedback taps since the reference channel impulse response consists of a single component (i.e. no multipath components.) For such a channel, equalization offers no advantage. Appendix D provides details of achievable system performance for various DFE configurations given a data rate of 10 Msps.

The secondary channel exhibited some multipath. Based on the magnitude of the RMS delay spread, the effect of the multipath is not expected to be significant. The output SNRs of the DFE associated with the secondary channel are 15.13, 19.34, and 19.66 dB for T-spaced DFEs with configurations (1,0), (3,1), and (4,2) respectively (see Table D13). Such results indicate that equalization offers an improvement in performance although the increase in performance seems to taper off as performance values approach 20 dB as expected. The output SNR for a DFE with configuration (3,1) indicates a near optimal performance. To achieve an improvement in performance, a simple linear equalizer can be implemented for such a channel with little multipath. The output SNR for a DFE configuration that mimics a linear equalizer (i.e. feedforward taps only, no feedback taps) indicates increasing performance with an increasing number of feedforward taps. No equalization at all is necessary. However, the use of increasing numbers of feedforward and feedback taps does improve performance. The simulation only considered combinations of up to 10 feedforward and 10 feedback taps. Due to space constraints only a few combinations are tabulated in Appendix D.

The simulation was conducted assuming an input SNR of 20 dB into the DFE. As such, the maximum theoretical output SNR is 20 dB. Some results (in Appendix D) indicate a very slight exceedence of the theoretical maximum output SNR. These small departures can be attributed to filtering effects.

Next, we considered the combination of diversity paths from both antennas to improve system performance. In the event that one of the two channels experiences severe

degradation, it is beneficial that a source of diversity be available. It is highly unlikely that both channels will experience severe degradation at the same time. Figure 5.3 depicts the diversity combining DFE structure investigated in the present study.

Figure 5.3: Diversity Combining Decision Feedback Equalizer

The combined diversity scenario was conducted assuming an average combined input SNR of 20dB. To accomplish this, the noise variance, σ_N^2 , was set to a level such that:

$$\frac{1}{2} \left(\frac{SP^{(ref)}}{\sigma_N^2} + \frac{SP^{(sec)}}{\sigma_N^2} \right) = 100 \quad (5.2)$$

where $SP^{(ref)}$ and $SP^{(sec)}$ are the received signal powers at the input to the combined-diversity DFE from the reference and secondary channels respectively. These quantities are obtained as follows:

$$SP^{(ref)} = \frac{1}{T} \sum_i \left| h_t(i\Delta t) \otimes h_c^{(ref)}(i\Delta t) \otimes h_r(i\Delta t) \right|^2 \Delta t$$

$$SP^{(sec)} = \frac{1}{T} \sum_i \left| h_t(i\Delta t) \otimes h_c^{(sec)}(i\Delta t) \otimes h_r(i\Delta t) \right|^2 \Delta t$$

where $h_t(t)$ is the impulse response of the transmitter

$h_c^{(ref)}(t)$ and $h_c^{(sec)}(t)$ are the impulse responses of the

reference and secondary channels respectively

$h_r(t)$ is the impulse response of the receiver front end

Δt is the sampling period = 160 MHz

$T = (\# \text{ of samples per symbol}) \Delta t$

The combined impulse response of the transmitter and receiver front end is a sampled raised cosine function with a rolloff factor of 0.25. The value 100 in equation (5.2) is the linear representation of 20dB.

The output SNR of the DFE for various combinations of number of feedforward and feedback taps indicates near optimal performance with little or no equalization. Due to the relatively non-dispersive nature of each of the channels, it is expected that near optimal performance would be achievable without a complex DFE structure. Regardless, the use of increasing numbers of feedforward and feedback taps improves performance. For T-spaced DFE configurations of (1,0), (3,1), and (4,2), diversity combining can achieve levels of 22.00, 22.87, and 22.96 dB respectively (see Table D13). The benefit of diversity in a communication system is evident by the higher attainable SNR at the output of the DFE. The results tabulated in Appendix D show that combined diversity

yields an output SNR in excess of that that would be possible with either of the diversity channels alone. Compared to the ideal reference channel, combined diversity offers a 2 to 3 dB performance improvement for the tap combinations tabulated in Appendix D.

With a constant average input power, the output SNR of the DFE increases with the number of diversity paths. In other words, for the same transmitter power, increasing the number of diversity paths can increase the output SNR of a communication system. In the case of two diversity paths (as is the case in the present investigation), for an average input SNR of 20 dB and depending on the characteristics of the multipath channels, it is possible to achieve a maximum output SNR of 23 dB since the received powers from the two antennas add when combined properly.

The second simulation, using the data recorded at 50 St-Clair Street, assumed a $T/2$ -spaced DFE to investigate the performance as compared to the T -spaced equalizer. A $T/2$ -spaced equalizer accepts two samples per symbol period into the feedforward filter. The feedforward span of the $T/2$ -spaced equalizer requires twice as many taps as the T -spaced counterpart to cover the same time span. Again, for the ideal reference channel, equalization offers no improvement in performance regardless of the configuration of the feedforward filter. Performance is optimal (i.e. 20 dB) regardless of the tap spacing in the FFF. In the event of a non-ideal channel, the $T/2$ -spaced equalizer whose delay line spans the same time as its T -spaced counterpart does indicate improved performance. The $T/2$ -spaced equalizer, for the same feedforward filter time span, offers more degrees of freedom in compensating for the non-ideal channel than the T -spaced equalizer.

The tabulated data in Appendix D provides a means of comparing the performance of a T-spaced versus a T/2-spaced equalizer for a data rate of 10Msps based on the achievable output SNR. Due to space constraint, the tabulated values consider DFE configurations of (1,0), (3,1), and (4,2) only for the T-spaced scenario and DFE configurations of (2,0), (6,1), and (8,2) only for the T/2-spaced scenario. Although the number of feedforward taps differs for these two scenarios, the time spans of the feedforward filters are identical for comparison purposes.

The reference channel exhibits optimum performance regardless of the particular configuration of the feedforward filter. The slight departure from the optimum level of 20 dB is attributed to filtering effects. No performance enhancement was seen as a result of selecting a T/2- over a T-spaced DFE for the reference channel alone. The results for output SNR associated with the secondary channel as well as for the combined-diversity case show a better performance using a T/2-spaced equalizer. The secondary channel sees an increase from 15.13 dB to 19.90 dB for a FFF of one symbol duration and no feedback taps. Similarly, note the increase from 19.34 dB to 20.14 dB for a FFF of three symbol durations and one feedback tap and an increase from 19.66 dB to 20.17 dB for a FFF of four symbol durations and two feedback taps (see Tables D13 and D14).

A graphical representation of achievable performance for a diversity-combining scenario as a result of increasing the number of feedforward and feedback taps is depicted in Figures 5.4 and 5.5. These figures are contour plots of constant output SNR as a function of the number of feedforward and feedback taps. Figures 5.4 and 5.5 represent the achievable performance of a T-spaced and a T/2-spaced DFE respectively assuming a

symbol rate of 10Mps. For example, Figure 5.4 indicates that, for the 50 St-Clair Street location, two feedforward taps at each antenna and one feedback tap would give an output SNR of approximately 22.7 dB which is only 0.3 dB worse than the SNR achieved with, say, six feedforward taps per antenna and three feedback taps.

Figure 5.4: Contour Plot of DFE Output SNR for Combined Diversity (Symbol Rate: 10Mps, 10λ , T-spaced, 50 St-Clair Street)

Figure 5.5: Contour Plot of DFE Output SNR for Combined Diversity (Symbol Rate: 10Msps, 10λ , T/2-spaced, 50 St-Clair Street)

Now that we have seen that satisfactory performance can be achieved at this location using a DFE for a data rate of 10Msps, let's see how such systems can handle a data rate of 40Msps.

5.1.2 Symbol Rate: 40Msps

A symbol rate of 40Msps implies a symbol duration of 25ns. As in the 10Msps case, compared to the symbol duration, the impulse response span for both channels is small at worst.

Due to the increased data rate, the signal will be affected differently than the 10Msps signal passing through the reference and secondary channels. Channel equalization is needed when the RMS delay spread becomes a significant fraction of the symbol duration [15]. As the symbol duration approaches the value of the RMS delay spread, equalization requirements increase. Since a symbol rate of 40Msps implies a shorter symbol duration than for a 10Msps symbol rate, the channel output will certainly require more equalization than previously seen for the 10Msps scenario in order to achieve similar levels of performance. Appendix E provides details of achievable system performance for various DFE configurations given a data rate of 40 Msps.

The same general statements can be made for the 40Msps investigation as the 10Msps investigation:

- An ideal channel does not require equalization.
- The use of increasing numbers of feedforward and feedback taps improves performance in multipath channels.
- The T/2-spaced equalizer whose delay line spans the same time as its T-spaced counterpart shows improved performance.
- Diversity-combining enables higher attainable SNR at the output of the DFE than is achievable without the use of a diversity technique.

Contour plots of constant output SNR as a function of the number of feedforward and feedback taps are depicted in Figures 5.6 and 5.7 for a diversity-combining scenario.

Figures 5.6 and 5.7 represent the achievable performance of a T-spaced and a T/2-spaced DFE respectively assuming a symbol rate of 40Msps.

Figure 5.6: Contour Plot of DFE Output SNR for Combined Diversity (Symbol Rate: 40Msps, 10λ , T-spaced, 50 St-Clair Street)

Figure 5.7: Contour Plot of DFE Output SNR for Combined Diversity (Symbol Rate: 40Msps, 10λ , T/2-spaced, 50 St-Clair Street)

Figure 5.6 indicates that a (2,2) T-spaced DFE can produce an output SNR of approximately 22.6 dB. That same contour line shows that increasing the number of feedforward filter tap to 3 or 4, while keeping the number of feedback taps at 2, does not offer an improvement in performance.

The results tabulated in Appendix E show that for similarly configured feedforward and feedback filters (i.e. the same number of taps), the output SNRs at 40Msps are lower than the associated 10Msps results for both T and T/2-spaced DFEs as expected.

As a result, the higher the data rate, the more likely equalization will be required to achieve satisfactory performance levels. Generally, to guarantee a particular level of performance, higher data rate applications will require more equalization than lower data rate applications.

At each transmitter location, measurements were recorded for a number of receiver antenna separations. As previously indicated, the results for only three different antenna separations were analyzed. The discussion thus far dealt with the results for the case of a 10λ separation. For a separation of 20λ , the reference antenna remained fixed and the secondary antenna was moved 10 more wavelengths away.

5.2 “50 St-Clair Street”, 20λ

As the receiving antenna array spacing is changed, the channel impulse response to each receiving antenna may change due to changes in multipath and antenna coupling behavior. The reference channel characteristics differ from those calculated in the previous section (i.e. 10λ .) Figures 5.8 and 5.9 illustrate the estimated impulse responses of the reference and secondary channels respectively, after noise thresholding. The secondary channel exhibited ideal behavior. However, the reference channel is characterized by an IR span of 50ns. This channel also exhibits a non-causal (or non-minimum-phase) characteristic, as the highest echo component is not the first non-zero component.

Figure 5.8: Estimated Impulse Response of the Reference Channel (50 St-Clair Street, 20λ)

Figure 5.9: Estimated Impulse Response of the Secondary Channel (50 St-Clair Street, 20λ)

It was noted that trees/leaves were observed in the LOS path between the transmitter and the receiver. The received signal is sensitive to even the smallest of obstacles. It is also possible that other unobserved movement/changes in the channels contributed to the presence or absence of multipath components. The differing channel characteristics tabulated in Appendix C can be explained by changes in the channel between the 10λ and the 20λ measurements.

5.2.1 Symbol Rate: 10Msps

For both T- and T/2-spaced equalizers, the output SNR of the DFE associated with the reference channel alone indicates near optimal performance with little or no equalization.

The reference channel shows performance levels of 19.38, 19.96 and 20.01 dB with combinations of feedforward and feedback taps of (1,0), (3,1) and (4,2) respectively when using a T-spaced equalizer. Better performance levels are achievable using similar length feedforward filters with T/2-spaced taps. A T-spaced DFE with (1,0) has the same feedforward filter length as a T/2-spaced DFE with (2,0). For the reference channel, comparing performance levels for similar length feedforward filters, a (2,0) T/2-spaced DFE outperforms the (1,0) T-spaced DFE by approximately 0.8 dB. Increasing the length of the feedforward filters will result in even smaller performance differences. Regardless, in the case of a non-ideal channel, the use of increasing numbers of feedforward and feedback taps does improve performance, although extremely moderately in this case.

The output SNR of the DFE associated with the secondary channel remained constant at optimum performance (20.04 dB for T-spaced, 20.32 dB for T/2-spaced) regardless of the number of feedforward and feedback taps. The slight departure from the optimum level of 20 dB is attributed to filtering effects. The impulse response of this channel consists of a single component. For such an ideal channel, equalization offers no advantage.

Combined diversity yields an output SNR in excess of that that would be possible with either of the diversity channels alone. The T-spaced combined-diversity DFE is capable of performance levels of 22.08, 22.93, and 22.99 dB for configurations of (1,0), (3,1), and (4,2) respectively (see Table D13). Similar configurations for either the reference channel or secondary channel alone yield performance levels approximately 2 or 3 dB lower.

Contour plots of achievable performance for a diversity-combining scenario as a result of increasing the number of feedforward and feedback taps are depicted in Figures 5.10 and 5.11. Figures 5.10 and 5.11 represent the achievable performance of a T-spaced and a T/2-spaced DFE respectively assuming a symbol rate of 10Msps.

Figure 5.10: Contour Plot of DFE Output SNR for Combined Diversity (Symbol Rate: 10Msps, 20λ , T-spaced, 50 St-Clair Street)

Figure 5.11: Contour Plot of DFE Output SNR for Combined Diversity (Symbol Rate: 10Msps, 20λ , T/2-spaced, 50 St-Clair Street)

Figure 5.10 indicates that a (2,2) T-spaced DFE offers the same performance capabilities as a (8,2) T-spaced DFE. Figure 5.11 indicates that no feedback taps are needed for a T/2 spacing in this scenario.

The upgrade to a T/2-spaced equalizer shows improved performance over its T-spaced counterpart and reduces any sensitivity to non-optimum sampling phase.

5.2.2 Symbol Rate: 40Msps

All ideas, concepts, and arguments described under the same heading in the discussion associated with the 10λ antenna separation investigation, in general, apply here.

A contour plot of achievable performance for a diversity-combining scenario as a result of increasing the number of feedforward and feedback taps is depicted in Figures 5.12 and 5.13. Figures 5.12 and 5.13 represent the achievable performance of a T-spaced and a T/2-spaced DFE respectively assuming a symbol rate of 40Mps.

Figure 5.12: Contour Plot of DFE Output SNR for Combined Diversity (Symbol Rate: 40Mps, 20λ , T-spaced, 50 St-Clair Street)

Figure 5.13: Contour Plot of DFE Output SNR for Combined Diversity (Symbol Rate: 40Msps, 20λ , T/2-spaced, 50 St-Clair Street)

Figure 5.12 indicates that T-spaced DFE structures ranging in complexity from (3,2) to (10,10) will not be capable of performing even 0.05 dB better than a (3,2) T-spaced DFE. Figure 5.13 indicates that no feedback taps are necessary for a T/2 spacing in this scenario.

The results tabulated in Appendix E show that for similarly configured feedforward and feedback filters (i.e. the same number of taps), the output SNRs at 40Msps are lower than the associated 10Msps results for both T and T/2-spaced DFEs as expected.

5.3 “50 St-Clair Street”, 500λ

The 500λ scenario exhibited vastly different reference channel characteristics as indicated in Appendix C. The IR span is 2337.5ns and the RMS delay spread is 0.3192μs (see Table C7). This marked departure from the behavior encountered previously for the reference channel can also be explained by the change in multipath with position. A delay spread of 2.3 ns corresponds to a path difference of approximately 690m ($2.3 \times 10^{-6} \text{s} \times 3 \times 10^8 \text{m/s}$). This distant echo is the result of a discrete reflection from a building or other large object in the general vicinity or noise that was not removed by thresholding. Figures 5.14 and 5.15 illustrate the estimated impulse responses of the reference and secondary channels respectively, after noise thresholding.

Figure 5.14: Estimated Impulse Response of the Reference Channel (50 St-Clair Street, 500λ)

Figure 5.15: Estimated Impulse Response of the Secondary Channel (50 St-Clair Street, 500λ)

The secondary channel exhibited relatively insignificant multipath and will not be discussed further. However, the reference channel characteristics indicate considerable delay spread. No definite conclusions as to the necessity of equalization can be drawn based on the IR span alone as this characteristic does not consider the relative sizes of the impulse response components. The RMS delay spread is a more useful quantity in establishing the need for equalization. The secondary channel has an RMS delay spread of $0.3192\mu\text{s}$. This relatively high RMS delay spread can be attributed to the time delay of the multipath component.

5.3.1 Symbol Rate: 10Msps

One source [15] claims that channel equalization is needed when the RMS delay spread becomes a significant fraction of the symbol duration. Based on the relative magnitudes of these two quantities (i.e. symbol duration = $0.1\mu\text{s}$, RMS delay spread = $0.3192\mu\text{s}$), it is expected that the output of the reference channel will require equalization. The output SNR does not reach the levels as discussed previously due to the more significant time dispersive characteristics of the reference channel. Assuming a T-spaced feedforward filter, the output SNR for a DFE with configurations (3,1) and (4,2) is 15.75 dB and 15.77 dB respectively. With no equalization at all (i.e. (1,0)), the DFE SNR is 15.73 dB (see Table D13). There is relatively no improvement in output SNR as the span of the feedforward and feedback filters is much smaller than the impulse response span. Due to the significant distant impulse response component (see Figure 5.14), the DFE is unable to handle/mitigate the effect of the time-delayed copy of the received signal since the number of feedforward and feedback taps is too small to counteract the echo at 2337 ns. This would require filter lengths of approximately 23 to 24 symbol intervals at 10 Msps.

Combined diversity shows an improvement in performance over the results for the reference channel only. The results tabulated in Appendix D indicate that the T-spaced DFE whose input is the combination of both channel outputs can achieve 18.29, 18.93, and 18.99 dB for configurations of (1,0), (3,1), and (4,2) respectively. In this case, note that combined diversity does not always indicate an improvement in performance over the secondary channel whose achievable performance for the same three configurations is 16.41, 19.41, and 19.75 dB respectively (see Table D13). The expected behavior is that combined diversity would attain a level of performance equal to or greater than that of

the best channel. The tabulated results do not reflect the expected norm and can be attributed to the scaling of the noise variance.

Consider the relative amplitudes of the components in the impulse responses of the reference and secondary channels (see Figures 5.14 and 5.15). The noise variance calculated as described in equation (5.1) above for the secondary channel results in a particular value, relative to the magnitude of the secondary channel impulse response components, which ensures an average input SNR of 20dB. The noise variance calculated as described in equation (5.2) above for the combined diversity scenario takes into account the reference channel input. As the magnitudes of the impulse response components of the reference channel are significantly greater than those of the secondary channel, the resulting noise variance (to ensure an average input SNR of 20dB) is larger than the value calculated for the single (secondary) channel investigation. The higher noise variance imposed on the secondary channel for the combined diversity scenario results in an apparent degradation in performance. Regardless, diversity combining produces satisfactory results in the event one of the two channels experiences performance degradation.

As encountered previously, upgrading to a $T/2$ -spaced equalizer will offer an improvement in performance. The level of improvement is minimal in this case. For example, consider the reference channel. When comparing the performance of a T -spaced equalizer with (3,1) and a $T/2$ -spaced equalizer with (6,1), the improvement in performance is 0.21 (15.96-15.75) dB. Similar improved behavior is noted for all other reference channel tap configurations for this location. The output SNR of the $T/2$ -spaced

DFE exceeds that of the T-spaced DFE for the secondary channel considered alone as well. Similar to the T-spaced scenario, the combined diversity output SNR for the T/2-spaced investigation indicates lower performance levels than the secondary channel alone. The T/2-spaced combined diversity scenario yields output SNRs of 19.17, 19.36, and 19.41 dB for configurations of (2,0), (6,1), and (8,2) respectively while the secondary channel alone reached levels of 19.82, 20.13, and 20.15 dB for the same configurations (see Table D14). This is attributed to the scaling of the noise variance as described previously.

Contour plots of achievable performance for a diversity-combining scenario as a result of increasing the number of feedforward and feedback taps are depicted in Figures 5.16 and 5.17. Figures 5.16 and 5.17 represent the achievable performance of a T-spaced and a T/2-spaced DFE respectively assuming a symbol rate of 10Msp/s.

Figure 5.16: Contour Plot of DFE Output SNR for Combined Diversity (Symbol Rate: 10Mps, 500 λ , T-spaced, 50 St-Clair Street)

Figure 5.17: Contour Plot of DFE Output SNR for Combined Diversity (Symbol Rate: 10Msps, 500λ , T/2-spaced, 50 St-Clair Street)

5.3.2 Symbol Rate: 40Msps

All ideas, concepts, and arguments described under the same heading in the discussion associated with the 10λ antenna separation investigation, in general, apply here.

Contour plots of achievable performance for a diversity-combining scenario as a result of increasing the number of feedforward and feedback taps are depicted in Figures 5.18 and 5.19. Figures 5.18 and 5.19 represent the achievable performance of a T-spaced and a T/2-spaced DFE respectively assuming a symbol rate of 40Msps.

Figure 5.18: Contour Plot of DFE Output SNR for Combined Diversity (Symbol Rate: 40Msps, 500 λ , T-spaced, 50 St-Clair Street)

Figure 5.19: Contour Plot of DFE Output SNR for Combined Diversity (Symbol Rate: 40Msps, 500 λ , T/2-spaced, 50 St-Clair Street)

Channel equalization is needed when the RMS delay spread becomes a significant fraction of the symbol duration. Since a data rate of 40Msps implies a shorter symbol duration than for the 10Msps data rate, channel outputs will require more equalization to achieve similar levels of performance.

The results tabulated in Appendix E show that, for similarly configured feedforward and feedback filters, the output SNRs associated with a symbol rate of 40Msps are lower than the associated 10Msps results for both T and T/2-spaced DFEs as expected.

5.4 General Results for All Measurement Locations

As opposed to the detailed investigation of the results obtained at 50 St-Clair Street as described in the previous sections, the remainder of this chapter will consider more general results. The following sections will provide general statements considering all measurement locations.

5.4.1 Modulation Considerations

The present investigation used the DFE output SNR as the measure of performance. This measure of performance is useful when selecting a modulation scheme for any given communication system. Quadrature Amplitude Modulation (QAM) schemes are important in LMDS systems. The following section demonstrates the relationship between SNR and the probability of bit error for commonly used QAM modulation schemes.

Rectangular signal constellations are commonly used in LMDS implementations. The current investigation employed QPSK (or 4-QAM) whose signal constellation consists of four modulating signals. LMDS commonly uses other higher-order modulating QAM schemes such as 16-QAM and 64-QAM. In these schemes, signal points are more closely spaced in the signal constellation plane. As such, higher order modulation schemes are more sensitive to noise and interference. To ensure a given probability of bit error, higher order modulation schemes require higher signal to noise ratios.

The probability of bit error is defined as [9]:

$$P_B \cong \frac{2(1-L^{-1})}{\log_2 L} Q \left[\sqrt{\left(\frac{3 \log_2 L}{L^2 - 1} \right) \frac{2E_b}{N_0}} \right] \quad (5.3)$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp\left(-\frac{u^2}{2}\right) du$

L^2 = number of signal points in the modulating signal constellation

However,

$$SNR = \frac{E_b}{N_0} \log_2 L^2 = 2 \frac{E_b}{N_0} \log_2 L$$

Therefore equation (5.3) can be rewritten as:

$$P_B \cong \frac{2(1-L^{-1})}{\log_2 L} Q \left[\sqrt{\left(\frac{3 \log_2 L}{L^2 - 1} \right) \frac{SNR}{\log_2 L}} \right] \quad (5.4)$$

Figure 5.20 shows the probability of bit error versus SNR for QPSK ($L=2$), 16-QAM ($L=4$), and 64-QAM ($L=8$) modulations.

Figure 5.20: Probability of Bit Error for QAM schemes

Consider an LMDS system whose quality of service ensures a bit error probability of 10^{-4} . If a QPSK modulation scheme is used, the required SNR is approximately 8dB. To ensure the same probability of bit error, 16-QAM and 64-QAM modulation schemes require SNRs of approximately 16dB and 23dB respectively.

In this investigation, the unequalized portion of the signal plus noise is assumed Gaussian. This assumption allows the SNR values discussed in this investigation to be used in conjunction with any of the curves in Figure 5.20 to find a suitable modulation scheme.

5.4.2 Space Diversity

The receiver antenna array consists of two antennas. The received signal was recorded at each antenna for a number of different antenna separations. The reference antenna remained fixed whereas the secondary antenna was displaced relative to the reference antenna by an integer number of wavelengths. The present study intended to investigate the performance characteristics related to the effect of antenna separation distance.

In a cluttered environment, it is generally accepted that two signals are independent if they are separated by a minimum of $\frac{1}{2} \lambda$. For non-cluttered environments, such as the rooftop considered in this investigation, larger separations are necessary to ensure independence of the diversity signals. Here we compare the frequency of achievable performance levels for the three antenna separations considered in this study given a symbol rate of 10 Msps. Figures 5.21, 5.22, and 5.23 show the frequency of occurrence

of achievable DFE output SNRs for antenna separations of 10λ , 20λ , and 500λ given (1,0), (3,1), and (4,2) T-spaced DFEs respectively.

Figure 5.21: Histogram of Output SNR of (1,0) T-Spaced DFE for Combined Diversity (Symbol Rate: 10Msps)

Figure 5.22: Histogram of Output SNR of (3,1) T-Spaced DFE for Combined Diversity (Symbol Rate: 10Msps)

Figure 5.23: Histogram of Output SNR of (4,2) T-Spaced DFE for Combined Diversity (Symbol Rate: 10Msps)

The above histograms are very noisy, making it difficult to extract any firm conclusions. Regardless, a simple comparative glance at Figures 5.21 to 5.23 clearly demonstrates that increasing the number of feedforward and feedback taps will improve performance levels. Notice how the frequency of occurrence rises in the 23 dB block, for all three antenna separations, as DFE complexity increases. This comparison reinforces conclusions drawn as a result of the detailed discussion associated with the 50 St-Clair Street location. A more meaningful representation of this data in terms of cumulative distributions is discussed later.

Notice that there are some outliers at lower output SNR levels, which raises the question: “Why didn’t equalization work for all locations?” Consider the lone instance at output SNR=13 dB in Figure 5.23. This outlier is associated with the Philips and Falaise Street measurement location whose reference and secondary channel estimated impulse responses are depicted below.

Figure 5.24: Impulse Response estimates of Reference and Secondary Channels at Philip and Falaise Measurement Location

The low SNR (13 dB) is likely due to the significant impulse response echos of the secondary channel at delay=4 μ s and the reference channel at approximately 7.2 μ s, the result of reflections from buildings or other large objects some distance away. For a 10Msps symbol rate, the symbol duration is 0.1 μ s. A T-spaced FFF with 4 feedforward

taps covers a time span of $0.4\mu\text{s}$ ($4 \times 0.1\mu\text{s}$) and the feedback portion with two taps covers $0.2\mu\text{s}$. Therefore, the entire DFE range is $0.6\mu\text{s}$. Considering a 10Msps symbol rate, the reference and secondary channel impulse responses span approximately 65 and 33 symbol intervals respectively, which is significantly longer than the 6-symbol DFE span. As such, both channels are characterized by distant echoes that fall outside the range of the DFE unless a delay is implemented in the feedback filter. The present study did not consider implementation of variable delays in the feedback filter based on channel echoes. However, let's see how the implementation of such a delay can improve performance capabilities in this case. The following lookup tables show the achievable output SNRs of a combined diversity scenario given the data recorded from the Philip and Falaise Street measurement location. Table 5.1 assumes no delay in the feedback filter whereas Table 5.2 assumes a delay of approximately 33 symbol intervals from the main impulse response echo. This delay is intended to handle the secondary channel's distant echo. The column number represents the number of feedforward filter taps. The row number represents the number of feedback filter taps.

Table 5.1: Output SNR of Combined Diversity without Delay in Feedback Filter at Philip and Falaise Street (T-spaced, 10 Msps)

FB\FF	1	2	3	4	5	6	7	8	9	10
0	12.60	12.76	13.25	13.28	13.37	13.37	13.40	13.40	13.40	13.40
1	13.12	13.30	13.33	13.36	13.44	13.44	13.47	13.47	13.48	13.48
2	13.20	13.39	13.41	13.44	13.45	13.46	13.48	13.48	13.49	13.49
3	13.21	13.41	13.43	13.46	13.47	13.48	13.48	13.49	13.50	13.50
4	13.22	13.41	13.43	13.47	13.48	13.49	13.49	13.49	13.50	13.50
5	13.22	13.41	13.43	13.47	13.48	13.49	13.49	13.50	13.50	13.50
6	13.22	13.41	13.43	13.47	13.48	13.49	13.49	13.50	13.50	13.50
7	13.22	13.41	13.43	13.47	13.48	13.49	13.49	13.50	13.50	13.50
8	13.22	13.41	13.43	13.47	13.48	13.49	13.49	13.50	13.50	13.50
9	13.22	13.41	13.43	13.47	13.48	13.49	13.49	13.50	13.50	13.50
10	13.22	13.41	13.43	13.47	13.48	13.49	13.49	13.50	13.50	13.50

Table 5.2: Output SNR of Combined Diversity with Delay in Feedback Filter at Philip and Falaise Street

FB\FF	1	2	3	4	5	6	7	8	9	10
0	12.60	12.76	13.25	13.28	13.37	13.37	13.40	13.40	13.40	13.40
1	12.60	12.76	13.25	13.28	13.37	13.37	13.40	13.40	13.40	13.40
2	12.60	12.77	13.25	13.28	13.37	13.38	13.40	13.40	13.41	13.41
3	12.61	12.78	13.27	13.31	13.40	13.42	13.44	13.44	13.45	13.45
4	12.69	13.02	13.54	13.63	13.73	13.77	13.79	13.80	13.81	13.82
5	16.59	16.98	18.10	18.16	18.37	18.38	18.44	18.44	18.46	18.46
6	17.40	17.83	18.45	18.51	18.86	18.87	18.94	18.94	18.96	18.96
7	17.60	18.04	18.73	18.79	18.95	18.96	19.07	19.07	19.09	19.09
8	17.65	18.10	18.80	18.87	19.03	19.04	19.09	19.09	19.12	19.12
9	17.66	18.11	18.82	18.88	19.05	19.06	19.11	19.11	19.13	19.13
10	17.66	18.11	18.82	18.89	19.05	19.06	19.12	19.12	19.13	19.13

Notice that higher output SNRs are achievable when a delay is implemented in the feedback filter to mitigate the effects of an impulse response echo that would otherwise be outside the range of the DFE. For example, a (3,5) T-spaced DFE without delay in the feedback filter can achieve an output SNR of 13.43 dB whereas a similarly configured DFE with an appropriate delay can achieve 18.10 dB at this location. In this case, for lower complexity DFEs, it appears that no implementation of delay achieves higher performance levels. For example, consider the (3,1) T-spaced DFE. Although only a mild difference, the “no delay” scenario shows a performance capability of 13.33 dB whereas the “delay” scenario shows a slightly lower performance capability of 13.25 dB. This can be attributed to the second impulse response echo of the reference channel. With no delay, the feedback filter handles the second echo from the reference channel due to its proximity to the main echo. With the delay, the feedback filter concentrates on the echo from the secondary channel and no longer operates on the second echo from the reference channel. In neither of the scenarios considered above (i.e. no delay versus 33 symbol delay) is the reference channel echo at $7.2\mu\text{s}$ handled.

An investigation into some of the other outlying instances with relatively low output SNR revealed similar channel characteristics (i.e. with distant echos).

The histogram representations do not easily permit commentary on the effects of antenna separation distance. Rather, a cumulative distribution view of the data will prove more useful. Another look at the same general data in terms of cumulative distributions is provided in Figures 5.25, 5.26, and 5.27.

Figure 5.25: Cumulative Distribution of Output SNR for (1,0) T-Spaced DFE for Combined Diversity (Symbol Rate: 10Msps)

Figure 5.26: Cumulative Distribution of Output SNR for (3,1) T-Spaced DFE for Combined Diversity (Symbol Rate: 10Msps)

Figure 5.27: Cumulative Distribution of Output SNR for (4,2) T-Spaced DFE for Combined Diversity (Symbol Rate: 10Msps)

In Figures 5.26 and 5.27 above, each of the three curves are very similar and mainly overlapping for the higher output SNRs. However, for output SNRs in the 15 to 20 dB range, the 20λ separation consistently shows a significant improvement over the 10λ separation. Figure 5.26 indicates that the probability that the output SNR of the DFE will

be less than or equal to 20 dB is approximately 0.22 and 0.17 for antenna separations of 10λ and 20λ respectively. Figure 5.27 indicates that the probability that the output SNR of the DFE will be less than or equal to 20 dB is approximately 0.18 and 0.12 for antenna separations of 10λ and 20λ respectively.

The 500λ results also show an improvement over the 10λ results in the 15 to 20 dB range. However, the relative performance of 20λ and 500λ is not always consistent. Two out of the three cases indicate 20λ outperforms 500λ . All results in this investigation were generated based on measurements recorded at 69 locations. Perhaps a more significant sample size would produce results with more consistent behavior. Furthermore, a comparison of the Figures 5.25 to 5.27 indicates improved performance levels with increasing DFE complexity. Consider the 20λ curves in each of the above three graphs. Figures 5.25, 5.26, and 5.27 indicate that the probability that the output SNR of the DFE will be less than or equal to 20 dB is approximately 0.45, 0.2 and 0.15 respectively.

Figures 5.28, 5.29, and 5.30 show the frequency of occurrence of achievable DFE output SNRs for antenna separations of 10λ , 20λ , and 500λ given (2,0), (6,1), and (8,2) T/2-spaced DFEs respectively.

Figure 5.28: Histogram of Output SNR of (2,0) T/2-Spaced DFE for Combined Diversity (Symbol Rate: 10Msps)

Figure 5.29: Histogram of Output SNR of (6,1) T/2-Spaced DFE for Combined Diversity (Symbol Rate: 10Msps)

Figure 5.30: Histogram of Output SNR of (8,2) T/2-Spaced DFE for Combined Diversity (Symbol Rate: 10Msps)

A quick comparison of the T-spaced histograms (Figures 5.21 to 5.23) and the T/2-spaced histograms above reinforce our earlier conclusion that a T/2-spaced DFE outperforms a T-spaced DFE of similar filter length. Considering the 20λ statistics in the 23 dB block, frequency of occurrence increases from 43 to 52 to 53 as the T/2-spaced DFE configuration changes from (2,0) to (6,1) to (8,2). These numbers surpass those encountered for the T-spaced DFE of the same length whose frequencies went from 14 for (1,0) to 36 for (3,1) to 44 for (4,2) proving the increased performance capabilities of a DFE with more closely spaced taps.

A comparative look at the cumulative distributions associated with the histograms presented in Figures 5.28 to 5.30 is presented in Figures 5.31 to 5.33 below.

Figure 5.31: Cumulative Distribution of Output SNR for (2,0) T/2-Spaced DFE for Combined Diversity (Symbol Rate: 10Msps)

Figure 5.32: Cumulative Distribution of Output SNR for (6,1) T/2-Spaced DFE for Combined Diversity (Symbol Rate: 10Msps)

Figure 5.33: Cumulative Distribution of Output SNR for (8,2) T/2-Spaced DFE for Combined Diversity (Symbol Rate: 10Msps)

In all three figures above, for the range between 18 and 22 dB, the 20λ separation consistently shows a significant improvement over the 10λ separation while the 500λ curve appears to generally fall between the 10λ and 20λ curves. Figure 5.31 indicates that the probability that the output SNR of the DFE will be less than or equal to 20 dB is approximately 0.20 and 0.12 for antenna separations of 10λ and 20λ respectively. Figure 5.32 indicates that the probability that the output SNR of the DFE will be less than or equal to 20 dB is approximately 0.12 and 0.07 for antenna separations of 10λ and 20λ respectively. Figure 5.33 indicates that the probability that the output SNR of the DFE will be less than or equal to 20 dB is approximately 0.11 and 0.05 for antenna separations of 10λ and 20λ respectively.

A comparison of the Figures 5.31 to 5.33 indicates improved performance levels with increasing DFE complexity. Consider the 20λ curves in each of the above three graphs. Figures 5.31, 5.32, and 5.33 indicate that the probability that the output SNR of the DFE

will be less than or equal to 20 dB is approximately 0.13, 0.07, and 0.05 respectively.

These lower probability values further reinforce the outperformance capabilities of a T/2-spaced DFE versus similar length T-spaced DFEs.

Based on the cumulative distribution curves, a 20λ antenna separation appears to show consistently better performance capabilities over a 10λ antenna separation. The curves associated with the 500λ antenna separation do not behave consistently. A larger sample size could possibly stabilize the 500λ curves to enable firm conclusions as to the relative performance capabilities of such an antenna separation. Given the analysis performed thus far, an antenna separation of 20λ is preferable.

The received signal is highly sensitive to obstacles in the transmission path. As such, each antenna should be strategically positioned to minimize the effects of these obstacles on the signal received at each antenna. For practical LMDS purposes, the antennas should be positioned high enough that the transmitter, randomly located in the service area, will have an unobstructed line-of-sight with each of the receiving antennas.

Based on the results thus far, a DFE with a feedforward filter spanning three symbol intervals with a single feedback tap appears sufficient to provide satisfactory performance given the present investigated setting/conditions. If cost/complexity permits, a T/2-spaced DFE is preferred.

5.5 Some Actual, Unsimulated Results

The discussion and results presented above are based on an assumed average input SNR of 20 dB. The actual/observed SNR for each channel (reference and secondary) used in the above analysis is not fixed at 20 dB. Appendix F provides details of achievable system performance for various DFE configurations given a data rate of 10 Msps and assuming the actual/observed SNR for each of the diversity signals. Figures 5.34 and 5.35 are histograms of the DFE output SNRs assuming the actual/observed input SNRs for various tap configurations. Thus these results reflect the full range of observed received signal powers. Figures 5.34 and 5.35 represent results for a T-spaced and a T/2-spaced DFE respectively. The results presented are for a single antenna separation: 20λ . This separation was selected based on its superiority to the 10λ antenna separation results shown in the previous section.

Figure 5.34: Histogram of Actual Output SNR of T-Spaced DFE for Combined Diversity (Symbol Rate: 10Mps, Antenna Separation: 20λ)

Figure 5.35: Histogram of Actual Output SNR of T/2-Spaced DFE for Combined Diversity (Symbol Rate: 10Msps, Antenna Separation: 20λ)

For a T-spaced DFE, the improvement in performance with increasing number of feedforward and feedback taps is evident. The (1,0) T-spaced DFE produces output SNRs ranging from 8 to 45 dB while the (3,1) and (4,2) T-spaced DFEs produce outputs ranging from 18 to 46 dB and 18 to 48 dB respectively. Figure 5.34 graphically shows that there is a distinct improvement in performance between the (1,0) T-spaced DFE and the other two investigated configurations. This is entirely due to equalization. The performance improvement between the (3,1) and (4,2) T-spaced DFEs is not as obvious.

For a T/2-spaced DFE, the improvement in performance with increasing number of feedforward and feedback taps is not as clear as for similar length T-spaced

configurations. The range of output SNRs for the configurations depicted in Figure 5.35 are very similar. As such, no firm conclusion as to the relative benefit of one configuration versus another can be established. However, comparing Figures 5.34 and 5.35, it is clear that T/2-spaced DFEs outperform similar length T-spaced DFEs. The worst performance at any given site using a T/2-spaced DFE is 18 dB whereas the worst performance using a T-spaced DFE is 8 dB. A more meaningful representation of the data is a cumulative distribution.

The same general data in terms of cumulative distributions is provided in Figures 5.36 and 5.37.

Figure 5.36: Cumulative Distribution of Output SNR for Combined Diversity T-Spaced DFEs (Symbol Rate: 10Msps)

Figure 5.37: Cumulative Distribution of Output SNR for Combined Diversity T/2-Spaced DFEs (Symbol Rate: 10Mps)

Figures 5.36 and 5.37 indicate that a DFE whose feedforward filter spans 3 or 4 symbol intervals and utilizes at least one feedback tap consistently shows a significant improvement over a DFE with a feedforward filter of one symbol duration and no feedback taps. For the T-spaced investigation depicted in Figure 5.36, the (4,2) DFE shows improved performance capabilities over the (3,1) DFE at least within the 23 to 47 dB range. The probability that the output SNR of the T-spaced DFE will be less than or equal to 30 dB is approximately 0.70, 0.42, and 0.37 for (1,0), (3,1), and (4,2) configurations respectively. The T/2-spaced investigation depicted in Figure 5.37 indicates similar performance capabilities of the (6,1) and (8,2) DFEs as these curves are mainly overlapping over the entire range of SNRs. Figure 5.37 indicates that the probability that the output SNR of the DFE will be less than or equal to 30 dB is approximately 0.38, 0.35, and 0.35 for (2,0), (6,1), and (8,2) configurations respectively.

proving the outperformance capabilities of a $T/2$ -spaced DFE versus similar length T -spaced DFEs.

Based on the cumulative distribution curves, a (6,1) $T/2$ -spaced DFE is the preferred configuration due to minimal improvement in performance expected with the more complex (8,2) $T/2$ -spaced DFE. To achieve similar probabilistic performance, at least in the vicinity of 30 dB, a (4,2) T -spaced DFE is required.

Chapter 6: Conclusions

6.1 Summary of Thesis

A radio propagation measurement campaign had been conducted in the Parkwood Hills area of Ottawa. The results of the campaign were analyzed in this thesis to characterize the outdoor radio channel in the band of frequencies allocated for LMCS/LMDS. LMDS is a possible means of providing wide access to subscribers for delivery of a full range of data, video, and telephony services. The main purpose of the measurement campaign was to study and compare the impulse responses of an LMCS type system as seen from the base station then subsequently determine the receiver equalization and diversity requirements to make the system suitable for LMDS services.

Differing channel characteristics were observed as a result of the analysis of measurements recorded at 69 locations within a 2km radius of the basestation. Due to the time-dispersive nature of many of the channels, a decision feedback equalizer was deemed suitable to compensate for the possible range of channel characteristics. Various DFE configurations were simulated as well as a diversity combining technique in order to comment on the space-time equalizer requirement for LMDS in a residential environment.

An antenna array at the receiver was employed to enable the investigation of the benefits of space diversity. The diversity combining DFE consisted of two equal-length feedforward filters and a single feedback filter. The achievable performance for both T- and T/2-spaced DFEs was investigated for all combinations of up to 10 feedforward and

10 feedback taps. Each diversity paths was first considered alone then in combination to explore the potential benefit of space diversity. The investigation was conducted for data rates of 10Msps and 40Msps. Diversity combining was investigated for three antenna separations: 10λ , 20λ , and 500λ in order to single out an optimum antenna spacing.

6.2 Summary of Results

Several conclusions can be drawn based on the results of the simulations described above.

Observed channel characteristics ranged from non-dispersive to highly-dispersive in nature. Non-dispersive channels consisted of a single impulse response component. Such ideal channels did not require equalization to achieve optimum performance levels. Time-dispersive channels, usually resulting from multipath components from one or more discrete reflecting objects, required equalization based on the extent of channel dispersion. RMS delay spread provided an indication of the extent of dispersion as a result of transmission through a particular channel. High RMS delay spread channels required more complex (i.e. generally more feedforward and feedback taps) DFE structures to provide levels of performance similar to those achievable by DFEs operating on less dispersive channels. Regardless, unless the channel is ideal, the use of increasing numbers of feedforward and feedback taps improves performance, especially if the feedback filter can be configured with a variable delay.

The feedforward filter spacing affects DFE performance capabilities. In the event of a non-ideal channel, the $T/2$ -spaced DFE whose feedforward filter spans the same time as a T -spaced DFE indicates improved performance. The $T/2$ -spaced equalizer, for the same feedforward filter time span, offers more degrees of freedom in compensating for the non-ideal channel than the T -spaced DFE.

Diversity-combining enables higher attainable SNR at the output of the DFE than is achievable without the use of a diversity technique. The results tabulated in Appendix D show that combined diversity yields an output SNR in excess of that that would be possible with either of the diversity channels alone. The combination of two ideal diversity channels offers a 3dB performance improvement.

The results tabulated in Appendix E show that for similarly configured feedforward and feedback filters (i.e. the same number of taps and FFF spacing), a DFE handling a symbol rate of 40Msps will require a more complex DFE structure than a DFE handling a symbol rate of 10Msps to achieve similar performance levels.

An investigation of cumulative distributions has enabled a well-founded conclusion as to the most favorable antenna separation to employ in this case. Of the three antenna separations considered, the 20λ scenario consistently showed a significant improvement over the 10λ separation. The 500λ cumulative distribution curves also showed an improvement over 10λ . However, the relative performance of 20λ and 500λ was not always consistent. For the T -spaced investigation of (1,0), (3,1), and (4,2) DFEs, two out

of the three instances indicated 20λ outperforms 500λ . Furthermore, since physical space for installation of digital communications system components is generally a contributing factor to cost, an antenna separation of 20λ is preferable to 500λ .

Based on the cumulative distribution curves, a (6,1) T/2-spaced DFE is the preferred configuration due to minimal improvement in performance expected with the more complex (8,2) T/2-spaced DFE. To achieve similar probabilistic performance levels, a longer T-spaced DFE is required.

6.3 Suggestions for Future Research

In order to complement the present study, the following additional work is suggested:

- 1) During the propagation measurement campaign, data was collected for 9 to 10 different antenna separations at each transmitter location. Investigate the relative performance capabilities for those antenna separations not considered in this study.
- 2) Conduct a more in-depth investigation into DFEs employing delay in the feedback filter.

Appendix A: MMSE Evaluation (single channel)

The input to the FFF of a DFE can be described by the following equation:

$$z(t) = \sum_n d_n g(t - nT) + \eta'(t) \quad (\text{A.1})$$

where $\{d_n\}$ are the complex-valued QPSK data symbols with four possible values

$$\frac{1}{\sqrt{2}}(\pm 1 \pm j)$$

$g(t)$ is the combined impulse response of the transmitter, channel, and receive filter

$\eta'(t)$ is the bandpass noise.

For simplicity, it is assumed that the transmitted symbols are independent with zero mean and unit variance. In other words,

$$E(d_n) = 0$$

$$E(|d_n|^2) = \sigma_d^2 = 1$$

It is desired to minimize the mean square error J given by:

$$J = E|d(n-D) - y(n)|^2 \quad (\text{A.2})$$

where $d(n-D)$ is the desired symbol and $y(n)$ is the output of the equalizer (input to the decision device) given by:

$$y(n) = \sum_{j=0}^{K_1} f_j^* z(nT - jT - \tau_0) + \sum_{j=1}^{K_2} b_j^* d(n - j - D) \quad (\text{A.3})$$

where τ_0 is the sampling delay

$\{f_j\}$ are the complex-valued feedforward tap coefficients

$\{b_j\}$ are the complex-valued feedback tap coefficients

$K_1 + 1$ and K_2 are the number of feedforward and feedback taps respectively

It is convenient to use vector and matrix algebra to rewrite equation (A.3) as follows:

$$y(n) = \mathbf{w}^H \mathbf{u}(n) \quad (\text{A.4})$$

$$\text{where } \mathbf{w}^H = [f_0 \quad f_1 \quad f_2 \quad \cdots \quad f_{K_1} \quad b_1 \quad b_2 \quad b_3 \quad \cdots \quad b_{K_2}]^* \quad (\text{A.5})$$

$$\text{and } \mathbf{u}(n) = \begin{bmatrix} z(n) \\ d(n-1-D) \end{bmatrix} \quad (\text{A.6})$$

$$\text{where } z(n) = [z(nT) \quad z(nT - T) \quad z(nT - 2T) \quad \cdots \quad z(nT - K_1 T)]^T \quad (\text{A.7})$$

$$\text{and } d(n-1-D) = [d(n-1-D) \quad d(n-2-D) \quad \cdots \quad d(n-K_2-D)]^T \quad (\text{A.8})$$

In order to find the optimum tap weights, set the gradient of the mean squared error J to zero. The MSE in (A.2) can also be written as:

$$MSE = J = 1 - 2\text{Re}(\mathbf{w}^H \mathbf{V}) + \mathbf{w}^H \mathbf{R} \mathbf{w} \quad (\text{A.9})$$

After some manipulation, (A.9) can be written as follows:

$$J = 1 + (\mathbf{w} - \mathbf{R}^{-1} \mathbf{V})^H \mathbf{R} (\mathbf{w} - \mathbf{R}^{-1} \mathbf{V}) - \mathbf{V}^H \mathbf{R}^{-1} \mathbf{V} \quad (\text{A.10})$$

$$\text{where } \mathbf{R} = E[\mathbf{u}(n) \mathbf{u}^H(n)] \quad (\text{A.11})$$

$$\text{and } \mathbf{V} = E[\mathbf{u}(n) d^*(n-D)] \quad (\text{A.12})$$

$\mathbf{R}$ is the $(K_1 + K_2 + 1) \times (K_1 + K_2 + 1)$ correlation matrix of tap inputs of feedforward and feedback filters.

$\mathbf{V}$ is the $(K_1 + K_2 + 1) \times 1$ cross correlation vector of tap inputs of the feedforward and feedback filters with the desired signal.

The computation of J_{min} requires the knowledge of the correlation matrix $\mathbf{R}$ and the cross correlation vector $\mathbf{V}$. These are computed as follows:

Let's first consider $\mathbf{R}$...

$$\begin{aligned}\mathbf{R} &= E[\mathbf{u}(n) \mathbf{u}^H(n)] \\ &= E\left[\begin{pmatrix} \mathbf{z}(n) \\ \mathbf{d}(n-1-D) \end{pmatrix} \begin{pmatrix} \mathbf{z}^H(n) & \mathbf{d}^H(n-1-D) \end{pmatrix}\right]\end{aligned}\quad (\text{A.13})$$

which can be written as:

$$\mathbf{R} = \begin{bmatrix} \mathbf{R}_1 & \mathbf{R}_2 \\ \mathbf{R}_2^H & \mathbf{I} \end{bmatrix} \quad (\text{A.14})$$

where $\mathbf{I}$ is an identity matrix (of size $K_2 \times K_2$) and matrices $\mathbf{R}_1$ (of size $(K_1 + 1) \times (K_1 + 1)$) and $\mathbf{R}_2$ (of size $(K_1 + 1) \times K_2$) are given as:

$$\begin{aligned}\mathbf{R}_1 &= E\left[\begin{pmatrix} \mathbf{z}(n) & \mathbf{z}^H(n) \end{pmatrix}\right] \\ &= E\left[\begin{pmatrix} z(nT) \\ z(nT-T') \\ \vdots \\ z(nT-K_1T') \end{pmatrix} \begin{pmatrix} z(nT) & z(nT-T') & \cdots & z(nT-K_1T') \end{pmatrix}^*\right]\end{aligned}\quad (\text{A.15})$$

On evaluating (A.15), we may represent the autocorrelation matrix $\mathbf{R}_1$ as:

$$\mathbf{R}_1 = \begin{bmatrix} r(0,0) & r(0,1) & \cdots & r(0,K_1) \\ r^*(0,1) & r(1,1) & \cdots & r(1,K_1) \\ \vdots & \vdots & \vdots & \vdots \\ r^*(0,K_1) & r^*(1,K_1) & \cdots & r^*(K_1,K_1) \end{bmatrix} \quad (\text{A.16})$$

where the quantity $r(j,k)$ is given by:

$$\begin{aligned}r(j,k) &= E[z(nT-jT') z^*(nT-kT')] \\ &= E\left[\left(\sum_l d_l g(nT-lT-jT') + \eta'(nT-jT')\right) \left(\sum_m d_m g(nT-mT-kT') + \eta'(nT-kT')\right)^*\right]\end{aligned}\quad (\text{A.17})$$

Equivalently,

$$r(j,k) = \sum_l \sum_m E[d_l d_m^*] g(nT - lT - jT') g^*(nT - mT - kT') + E[\eta'(nT - jT') \eta'^*(nT - kT')] \quad (\text{A.18})$$

which can be further simplified to:

$$r(j,k) = \sum_i g(iT - jT') g^*(iT - kT') + \phi((j - k)T') \quad (\text{A.19})$$

where $\phi(t)$ is the autocorrelation function of the power spectral density (PSD) of bandpass noise at the receiver filter output.

In (A.16), $r(j,k) = r^*(k,j)$.

Next, we find matrix $\mathbf{R}_2 \dots$

$$\begin{aligned} \mathbf{R}_2 &= E \begin{bmatrix} \mathbf{z}(n) & \mathbf{d}^H(n-1-D) \end{bmatrix} \\ &= E \left[\begin{pmatrix} z(nT) \\ z(nT - T') \\ \vdots \\ z(nT - K_1 T') \end{pmatrix} \begin{pmatrix} d(n-1-D) & d(n-2-D) & \dots & d(n-K_2-D) \end{pmatrix}^* \right] \quad (\text{A.20}) \end{aligned}$$

On solving, we have:

$$\mathbf{R}_2 = \begin{bmatrix} g((D+1)T) & g((D+2)T) & \dots & g((D+K_2)T) \\ g((D+1)T - T') & g((D+2)T - T') & \dots & g((D+K_2)T - T') \\ g((D+1)T - 2T') & g((D+2)T - 2T') & \dots & g((D+K_2)T - 2T') \\ \vdots & \vdots & \vdots & \vdots \\ g((D+1)T - K_1 T') & g((D+2)T - K_1 T') & \dots & g((D+K_2)T - K_1 T') \end{bmatrix} \quad (\text{A.21})$$

The vector $\mathbf{P}$ is given by:

$$\mathbf{P} = E \begin{bmatrix} \mathbf{u}(n) & \mathbf{d}^*(n-D) \end{bmatrix}$$

$$= E \begin{bmatrix} z(nT)d^*(n-D) \\ z(nT-T')d^*(n-D) \\ \vdots \\ z(nT-K_1T')d^*(n-D) \\ d(n-1-D)d^*(n-D) \\ d(n-2-D)d^*(n-D) \\ \vdots \\ d(n-K_2-D)d^*(n-D) \end{bmatrix} \quad (\text{A.22})$$

On solving, we can write P as:

$$P = \begin{bmatrix} g(DT) \\ g(DT-T') \\ \vdots \\ g(DT-K_1T') \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad (\text{A.23})$$

Appendix B: MMSE Evaluation (two channels in combination)

The following derivation is an adaptation of the theory outlined in Appendix A. It is intended to highlight how the previous theory can be adapted to handle the determination of the MMSE when the output from two channels is combined. Let $^{(ref)}$ and $^{(sec)}$ denote the reference and secondary channels respectively. The equation numbers correspond to those in the previous appendix for ease of reference and comparison. Let $z(t)$ represent the output of the wireless channel.

$$z^{(ref)}(t) = \sum_n d_n g^{(ref)}(t - nT) + \eta'(t) \quad (B.1a)$$

$$z^{(sec)}(t) = \sum_n d_n g^{(sec)}(t - nT) + \eta'(t) \quad (B.1b)$$

It is desired to minimize the mean square error J given by:

$$J = E |d(n-D) - y(n)|^2 \quad (B.2)$$

where $d(n-D)$ is the desired symbol and $y(n)$ is the output of the DFE (input to the decision device) given by:

$$y(n) = \sum_{j=0}^{K_1} f_j^{*(ref)} z^{(ref)}(nT - jT - \tau_0^{(ref)}) + \sum_{j=0}^{K_1} f_j^{*(sec)} z^{(sec)}(nT - jT - \tau_0^{(sec)}) + \sum_{j=1}^{K_2} b_j^* d(n-j-D) \quad (B.3)$$

where $\tau_0^{(ref)}$ is the sampling delay associated with the reference channel

$\tau_0^{(\text{sec})}$ is the sampling delay associated with the secondary channel

$\{f_f^{(\text{ref})}\}$ are the complex-valued feedforward tap coefficients associated with the reference channel

$\{f_f^{(\text{sec})}\}$ are the complex-valued feedforward tap coefficients associated with the secondary channel

$\{b_j\}$ are the complex-valued feedback tap coefficients

$K_I + 1$ and K_2 are the number of feedforward and feedback taps respectively. Each feedforward filter has the same number of taps.

It is convenient to use vector and matrix algebra to rewrite equation (B.3) as follows:

$$y(n) = \mathbf{w}^H \mathbf{u}(n) \quad (\text{B.4})$$

$$\text{where } \mathbf{w}^H = \begin{bmatrix} f_0^{(\text{ref})} & f_1^{(\text{ref})} & \dots & f_{K_I}^{(\text{ref})} & f_0^{(\text{sec})} & f_1^{(\text{sec})} & \dots & f_{K_2}^{(\text{sec})} & b_1 & \dots & b_{K_2} \end{bmatrix} \quad (\text{B.5})$$

$$\mathbf{u}(n) = \begin{bmatrix} \mathbf{z}^{(\text{ref})}(n) \\ \mathbf{z}^{(\text{sec})}(n) \\ d(n-1-D) \end{bmatrix} \quad (\text{B.6})$$

$$\text{where } \mathbf{z}^{(\text{ref})}(n) = \begin{bmatrix} \mathbf{z}^{(\text{ref})}(nT) & \mathbf{z}^{(\text{ref})}(nT - T') & \mathbf{z}^{(\text{ref})}(nT - 2T') & \dots & \mathbf{z}^{(\text{ref})}(nT - K_1 T') \end{bmatrix}^T \quad (\text{B.7a})$$

$$\mathbf{z}^{(sec)}(n) = \begin{bmatrix} z^{(sec)}(nT) & z^{(sec)}(nT - T') & z^{(sec)}(nT - 2T') & \dots & z^{(sec)}(nT - K_1 T') \end{bmatrix}^T \quad (\text{B.7b})$$

$$\mathbf{d}(n-1-D) = \begin{bmatrix} d(n-1-D) & d(n-2-D) & \dots & d(n-K_2-D) \end{bmatrix}^T \quad (\text{B.8})$$

In order to find the optimum tap weights, set the gradient of the mean squared error J to zero. The MSE in (B.2) can also be written as:

$$MSE = J = 1 - 2\text{Re}(\mathbf{w}^H \mathbf{V}) + \mathbf{w}^H \mathbf{R} \mathbf{w} \quad (\text{B.9})$$

After some manipulation, (B.9) can be written as follows:

$$J = 1 + (\mathbf{w} - \mathbf{R}^{-1} \mathbf{V})^H \mathbf{R} (\mathbf{w} - \mathbf{R}^{-1} \mathbf{V}) - \mathbf{V}^H \mathbf{R}^{-1} \mathbf{V} \quad (\text{B.10})$$

$$\text{where } \mathbf{R} = E[\mathbf{u}(n) \mathbf{u}^H(n)] \quad (\text{B.11})$$

$$\mathbf{V} = E[\mathbf{u}(n) d^*(n-D)] \quad (\text{B.12})$$

$\mathbf{R}$ is the $(2K_1 + K_2 + 2) \times (2K_1 + K_2 + 2)$ correlation matrix of tap inputs of feedforward and feedback filters.

$\mathbf{V}$ is the $(2K_1 + K_2 + 2) \times 1$ cross correlation vector of tap inputs of the feedforward and feedback filters with the desired signal.

The computation of J_{min} requires the knowledge of the correlation matrix $\mathbf{R}$ and the cross correlation vector $\mathbf{V}$. These are computed as follows:

Let's first consider $\mathbf{R} \dots$

$$\begin{aligned} \mathbf{R} &= E[\mathbf{u}(n) \mathbf{u}^H(n)] \\ &= E \left[\begin{pmatrix} \mathbf{z}^{(ref)}(n) \\ \mathbf{z}^{(sec)}(n) \\ d(n-1-D) \end{pmatrix} \begin{pmatrix} \mathbf{z}^{(ref)H}(n) & \mathbf{z}^{(sec)H}(n) & d^H(n-1-D) \end{pmatrix} \right] \end{aligned} \quad (\text{B.13})$$

on solving which can be written as:

$$\mathbf{R} = \begin{bmatrix} \mathbf{R}_1 & \mathbf{R}_2 \\ \mathbf{R}_1^H & \mathbf{I} \end{bmatrix} \quad (\text{B.14})$$

where $\mathbf{I}$ is an identity matrix (of size $K_2 \times K_2$) and matrices $\mathbf{R}_1$ (of size $(2K_I + 2) \times (2K_I + 2)$) and $\mathbf{R}_2$ (of size $(2K_I + 2) \times K_2$) are given as:

$$\mathbf{R}_1 = E \left[\begin{pmatrix} \mathbf{z}^{(ref)}(n) \\ \mathbf{z}^{(sec)}(n) \end{pmatrix} \begin{pmatrix} \mathbf{z}^{(ref)H}(n) & \mathbf{z}^{(sec)H}(n) \end{pmatrix} \right]$$

$$\begin{aligned}
& \left[\begin{array}{c} z^{(ref)}_{(nT)} \\ z^{(ref)}_{(nT-T')} \\ \vdots \\ z^{(ref)}_{(nT-K_1T')} \\ z^{(sec)}_{(nT)} \\ z^{(sec)}_{(nT-T')} \\ \vdots \\ z^{(sec)}_{(nT-K_1T')} \end{array} \right] \left(\begin{array}{cccc} z^{(ref)}_{(nT)} & z^{(ref)}_{(nT-T')} & \dots & z^{(ref)}_{(nT-K_1T')} \\ z^{(ref)}_{(nT-T')} & z^{(ref)}_{(nT-2T')} & \dots & z^{(ref)}_{(nT-K_1T')} \\ \vdots & \vdots & \ddots & \vdots \\ z^{(ref)}_{(nT-K_1T')} & z^{(ref)}_{(nT-K_2T')} & \dots & z^{(ref)}_{(nT-K_1T')} \\ z^{(sec)}_{(nT)} & z^{(sec)}_{(nT-T')} & \dots & z^{(sec)}_{(nT-K_1T')} \\ z^{(sec)}_{(nT-T')} & z^{(sec)}_{(nT-2T')} & \dots & z^{(sec)}_{(nT-K_1T')} \\ \vdots & \vdots & \ddots & \vdots \\ z^{(sec)}_{(nT-K_1T')} & z^{(sec)}_{(nT-K_2T')} & \dots & z^{(sec)}_{(nT-K_1T')} \end{array} \right)^* \quad (B.15)
\end{aligned}$$

On evaluating (B.15), we may represent the autocorrelation matrix $\mathbf{R}_I$, equation (B.16), as:

$$\left[\begin{array}{cccc} r^{(ref-ref)}_{(0,0)} & r^{(ref-ref)}_{(0,1)} & \dots & r^{(ref-ref)}_{(0,K_1)} \\ r^{(ref-ref)*}_{(0,1)} & r^{(ref-ref)*}_{(1,1)} & \dots & r^{(ref-ref)*}_{(1,K_1)} \\ \vdots & \vdots & \ddots & \vdots \\ r^{(ref-ref)*}_{(0,K_1)} & r^{(ref-ref)*}_{(1,K_1)} & \dots & r^{(ref-ref)*}_{(K_1,K_1)} \\ r^{(sec-ref)}_{(0,0)} & r^{(sec-ref)}_{(0,1)} & \dots & r^{(sec-ref)}_{(0,K_1)} \\ r^{(sec-ref)*}_{(0,1)} & r^{(sec-ref)*}_{(1,1)} & \dots & r^{(sec-ref)*}_{(1,K_1)} \\ \vdots & \vdots & \ddots & \vdots \\ r^{(sec-ref)*}_{(0,K_1)} & r^{(sec-ref)*}_{(1,K_1)} & \dots & r^{(sec-ref)*}_{(K_1,K_1)} \end{array} \right] \left[\begin{array}{cccc} r^{(ref-sec)}_{(0,0)} & r^{(ref-sec)}_{(0,1)} & \dots & r^{(ref-sec)}_{(0,K_1)} \\ r^{(ref-sec)*}_{(0,1)} & r^{(ref-sec)*}_{(1,1)} & \dots & r^{(ref-sec)*}_{(1,K_1)} \\ \vdots & \vdots & \ddots & \vdots \\ r^{(ref-sec)*}_{(0,K_1)} & r^{(ref-sec)*}_{(1,K_1)} & \dots & r^{(ref-sec)*}_{(K_1,K_1)} \\ r^{(sec-sec)}_{(0,0)} & r^{(sec-sec)}_{(0,1)} & \dots & r^{(sec-sec)}_{(0,K_1)} \\ r^{(sec-sec)*}_{(0,1)} & r^{(sec-sec)*}_{(1,1)} & \dots & r^{(sec-sec)*}_{(1,K_1)} \\ \vdots & \vdots & \ddots & \vdots \\ r^{(sec-sec)*}_{(0,K_1)} & r^{(sec-sec)*}_{(1,K_1)} & \dots & r^{(sec-sec)*}_{(K_1,K_1)} \end{array} \right]$$

where the quantity $r^{(a-b)}(j,k)$ is given by:

$$r^{(a-b)}(j,k) = E[z^{(a)}(nT-jT') z^{(b)*}(nT-kT')]$$

Therefore,

$$\mathbf{r}^{(\text{ref-ref})}(\mathbf{j}, \mathbf{k}) = \mathbb{E} \left[\left(\sum_l d_l g^{(\text{ref})}(nT - lT - jT'') + \eta'(nT - jT'') \right) \left(\sum_m d_m g^{(\text{ref})}(nT - mT - kT'') + \eta'(nT - kT'') \right)^* \right] \quad (\text{B.17a})$$

$$\mathbf{r}^{(\text{sec-sec})}(\mathbf{j}, \mathbf{k}) = \mathbb{E} \left[\left(\sum_l d_l g^{(\text{sec})}(nT - lT - jT'') + \eta'(nT - jT'') \right) \left(\sum_m d_m g^{(\text{sec})}(nT - mT - kT'') + \eta'(nT - kT'') \right)^* \right] \quad (\text{B.17b})$$

$$\mathbf{r}^{(\text{ref-sec})}(\mathbf{j}, \mathbf{k}) = \mathbb{E} \left[\left(\sum_l d_l g^{(\text{ref})}(nT - lT - jT'') + \eta'(nT - jT'') \right) \left(\sum_m d_m g^{(\text{sec})}(nT - mT - kT'') + \eta'(nT - kT'') \right)^* \right] \quad (\text{B.17c})$$

$$\mathbf{r}^{(\text{sec-ref})}(\mathbf{j}, \mathbf{k}) = \mathbf{r}^{(\text{ref-sec})*}(\mathbf{j}, \mathbf{k}) \quad (\text{B.17d})$$

Equivalently,

$$\mathbf{r}^{(\text{ref-ref})}(\mathbf{j}, \mathbf{k}) = \sum_l \sum_m E[d_l d_m^*] g^{(\text{ref})}(nT - lT - jT'') g^{(\text{ref})*}(nT - mT - kT'') + E[\eta'(nT - jT'') \eta'^*(nT - kT'')] \quad (\text{B.18a})$$

$$\mathbf{r}^{(\text{sec-sec})}(\mathbf{j}, \mathbf{k}) = \sum_l \sum_m E[d_l d_m^*] g^{(\text{sec})}(nT - lT - jT'') g^{(\text{sec})*}(nT - mT - kT'') + E[\eta'(nT - jT'') \eta'^*(nT - kT'')] \quad (\text{B.18b})$$

$$\mathbf{r}^{(\text{ref-sec})}(\mathbf{j}, \mathbf{k}) = \sum_l \sum_m E[d_l d_m^*] g^{(\text{ref})}(nT - lT - jT'') g^{(\text{sec})*}(nT - mT - kT'') + E[\eta'(nT - jT'') \eta'^*(nT - kT'')] \quad (\text{B.18c})$$

$$\mathbf{r}^{(\text{sec-ref})}(\mathbf{j}, \mathbf{k}) = \mathbf{r}^{(\text{ref-sec})*}(\mathbf{j}, \mathbf{k}) \quad (\text{B.18d})$$

which can be further simplified to:

$$\mathbf{r}^{(\text{ref-ref})}(\mathbf{j}, \mathbf{k}) = \sum_i \mathbf{g}^{(\text{ref})}(iT - jT'') \mathbf{g}^{(\text{ref})*}(iT - kT'') + \phi((j - k)T'') \quad (\text{B.19a})$$

$$\mathbf{r}^{(\text{sec-sec})}(\mathbf{j}, \mathbf{k}) = \sum_i \mathbf{g}^{(\text{sec})}(iT - jT'') \mathbf{g}^{(\text{sec})*}(iT - kT'') + \phi((j - k)T'') \quad (\text{B.19b})$$

$$\mathbf{r}^{(\text{ref-sec})}(\mathbf{j}, \mathbf{k}) = \sum_i \mathbf{g}^{(\text{ref})}(iT - jT'') \mathbf{g}^{(\text{sec})*}(iT - kT'') + \phi((j - k)T'') \quad (\text{B.19c})$$

$$\mathbf{r}^{(\text{sec-ref})}(\mathbf{j}, \mathbf{k}) = \mathbf{r}^{(\text{ref-sec})*}(\mathbf{j}, \mathbf{k}) \quad (\text{B.19d})$$

where $\phi(t)$ is the autocorrelation function of the power spectral density (PSD) of bandpass noise at the receiver filter output.

In (B.16), $\mathbf{r}^{(\text{a-b})}(\mathbf{j}, \mathbf{k}) = \mathbf{r}^{(\text{a-b})*}(\mathbf{k}, \mathbf{j})$.

Next, we find matrix $\mathbf{R}_2 \dots$

$$\mathbf{R}_2 = E \left[\begin{pmatrix} \mathbf{z}^{(\text{ref})}(n) \\ \mathbf{z}^{(\text{sec})}(n) \end{pmatrix} \mathbf{d}^H(n-1-D) \right]$$

$$\begin{aligned}
& \begin{bmatrix} \mathbf{z}^{(\text{ref})}(nT) \\ \mathbf{z}^{(\text{ref})}(nT - T') \\ \vdots \\ \mathbf{z}^{(\text{ref})}(nT - K_1 T') \\ \mathbf{z}^{(\text{sec})}(nT) \\ \mathbf{z}^{(\text{sec})}(nT - T') \\ \vdots \\ \mathbf{z}^{(\text{sec})}(nT - K_1 T') \end{bmatrix} \\
& = E \begin{bmatrix} d(n-1-D) & d(n-2-D) & \dots & d(n-K_2-D) \end{bmatrix}^*
\end{aligned} \tag{B.20}$$

On solving, we have:

$$\begin{aligned}
\mathbf{R}_2 = & \begin{bmatrix} \mathbf{g}^{(\text{ref})}((D+1)T) & \mathbf{g}^{(\text{ref})}((D+2)T) & \dots & \mathbf{g}^{(\text{ref})}((D+K_2)T) \\ \mathbf{g}^{(\text{ref})}((D+1)T - T') & \mathbf{g}^{(\text{ref})}((D+2)T - T') & \dots & \mathbf{g}^{(\text{ref})}((D+K_2)T - T') \\ \mathbf{g}^{(\text{ref})}((D+1)T - 2T') & \mathbf{g}^{(\text{ref})}((D+2)T - 2T') & \dots & \mathbf{g}^{(\text{ref})}((D+K_2)T - 2T') \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{g}^{(\text{ref})}((D+1)T - K_1 T') & \mathbf{g}^{(\text{ref})}((D+2)T - K_1 T') & \dots & \mathbf{g}^{(\text{ref})}((D+K_2)T - K_1 T') \\ \mathbf{g}^{(\text{sec})}((D+1)T) & \mathbf{g}^{(\text{sec})}((D+2)T) & \dots & \mathbf{g}^{(\text{sec})}((D+K_2)T) \\ \mathbf{g}^{(\text{sec})}((D+1)T - T') & \mathbf{g}^{(\text{sec})}((D+2)T - T') & \dots & \mathbf{g}^{(\text{sec})}((D+K_2)T - T') \\ \mathbf{g}^{(\text{sec})}((D+1)T - 2T') & \mathbf{g}^{(\text{sec})}((D+2)T - 2T') & \dots & \mathbf{g}^{(\text{sec})}((D+K_2)T - 2T') \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{g}^{(\text{sec})}((D+1)T - K_1 T') & \mathbf{g}^{(\text{sec})}((D+2)T - K_1 T') & \dots & \mathbf{g}^{(\text{sec})}((D+K_2)T - K_1 T') \end{bmatrix}
\end{aligned} \tag{B.21}$$

The vector $\mathbf{P}$ is given by:

$$\mathbf{P} = E[u(n) \quad d^*(n-D)]$$

$$= E \left[\begin{pmatrix} \mathbf{z}^{(ref)}(n) \\ \mathbf{z}^{(sec)}(n) \\ d(n-1-D) \end{pmatrix} d^*(n-D) \right]$$

$$= E \begin{bmatrix} \mathbf{z}^{(ref)}(nT)d^*(n-D) \\ \mathbf{z}^{(ref)}(nT-T')d^*(n-D) \\ \vdots \\ \mathbf{z}^{(ref)}(nT-K_1T')d^*(n-D) \\ \mathbf{z}^{(sec)}(nT)d^*(n-D) \\ \mathbf{z}^{(sec)}(nT-T')d^*(n-D) \\ \vdots \\ \mathbf{z}^{(sec)}(nT-K_1T')d^*(n-D) \\ d(n-1-D)d^*(n-D) \\ d(n-2-D)d^*(n-D) \\ \vdots \\ d(n-K_2-D)d^*(n-D) \end{bmatrix}$$

(B.22)

On solving, we can write $\mathbf{P}$ as:

$$\mathbf{p} = \begin{bmatrix} g^{(ref)}(DT) \\ g^{(ref)}(DT - T'') \\ \vdots \\ g^{(ref)}(DT - K_1 T'') \\ g^{(sec)}(DT) \\ g^{(sec)}(DT - T'') \\ \vdots \\ g^{(sec)}(DT - K_1 T'') \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

(B.23)

Appendix C: Parkwood Hills Channel Characteristics

Table C1: Channel Characteristics (0819-0820)

File Name	Reference Channel		Secondary Channel	
	IR Span (ns)	RMS Delay Spread (μ s)	IR Span (ns)	RMS Delay Spread (μ s)
3kilmory_A1	3812.50	0.08	1831.25	0.04
3kilmory_A3	68.75	0.01	68.75	0.01
3kilmory_A9	8193.75	0.18	31.25	0.01
42newbury_A1	156.25	0.03	2025.00	0.24
42newbury_A3	156.25	0.03	150.00	0.02
42newbury_A9	150.00	0.02	3737.50	0.40
banson1_A1	137.50	0.02	31.25	0.01
banson1_A3	7568.75	1.25	31.25	0.02
banson1_A9	156.25	0.02	62.50	0.01
bowmoon1_A1	9956.25	4.19	0.00	0.00
bowmoon1_A3	0.00	0.00	0.00	0.00
bowmoon1_A9	0.00	0.00	0.00	0.00
dharkay1_A1	6843.75	0.17	231.25	0.01
dharkay1_A3	231.25	0.01	225.00	0.01
dharkay1_A9	231.25	0.01	5618.75	0.20
kilmory1_A1	843.75	0.01	1512.50	0.04
kilmory1_A3	425.00	0.02	537.50	0.03
kilmory1_A9	843.75	0.02	68.75	0.00
newbjry1_A1	568.75	0.03	68.75	0.01
newbjry1_A3	575.00	0.05	568.75	0.05
newbjry1_A9	575.00	0.07	581.25	0.28
tivtrton1_A1	7237.50	0.13	2425.00	0.04
tivtrton1_A3	1612.50	0.06	11931.25	0.22
tivtrton1_A9	2462.50	0.07	1625.00	0.10
woumount1_A1	762.50	0.02	4487.50	0.21
woumount1_A3	156.25	0.01	75.00	0.00
woumount1_A9	856.25	0.02	831.25	0.06

Table C2: Channel Characteristics (0823-0824)

File Name	Reference Channel		Secondary Channel	
	IR Span (ns)	RMS Delay Spread (μ s)	IR Span (ns)	RMS Delay Spread (μ s)
113ashburn_A1	0.00	0.00	0.00	0.00
113ashburn_A3	0.00	0.00	0.00	0.00
113ashburn_A9	0.00	0.00	0.00	0.00
11charkay_A1	75.00	0.00	68.75	0.01
11charkay_A3	818.75	0.05	818.75	0.09
11charkay_A9	75.00	0.00	0.00	0.00
23kilmory_A1	0.00	0.00	4075.00	2.04
23kilmory_A3	0.00	0.00	0.00	0.00
23kilmory_A9	0.00	0.00	0.00	0.00
28mulvage_A1	112.50	0.01	118.75	0.01
28mulvage_A3	2468.75	0.15	62.50	0.01
28mulvage_A9	9975.00	0.35	11143.75	0.85
40walgate_A1	118.75	0.02	125.00	0.02
40walgate_A3	1837.50	0.11	268.75	0.02
40walgate_A9	125.00	0.01	4818.75	0.41
56mulvage_A1	425.00	0.03	1775.00	0.20
56mulvage_A3	118.75	0.02	118.75	0.02
56mulvage_A9	118.75	0.02	7325.00	0.61
5walgate_A1	62.50	0.01	0.00	0.00
5walgate_A3	143.75	0.01	31.25	0.01
5walgate_A9	112.50	0.01	31.25	0.02
62wigan_A1	62.50	0.01	0.00	0.00
62wigan_A3	56.25	0.01	62.50	0.01
62wigan_A9	0.00	0.00	68.75	0.02
wigan1_A1	0.00	0.00	0.00	0.00
wigan1_A3	0.00	0.00	0.00	0.00
wigan1_A9	0.00	0.00	0.00	0.00

Table C3: Channel Characteristics (0825-0826)

File Name	Reference Channel		Secondary Channel	
	IR Span (ns)	RMS Delay Spread (μ s)	IR Span (ns)	RMS Delay Spread (μ s)
10inverness_A1	62.50	0.03	137.50	0.03
10inverness_A3	131.25	0.03	131.25	0.03
10inverness_A9	62.50	0.03	431.25	0.12
17lynhevan_A1	62.50	0.03	62.50	0.03
17lynhevan_A3	3387.50	0.29	125.00	0.03
17lynhevan_A9	125.00	0.03	93.75	0.03
27inverness_A1	56.25	0.00	68.75	0.01
27inverness_A3	62.50	0.00	0.00	0.00
27inverness_A9	1456.25	0.05	6837.50	0.63
48tiverton_A1	0.00	0.00	0.00	0.00
48tiverton_A3	0.00	0.00	0.00	0.00
48tiverton_A9	0.00	0.00	3756.25	1.77
53tiverton_A1	4775.00	1.72	0.00	0.00
53tiverton_A3	50.00	0.01	0.00	0.00
53tiverton_A9	0.00	0.00	0.00	0.00
5beliveau_A1	43.75	0.01	37.50	0.02
5beliveau_A3	1887.50	0.94	37.50	0.02
5beliveau_A9	37.50	0.02	0.00	0.00
5rockfield_A1	6906.25	0.18	112.50	0.03
5rockfield_A3	8187.50	0.18	125.00	0.03
5rockfield_A9	62.50	0.00	4743.75	0.12
lyrockfield_A1	156.25	0.04	162.50	0.04
lyrockfield_A3	156.25	0.04	87.50	0.04
lyrockfield_A9	137.50	0.04	150.00	0.03
philip_f_A1	6587.50	1.59	3368.75	1.39
philip_f_A3	500.00	0.19	43.75	0.02
philip_f_A9	50.00	0.02	43.75	0.02

Table C4: Channel Characteristics (0827-0909)

File Name	Reference Channel		Secondary Channel	
	IR Span (ns)	RMS Delay Spread (μ s)	IR Span (ns)	RMS Delay Spread (μ s)
114 Fourseasons_A1	50.00	0.01	68.75	0.00
114 Fourseasons_A3	50.00	0.00	0.00	0.00
114 Fourseasons_A9	56.25	0.01	50.00	0.01
35seymour_A1	843.75	0.04	50.00	0.01
35seymour_A3	456.25	0.03	181.25	0.01
35seymour_A9	131.25	0.01	6231.25	0.58
Coolspring & Viewmunt_A1	787.50	0.13	2275.00	0.44
Coolspring & Viewmunt_A3	37.50	0.01	831.25	0.40
Coolspring & Viewmunt_A9	787.50	0.08	843.75	0.40
e_argue_A1	2443.75	0.07	6731.25	0.30
e_argue_A3	775.00	0.02	62.50	0.00
e_argue_A9	2093.75	0.06	787.50	0.05
Fourseasons & Shadetree_A1	56.25	0.02	62.50	0.02
Fourseasons & Shadetree_A3	56.25	0.03	56.25	0.03
Fourseasons & Shadetree_A9	62.50	0.03	50.00	0.01
seymour_ch_A1	381.25	0.06	375.00	0.05
seymour_ch_A3	381.25	0.08	381.25	0.05
seymour_ch_A9	375.00	0.05	375.00	0.09

Table C5: Channel Characteristics (0913-0915)

File Name	Reference Channel		Secondary Channel	
	IR Span (ns)	RMS Delay Spread (μ s)	IR Span (ns)	RMS Delay Spread (μ s)
18 Welkin_A1	75.00	0.01	62.50	0.01
18 Welkin_A3	50.00	0.01	68.75	0.01
18 Welkin_A9	43.75	0.00	5931.25	0.52
22 Welkin_A1	0.00	0.00	0.00	0.00
22 Welkin_A3	7881.25	1.01	1837.50	0.35
22 Welkin_A9	187.50	0.01	4537.50	2.06
25 Southview_A1	662.50	0.06	668.75	0.05
25 Southview_A3	656.25	0.11	656.25	0.06
25 Southview_A9	662.50	0.07	262.50	0.13
46 Laird_A1	818.75	0.02	43.75	0.01
46 Laird_A3	56.25	0.00	56.25	0.01
46 Laird_A9	312.50	0.01	356.25	0.02
Chesterton & Assinboine_A1	6812.50	0.19	81.25	0.00
Chesterton & Assinboine_A3	81.25	0.00	0.00	0.00
Chesterton & Assinboine_A9	87.50	0.00	68.75	0.00
Meadowlands&Peter_A1	5168.75	0.17	43.75	0.01
Meadowlands&Peter_A3	43.75	0.01	50.00	0.01
Meadowlands&Peter_A9	1843.75	0.05	50.00	0.00
Southview & Chesterton_A1	325.00	0.03	100.00	0.04
Southview & Chesterton_A3	318.75	0.03	318.75	0.04
Southview & Chesterton_A9	318.75	0.03	325.00	0.06
Viewmount & Homstead_A1	56.25	0.01	50.00	0.02
Viewmount & Homstead_A3	56.25	0.01	356.25	0.02
Viewmount & Homstead_A9	56.25	0.01	2418.75	0.11

Table C6: Channel Characteristics (0916-0917)

File Name	Reference Channel		Secondary Channel	
	IR Span (ns)	RMS Delay Spread (μ s)	IR Span (ns)	RMS Delay Spread (μ s)
14 harris_A1	50.00	0.01	1293.75	0.15
14 harris_A3	43.75	0.00	37.50	0.01
14 harris_A9	912.50	0.07	37.50	0.01
23 david_A1	7468.75	0.15	93.75	0.01
23 david_A3	87.50	0.01	4631.25	0.18
23 david_A9	7287.50	0.18	87.50	0.01
26 harris_A1	50.00	0.01	50.00	0.01
26 harris_A3	837.50	0.02	50.00	0.01
26 harris_A9	50.00	0.01	2475.00	0.12
26 Withrow_A1	0.00	0.00	0.00	0.00
26 Withrow_A3	0.00	0.00	0.00	0.00
26 Withrow_A9	0.00	0.00	0.00	0.00
35 david_A1	50.00	0.01	50.00	0.01
35 david_A3	37.50	0.01	50.00	0.01
35 david_A9	2431.25	0.08	50.00	0.01
3a joan_A1	0.00	0.00	2500.00	0.40
3a joan_A3	31.25	0.01	306.25	0.08
3a joan_A9	300.00	0.07	1337.50	0.24
5 david_A1	0.00	0.00	3575.00	0.73
5 david_A3	31.25	0.01	37.50	0.01
5 david_A9	43.75	0.01	31.25	0.01
bayne & david_A1	0.00	0.00	0.00	0.00
bayne & david_A3	431.25	0.04	1212.50	0.34
bayne & david_A9	0.00	0.00	1212.50	0.39
canter & bayne_A1	3350.00	0.76	75.00	0.02
canter & bayne_A3	168.75	0.03	0.00	0.00
canter & bayne_A9	562.50	0.08	0.00	0.00
Rosslund & Pender_A1	43.75	0.00	1500.00	0.11
Rosslund & Pender_A3	31.25	0.01	31.25	0.02
Rosslund & Pender_A9	56.25	0.00	4631.25	0.61

Table C7: Channel Characteristics (0920-0921-0922)

File Name	Reference Channel		Secondary Channel	
	IR Span (ns)	RMS Delay Spread (μ s)	IR Span (ns)	RMS Delay Spread (μ s)
10 granton_A1	37.50	0.02	312.50	0.02
10 granton_A3	37.50	0.01	318.75	0.02
10 granton_A9	37.50	0.01	331.25	0.02
10a granton_A1	231.25	0.02	231.25	0.02
10a granton_A3	43.75	0.02	37.50	0.02
10a granton_A9	43.75	0.02	37.50	0.02
27 Lotta_A1	43.75	0.00	0.00	0.00
27 Lotta_A3	37.50	0.01	0.00	0.00
27 Lotta_A9	1431.25	0.13	6631.25	0.75
28 canter_A1	50.00	0.02	50.00	0.02
28 canter_A3	62.50	0.03	56.25	0.03
28 canter_A9	0.00	0.00	0.00	0.00
50 st-clair_A1	0.00	0.00	37.50	0.01
50 st-clair_A3	50.00	0.01	0.00	0.00
50 st-clair_A9	2337.50	0.32	43.75	0.02
63 David_A1	4625.00	1.40	56.25	0.03
63 David_A3	56.25	0.03	56.25	0.03
63 David_A9	56.25	0.03	562.50	0.20
70 harris_A1	56.25	0.03	3112.50	1.45
70 harris_A3	0.00	0.00	0.00	0.00
70 harris_A9	0.00	0.00	0.00	0.00
Bayne & Meadowlands_A1	6618.75	0.68	4887.50	0.83
Bayne & Meadowlands_A3	2487.50	0.28	1106.25	0.08
Bayne & Meadowlands_A9	4756.25	0.29	62.50	0.03
End of cote des neiges_A1	0.00	0.00	4556.25	2.21
End of cote des neiges_A3	0.00	0.00	0.00	0.00
End of cote des neiges_A9	0.00	0.00	0.00	0.00
Joan & Meadowlands_A1	56.25	0.03	5225.00	1.15
Joan & Meadowlands_A3	62.50	0.03	50.00	0.02
Joan & Meadowlands_A9	2437.50	1.08	62.50	0.03
tower & ST-Helens_A1	5300.00	0.42	0.00	0.00
tower & ST-Helens_A3	43.75	0.00	6231.25	0.70
tower & ST-Helens_A9	206.25	0.04	43.75	0.01

Table C8: Channel Characteristics (0923-0927)

File Name	Reference Channel		Secondary Channel	
	IR Span (ns)	RMS Delay Spread (μ s)	IR Span (ns)	RMS Delay Spread (μ s)
106 rossland_A1	0.00	0.00	0.00	0.00
106 rossland_A3	0.00	0.00	0.00	0.00
106 rossland_A9	0.00	0.00	0.00	0.00
118 rossland_A1	0.00	0.00	2562.50	0.30
118 rossland_A3	43.75	0.01	0.00	0.00
118 rossland_A9	87.50	0.01	0.00	0.00
41 paulsen_A1	0.00	0.00	0.00	0.00
41 paulsen_A3	50.00	0.01	0.00	0.00
41 paulsen_A9	43.75	0.01	37.50	0.02
61 paulsen_A1	0.00	0.00	0.00	0.00
61 paulsen_A3	56.25	0.01	0.00	0.00
61 paulsen_A9	43.75	0.01	0.00	0.00
79 tower_A1	31.25	0.01	31.25	0.01
79 tower_A3	0.00	0.00	0.00	0.00
79 tower_A9	4106.25	0.85	0.00	0.00
96 rossland_A1	43.75	0.01	37.50	0.01
96 rossland_A3	0.00	0.00	0.00	0.00
96 rossland_A9	0.00	0.00	50.00	0.02

Appendix D: Equalizer Performance at 10Msps

Table D1: T-Spaced Equalizer Performance at 10Msps (0819-0820)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
3kilmory_A1	18.27	19.72	19.80	18.67	19.72	19.77	20.33	22.58	22.72
3kilmory_A3	17.29	19.79	19.95	17.50	19.83	19.98	20.98	22.77	22.96
3kilmory_A9	18.19	19.69	19.79	12.61	18.47	19.13	21.44	22.62	22.71
42newbury_A1	12.71	14.18	18.93	14.59	15.22	15.93	15.06	16.46	20.84
42newbury_A3	14.10	15.42	19.28	14.50	18.67	19.84	19.89	21.77	22.88
42newbury_A9	15.62	17.18	19.59	15.54	16.80	16.95	19.03	19.43	21.99
banson1_A1	16.82	18.83	19.83	15.88	19.05	19.15	19.00	21.30	22.80
banson1_A3	14.50	14.52	14.53	3.29	12.13	15.17	15.20	16.51	16.68
banson1_A9	14.06	17.17	19.57	15.02	19.33	19.79	20.31	20.86	22.80
bowmoon1_A1	6.65	6.72	6.78	20.04	20.04	20.04	16.41	16.42	16.42
bowmoon1_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
bowmoon1_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
dharkay1_A1	19.30	19.32	19.69	18.47	19.14	19.94	21.94	22.13	22.69
dharkay1_A3	19.48	19.50	19.93	19.45	19.47	19.97	22.64	22.66	22.94
dharkay1_A9	18.68	19.49	19.92	19.03	19.51	19.54	21.77	22.42	22.83
kilmory1_A1	19.75	19.89	19.89	18.65	19.69	19.76	22.72	22.80	22.83
kilmory1_A3	19.04	19.75	19.79	17.28	19.62	19.76	20.82	22.45	22.55
kilmory1_A9	19.05	19.56	19.81	18.75	19.95	20.01	21.76	22.41	22.73
newbjry1_A1	18.88	18.88	18.88	18.46	19.92	20.01	21.44	21.57	21.58
newbjry1_A3	17.87	17.87	17.88	17.68	17.68	17.68	20.34	20.35	20.35
newbjry1_A9	16.57	16.57	16.57	4.01	4.06	4.06	19.31	19.38	19.38
tivtrton1_A1	19.73	19.90	19.91	19.33	19.67	19.68	22.41	22.81	22.84
tivtrton1_A3	19.57	19.57	19.57	19.04	19.33	19.36	22.57	22.63	22.64
tivtrton1_A9	18.98	19.22	19.24	18.37	18.62	18.63	21.55	21.78	21.81
woumount1_A1	19.77	19.77	19.77	17.60	18.60	19.12	22.49	22.57	22.61
woumount1_A3	19.50	19.69	20.01	19.05	19.99	20.02	22.32	22.62	22.99
woumount1_A9	18.16	19.59	19.68	18.23	18.23	18.23	20.57	21.83	21.94

Table D2: T/2-Spaced Equalizer Performance at 10Msps (0819-0820)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
3kilmory_A1	20.04	20.08	20.08	20.01	20.04	20.04	22.98	23.01	23.02
3kilmory_A3	20.21	20.28	20.28	20.32	20.35	20.35	23.27	23.30	23.30
3kilmory_A9	20.02	20.06	20.06	19.07	19.83	19.91	22.99	23.03	23.04
42newbury_A1	18.46	19.97	20.11	14.89	16.22	16.32	20.98	22.10	22.36
42newbury_A3	19.05	20.10	20.19	16.86	20.21	20.24	23.10	23.26	23.28
42newbury_A9	16.24	20.19	20.23	16.97	17.18	17.21	22.46	22.74	22.77
banson1_A1	19.66	20.27	20.28	19.88	20.14	20.16	22.81	23.27	23.28
banson1_A3	14.58	14.79	14.86	8.93	16.85	17.53	16.74	17.24	17.36
banson1_A9	15.84	20.07	20.12	19.97	20.16	20.17	23.11	23.22	23.24
bowmoon1_A1	6.76	7.31	7.54	20.32	20.32	20.32	16.63	17.08	17.17
bowmoon1_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
bowmoon1_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
dharkay1_A1	19.71	20.04	20.05	19.86	20.28	20.29	22.69	23.04	23.05
dharkay1_A3	19.92	20.31	20.32	19.96	20.31	20.31	23.04	23.31	23.31
dharkay1_A9	19.94	20.28	20.29	19.77	19.78	19.78	22.85	23.23	23.23
kilmory1_A1	20.17	20.18	20.19	20.00	20.03	20.04	23.10	23.12	23.13
kilmory1_A3	20.04	20.27	20.30	19.94	20.26	20.29	22.79	23.24	23.29
kilmory1_A9	20.11	20.13	20.14	20.26	20.28	20.28	23.05	23.08	23.09
newbjry1_A1	19.10	19.23	19.96	20.33	20.35	20.35	21.80	21.99	22.92
newbjry1_A3	18.04	18.30	19.48	17.83	18.04	17.98	20.55	20.85	22.37
newbjry1_A9	16.70	17.15	17.09	4.24	6.21	6.78	19.58	20.04	20.05
tivtrton1_A1	20.14	20.18	20.18	19.84	19.92	19.92	23.03	23.10	23.10
tivtrton1_A3	19.79	19.82	19.82	19.56	19.59	19.59	22.84	22.89	22.90
tivtrton1_A9	19.44	19.47	19.48	18.82	18.86	18.87	22.00	22.04	22.05
woumount1_A1	20.01	20.05	20.06	19.17	19.34	19.35	22.81	22.89	22.92
woumount1_A3	20.29	20.32	20.32	20.30	20.32	20.32	23.28	23.31	23.31
woumount1_A9	19.90	19.94	19.96	18.42	18.57	18.69	22.14	22.23	22.30

Table D3: T-Spaced Equalizer Performance at 10Msps (0823-0824)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
113ashburn_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
113ashburn_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
113ashburn_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
11charkay_A1	19.08	19.99	20.02	18.11	19.88	19.98	21.26	22.91	23.00
11charkay_A3	18.85	18.85	18.85	16.56	16.56	16.56	22.32	22.32	22.32
11charkay_A9	18.64	19.96	20.02	20.04	20.04	20.04	22.19	22.98	23.02
23kilmory_A1	20.04	20.04	20.04	2.95	3.07	3.09	19.25	19.25	19.26
23kilmory_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
23kilmory_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
28mulvage_A1	17.36	19.92	19.99	16.76	19.73	19.95	22.27	23.00	23.02
28mulvage_A3	16.87	18.51	18.65	17.66	19.73	19.91	18.65	21.20	21.35
28mulvage_A9	16.14	16.45	16.48	0.79	0.82	0.86	17.09	17.50	17.65
40walgate_A1	13.99	19.25	19.80	14.73	18.95	19.79	22.19	22.83	22.97
40walgate_A3	13.35	17.56	18.40	16.46	17.36	19.60	17.57	19.67	21.46
40walgate_A9	16.79	19.51	19.92	17.72	17.72	17.73	19.17	22.18	22.78
56mulvage_A1	14.98	16.34	17.57	8.76	16.07	16.08	16.86	19.10	20.11
56mulvage_A3	12.35	19.29	19.61	7.54	16.91	18.89	13.28	22.24	22.58
56mulvage_A9	12.95	19.22	19.64	15.88	17.45	17.61	15.84	21.70	22.18
5walgate_A1	18.29	19.88	19.99	20.04	20.04	20.04	21.05	22.83	22.98
5walgate_A3	18.27	19.23	19.92	14.42	19.26	19.59	20.58	21.73	22.89
5walgate_A9	16.62	19.60	19.68	4.03	15.78	16.19	20.65	22.92	22.99
62wigan_A1	17.91	19.84	19.98	20.04	20.04	20.04	20.53	22.76	22.96
62wigan_A3	14.90	19.15	19.74	15.23	19.38	19.81	22.37	22.82	22.96
62wigan_A9	20.04	20.04	20.04	9.17	17.31	18.99	22.38	22.90	22.99
wigan1_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
wigan1_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
wigan1_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03

Table D4: T/2-Spaced Equalizer Performance at 10Msps (0823-0824)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
113ashburn_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
113ashburn_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
113ashburn_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
11charkay_A1	20.27	20.29	20.29	20.24	20.28	20.29	23.26	23.28	23.28
11charkay_A3	19.05	19.15	19.26	16.69	16.98	17.20	22.57	22.64	22.70
11charkay_A9	20.33	20.34	20.34	20.32	20.32	20.32	23.32	23.33	23.33
23kilmory_A1	20.32	20.32	20.32	3.40	4.07	4.33	19.50	19.63	19.65
23kilmory_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
23kilmory_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
28mulvage_A1	20.19	20.24	20.24	20.11	20.30	20.30	23.26	23.28	23.28
28mulvage_A3	18.81	18.91	18.92	20.12	20.22	20.22	21.52	21.65	21.66
28mulvage_A9	16.57	16.64	16.67	0.83	1.24	1.43	17.79	18.17	18.29
40walgate_A1	19.80	20.14	20.15	19.84	20.20	20.22	23.18	23.26	23.26
40walgate_A3	18.26	18.75	18.80	17.55	20.15	20.21	21.41	21.78	21.85
40walgate_A9	20.14	20.28	20.28	17.88	17.92	17.92	23.04	23.17	23.17
56mulvage_A1	17.79	19.73	19.88	13.77	16.36	16.40	20.41	22.53	22.64
56mulvage_A3	19.53	20.03	20.05	12.64	19.58	19.61	22.34	23.02	23.04
56mulvage_A9	17.72	20.10	20.12	17.75	17.87	17.89	22.37	22.69	22.71
5walgate_A1	20.23	20.27	20.27	20.32	20.32	20.32	23.24	23.27	23.27
5walgate_A3	20.24	20.29	20.30	19.88	20.14	20.17	23.22	23.29	23.29
5walgate_A9	20.15	20.26	20.26	9.38	17.13	17.49	23.27	23.32	23.32
62wigan_A1	20.21	20.26	20.26	20.32	20.32	20.32	23.23	23.26	23.26
62wigan_A3	19.99	20.18	20.20	20.00	20.17	20.18	23.25	23.29	23.29
62wigan_A9	20.32	20.32	20.32	18.16	19.55	19.61	23.27	23.29	23.29
wigan1_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
wigan1_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
wigan1_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31

Table D5: T-Spaced Equalizer Performance at 10Msps (0825-0826)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
10inverness_A1	2.97	13.75	16.29	3.29	16.38	16.67	5.72	21.61	21.91
10inverness_A3	3.18	13.28	16.73	4.98	11.91	15.69	7.77	19.20	19.49
10inverness_A9	2.96	16.19	16.56	9.86	16.01	16.23	11.95	21.69	22.13
17lynhevan_A1	5.67	14.88	15.57	6.03	14.74	17.92	10.01	22.09	22.32
17lynhevan_A3	2.79	11.50	14.31	7.50	14.52	15.80	9.97	20.47	20.88
17lynhevan_A9	3.81	15.36	15.54	4.48	13.37	16.83	7.00	22.79	22.86
27inverness_A1	19.56	20.00	20.03	17.58	19.85	19.98	21.95	22.93	23.00
27inverness_A3	19.51	20.00	20.03	20.04	20.04	20.04	22.35	22.98	23.02
27inverness_A9	19.65	19.65	19.65	8.01	15.62	16.05	22.15	22.31	22.32
48tiverton_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
48tiverton_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
48tiverton_A9	20.04	20.04	20.04	4.91	5.01	5.02	19.60	19.60	19.60
53tiverton_A1	4.86	6.40	6.51	20.04	20.04	20.04	17.23	17.38	17.40
53tiverton_A3	18.32	19.87	19.98	20.04	20.04	20.04	20.24	22.74	22.95
53tiverton_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
5beliveau_A1	13.51	19.16	19.49	16.44	19.33	19.44	16.03	21.96	22.41
5beliveau_A3	3.36	3.40	3.40	18.28	19.75	19.78	18.92	20.61	20.64
5beliveau_A9	5.50	12.34	13.72	20.04	20.04	20.04	21.90	22.66	22.81
5rockfield_A1	8.14	13.56	15.58	4.14	15.56	16.01	12.55	17.37	19.24
5rockfield_A3	19.58	19.78	19.82	2.96	12.83	16.33	21.11	22.15	22.50
5rockfield_A9	19.71	20.02	20.03	16.35	19.55	19.59	22.28	22.91	22.95
lyrockfield_A1	3.10	16.42	17.04	4.26	17.37	17.47	4.14	20.00	20.18
lyrockfield_A3	5.33	13.57	18.08	3.29	17.03	17.05	7.14	16.33	20.84
lyrockfield_A9	2.99	16.90	16.93	3.20	13.56	16.62	10.97	19.84	20.77
philip_f_A1	11.64	12.46	12.59	6.57	6.69	6.70	12.60	13.33	13.44
philip_f_A3	7.43	7.43	7.43	9.97	16.21	16.45	11.57	16.82	17.10
philip_f_A9	7.89	15.74	18.38	11.49	17.52	17.63	11.37	20.60	21.32

Table D6: T/2-Spaced Equalizer Performance at 10Msps (0825-0826)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
10inverness_A1	8.86	17.63	18.07	7.08	17.40	17.70	21.91	22.82	22.88
10inverness_A3	10.56	18.11	18.51	12.16	18.72	19.15	14.55	21.10	21.59
10inverness_A9	9.23	17.76	18.16	15.93	19.42	19.56	22.57	23.09	23.10
17lynhevan_A1	12.12	18.53	18.84	13.65	18.80	19.01	22.78	23.15	23.16
17lynhevan_A3	11.19	16.02	16.41	14.44	19.11	19.38	21.74	21.80	21.80
17lynhevan_A9	7.65	17.00	17.44	10.31	17.45	17.84	23.14	23.31	23.31
27inverness_A1	20.27	20.30	20.30	20.21	20.25	20.25	23.24	23.28	23.28
27inverness_A3	20.33	20.34	20.34	20.32	20.32	20.32	23.32	23.33	23.33
27inverness_A9	19.90	19.90	19.91	13.57	16.40	16.49	22.56	22.58	22.59
48tiverton_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
48tiverton_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
48tiverton_A9	20.32	20.32	20.32	5.17	5.78	6.08	19.81	20.04	20.07
53tiverton_A1	5.95	7.19	7.45	20.32	20.32	20.32	17.68	17.91	17.96
53tiverton_A3	20.11	20.22	20.23	20.32	20.32	20.32	23.06	23.22	23.22
53tiverton_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
5beliveau_A1	19.57	20.02	20.06	19.89	20.13	20.15	22.67	23.04	23.09
5beliveau_A3	3.50	4.05	4.22	20.14	20.21	20.22	21.06	21.16	21.17
5beliveau_A9	9.73	18.26	18.55	20.32	20.32	20.32	23.19	23.28	23.30
5rockfield_A1	15.44	19.06	19.18	9.44	17.88	18.27	18.61	21.76	21.94
5rockfield_A3	20.06	20.09	20.09	9.83	17.88	18.37	22.84	23.00	23.02
5rockfield_A9	20.30	20.31	20.31	19.92	20.02	20.03	23.26	23.27	23.27
lyrockfield_A1	6.38	17.52	17.57	7.74	18.01	18.12	9.08	20.69	20.74
lyrockfield_A3	9.67	18.45	18.74	6.67	17.52	17.61	13.25	21.37	21.60
lyrockfield_A9	6.85	17.33	17.43	7.15	18.60	18.92	18.08	21.88	21.97
philip_f_A1	12.50	13.20	13.39	6.88	7.48	7.73	13.44	14.10	14.32
philip_f_A3	7.46	8.09	8.91	16.94	19.38	19.53	17.43	19.45	20.05
philip_f_A9	16.95	19.15	19.33	17.95	19.59	19.71	20.57	22.30	22.48

Table D7: T-Spaced Equalizer Performance at 10Msps (0827-0909)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
114 Fourseasns_A1	18.23	19.83	19.96	19.17	19.22	19.97	20.96	22.79	22.94
114 Fourseasns_A3	19.73	20.01	20.03	20.04	20.04	20.04	22.70	23.00	23.02
114 Fourseasns_A9	12.94	19.02	19.39	17.52	19.76	19.92	21.09	22.60	22.77
35seymour_A1	19.34	19.34	19.34	18.19	19.83	19.96	21.99	22.35	22.39
35seymour_A3	18.92	18.93	18.93	18.55	18.61	19.98	21.67	21.70	22.15
35seymour_A9	14.94	19.21	19.81	17.52	17.53	17.54	18.86	21.78	22.33
Coolspring & Vi_A1	14.46	14.46	14.46	7.73	7.73	7.73	17.05	17.41	17.42
Coolspring & Vi_A3	13.59	18.87	19.37	4.60	4.67	4.68	14.33	20.86	21.53
Coolspring & Vi_A9	16.99	16.99	16.99	4.66	4.76	4.79	19.03	19.96	20.03
e_argue_A1	15.95	19.13	19.49	14.35	18.55	19.02	21.92	22.34	22.48
e_argue_A3	17.83	19.46	19.60	18.87	19.93	20.00	22.07	22.61	22.69
e_argue_A9	16.53	19.59	19.60	18.40	18.40	18.40	18.69	22.34	22.35
Fourseas & Sh_A1	8.96	16.33	18.69	8.50	17.08	18.81	20.47	21.98	22.63
Fourseas & Sh_A3	11.90	18.88	19.24	13.55	18.91	19.39	16.88	22.25	22.45
Fourseas & Sh_A9	11.47	18.91	19.22	13.98	19.34	19.61	19.75	22.63	22.70
seymour_ch_A1	12.61	13.38	13.46	15.46	15.47	15.50	15.33	15.39	15.43
seymour_ch_A3	13.12	13.13	13.15	16.19	16.19	16.21	19.42	19.42	19.43
seymour_ch_A9	14.35	14.83	14.84	12.08	12.09	12.13	15.09	15.76	15.77

Table D8: T/2-Spaced Equalizer Performance at 10Msps (0827-0909)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
114 Fourseasns_A1	20.12	20.27	20.28	20.27	20.29	20.29	23.22	23.27	23.27
114 Fourseasns_A3	20.33	20.33	20.33	20.32	20.32	20.32	23.32	23.32	23.32
114 Fourseasns_A9	19.76	20.08	20.13	20.06	20.25	20.26	23.17	23.28	23.29
35seymour_A1	19.57	19.62	19.67	20.12	20.27	20.27	22.64	22.69	22.74
35seymour_A3	19.17	19.99	20.04	20.06	20.32	20.33	22.40	23.10	23.14
35seymour_A9	19.96	20.20	20.21	17.68	17.73	17.75	22.58	22.70	22.71
Coolspring & Vi_A1	14.54	14.89	15.09	7.74	8.09	8.50	17.94	18.39	18.52
Coolspring & Vi_A3	19.34	19.96	20.02	4.84	5.48	5.77	21.64	22.38	22.46
Coolspring & Vi_A9	17.11	17.26	17.46	4.82	5.77	6.27	20.47	20.63	20.78
e_argue_A1	19.72	19.86	19.88	19.16	19.38	19.40	22.75	22.79	22.80
e_argue_A3	19.91	19.96	19.98	20.26	20.29	20.29	22.98	23.03	23.05
e_argue_A9	19.79	19.89	19.94	18.58	18.68	18.80	22.56	22.65	22.75
Fourseas & Sh_A1	17.58	19.36	19.49	17.94	19.50	19.58	22.85	23.11	23.14
Fourseas & Sh_A3	18.60	19.77	19.83	19.12	19.87	19.91	22.54	22.99	23.02
Fourseas & Sh_A9	18.25	19.71	19.76	19.51	20.08	20.11	22.82	23.09	23.10
seymour_ch_A1	13.46	14.02	19.42	15.55	18.25	19.98	15.49	19.88	22.49
seymour_ch_A3	13.20	13.90	19.35	16.30	18.86	20.10	19.67	20.20	23.00
seymour_ch_A9	14.98	15.55	19.88	12.14	12.92	18.88	16.01	16.79	22.69

Table D9: T-Spaced Equalizer Performance at 10Msps (0913-0915)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
18 Welkin_A1	16.91	19.81	19.95	17.33	19.74	19.94	18.44	22.57	22.89
18 Welkin_A3	18.36	19.85	19.97	16.86	19.75	19.94	19.88	22.62	22.91
18 Welkin_A9	19.51	19.97	20.02	17.72	17.73	17.73	22.13	22.67	22.72
22 Welkin_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
22 Welkin_A3	15.89	15.89	15.89	13.61	13.61	13.61	17.93	17.93	17.93
22 Welkin_A9	17.93	17.96	19.98	5.42	5.52	5.54	19.53	19.58	22.89
25 Southview_A1	12.57	16.75	16.80	13.71	17.69	17.72	20.51	22.58	22.67
25 Southview_A3	12.10	13.73	13.77	15.57	16.93	16.94	18.09	22.57	22.58
25 Southview_A9	13.82	15.87	15.96	2.55	3.02	4.82	14.76	16.92	17.19
46 Laird_A1	19.81	19.81	19.81	19.11	19.87	19.90	22.66	22.75	22.75
46 Laird_A3	19.26	19.96	20.01	17.74	19.75	19.94	21.19	22.81	22.97
46 Laird_A9	18.63	19.59	19.69	19.13	19.13	19.16	21.21	22.19	22.28
Chesterton & As_A1	19.73	19.73	19.73	19.08	20.01	20.03	22.55	22.62	22.63
Chesterton & As_A3	19.75	20.03	20.04	20.04	20.04	20.04	22.65	23.02	23.03
Chesterton & As_A9	19.74	20.04	20.04	18.92	19.96	20.01	22.43	23.01	23.03
Meadowlands&P_A1	19.02	19.56	19.61	17.91	19.77	19.95	21.04	22.35	22.47
Meadowlands&P_A3	19.36	19.47	19.92	16.49	19.64	19.85	21.74	22.84	22.87
Meadowlands&P_A9	18.59	19.64	19.74	19.02	19.92	20.00	20.66	22.42	22.57
Southview & Che_A1	11.09	17.14	17.20	7.95	19.34	19.34	13.13	19.55	19.66
Southview & Che_A3	11.00	18.24	18.27	9.95	14.73	14.86	16.25	21.27	21.31
Southview & Che_A9	10.72	17.58	17.62	13.89	13.91	14.02	14.66	21.40	21.54
Viewmount & Ho_A1	14.73	19.62	19.78	6.81	14.88	17.99	20.66	22.72	22.88
Viewmount & Ho_A3	9.80	18.31	18.80	12.92	18.20	18.81	13.81	20.69	21.49
Viewmount & Ho_A9	13.31	19.32	19.59	19.30	19.30	19.30	20.98	22.23	22.33

Table D10: T/2-Spaced Equalizer Performance at 10Msps (0913-0915)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
18 Welkin_A1	20.19	20.26	20.27	20.21	20.28	20.28	23.19	23.26	23.26
18 Welkin_A3	20.14	20.27	20.28	20.16	20.23	20.23	23.16	23.25	23.26
18 Welkin_A9	20.21	20.30	20.30	17.88	17.93	17.95	22.96	23.00	23.00
22 Welkin_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
22 Welkin_A3	15.99	16.09	16.11	13.68	13.90	14.10	18.04	18.17	18.22
22 Welkin_A9	19.80	20.28	20.31	5.66	6.31	6.60	22.37	23.22	23.25
25 Southview_A1	16.65	17.26	17.53	17.81	18.11	18.15	22.95	23.02	23.10
25 Southview_A3	13.57	14.29	14.26	17.08	17.45	17.53	22.73	22.84	22.85
25 Southview_A9	16.08	16.71	16.94	3.28	7.99	12.56	17.05	18.40	20.49
46 Laird_A1	20.08	20.10	20.12	20.15	20.27	20.28	23.02	23.06	23.08
46 Laird_A3	20.28	20.30	20.30	20.22	20.28	20.29	23.26	23.29	23.29
46 Laird_A9	19.86	20.29	20.29	19.39	20.06	20.29	22.48	23.28	23.29
Chesterton & As_A1	19.98	19.98	19.98	20.27	20.29	20.29	22.88	22.88	22.88
Chesterton & As_A3	20.31	20.31	20.31	20.32	20.32	20.32	23.30	23.30	23.30
Chesterton & As_A9	20.30	20.31	20.31	20.30	20.31	20.32	23.30	23.30	23.30
Meadowlands&P_A1	19.80	19.87	19.87	20.13	20.27	20.27	22.72	22.75	22.75
Meadowlands&P_A3	20.17	20.28	20.28	19.94	20.21	20.22	23.23	23.27	23.27
Meadowlands&P_A9	19.99	20.00	20.01	20.20	20.29	20.29	22.84	22.86	22.87
Southview & Che_A1	16.76	19.68	19.87	17.95	19.43	19.43	19.20	22.67	22.85
Southview & Che_A3	18.70	19.87	20.02	15.04	19.20	19.61	21.74	22.94	23.06
Southview & Che_A9	17.67	19.66	19.99	14.58	18.32	19.75	21.41	22.90	23.09
Viewmount & Ho_A1	20.11	20.26	20.27	15.49	18.80	19.04	23.20	23.29	23.30
Viewmount & Ho_A3	18.82	19.62	19.72	18.52	19.74	19.92	21.60	22.82	22.91
Viewmount & Ho_A9	19.84	20.11	20.14	19.52	19.54	19.54	22.60	22.65	22.66

Table D11: T-Spaced Equalizer Performance at 10Msps (0916-0917)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
14 harris_A1	18.24	19.84	19.97	16.31	16.31	16.31	20.54	22.47	22.68
14 harris_A3	19.08	19.89	19.91	19.27	19.91	19.94	21.70	22.81	22.83
14 harris_A9	18.24	18.24	18.24	16.18	19.49	19.78	20.51	21.60	21.71
23 david_A1	19.22	19.84	19.85	18.91	20.03	20.03	21.64	22.80	22.80
23 david_A3	18.59	19.91	19.91	15.76	19.21	19.35	20.63	22.81	22.84
23 david_A9	19.14	19.70	19.75	15.70	19.56	19.87	22.17	22.61	22.63
26 harris_A1	15.12	19.49	19.74	15.97	19.59	19.79	16.32	22.35	22.62
26 harris_A3	18.90	19.70	19.77	17.09	19.80	19.92	21.22	22.54	22.66
26 harris_A9	16.95	19.70	19.88	19.23	19.23	19.23	19.92	22.63	22.80
26 Withrow_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
26 Withrow_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
26 Withrow_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
35 david_A1	17.42	19.75	19.91	17.84	19.73	19.94	22.12	22.84	22.97
35 david_A3	14.54	19.25	19.60	16.45	19.54	19.80	21.27	22.63	22.82
35 david_A9	16.62	19.24	19.46	15.83	19.57	19.80	17.47	22.12	22.41
3a joan_A1	20.04	20.04	20.04	14.48	14.48	14.48	20.85	20.85	20.85
3a joan_A3	17.41	19.71	19.90	10.52	10.53	10.57	18.29	20.36	20.56
3a joan_A9	11.65	11.65	11.67	14.06	14.06	14.06	15.94	15.96	16.12
5 david_A1	20.04	20.04	20.04	13.01	13.02	13.03	22.19	22.19	22.19
5 david_A3	18.55	19.81	19.96	13.28	19.39	19.60	21.34	22.85	22.96
5 david_A9	17.45	19.64	19.87	16.85	19.55	19.83	18.67	22.38	22.75
bayne & david_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
bayne & david_A3	17.17	17.18	17.19	10.35	10.35	10.35	18.71	18.72	18.73
bayne & david_A9	20.04	20.04	20.04	9.08	9.09	9.08	22.73	22.73	22.73
canter & bayne_A1	9.43	11.90	12.11	13.25	19.27	19.74	13.48	19.90	20.53
canter & bayne_A3	9.27	14.71	19.18	20.04	20.04	20.04	17.72	19.52	22.50
canter & bayne_A9	15.30	15.31	15.31	20.04	20.04	20.04	17.56	17.57	17.59
Rossland & Pe_A1	19.45	19.97	20.02	18.21	18.21	18.21	22.12	22.67	22.73
Rossland & Pe_A3	12.68	18.50	19.15	10.81	17.46	18.52	13.09	20.75	21.74
Rossland & Pe_A9	19.19	19.96	20.02	12.11	15.20	15.55	21.38	22.71	22.85

Table D12: T/2-Spaced Equalizer Performance at 10Msps (0916-0917)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
14 harris_A1	20.14	20.27	20.27	16.41	16.46	16.47	22.96	23.00	23.01
14 harris_A3	20.23	20.29	20.29	20.16	20.28	20.28	23.26	23.28	23.29
14 harris_A9	18.42	18.52	18.63	20.02	20.19	20.21	21.95	22.09	22.18
23 david_A1	20.07	20.09	20.09	20.27	20.28	20.28	23.03	23.04	23.04
23 david_A3	20.06	20.23	20.23	19.49	19.62	19.62	22.98	23.19	23.19
23 david_A9	19.98	20.00	20.00	20.14	20.25	20.26	22.87	22.88	22.89
26 harris_A1	19.75	20.15	20.17	19.81	20.14	20.15	22.63	23.13	23.15
26 harris_A3	20.03	20.07	20.09	20.27	20.33	20.33	22.94	23.00	23.02
26 harris_A9	20.14	20.24	20.25	19.44	19.46	19.47	23.11	23.18	23.19
26 Withrow_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
26 Withrow_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
26 Withrow_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
35 david_A1	20.20	20.27	20.28	20.23	20.29	20.29	23.29	23.31	23.31
35 david_A3	19.84	20.12	20.15	19.85	20.18	20.19	23.17	23.25	23.27
35 david_A9	19.63	19.80	19.81	19.83	20.18	20.20	22.73	22.86	22.88
3a joan_A1	20.32	20.32	20.32	14.55	14.55	14.55	21.09	21.09	21.09
3a joan_A3	20.23	20.30	20.31	11.28	17.78	18.43	20.70	22.69	23.07
3a joan_A9	12.26	18.28	19.07	14.07	14.40	14.51	16.26	20.10	20.75
5 david_A1	20.32	20.32	20.32	13.04	13.36	13.44	22.45	22.48	22.48
5 david_A3	20.28	20.32	20.33	19.97	20.21	20.23	23.31	23.34	23.34
5 david_A9	20.00	20.22	20.23	20.12	20.24	20.25	23.09	23.22	23.23
bayne & david_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
bayne & david_A3	17.35	18.04	18.23	10.38	10.71	10.78	18.88	19.92	20.16
bayne & david_A9	20.32	20.32	20.32	9.14	9.54	9.68	23.01	23.01	23.01
canter & bayne_A1	11.62	12.50	12.65	19.82	20.07	20.08	20.67	21.05	21.07
canter & bayne_A3	13.08	19.43	19.62	20.32	20.32	20.32	21.80	22.81	22.90
canter & bayne_A9	15.41	15.75	15.77	20.32	20.32	20.32	17.76	18.18	18.26
Rossland & Pe_A1	20.21	20.30	20.30	18.39	18.39	18.40	22.97	23.00	23.00
Rossland & Pe_A3	19.09	19.83	19.92	17.92	19.47	19.62	21.82	22.71	22.83
Rossland & Pe_A9	20.25	20.29	20.29	15.45	15.87	15.94	23.08	23.15	23.15

Table D13: T-Spaced Equalizer Performance at 10Msps (0920-0921-0922)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
10 granton_A1	8.25	17.96	18.38	16.37	18.08	18.24	17.83	20.64	20.59
10 granton_A3	16.42	19.53	19.80	17.71	18.58	18.68	19.60	22.57	22.83
10 granton_A9	14.93	19.30	19.64	16.99	18.39	18.76	20.52	22.60	22.76
10a granton_A1	8.81	14.42	18.86	11.19	16.83	18.89	19.24	21.89	22.72
10a granton_A3	8.94	17.59	18.31	10.45	17.98	18.70	10.59	19.96	21.15
10a granton_A9	10.75	18.24	18.83	11.07	17.42	18.54	20.11	22.56	22.76
27 Lotta_A1	18.62	19.80	19.83	20.04	20.04	20.04	21.17	22.72	22.76
27 Lotta_A3	16.43	19.57	19.82	20.04	20.04	20.04	20.68	22.70	22.88
27 Lotta_A9	17.52	17.52	17.52	16.64	16.65	16.66	20.09	20.09	20.09
28 canter_A1	9.07	17.94	18.50	10.39	17.04	18.25	10.69	20.01	21.10
28 canter_A3	6.56	15.61	18.15	5.19	14.51	17.49	18.95	22.74	22.83
28 canter_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
50 st-clair_A1	20.04	20.04	20.04	15.13	19.34	19.66	22.00	22.87	22.96
50 st-clair_A3	19.38	19.96	20.01	20.04	20.04	20.04	22.08	22.93	22.99
50 st-clair_A9	15.73	15.75	15.77	16.41	19.41	19.75	18.29	18.93	18.99
63 David_A1	9.78	9.80	9.81	6.07	14.78	17.88	10.91	16.73	19.42
63 David_A3	7.90	14.45	15.78	3.11	13.59	16.65	9.00	19.10	19.85
63 David_A9	7.82	17.75	18.25	5.95	8.46	8.57	11.64	20.33	20.37
70 harris_A1	3.15	15.99	16.49	4.77	4.83	4.84	5.89	14.62	17.02
70 harris_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
70 harris_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
Bayne & Meado_A1	2.88	12.28	13.63	14.13	14.70	14.76	14.06	17.60	18.01
Bayne & Meado_A3	14.20	14.41	15.36	4.46	12.85	15.20	14.48	19.16	19.27
Bayne & Meado_A9	15.53	18.38	18.65	5.20	14.53	17.59	20.30	21.63	21.77
End of cote des_A1	20.04	20.04	20.04	4.34	4.43	4.43	21.52	21.53	21.53
End of cote des_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
End of cote des_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
Joan & Meadow_A1	5.43	14.23	17.58	7.20	10.20	10.33	11.47	16.58	16.86
Joan & Meadow_A3	3.06	16.08	16.36	9.26	15.80	16.19	13.31	22.22	22.52
Joan & Meadow_A9	6.01	6.22	6.24	3.16	13.33	15.78	7.75	14.86	16.44
tower & ST-Hel_A1	17.89	17.89	17.89	20.04	20.04	20.04	21.55	21.55	21.55
tower & ST-Hel_A3	19.72	20.00	20.03	16.71	16.72	16.73	22.41	22.84	22.89
tower & ST-Hel_A9	13.96	13.98	19.85	15.47	19.47	19.85	17.84	19.32	22.82

Table D14: T/2-Spaced Equalizer Performance at 10Msps (0920-0921-0922)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
10 granton_A1	17.60	19.20	19.38	18.87	20.12	20.26	21.48	23.05	23.19
10 granton_A3	20.05	20.20	20.22	19.19	20.18	20.32	23.09	23.24	23.25
10 granton_A9	19.84	20.12	20.15	19.26	20.16	20.24	22.99	23.25	23.26
10a granton_A1	16.20	19.26	19.45	16.51	19.50	19.72	22.83	23.17	23.21
10a granton_A3	16.84	19.17	19.36	18.05	19.50	19.64	20.31	22.25	22.46
10a granton_A9	18.14	19.55	19.67	17.79	19.51	19.65	23.26	23.29	23.29
27 Lotta_A1	20.22	20.28	20.29	20.32	20.32	20.32	23.22	23.28	23.28
27 Lotta_A3	20.15	20.26	20.27	20.32	20.32	20.32	23.24	23.29	23.30
27 Lotta_A9	17.68	17.75	17.77	16.76	16.86	16.89	20.23	20.31	20.35
28 canter_A1	16.53	19.27	19.44	16.76	19.34	19.49	19.67	22.24	22.44
28 canter_A3	15.35	18.84	19.03	12.99	18.24	18.56	23.29	23.32	23.32
28 canter_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
50 st-clair_A1	20.32	20.32	20.32	19.90	20.14	20.17	23.26	23.29	23.30
50 st-clair_A3	20.17	20.27	20.27	20.32	20.32	20.32	23.17	23.26	23.27
50 st-clair_A9	15.83	15.96	16.02	19.82	20.13	20.15	19.17	19.36	19.41
63 David_A1	9.82	10.30	10.45	13.67	18.74	18.98	17.99	20.37	20.57
63 David_A3	15.10	19.13	19.33	11.86	18.24	18.58	17.51	21.71	22.01
63 David_A9	15.37	19.06	19.24	8.30	10.75	11.37	19.15	21.73	21.78
70 harris_A1	12.34	18.46	18.79	4.94	5.48	5.60	14.72	19.12	19.38
70 harris_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
70 harris_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
Bayne & Meado_A1	8.18	14.77	15.18	14.79	15.01	15.03	17.85	18.84	18.94
Bayne & Meado_A3	15.58	15.89	15.96	11.14	16.40	16.74	19.18	20.07	20.17
Bayne & Meado_A9	18.74	18.98	19.00	11.78	18.39	18.68	22.03	22.12	22.13
End of cote des_A1	20.32	20.32	20.32	4.60	5.23	5.50	21.75	21.85	21.86
End of cote des_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
End of cote des_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
Joan & Meadow_A1	12.94	18.52	18.81	9.10	11.64	11.93	17.40	17.85	17.89
Joan & Meadow_A3	6.96	17.15	17.60	15.56	19.06	19.27	23.01	23.18	23.20
Joan & Meadow_A9	6.18	6.98	7.16	7.60	16.91	17.42	13.28	17.98	18.27
tower & ST-Hel_A1	18.06	18.06	18.06	20.32	20.32	20.32	21.76	21.76	21.76
tower & ST-Hel_A3	20.22	20.31	20.31	16.83	16.93	16.95	23.10	23.16	23.16
tower & ST-Hel_A9	17.52	19.94	20.11	20.26	20.35	20.35	20.92	23.11	23.20

Table D15: T-Spaced Equalizer Performance at 10Msps (0923-0927)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
106 rossland_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
106 rossland_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
106 rossland_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
118 rossland_A1	20.04	20.04	20.04	16.55	16.57	16.59	22.42	22.42	22.42
118 rossland_A3	18.17	19.71	19.75	20.04	20.04	20.04	21.65	22.81	22.84
118 rossland_A9	19.04	19.92	20.00	20.04	20.04	20.04	21.29	22.83	22.96
41 paulsen_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
41 paulsen_A3	18.09	19.84	19.95	20.04	20.04	20.04	20.26	22.76	22.91
41 paulsen_A9	18.46	19.74	19.75	9.83	18.56	18.89	20.97	22.72	22.93
61 paulsen_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
61 paulsen_A3	16.71	19.60	19.90	20.04	20.04	20.04	20.30	22.61	22.91
61 paulsen_A9	16.24	19.56	19.80	20.04	20.04	20.04	19.37	22.56	22.79
79 tower_A1	12.03	18.85	19.23	9.50	18.22	18.68	20.70	22.81	22.84
79 tower_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
79 tower_A9	12.68	12.68	12.68	20.04	20.04	20.04	14.73	14.74	14.74
96 rossland_A1	18.99	19.87	19.91	17.09	19.58	19.84	20.79	22.68	22.91
96 rossland_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
96 rossland_A9	20.04	20.04	20.04	12.39	18.93	19.30	22.74	22.99	23.01

Table D16: T/2-Spaced Equalizer Performance at 10Msps (0923-0927)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
106 rossland_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
106 rossland_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
106 rossland_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
118 rossland_A1	20.32	20.32	20.32	16.67	16.78	16.81	22.68	22.70	22.70
118 rossland_A3	20.16	20.27	20.27	20.32	20.32	20.32	23.24	23.28	23.29
118 rossland_A9	20.19	20.28	20.28	20.32	20.32	20.32	23.13	23.27	23.28
41 paulsen_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
41 paulsen_A3	20.06	20.22	20.22	20.32	20.32	20.32	23.03	23.22	23.22
41 paulsen_A9	20.10	20.23	20.23	18.88	19.69	19.78	23.21	23.26	23.26
61 paulsen_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
61 paulsen_A3	20.12	20.23	20.23	20.32	20.32	20.32	23.20	23.25	23.26
61 paulsen_A9	19.99	20.20	20.21	20.32	20.32	20.32	23.10	23.22	23.24
79 tower_A1	19.41	19.92	19.99	18.40	19.50	19.64	23.16	23.27	23.29
79 tower_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
79 tower_A9	12.73	12.79	12.80	20.32	20.32	20.32	14.85	14.92	14.93
96 rossland_A1	20.13	20.26	20.27	19.94	20.19	20.21	23.02	23.24	23.25
96 rossland_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
96 rossland_A9	20.32	20.32	20.32	18.78	19.85	19.91	23.29	23.30	23.30

Appendix E: Equalizer Performance at 40Msps

Table E1: T-Spaced Equalizer Performance at 40Msps (0819-0820)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
3kilmory_A1	18.01	18.03	18.17	18.44	18.46	18.56	19.96	19.98	20.17
3kilmory_A3	16.91	16.94	17.15	17.25	17.28	17.46	20.77	20.79	20.93
3kilmory_A9	17.74	17.80	18.64	6.29	13.86	17.75	18.69	20.34	21.11
42newbury_A1	12.30	12.30	12.30	14.19	14.19	14.19	14.69	14.82	14.83
42newbury_A3	13.81	13.81	13.82	15.62	15.62	15.62	21.21	21.33	21.34
42newbury_A9	15.05	15.05	15.05	14.19	14.19	16.88	17.50	17.53	18.46
banson1_A1	16.67	16.68	16.68	6.86	10.68	12.36	17.90	18.09	18.19
banson1_A3	14.42	14.43	14.44	3.99	13.35	14.97	15.05	16.74	16.87
banson1_A9	11.34	11.35	13.93	14.09	14.23	16.05	16.83	17.06	18.45
bowmoon1_A1	6.45	6.46	6.47	20.04	20.04	20.04	16.34	16.34	16.34
bowmoon1_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
bowmoon1_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
dharkay1_A1	19.27	19.27	19.27	17.57	17.61	19.14	21.76	21.78	22.07
dharkay1_A3	19.46	19.46	19.46	19.41	19.41	19.41	22.61	22.61	22.61
dharkay1_A9	18.13	18.16	19.34	18.90	18.92	19.21	21.25	21.32	22.23
kilmory1_A1	19.74	19.74	19.74	18.38	18.43	19.03	22.45	22.46	22.55
kilmory1_A3	18.85	18.89	19.30	16.93	16.95	17.12	20.58	20.66	21.11
kilmory1_A9	17.49	17.49	19.63	18.49	18.50	18.62	20.14	20.34	22.43
newbjry1_A1	18.86	18.86	18.86	18.26	18.28	18.41	21.42	21.42	21.44
newbjry1_A3	17.76	17.76	17.76	17.63	17.63	17.63	20.23	20.28	20.23
newbjry1_A9	16.41	16.41	16.41	4.21	4.22	4.23	18.94	19.02	19.02
tivtrton1_A1	19.43	19.48	19.89	19.36	19.37	19.38	22.35	22.42	22.80
tivtrton1_A3	19.62	19.62	19.62	18.66	18.66	19.33	22.50	22.51	22.65
tivtrton1_A9	18.70	18.70	19.24	18.31	18.31	18.31	21.10	21.11	21.80
woumount1_A1	19.77	19.78	19.78	17.33	17.33	17.33	22.48	22.48	22.48
woumount1_A3	19.46	19.46	19.46	18.91	18.91	18.91	22.23	22.23	22.23
woumount1_A9	18.32	18.35	18.70	18.19	18.20	18.20	21.06	21.12	21.40

Table E2: T/2-Spaced Equalizer Performance at 40Msps (0819-0820)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
3kilmory_A1	18.24	20.07	20.08	18.67	20.01	20.02	20.18	23.00	23.02
3kilmory_A3	17.13	20.15	20.23	17.47	20.20	20.27	21.09	23.22	23.27
3kilmory_A9	18.03	20.04	20.06	7.95	19.17	19.34	22.20	22.98	23.00
42newbury_A1	12.37	13.54	13.08	14.26	14.62	15.12	15.06	15.80	16.17
42newbury_A3	13.90	14.98	14.46	15.66	16.16	16.22	21.82	22.16	22.18
42newbury_A9	15.10	15.61	15.68	15.90	16.96	17.12	18.18	19.16	19.46
banson1_A1	16.83	17.09	17.17	11.30	18.62	19.22	18.63	19.33	19.47
banson1_A3	14.50	14.71	14.76	6.10	17.83	18.01	17.18	18.79	18.81
banson1_A9	13.09	14.43	14.69	14.43	19.70	20.11	18.01	21.93	22.43
bowmoon1_A1	6.49	7.13	7.36	20.32	20.32	20.32	16.56	16.91	16.97
bowmoon1_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
bowmoon1_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
dharkay1_A1	19.50	19.53	19.56	18.39	19.65	19.72	22.14	22.40	22.45
dharkay1_A3	19.70	19.74	19.77	19.65	19.68	19.72	22.87	22.91	22.93
dharkay1_A9	18.86	19.77	19.82	19.17	19.79	19.80	21.96	22.67	22.72
kilmory1_A1	20.00	20.10	20.15	18.70	20.05	20.06	22.72	23.05	23.10
kilmory1_A3	19.16	20.05	20.06	17.13	19.62	19.72	20.87	22.73	22.77
kilmory1_A9	19.25	19.90	20.08	18.72	20.26	20.27	22.05	22.84	23.02
newbjry1_A1	19.06	19.08	19.08	18.51	20.27	20.30	21.62	21.81	21.82
newbjry1_A3	17.92	17.92	17.92	17.79	17.84	17.86	20.45	20.50	20.51
newbjry1_A9	16.48	16.53	16.53	4.25	4.97	5.28	19.33	19.40	19.40
tivtrton1_A1	20.13	20.19	20.19	19.48	19.93	19.94	23.03	23.12	23.12
tivtrton1_A3	19.87	19.87	19.87	19.37	19.58	19.59	22.87	22.91	22.92
tivtrton1_A9	19.30	19.47	19.49	18.39	18.58	18.73	21.79	22.03	22.05
woumount1_A1	19.94	20.04	20.04	17.65	18.66	18.71	22.70	22.82	22.83
woumount1_A3	19.70	19.86	19.91	19.29	20.30	20.30	22.50	22.85	22.92
woumount1_A9	18.58	19.46	19.63	18.37	18.40	18.41	21.35	22.24	22.40

Table E3: T-Spaced Equalizer Performance at 40Msps (0823-0824)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
113ashburn_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
113ashburn_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
113ashburn_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
11charkay_A1	18.91	18.91	18.91	17.79	17.82	17.98	21.03	21.04	21.07
11charkay_A3	18.91	18.91	18.91	17.79	17.82	17.98	21.03	21.04	21.07
11charkay_A9	18.49	18.49	18.49	20.04	20.04	20.04	22.08	22.08	22.09
23kilmory_A1	20.04	20.04	20.04	3.10	3.10	3.10	19.21	19.21	19.21
23kilmory_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
23kilmory_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
28mulvage_A1	17.60	17.61	17.62	16.71	16.71	16.72	22.00	22.16	22.22
28mulvage_A3	15.91	15.97	18.22	15.65	15.76	17.27	17.18	17.41	20.19
28mulvage_A9	16.00	16.01	16.44	0.62	0.70	0.71	16.92	16.94	17.50
40walgate_A1	14.11	14.12	14.12	14.48	14.48	14.48	21.42	21.78	21.82
40walgate_A3	13.09	13.09	13.09	13.89	14.91	15.23	15.89	16.24	16.32
40walgate_A9	16.56	16.56	16.56	17.77	17.77	17.77	18.97	18.97	18.97
56mulvage_A1	10.98	11.18	13.02	7.66	8.68	10.34	12.99	13.70	15.45
56mulvage_A3	9.53	9.81	13.94	7.54	7.94	12.13	12.34	13.37	16.51
56mulvage_A9	9.84	9.87	13.79	14.63	14.64	17.62	15.17	15.25	18.62
5walgate_A1	17.83	17.90	18.78	20.04	20.04	20.04	20.66	20.76	21.58
5walgate_A3	18.15	18.15	18.16	10.12	16.80	19.08	19.87	20.35	20.51
5walgate_A9	16.48	17.02	17.68	4.41	11.68	16.24	17.75	18.67	22.22
62wigan_A1	17.34	17.42	18.46	20.04	20.04	20.04	20.06	20.18	21.15
62wigan_A3	13.58	13.70	18.57	14.32	14.45	16.23	21.08	21.81	22.95
62wigan_A9	20.04	20.04	20.04	8.35	8.42	8.84	22.36	22.37	22.48
wigan1_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
wigan1_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
wigan1_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03

Table E4: T/2-Spaced Equalizer Performance at 40Msps (0823-0824)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
113ashburn_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
113ashburn_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
113ashburn_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
11charkay_A1	19.28	20.28	20.28	18.02	20.22	20.26	21.44	23.26	23.27
11charkay_A3	19.28	20.28	20.28	18.02	20.22	20.26	21.44	23.26	23.27
11charkay_A9	18.92	20.24	20.30	20.32	20.32	20.32	22.47	23.31	23.31
23kilmory_A1	20.32	20.32	20.32	3.11	3.11	3.11	19.48	19.48	19.48
23kilmory_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
23kilmory_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
28mulvage_A1	17.83	19.71	19.79	16.87	18.86	17.46	22.52	23.10	23.16
28mulvage_A3	16.93	18.77	18.84	15.95	20.03	20.19	18.33	21.47	21.56
28mulvage_A9	16.36	16.61	16.62	0.82	0.90	0.91	17.32	17.65	17.68
40walgate_A1	14.19	17.41	14.88	14.57	17.08	15.65	22.22	22.59	22.72
40walgate_A3	13.16	15.60	14.25	14.93	16.76	17.11	16.37	18.53	19.18
40walgate_A9	16.69	18.48	17.50	17.93	17.98	17.98	19.12	20.03	21.23
56mulvage_A1	12.53	15.57	14.76	9.58	10.18	11.25	14.69	18.44	18.74
56mulvage_A3	12.48	16.32	15.51	11.27	13.68	16.06	14.82	20.92	21.08
56mulvage_A9	11.86	16.26	15.81	16.68	17.69	17.77	17.37	20.22	20.73
5walgate_A1	18.14	20.25	20.27	20.32	20.32	20.32	21.06	23.26	23.28
5walgate_A3	18.35	18.66	19.62	16.54	19.94	19.97	20.73	21.78	22.73
5walgate_A9	16.89	20.18	20.21	6.05	18.37	18.47	20.08	23.13	23.16
62wigan_A1	17.64	20.22	20.26	20.32	20.32	20.32	20.48	23.24	23.26
62wigan_A3	15.52	19.87	20.14	14.65	19.76	20.13	22.71	23.23	23.27
62wigan_A9	20.32	20.32	20.32	8.58	15.34	17.52	22.65	23.27	23.28
wigan1_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
wigan1_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
wigan1_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31

Table E5: T-Spaced Equalizer Performance at 40Msps (0825-0826)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
10inverness_A1	3.50	4.41	6.73	3.56	4.29	6.16	5.31	7.91	17.10
10inverness_A3	2.62	5.55	11.43	3.93	4.28	5.29	5.76	7.32	12.36
10inverness_A9	2.55	5.41	10.66	3.54	5.05	13.37	4.81	18.15	19.25
17lynhevan_A1	5.18	5.72	7.61	3.17	5.81	11.83	6.38	15.09	16.71
17lynhevan_A3	2.50	5.48	9.12	2.37	5.72	9.44	2.58	7.20	17.34
17lynhevan_A9	3.76	3.88	5.15	2.67	3.39	5.50	4.02	6.36	19.24
27inverness_A1	19.27	19.29	19.95	17.07	17.10	17.30	21.58	21.75	22.52
27inverness_A3	19.39	19.42	19.70	20.04	20.04	20.04	22.20	22.24	22.59
27inverness_A9	19.62	19.62	19.62	6.26	6.76	7.17	22.01	22.02	22.10
48tiverton_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
48tiverton_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
48tiverton_A9	20.04	20.04	20.04	4.86	4.87	4.88	19.55	19.55	19.55
53tiverton_A1	4.86	5.13	6.79	20.04	20.04	20.04	16.77	16.84	16.99
53tiverton_A3	11.94	11.95	19.80	20.04	20.04	20.04	13.79	13.87	22.81
53tiverton_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
5beliveau_A1	10.20	10.59	18.48	2.30	4.98	16.22	10.50	18.12	22.10
5beliveau_A3	3.73	3.79	3.84	2.61	5.35	16.73	4.17	7.87	16.43
5beliveau_A9	3.55	10.67	16.47	20.04	20.04	20.04	19.70	20.89	21.45
5rockfield_A1	7.66	7.87	9.14	3.90	4.62	7.04	12.01	12.37	13.22
5rockfield_A3	15.23	15.25	17.82	2.41	5.49	9.42	15.62	18.47	21.11
5rockfield_A9	19.62	19.64	19.82	13.76	13.91	15.70	21.97	22.01	22.30
lyrockfield_A1	3.59	3.71	4.32	2.08	3.29	3.33	4.63	5.45	6.30
lyrockfield_A3	5.33	5.55	5.92	3.64	3.82	4.40	6.38	6.58	8.13
lyrockfield_A9	2.63	3.13	3.38	2.76	7.77	9.31	2.67	10.67	12.79
philip_f_A1	6.65	10.30	11.00	6.71	6.73	6.74	9.12	11.76	12.33
philip_f_A3	7.43	7.43	7.43	5.38	5.94	14.75	9.03	10.02	14.68
philip_f_A9	6.12	6.44	18.90	3.98	4.99	15.78	7.41	11.60	20.87

Table E6: T/2-Spaced Equalizer Performance at 40Msps (0825-0826)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
10inverness_A1	3.89	8.02	16.57	4.17	7.73	16.35	6.22	21.82	22.45
10inverness_A3	4.24	7.68	16.94	4.36	9.71	13.14	7.50	14.34	19.82
10inverness_A9	4.11	7.62	16.78	4.14	7.64	16.85	6.42	22.27	22.66
17lynhevan_A1	5.52	9.44	15.95	4.95	8.62	17.49	7.79	22.81	23.01
17lynhevan_A3	4.07	7.58	14.64	3.66	8.31	16.43	6.19	21.59	21.72
17lynhevan_A9	4.03	8.23	13.24	4.22	8.42	16.69	6.67	23.02	23.13
27inverness_A1	19.84	20.31	20.32	17.29	20.15	20.20	22.23	23.29	23.30
27inverness_A3	19.53	20.31	20.31	20.32	20.32	20.32	22.51	23.30	23.30
27inverness_A9	19.88	19.88	19.88	7.12	12.27	13.73	22.27	22.54	22.54
48tiverton_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
48tiverton_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
48tiverton_A9	20.32	20.32	20.32	4.91	5.60	5.88	19.78	19.93	19.94
53tiverton_A1	5.44	6.84	7.63	20.32	20.32	20.32	17.05	17.30	17.32
53tiverton_A3	13.86	19.61	20.19	20.32	20.32	20.32	16.60	22.69	23.20
53tiverton_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
5beliveau_A1	15.83	19.33	19.91	6.73	11.93	17.39	20.00	22.11	22.83
5beliveau_A3	3.85	4.52	4.83	4.82	9.58	17.32	7.90	11.68	17.04
5beliveau_A9	6.39	17.47	18.11	20.32	20.32	20.32	21.70	22.96	23.05
5rockfield_A1	8.05	14.33	16.86	4.28	8.10	16.56	12.62	18.10	19.86
5rockfield_A3	17.07	18.96	19.76	3.76	7.97	16.52	17.83	22.62	22.82
5rockfield_A9	19.91	20.31	20.31	14.14	19.41	19.76	22.29	23.20	23.21
lyrockfield_A1	3.86	5.93	7.07	3.65	6.60	8.35	5.84	10.17	11.15
lyrockfield_A3	5.57	7.30	9.85	3.95	5.96	7.14	6.85	10.22	13.21
lyrockfield_A9	3.82	6.24	7.68	6.21	11.95	16.88	10.85	18.17	19.06
philip_f_A1	9.79	11.47	11.67	6.81	7.39	7.60	11.79	12.87	13.09
philip_f_A3	7.44	7.44	7.48	5.99	12.97	17.43	11.91	16.19	18.17
philip_f_A9	8.96	13.08	19.14	4.96	10.37	17.16	12.64	18.65	22.02

Table E7: T-Spaced Equalizer Performance at 40Msps (0827-0909)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
114 Fourseasns_A1	16.77	16.77	20.00	18.98	18.98	18.99	19.88	19.92	22.89
114 Fourseasns_A3	19.45	19.45	20.04	20.04	20.04	20.04	22.39	22.39	23.03
114 Fourseasns_A9	7.46	15.70	17.65	15.64	15.64	19.97	14.28	19.83	20.63
35seymour_A1	19.30	19.30	19.30	16.67	16.67	19.99	21.67	21.68	22.33
35seymour_A3	18.86	18.86	18.86	18.58	18.58	18.58	21.70	21.70	21.70
35seymour_A9	12.56	15.89	16.81	17.48	17.48	17.48	17.31	19.11	19.76
Coolspring & Vi_A1	14.81	14.85	14.89	7.57	7.58	7.58	15.80	15.93	16.18
Coolspring & Vi_A3	8.58	10.98	17.28	4.68	4.70	4.71	9.65	11.88	18.60
Coolspring & Vi_A9	17.23	17.25	17.26	4.61	4.63	4.64	18.56	18.60	18.66
e_argue_A1	14.86	14.96	18.75	13.65	13.80	15.54	20.75	21.28	22.40
e_argue_A3	17.19	17.25	19.30	18.58	18.63	19.24	21.57	21.65	22.55
e_argue_A9	16.04	16.11	18.76	18.55	18.56	18.57	18.28	18.39	21.19
Fourseas & Sh_A1	7.19	7.51	14.67	8.02	8.28	10.50	17.08	20.63	22.50
Fourseas & Sh_A3	5.92	6.41	13.45	5.75	6.27	13.26	16.59	17.73	18.58
Fourseas & Sh_A9	6.82	7.12	9.30	11.07	11.09	19.74	14.68	18.49	19.27
seymour_ch_A1	11.06	12.40	12.51	15.26	15.26	15.26	15.13	15.58	15.80
seymour_ch_A3	13.19	13.20	13.19	16.26	16.26	16.26	19.45	19.45	19.45
seymour_ch_A9	13.22	13.22	14.46	11.84	11.84	11.84	13.80	13.83	15.31

Table E8: T/2-Spaced Equalizer Performance at 40Msps (0827-0909)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
114 Fourseasns_A1	19.02	20.24	20.29	19.19	20.28	20.28	22.02	23.26	23.29
114 Fourseasns_A3	20.13	20.29	20.30	20.32	20.32	20.32	23.12	23.29	23.29
114 Fourseasns_A9	8.52	19.53	19.54	18.38	20.19	20.27	17.74	22.84	22.86
35seymour_A1	19.53	19.53	19.54	18.97	20.24	20.29	22.34	22.58	22.59
35seymour_A3	19.07	19.08	19.10	18.78	19.00	19.18	21.90	21.99	22.07
35seymour_A9	16.52	18.84	19.15	17.63	17.68	17.69	20.11	22.05	22.18
Coolspring & Vi_A1	14.83	15.07	15.15	7.59	7.79	7.83	15.95	17.55	17.81
Coolspring & Vi_A3	13.85	19.04	19.72	4.73	5.43	5.72	15.45	21.47	22.03
Coolspring & Vi_A9	17.37	17.43	17.46	4.74	5.38	5.63	18.79	20.85	20.91
e_argue_A1	16.63	19.68	19.81	14.10	18.94	19.31	22.14	22.72	22.74
e_argue_A3	18.44	19.82	19.86	18.91	20.28	20.29	22.40	22.92	22.93
e_argue_A9	17.20	19.55	19.80	18.75	18.77	18.78	19.55	22.27	22.56
Fourseas & Sh_A1	8.57	13.44	19.28	8.55	14.88	18.59	20.91	22.73	23.05
Fourseas & Sh_A3	6.66	10.64	19.02	6.41	10.26	18.96	17.56	20.95	22.57
Fourseas & Sh_A9	7.01	12.20	18.55	14.72	19.56	20.06	19.60	22.33	22.79
seymour_ch_A1	12.50	14.11	14.21	15.35	15.36	15.37	16.13	16.63	16.67
seymour_ch_A3	13.25	13.51	13.58	16.37	16.49	16.53	19.69	19.85	19.87
seymour_ch_A9	14.10	14.49	14.55	11.88	11.88	11.89	14.82	15.33	15.41

Table E9: T-Spaced Equalizer Performance at 40Msps (0913-0915)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
18 Welkin_A1	16.55	16.55	16.55	16.86	16.96	18.13	18.38	18.57	18.94
18 Welkin_A3	16.94	16.94	20.00	16.27	16.30	16.54	18.89	19.56	22.65
18 Welkin_A9	18.77	18.88	19.98	17.68	17.68	17.68	21.36	21.47	22.63
22 Welkin_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
22 Welkin_A3	15.95	15.96	15.96	13.67	13.72	13.77	18.00	18.01	18.03
22 Welkin_A9	18.12	18.12	18.12	5.66	5.73	5.79	19.80	19.80	19.80
25 Southview_A1	12.50	12.58	13.77	12.90	12.96	13.14	16.08	16.25	17.26
25 Southview_A3	11.39	11.43	11.79	15.56	15.56	15.57	18.46	18.52	18.80
25 Southview_A9	12.46	12.47	12.49	2.40	2.82	2.83	12.96	13.18	13.02
46 Laird_A1	19.82	19.82	19.82	15.56	15.82	19.69	22.33	22.38	22.72
46 Laird_A3	18.83	18.86	19.89	16.84	16.91	19.53	20.46	20.53	22.62
46 Laird_A9	16.92	17.11	19.38	19.07	19.07	19.07	20.21	20.39	22.37
Chesterton & As_A1	19.76	19.76	19.76	19.05	19.05	19.08	22.59	22.59	22.59
Chesterton & As_A3	19.75	19.75	19.76	20.04	20.04	20.04	22.64	22.65	22.66
Chesterton & As_A9	19.77	19.77	19.78	18.73	18.74	18.85	22.52	22.52	22.54
Meadowlands&P_A1	18.36	18.36	19.58	15.60	15.86	19.69	19.82	19.88	22.42
Meadowlands&P_A3	15.91	16.15	19.73	14.23	14.23	19.92	18.18	18.59	22.65
Meadowlands&P_A9	17.41	17.41	19.70	18.04	18.04	20.02	19.01	19.02	22.55
Southview & Che_A1	10.89	10.89	10.89	7.95	7.95	7.95	12.85	12.85	12.85
Southview & Che_A3	11.05	11.05	11.05	10.18	10.19	10.23	15.55	15.69	15.74
Southview & Che_A9	10.62	10.62	10.62	13.72	13.72	13.72	14.53	14.53	14.53
Viewmount & Ho_A1	12.21	12.34	17.96	5.03	5.59	18.50	18.95	20.34	21.77
Viewmount & Ho_A3	6.35	11.18	16.92	5.95	6.53	15.70	9.36	17.49	19.85
Viewmount & Ho_A9	11.93	12.07	17.84	19.32	19.32	19.32	20.70	20.81	21.94

Table E10: T/2-Spaced Equalizer Performance at 40Msps (0913-0915)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
18 Welkin_A1	17.07	20.01	20.19	17.28	20.19	20.25	19.17	23.06	23.21
18 Welkin_A3	19.10	20.25	20.30	16.49	20.07	20.16	21.16	23.24	23.29
18 Welkin_A9	20.15	20.31	20.33	17.83	17.88	17.89	22.79	22.97	22.98
22 Welkin_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
22 Welkin_A3	16.06	16.18	16.21	13.74	13.98	14.08	18.11	18.24	18.29
22 Welkin_A9	18.30	18.51	18.64	5.76	6.36	6.62	19.94	20.30	20.59
25 Southview_A1	13.43	15.47	16.61	13.21	15.81	17.28	18.61	21.16	22.26
25 Southview_A3	11.88	12.28	13.30	15.76	16.87	16.92	19.36	22.51	22.67
25 Southview_A9	12.80	14.22	15.91	3.30	3.99	4.38	13.34	15.49	17.19
46 Laird_A1	20.08	20.08	20.08	19.47	20.22	20.29	22.95	23.02	23.02
46 Laird_A3	19.56	20.30	20.31	18.18	20.21	20.26	21.63	23.27	23.29
46 Laird_A9	18.50	19.75	19.80	19.29	19.30	19.30	22.31	22.81	22.83
Chesterton & As_A1	20.02	20.02	20.02	19.46	20.29	20.29	22.85	22.92	22.92
Chesterton & As_A3	20.07	20.31	20.31	20.32	20.32	20.32	22.98	23.30	23.30
Chesterton & As_A9	19.91	20.31	20.32	18.98	20.29	20.30	22.78	23.30	23.31
Meadowlands&P_A1	19.44	19.84	19.85	19.42	20.21	20.28	21.96	22.68	22.71
Meadowlands&P_A3	19.59	20.24	20.30	17.45	20.08	20.23	22.15	23.24	23.29
Meadowlands&P_A9	19.13	19.96	20.00	19.62	20.29	20.32	21.42	22.80	22.83
Southview & Che_A1	11.05	11.99	16.06	8.10	8.67	13.74	13.04	14.15	18.18
Southview & Che_A3	11.20	12.13	17.09	10.29	11.30	14.52	16.15	17.33	20.85
Southview & Che_A9	10.76	11.77	16.42	13.76	13.80	13.81	14.69	15.84	20.64
Viewmount & Ho_A1	15.04	19.51	20.00	7.20	10.73	18.75	21.55	22.89	23.09
Viewmount & Ho_A3	14.02	18.53	19.17	9.94	13.80	18.33	19.34	21.92	22.26
Viewmount & Ho_A9	14.19	19.44	20.02	19.55	19.56	19.56	21.52	22.64	22.69

Table E11: T-Spaced Equalizer Performance at 40Msps (0916-0917)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
14 harris_A1	16.69	16.69	19.99	16.46	16.46	16.47	19.12	19.13	22.71
14 harris_A3	17.82	17.83	17.86	14.33	16.12	19.34	19.82	20.38	20.72
14 harris_A9	18.40	18.41	18.41	12.86	14.93	19.01	19.90	20.48	21.57
23 david_A1	19.15	19.16	19.33	18.95	18.96	18.97	21.63	21.64	21.83
23 david_A3	16.27	16.57	18.88	16.21	16.39	17.64	18.50	19.07	21.50
23 david_A9	17.02	17.58	18.59	16.02	16.09	18.26	19.02	19.71	20.91
26 harris_A1	12.43	12.44	19.84	10.39	10.43	19.68	14.24	14.36	22.79
26 harris_A3	18.06	18.06	19.79	13.36	13.37	19.88	21.15	21.19	22.73
26 harris_A9	15.08	15.08	19.95	19.18	19.18	19.18	18.68	18.72	22.90
26 Withrow_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
26 Withrow_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
26 Withrow_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
35 david_A1	15.84	15.84	19.97	16.43	16.43	19.99	21.71	21.77	23.01
35 david_A3	11.59	13.81	18.63	12.69	12.70	19.85	17.85	21.37	21.72
35 david_A9	14.10	14.40	19.10	13.41	13.42	19.89	14.60	15.02	22.28
3a joan_A1	20.04	20.04	20.04	14.48	14.48	14.48	20.85	20.85	20.85
3a joan_A3	12.16	17.91	19.46	10.76	10.77	10.76	14.38	19.08	20.69
3a joan_A9	11.65	11.65	11.65	14.12	14.17	14.21	15.99	16.03	16.05
5 david_A1	20.04	20.04	20.04	12.79	12.79	12.79	22.17	22.17	22.17
5 david_A3	14.08	18.72	19.71	9.28	11.65	17.64	16.31	20.86	22.24
5 david_A9	13.19	13.51	19.31	13.08	18.35	19.62	16.08	19.99	22.41
bayne & david_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
bayne & david_A3	17.12	17.12	17.13	10.76	10.82	10.88	18.67	18.68	18.69
bayne & david_A9	20.04	20.04	20.04	9.49	9.56	9.62	22.75	22.75	22.75
canter & bayne_A1	8.58	8.61	8.83	12.43	12.43	12.44	12.68	12.75	12.82
canter & bayne_A3	7.91	7.92	7.94	20.04	20.04	20.04	17.88	17.88	17.91
canter & bayne_A9	15.36	15.40	15.36	20.04	20.04	20.04	17.61	17.65	17.63
Rosslund & Pen_A1	18.60	18.71	19.96	18.21	18.21	18.21	21.34	21.45	22.63
Rosslund & Pen_A3	6.14	13.73	17.68	3.63	11.02	15.83	9.86	14.82	19.32
Rosslund & Pen_A9	18.69	18.73	19.86	10.67	10.80	14.61	20.95	21.06	22.49

Table E12: T/2-Spaced Equalizer Performance at 40Msps (0916-0917)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
14 harris_A1	18.97	20.25	20.30	16.58	16.68	16.70	21.50	22.97	23.01
14 harris_A3	18.07	20.30	20.32	19.62	20.14	20.21	20.43	23.28	23.31
14 harris_A9	18.50	18.61	18.62	18.42	20.01	20.13	21.53	22.08	22.11
23 david_A1	19.17	20.09	20.11	19.18	20.29	20.29	21.88	23.06	23.06
23 david_A3	17.69	20.21	20.29	17.93	19.52	19.58	21.31	23.17	23.23
23 david_A9	17.88	19.96	20.02	16.42	20.01	20.19	20.19	22.87	22.91
26 harris_A1	15.99	19.87	20.15	12.06	18.23	20.05	17.82	22.75	23.13
26 harris_A3	19.47	20.04	20.06	17.39	19.88	20.08	22.38	22.96	22.99
26 harris_A9	18.11	20.12	20.23	19.41	19.41	19.41	21.35	23.10	23.17
26 Withrow_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
26 Withrow_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
26 Withrow_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
35 david_A1	18.60	20.15	20.23	18.92	20.18	20.24	22.75	23.25	23.27
35 david_A3	14.70	19.89	20.04	16.18	19.92	20.18	22.12	23.16	23.20
35 david_A9	18.37	19.62	19.74	16.85	19.99	20.19	19.93	22.67	22.83
3a joan_A1	20.32	20.32	20.32	14.55	14.55	14.55	21.09	21.09	21.09
3a joan_A3	18.46	20.12	20.13	10.80	11.28	11.45	20.13	21.43	21.44
3a joan_A9	11.69	11.70	11.73	14.19	14.41	14.50	16.11	16.33	16.41
5 david_A1	20.32	20.32	20.32	12.84	12.84	12.84	22.43	22.43	22.43
5 david_A3	19.52	20.22	20.22	12.57	19.54	19.76	22.29	23.15	23.17
5 david_A9	18.35	20.02	20.19	19.16	20.16	20.18	21.75	23.17	23.23
bayne & david_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
bayne & david_A3	17.26	17.33	17.35	10.81	11.20	11.36	18.78	18.91	18.95
bayne & david_A9	20.32	20.32	20.32	9.55	10.00	10.18	23.02	23.04	23.04
canter & bayne_A1	8.69	11.09	11.30	13.07	18.87	19.47	13.69	19.54	20.09
canter & bayne_A3	8.32	12.10	11.24	20.32	20.32	20.32	18.19	19.12	19.36
canter & bayne_A9	15.39	15.60	15.69	20.32	20.32	20.32	17.72	17.99	18.10
Rossland & Pen_A1	20.14	20.32	20.33	18.39	18.39	18.39	22.80	22.97	22.98
Rossland & Pen_A3	7.85	19.12	19.30	6.11	18.09	18.30	12.59	21.95	22.14
Rossland & Pen_A9	19.43	20.30	20.32	11.90	15.01	15.73	21.88	23.14	23.16

Table E13: T-Spaced Equalizer Performance at 40Msps (0920-0921-0922)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
10 granton_A1	4.44	13.29	17.41	12.57	17.52	18.66	14.57	20.11	21.50
10 granton_A3	13.26	15.27	19.12	14.10	15.80	18.57	18.77	19.61	21.98
10 granton_A9	11.51	13.73	18.60	12.03	13.70	16.27	20.64	21.21	22.46
10a granton_A1	6.47	6.72	17.35	2.58	4.88	10.59	7.13	18.28	19.14
10a granton_A3	4.33	5.32	14.62	4.98	7.46	14.60	5.03	11.24	16.27
10a granton_A9	6.20	6.78	16.30	2.59	4.86	13.31	6.99	20.63	21.29
27 Lotta_A1	16.87	16.88	16.94	20.04	20.04	20.04	19.56	19.58	19.63
27 Lotta_A3	13.04	15.09	19.06	20.04	20.04	20.04	18.71	19.62	22.14
27 Lotta_A9	17.47	17.47	17.48	16.58	16.59	16.59	20.04	20.04	20.04
28 canter_A1	4.72	5.38	18.35	3.11	4.72	17.02	6.03	10.16	20.65
28 canter_A3	6.19	6.56	8.70	4.81	5.51	12.32	15.73	21.28	22.65
28 canter_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
50 st-clair_A1	20.04	20.04	20.04	12.01	14.19	18.77	21.42	21.81	22.72
50 st-clair_A3	15.54	15.54	15.75	20.04	20.04	20.04	18.48	18.51	18.67
50 st-clair_A9	15.78	15.81	15.84	7.80	8.23	17.35	16.92	17.21	18.20
63 David_A1	9.55	9.55	9.55	4.90	5.61	12.43	10.38	11.60	14.73
63 David_A3	5.73	6.24	13.19	3.20	4.71	10.41	6.95	10.84	14.78
63 David_A9	4.41	5.30	11.86	5.62	6.06	8.11	7.37	13.41	15.33
70 harris_A1	3.26	4.85	13.88	5.23	5.31	5.36	6.48	8.52	14.48
70 harris_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
70 harris_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
Bayne & Mead_A1	3.38	4.28	6.48	10.41	10.65	13.83	10.54	13.21	14.39
Bayne & Mead_A3	5.45	11.68	13.12	3.22	4.45	13.27	6.77	15.62	18.27
Bayne & Mead_A9	12.64	12.94	18.04	4.68	5.23	7.23	14.61	19.47	20.04
End of cote de_A1	20.04	20.04	20.04	4.28	4.30	4.31	21.50	21.50	21.50
End of cote de_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
End of cote de_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
Joan & Meado_A1	4.21	5.16	11.65	3.31	4.51	9.40	5.66	13.72	14.09
Joan & Meado_A3	2.57	3.18	5.12	3.19	4.73	16.95	3.44	15.89	20.37
Joan & Meado_A9	2.29	3.20	3.74	2.65	2.97	4.94	3.85	5.89	7.72
tower & ST-He_A1	17.89	17.89	17.89	20.04	20.04	20.04	21.55	21.55	21.55
tower & ST-He_A3	19.24	19.31	20.00	16.65	16.65	16.66	21.74	21.83	22.83
tower & ST-He_A9	14.18	14.18	14.18	11.48	11.87	18.91	16.02	16.37	19.14

Table E14: T/2-Spaced Equalizer Performance at 40Msps (0920-0921-0922)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
10 granton_A1	9.90	18.90	19.36	16.55	19.16	19.18	18.46	21.99	22.06
10 granton_A3	18.65	20.05	20.15	16.49	19.25	19.29	22.04	23.05	23.11
10 granton_A9	17.25	19.86	20.04	16.13	18.54	18.89	22.44	23.01	23.06
10a granton_A1	9.15	13.18	17.74	5.83	15.91	17.19	15.24	22.00	22.33
10a granton_A3	5.54	13.69	18.41	6.54	17.58	18.85	9.04	19.34	21.71
10a granton_A9	10.56	15.74	19.12	6.21	16.47	18.11	19.69	23.23	23.24
27 Lotta_A1	17.10	20.27	20.31	20.32	20.32	20.32	19.83	23.28	23.31
27 Lotta_A3	15.97	20.04	20.12	20.32	20.32	20.32	22.33	23.16	23.20
27 Lotta_A9	17.62	17.67	17.69	16.70	16.79	16.81	20.17	20.24	20.25
28 canter_A1	6.52	9.81	18.69	3.42	7.16	17.54	8.60	13.56	21.24
28 canter_A3	6.76	11.57	18.08	5.83	9.33	18.45	21.52	23.13	23.20
28 canter_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
50 st-clair_A1	20.32	20.32	20.32	15.04	19.93	20.08	23.11	23.26	23.28
50 st-clair_A3	15.92	20.17	20.31	20.32	20.32	20.32	18.91	23.21	23.31
50 st-clair_A9	15.88	16.01	16.07	13.52	16.63	19.64	17.86	18.53	18.74
63 David_A1	9.57	9.57	9.57	5.80	9.27	18.55	11.70	15.63	20.06
63 David_A3	6.22	10.43	16.35	3.83	7.39	17.59	8.09	14.11	20.43
63 David_A9	5.12	8.38	18.35	6.22	10.63	11.44	9.76	17.45	20.32
70 harris_A1	3.89	7.45	17.52	5.34	5.95	6.23	6.92	11.47	18.35
70 harris_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
70 harris_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
Bayne & Mead_A1	3.77	7.79	14.34	12.94	13.88	14.32	12.89	17.14	18.25
Bayne & Mead_A3	9.29	15.55	15.97	4.67	7.86	15.55	14.04	18.94	19.91
Bayne & Mead_A9	17.07	18.52	18.73	5.20	8.97	17.48	20.27	21.73	21.83
End of cote de_A1	20.32	20.32	20.32	4.33	5.04	5.34	21.74	21.80	21.80
End of cote de_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
End of cote de_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
Joan & Meado_A1	4.99	8.23	18.22	3.89	6.49	10.10	9.20	17.02	17.35
Joan & Meado_A3	3.99	7.92	16.68	3.93	7.30	17.41	10.37	22.35	22.87
Joan & Meado_A9	3.55	4.80	5.37	4.10	8.09	16.27	7.24	11.97	17.52
tower & ST-He_A1	18.06	18.06	18.06	20.32	20.32	20.32	21.76	21.76	21.76
tower & ST-He_A3	20.23	20.32	20.33	16.77	16.86	16.88	23.02	23.16	23.16
tower & ST-He_A9	14.25	14.66	14.98	16.57	19.67	19.95	18.61	20.21	20.40

Table E15: T-Spaced Equalizer Performance at 40Msps (0923-0927)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
106 rossland_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
106 rossland_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
106 rossland_A9	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
118 rossland_A1	20.04	20.04	20.04	16.60	16.63	16.65	22.42	22.43	22.43
118 rossland_A3	16.21	16.23	16.34	20.04	20.04	20.04	20.73	20.75	20.79
118 rossland_A9	15.53	16.43	16.51	20.04	20.04	20.04	16.79	17.81	17.91
41 paulsen_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
41 paulsen_A3	12.63	12.64	19.85	20.04	20.04	20.04	15.89	15.99	22.87
41 paulsen_A9	9.65	10.02	18.26	4.84	13.75	17.54	11.99	19.30	22.69
61 paulsen_A1	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
61 paulsen_A3	15.28	15.37	19.14	20.04	20.04	20.04	19.67	19.83	22.19
61 paulsen_A9	13.44	13.77	19.36	20.04	20.04	20.04	17.92	18.19	22.28
79 tower_A1	8.37	15.56	18.56	6.91	14.33	17.96	17.98	19.63	21.53
79 tower_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
79 tower_A9	12.89	12.90	12.91	20.04	20.04	20.04	14.89	14.90	14.91
96 rossland_A1	14.66	14.94	19.57	10.68	12.92	18.25	15.91	16.53	22.02
96 rossland_A3	20.04	20.04	20.04	20.04	20.04	20.04	23.03	23.03	23.03
96 rossland_A9	20.04	20.04	20.04	7.69	7.83	19.29	22.65	22.72	23.03

Table E16: T/2-Spaced Equalizer Performance at 40Msps (0923-0927)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
106 rossland_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
106 rossland_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
106 rossland_A9	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
118 rossland_A1	20.32	20.32	20.32	16.73	16.81	16.86	22.69	22.71	22.71
118 rossland_A3	16.41	20.22	20.28	20.32	20.32	20.32	21.03	23.28	23.30
118 rossland_A9	17.13	20.27	20.32	20.32	20.32	20.32	19.41	23.25	23.31
41 paulsen_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
41 paulsen_A3	14.46	19.79	20.21	20.32	20.32	20.32	18.81	22.98	23.23
41 paulsen_A9	16.08	18.53	19.99	10.97	19.19	19.54	22.26	23.19	23.29
61 paulsen_A1	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
61 paulsen_A3	16.65	20.13	20.25	20.32	20.32	20.32	20.92	23.23	23.28
61 paulsen_A9	18.31	20.00	20.17	20.32	20.32	20.32	21.77	23.11	23.21
79 tower_A1	9.38	19.68	19.73	7.91	19.36	19.43	19.73	22.93	22.96
79 tower_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
79 tower_A9	12.94	13.24	13.32	20.32	20.32	20.32	15.02	15.38	15.49
96 rossland_A1	19.16	20.17	20.27	16.98	19.71	19.97	21.64	23.12	23.23
96 rossland_A3	20.32	20.32	20.32	20.32	20.32	20.32	23.31	23.31	23.31
96 rossland_A9	20.32	20.32	20.32	10.76	15.43	19.64	23.12	23.30	23.31

Appendix F: Actual Equalizer Performance at 10Msps

Table F1: Measured Input SNR

File Name	Input SNR [dB]	
	REFERENCE	SECONDARY
3kilmory_A3	46.40	43.94
42newbury_A3	33.66	32.61
banson1_A3	29.29	22.63
bowmoon1_A3	16.89	15.70
dharkay1_A3	45.70	43.12
kilmory1_A3	46.54	45.97
newbjry1_A3	41.60	39.06
tivtrton1_A3	48.57	47.76
woumount1_A3	43.64	40.03
113ashburn_A3	15.10	13.92
11charkay_A3	39.32	33.93
23kilmory_A3	19.06	16.60
28mulvage_A3	38.64	32.27
35kilmory_A3	12.30	14.78
40walgate_A3	38.32	33.93
56mulvage_A3	38.16	32.00
5walgate_A3	36.66	28.89
62wigan_A3	31.27	28.96
wigan1_A3	24.18	18.78
10inverness_A3	41.38	37.42
17lynhevan_A3	33.14	31.51
27inverness_A3	44.93	39.79
48tiverton_A3	20.25	18.59
53tiverton_A3	27.28	14.44
5beliveau_A3	16.67	17.77
5rockfield_A3	46.74	41.95
lyrockfield_A3	40.14	34.82
philip_f_A3	22.11	20.53
114 Fourseasons_A3	43.49	40.82
35seymour_A3	38.95	38.19
Coolspring & Viewmount_A3	27.38	20.05
e_argue_A3	44.58	42.41
Fourseasons & Shadetree_A3	38.70	33.81
seymour_ch_A3	34.99	33.58

Table F1 con't: Measured Input SNR

File Name	Input SNR [dB]	
	REFERENCE	SECONDARY
18 Welkin_A3	37.49	33.85
22 Welkin_A3	32.41	28.49
25 Southview_A3	34.81	36.79
46 Laird_A3	44.03	41.63
Chesterton & Assiniboine_A3	45.12	40.62
Meadowlands&Peter_A3	42.76	37.73
Southview & Chesterton_A3	39.31	32.37
Viewmount & Homestead_A3	38.84	40.56
14 harris_A3	39.82	33.14
23 david_A3	46.56	42.96
26 harris_A3	46.13	41.61
26 Withrow_A3	13.96	16.16
35 david_A3	41.43	37.75
3a joan_A3	26.02	24.58
5 david_A3	29.48	23.85
bayne & david_A3	34.00	24.60
canter & bayne_A3	26.20	23.42
Rossland & Pender_A3	36.48	31.42
10 granton_A3	44.12	40.74
10a granton_A3	40.84	40.61
27 Lotta_A3	33.57	30.46
28 canter_A3	20.07	20.40
50 st-clair_A3	31.82	25.39
63 David_A3	27.06	25.63
70 harris_A3	12.34	14.59
Bayne & Meadowlands_A3	32.18	33.17
End of cote des neiges_A3	18.38	14.33
Joan & Meadowlands_A3	16.81	20.56
tower & ST-Helens_A3	40.57	33.22
106 rossland_A3	14.40	14.65
118 rossland_A3	33.87	32.09
41 paulsen_A3	31.14	22.91
61 paulsen_A3	30.99	27.37
79 tower_A3	26.33	22.83
96 rossland_A3	29.49	23.95

Table F2: Actual T-Spaced Equalizer Performance at 10Msps (0819-0820)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
3kilmory_A3	20.52	32.84	44.39	20.98	33.10	42.50	44.79	45.21	48.06
42newbury_A3	15.27	17.13	26.77	15.79	23.83	31.25	23.44	33.97	35.73
banson1_A3	15.69	15.72	15.75	3.32	12.73	17.37	15.87	19.10	19.99
bowmoon1_A3	16.98	16.98	16.98	15.81	15.81	15.81	19.43	19.43	19.43
dharkay1_A3	28.52	28.69	35.62	28.20	28.33	36.89	45.08	45.53	45.68
kilmory1_A3	25.83	31.52	32.30	20.49	30.16	32.27	29.51	33.16	33.45
newbjry1_A3	21.84	21.84	21.84	21.33	21.33	21.33	35.24	36.09	36.38
tivtrton1_A3	29.36	29.36	29.36	25.84	27.46	27.63	34.86	38.59	38.90
woumount1_A3	28.63	30.47	39.32	25.72	36.90	39.52	31.19	40.00	42.65

Table F3: Actual T/2-Spaced Equalizer Performance at 10Msps (0819-0820)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
3kilmory_A3	46.00	46.62	46.62	44.12	44.25	44.25	48.87	48.96	48.96
42newbury_A3	25.94	33.61	33.78	19.25	32.75	32.80	36.25	36.45	36.48
banson1_A3	15.72	16.19	16.43	9.31	19.09	19.88	19.49	21.34	21.66
bowmoon1_A3	17.26	17.26	17.26	16.09	16.09	16.09	19.70	19.70	19.70
dharkay1_A3	30.35	45.92	45.98	30.78	43.36	43.39	46.37	48.24	48.24
kilmory1_A3	32.40	42.65	46.73	31.43	43.08	46.16	33.42	44.94	49.50
newbjry1_A3	21.85	23.60	33.48	21.34	22.12	22.84	36.49	37.34	38.75
tivtrton1_A3	29.17	29.43	29.69	27.56	27.84	28.29	37.37	39.50	39.61
woumount1_A3	40.81	43.92	43.92	40.26	40.30	40.30	44.17	45.78	45.78

Table F4: Actual T-Spaced Equalizer Performance at 10Msps (0823-0824)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
113ashburn_A3	15.23	15.23	15.23	14.09	14.09	14.09	17.73	17.73	17.73
11charkay_A3	24.85	24.86	24.85	18.96	18.96	18.96	39.23	39.23	39.23
23kilmory_A3	19.11	19.11	19.11	16.70	16.70	16.70	21.15	21.15	21.15
28mulvage_A3	19.62	23.68	24.17	21.03	29.91	31.30	21.77	31.49	32.16
40walgate_A3	14.34	21.19	23.49	18.78	20.53	30.15	20.93	23.33	32.08
56mulvage_A3	13.10	29.59	35.14	7.73	20.35	30.21	15.18	37.49	39.09
5walgate_A3	22.79	26.50	33.49	15.57	26.78	27.75	24.91	30.81	37.79
62wigan_A3	16.31	25.63	30.27	16.67	25.65	28.29	32.46	32.77	33.19
wigan1_A3	24.20	24.20	24.20	18.84	18.84	18.84	25.57	25.57	25.57

Table F5: Actual T/2-Spaced Equalizer Performance at 10Msps (0823-0824)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
113ashburn_A3	15.50	15.50	15.50	14.36	14.36	14.36	18.00	18.00	18.00
11charkay_A3	24.84	26.07	27.00	18.99	20.16	20.62	39.34	39.62	39.70
23kilmory_A3	19.39	19.39	19.39	16.97	16.97	16.97	21.43	21.43	21.43
28mulvage_A3	24.25	24.66	24.89	31.93	32.44	32.45	32.51	33.27	33.40
40walgate_A3	22.85	24.24	24.58	20.73	33.56	34.08	30.20	34.46	34.66
56mulvage_A3	31.03	38.07	38.11	13.73	31.50	31.54	38.71	40.09	40.12
5walgate_A3	35.75	36.91	36.92	28.71	28.94	29.00	37.69	38.54	38.55
62wigan_A3	31.18	31.37	31.41	28.81	29.07	29.09	33.56	33.60	33.61
wigan1_A3	24.47	24.47	24.47	19.12	19.12	19.12	25.85	25.85	25.85

Table F6: Actual T-Spaced Equalizer Performance at 10Msps (0825-0826)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
10inverness_A3	3.22	14.93	33.29	5.07	12.90	29.16	8.18	32.60	37.81
17lynhevan_A3	2.83	12.37	17.04	7.69	16.85	24.60	10.30	26.80	29.32
27inverness_A3	28.70	39.03	44.07	39.79	39.79	39.79	39.43	42.37	45.78
48tiverton_A3	20.29	20.29	20.29	18.65	18.65	18.65	22.68	22.68	22.68
53tiverton_A3	21.71	26.55	27.12	14.60	14.60	14.60	22.50	27.62	28.31
5beliveau_A3	3.31	3.34	3.35	16.71	17.65	17.67	17.12	18.11	18.14
5rockfield_A3	29.38	32.06	32.67	3.00	14.36	33.27	30.96	33.86	38.97
lyrockfield_A3	5.44	15.05	34.46	3.34	27.37	30.54	8.93	30.04	35.81
philip_f_A3	7.50	7.50	7.50	10.02	16.49	16.77	11.67	17.60	17.94

Table F7: Actual T/2-Spaced Equalizer Performance at 10Msps (0825-0826)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
10inverness_A3	12.27	37.47	38.70	13.65	34.44	35.63	30.61	40.25	41.23
17lynhevan_A3	12.64	19.18	19.86	17.21	29.96	30.62	29.72	31.59	31.72
27inverness_A3	45.21	45.22	45.22	40.07	40.07	40.07	46.72	46.72	46.73
48tiverton_A3	20.57	20.57	20.57	18.93	18.93	18.93	22.95	22.95	22.95
53tiverton_A3	27.07	27.47	27.47	14.87	14.87	14.87	28.35	28.72	28.72
5beliveau_A3	3.44	3.82	3.94	17.95	18.01	18.02	18.45	18.53	18.54
5rockfield_A3	32.48	32.92	33.02	10.75	37.62	38.95	38.58	41.81	42.05
lyrockfield_A3	10.47	38.30	38.61	6.87	32.01	32.09	27.51	39.46	39.68
philip_f_A3	7.53	8.28	9.10	17.33	19.89	20.06	18.45	20.72	21.33

Table F8: Actual T-Spaced Equalizer Performance at 10Msps (0827-0909)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
114 Fourseas_A3	31.08	42.11	42.76	40.82	40.82	40.82	40.22	44.75	45.14
35seymour_A3	25.14	25.14	25.18	23.70	23.90	35.95	27.28	27.98	37.13
Coolspring & Vi_A3	14.45	24.36	25.87	4.60	4.67	4.68	14.78	24.50	25.99
e_argue_A3	21.76	28.42	29.80	25.00	35.62	41.43	36.60	39.13	41.87
Fourseas & Sh_A3	12.57	28.07	33.48	14.56	26.49	30.34	19.62	37.35	39.09
seymour_ch_A3	14.03	14.04	14.07	18.32	18.32	18.35	32.90	32.90	32.91

Table F9: Actual T/2-Spaced Equalizer Performance at 10Msps (0827-0909)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
114 Fourseas_A3	43.78	43.78	43.78	41.10	41.10	41.10	45.95	45.95	45.95
35seymour_A3	25.30	34.32	35.74	31.60	38.46	38.48	34.58	40.08	40.55
Coolspring & Vi_A3	26.26	27.22	27.32	4.84	5.49	5.77	26.40	27.47	27.55
e_argue_A3	30.14	31.48	33.37	41.66	42.66	42.66	42.47	43.38	43.95
Fourseas & Sh_A3	28.86	38.05	38.25	29.72	33.48	33.61	38.76	39.97	40.05
seymour_ch_A3	14.07	15.42	28.17	18.32	27.06	32.47	33.11	33.67	37.29

Table F10: Actual T-Spaced Equalizer Performance at 10Msps (0913-0915)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
18 Welkin_A3	23.09	35.60	36.54	19.51	29.96	33.19	27.28	32.79	38.32
22 Welkin_A3	17.80	17.80	17.81	14.51	14.51	14.52	19.42	19.43	19.44
25 Southview_A3	12.79	14.83	14.89	17.40	19.75	19.76	20.14	37.99	38.12
46 Laird_A3	26.93	36.88	42.94	21.51	31.80	40.09	37.57	39.73	45.26
Chesterton & As_A3	31.44	43.13	44.78	40.62	40.62	40.62	40.06	45.13	46.60
Meadowlands&P_A3	27.53	34.20	37.49	18.92	33.99	36.18	28.27	42.91	43.20
Southview & Che_A3	11.53	23.39	23.48	10.32	16.21	16.39	23.39	36.89	37.01
Viewmount & Ho_A3	10.18	26.60	32.87	13.80	24.16	26.37	15.15	31.91	35.87

Table F11: Actual T/2-Spaced Equalizer Performance at 10Msps (0913-0915)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
18 Welkin_A3	34.52	37.71	37.72	33.63	34.03	34.04	39.19	39.60	39.61
22 Welkin_A3	17.81	18.28	18.52	14.55	14.95	15.37	19.50	20.06	20.35
25 Southview_A3	14.59	15.86	16.11	19.87	21.43	23.07	38.11	38.46	38.47
46 Laird_A3	42.90	44.29	44.29	41.78	41.86	41.86	46.44	46.54	46.54
Chesterton & As_A3	45.36	45.39	45.39	40.90	40.90	40.90	47.17	47.18	47.18
Meadowlands&P_A3	35.61	43.00	43.00	33.16	37.85	37.88	43.80	44.69	44.69
Southview & Che_A3	25.24	36.18	38.88	16.87	28.89	31.23	37.04	39.81	40.46
Viewmount & Ho_A3	33.80	38.18	38.28	26.86	37.90	40.16	37.07	42.50	42.75

Table F12: Actual T-Spaced Equalizer Performance at 10Msps (0916-0917)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
14 harris_A3	25.89	35.28	35.43	26.14	31.61	31.70	31.08	38.64	38.68
23 david_A3	23.97	36.01	40.36	17.72	27.04	28.00	25.84	40.36	42.87
26 harris_A3	25.19	31.63	32.04	20.08	36.41	39.68	28.73	37.89	39.81
26 Withrow_A3	14.13	14.13	14.13	16.27	16.27	16.27	18.21	18.21	18.21
35 david_A3	15.92	31.06	36.26	18.85	31.65	35.09	31.75	41.89	42.51
3a joan_A3	19.67	25.36	25.69	10.82	10.83	10.87	20.20	25.11	25.41
5 david_A3	22.82	28.48	29.09	13.83	22.95	23.22	25.54	30.48	30.90
bayne & david_A3	20.10	20.14	20.17	10.64	10.64	10.64	20.54	20.57	20.60
canter & bayne_A3	9.52	15.91	24.66	23.44	23.44	23.44	22.56	23.64	27.59
Rossland & Pen_A3	13.50	26.18	31.00	11.28	22.28	26.44	17.76	31.50	34.75

Table F13: Actual T/2-Spaced Equalizer Performance at 10Msps (0916-0917)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
14 harris_A3	37.11	40.07	40.07	31.74	33.37	33.38	40.88	40.98	40.99
23 david_A3	35.06	46.75	46.75	28.08	28.49	28.69	40.88	48.25	48.25
26 harris_A3	32.41	33.39	33.90	41.63	41.89	41.89	41.09	42.00	42.33
26 Withrow_A3	14.40	14.40	14.40	16.54	16.54	16.54	18.49	18.49	18.49
35 david_A3	41.06	41.38	41.42	32.83	37.83	37.86	43.18	43.25	43.26
3a joan_A3	26.22	26.29	26.30	11.66	20.52	22.09	25.52	27.72	28.25
5 david_A3	29.72	29.76	29.76	23.74	24.03	24.05	31.42	31.45	31.45
bayne & david_A3	20.20	23.78	24.58	10.66	11.22	11.38	20.69	24.31	25.20
canter & bayne_A3	13.94	25.51	25.76	23.72	23.72	23.72	26.69	28.11	28.21
Rossland & Pen_A3	34.21	35.93	36.13	27.65	30.44	30.80	36.12	37.00	37.27

Table F14: Actual T-Spaced Equalizer Performance at 10Msps (0920-0921-0922)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
10 granton_A3	18.84	34.25	39.48	21.43	24.11	24.31	26.08	41.64	44.65
10a granton_A3	9.25	23.94	30.34	10.90	24.92	31.08	19.01	28.32	34.82
27 Lotta_A3	18.72	31.01	32.36	30.47	30.47	30.47	30.85	34.27	34.68
28 canter_A3	6.56	15.64	18.21	5.20	14.66	17.84	19.08	22.97	23.07
50 st-clair_A3	26.36	31.42	31.59	25.40	25.40	25.40	28.60	32.92	33.06
63 David_A3	8.08	18.92	20.80	3.14	14.85	21.67	9.19	24.10	25.61
Bayne & Meado_A3	15.38	15.67	17.01	4.54	14.17	18.58	16.34	21.96	22.10
End of cote des_A3	18.44	18.44	18.44	14.49	14.49	14.49	20.11	20.11	20.11
Joan & Meado_A3	3.01	13.51	13.68	9.30	16.07	16.54	13.19	21.42	21.71
tower & ST-Hel_A3	30.65	39.47	39.99	19.20	19.23	19.27	30.98	39.91	40.46

Table F15: Actual T/2-Spaced Equalizer Performance at 10Msps (0920-0921-0922)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
10 granton_A3	43.88	44.20	44.22	25.43	36.31	40.77	45.78	46.56	46.58
10a granton_A3	28.73	38.73	39.33	33.02	39.25	39.62	36.47	41.93	42.52
27 Lotta_A3	33.66	33.75	33.77	30.75	30.75	30.75	35.46	35.50	35.51
28 canter_A3	15.40	18.90	19.09	13.23	18.61	18.94	23.52	23.56	23.56
50 st-clair_A3	30.97	32.05	32.05	25.68	25.68	25.68	33.28	33.53	33.53
63 David_A3	17.93	25.89	26.25	13.92	23.45	23.97	22.95	27.78	28.21
Bayne & Meado_A3	17.29	17.90	18.15	13.67	20.44	21.25	22.05	23.63	24.06
End of cote des_A3	18.72	18.72	18.72	14.76	14.76	14.76	20.39	20.39	20.39
Joan & Meado_A3	6.60	14.36	14.74	15.94	19.60	19.82	22.20	22.37	22.39
tower & ST-Hel_A3	35.54	40.84	40.84	19.21	19.58	19.82	39.83	41.39	41.39

Table F16: Actual T-Spaced Equalizer Performance at 10Msps (0923-0927)

File Name	T-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)	(1,0)	(3,1)	(4,2)
106 rossland_A3	14.55	14.55	14.55	14.79	14.79	14.79	17.58	17.58	17.58
118 rossland_A3	22.37	30.53	30.58	32.09	32.09	32.09	32.04	35.38	35.46
41 paulsen_A3	21.91	30.12	30.63	22.93	22.93	22.93	24.78	31.57	32.05
61 paulsen_A3	19.10	27.56	30.32	27.38	27.38	27.38	27.56	30.57	32.28
79 tower_A3	26.34	26.34	26.34	22.85	22.85	22.85	28.14	28.14	28.14
96 rossland_A3	29.50	29.50	29.50	23.97	23.97	23.97	30.89	30.89	30.89

Table F17: Actual T/2-Spaced Equalizer Performance at 10Msps (0923-0927)

File Name	T/2-spaced DFE Output SNR [dB]								
	REFERENCE			SECONDARY			COMBINED		
	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)	(2,0)	(6,1)	(8,2)
106 rossland_A3	14.82	14.82	14.82	15.07	15.07	15.07	17.85	17.85	17.85
118 rossland_A3	32.82	34.09	34.10	32.38	32.38	32.38	36.37	36.44	36.44
41 paulsen_A3	30.20	31.31	31.32	23.21	23.21	23.21	32.06	32.75	32.76
61 paulsen_A3	30.74	31.16	31.18	27.66	27.66	27.66	32.90	32.96	32.96
79 tower_A3	26.62	26.62	26.62	23.13	23.13	23.13	28.42	28.42	28.42
96 rossland_A3	29.78	29.78	29.78	24.25	24.25	24.25	31.17	31.17	31.17

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