MODELING THE NETWORK PERFORMANCE OF DSL CONNECTIONS USING NETEM

BY

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DEDICATION

I dedicate this to Lou, for her support and continued push to getting this done!

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ABSTRACT

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With the increased use of internet based applications requiring low latency, and high bandwidth, the performance demands of the last mile network continue to grow. Additionally, the highly variant deployment scenarios of these technologies, have a high impact on their performance, creating difficult to replicate environments for application developers to test in, often requiring expensive and difficult to obtain equipment. This thesis attempts to model the networking performance of DSL using the open source tool NetEm. This is done by studying the latency performance of DSL connections under a range of conditions and configurations, to quantify the performance. That performance data can then be used to create delay models for using NetEm's custom distribution delay models. These models can provide a powerful tool to test devices and software under simulated DSL conditions.

CHAPTER 1

Introduction

1.1 Objectives

The intention of the study was to map the network performance of a DSL (Digital Subscriber Line) connection, and to use this data to create a network model using the open source tool NetEm. With the intention that these models could be used to test applications and network hardware over a more accurate simulated link.

The study began with an extensive look at the performance of DSL lines from a network layer perspective. Experiments were performed on a wide variety of DSL configurations with varying levels of noise interference, different cable lengths, and differing levels of offered traffic.

These measurements were then analyzed and turned into distribution data to be provided to NetEm on an experimental setup. The traffic run to measure the DSL lines was then run on the simulated setup and its performance compared to the original DSL measurements.

This testing resulted in the creation of several different NetEm profiles modeling a variety of different possible deployments and noise conditions encountered by a VDSL (Very high-bitrate digital subscriber) line.

1.2 Motivation for Studying DSL

1.2.1 Ubiquity of DSL

DSL remains one of the most popular and widely deployed last-mile networking technologies worldwide. One 2014 US based study by the National Broadband Map, a US government funded institution, suggests that around 81% of US homes have access to some form of DSL connection [1]. In Europe and other parts of the world, the relative scarcity of coaxial cables and DOCSIS deployments lead to even more prevalent DSL deployments.

As one of the most popular last mile technologies worldwide, many end users of a variety of applications will be running on a DSL link. Due to this commonality, the testing and performance of applications over these types of links is paramount to any party concerned with delivering services into a home. Any product running over the open network will have to be deployed on a DSL link, and many are unable to test directly on this type of link before deployment.

1.2.2 Scarcity of Lab Based Infrastructure

Though DSL is relatively omnipresent in deployment across the world, it is quite rare in lab based environments, outside of a service provider's own laboratory.

The Central Office or CO side of a DSL connection is a DSLAM (Digital Signal Line Access Multiplexer). Multiple DSLAMs are deployed within a few miles of homes which are serviced by DSL. These devices are costly and are not generally available to a consumer or researcher directly from an equipment vendor.

This means the only laboratories containing DSLAMs are either based directly in service providers, equipment providers, and third party test labs. The UNH-IOL is one of the leading DSL test labs worldwide and possesses what is likely the largest variety of CO equipment worldwide. As an academic institution this presents a unique opportunity to study these connections and their application behavior.

1.2.3 Application Layer Protocol Performance

One particular concern with DSL based connections is their relatively high latency. This higher than average latency is due to the usage of data interleaving in many DSL connections. This study observed latency of connections using data interleaving to be anywhere from 5 ms to 50 ms on average with spikes as high as 200 ms or more in very stressed cases. This is over the physical medium in the last mile and will be additional to any other latency on a route.

Because of this latency, applications relying on TCP (Transmission Control Protocol) will have high round trip times, heavily affecting their usability on limited connections. Many commonly used user applications, in particular, gaming and web-browsing, rely heavily on quick responses from a server to preserve user QoE (Quality of Experience). Studying and replicating these high latency connections can identify issues for application implementers, whose software would potentially encounter these issues in actual deployments.

1.3 Model Use Cases

Considering the scarcity and limited access to DSL equipment that an average application developer would have, there is many possible use cases for an accurate and easy to use simulation of DSL connections. This section details a few possible use cases for such models.

1.3.1 Application Development Testing

With the ease of deploying NetEm models an application developer can easily use these models to gauge how their application performs over a variety of different DSL connection scenarios. This can afford a higher level of certainty that an end user will not run into unforeseen issues and user QoE is high across the board.

1.3.2 Hardware Developers

Any developers of IoT software requiring low latency (such as some forms of sensor) would also find potential benefit in testing over these simulated connections. Giving better assurance that these would behave properly in a wide range of deployment scenarios.

1.3.3 Providers of Internet Based Services

Anyone developing low latency services to be provided into a user's home, such as web application or real-time streamed gaming, can also benefit from the deeper understanding and simulation of high latency subscriber connections. These models could be used to understand if their technology is feasible for all of their consumers.

CHAPTER 2

Background

2.1 Basics of DSL

DSL is one technology that defines a method for encoding and transmitting network traffic over copper cable digitally. DSL is a range locked technology, the longer that cable, the worse the performance in terms of bandwidth and latency.

DSL is a frequency domain duplexing technology. Upstream and downstream traffic is divided into different frequencies and transmitted simultaneously. These divided areas are typically referred to as *bands*. The amount and size of these bands depends on the variety of DSL being used and the configuration of the individual line (a term often used to refer to a single DSL connection). DSL typically uses frequencies between 25 kHz and 35 MHz.

When a DSL connection is established, it first starts with a training process (referred to has handshaking.) During handshaking a CO and CPE (Customer Premise Equipment) agree on which variety of DSL to use. Typically a CO is configured to allow certain parameters (know as a profile), with which limits on a users access and allowable settings and technologies are defined. During handshaking the condition of the line is also assessed and decisions are made about where to transmit the data, what power levels to use, and what optional technologies are enabled and what parameters those technologies use.

It is at this point when a DSL connection also determines parameters that affect its networking performance, such as its actual interleaver delay and actual INP (Impulse Noise Protection). Newer devices are able to change some of these parameters post training when the features to do so are enabled.

2.2 DSL Equipment and Deployment

There are two major pieces of equipment involved in the deliver of a DSL connection to an end user. These pieces of equipment are DSLAMs and modems. These are commonly referred to as the CO and CPE respectively.

The main purpose of a DSLAM is to take one or more high bandwidth connections (typically fiber) and multiplex these connection to multiple customer connections over twisted-pair connections (phone lines, typically referred to as the *last mile*.) DSLAMs also de-multiplex these connections when heading in other direction. This method allows access to be provided to a home over existing copper infrastructure (phone lines), and no new lines are required to be run to a customers home. This use of existing infrastructure is one reason DSL is a popular technology worldwide.

DSLAMs are also responsible for managing many network functions and enforcing QOS (Quality of Service) rules put forth by a service provider. Typically these are very complex and highly expensive devices. They are commonly found in a cabinet nearby to a neighborhood or apartment building delivering connections to the different household or apartments.

The other piece of equipment involved is a CPE or Modem. These are typically very cheap and relatively simple devices provided by a service provider to each subscriber on their network. A CPEs main responsibility is to receive the DSL traffic downstream from the DSLAM and send it as IP based network traffic providing access to the home network, and the opposite for any upstream traffic.

These two pieces of equipment are the main providers of DSL access. Both CPE and COs often rely upon exactly the same or very similar DSL chipsets on either side. A CO contains multiple modems with overlying hardware to control the multiplexing/demultiplexing/network access.

2.2.1 DSL Deployment

DSL is deployed in a hugely wide and varied number of locations worldwide. The quality and performance of the deployments varies highly depending on a number of factors including cable type and quality, line conditions, and distance from a CO.

2.2.1.1 CO Distance

Since DSL is a range locked technology, typically connections range between 100 and 20,000 feet for ADSL (Asymmetric Digital Subscriber Line) connections, and 100 and 9,000 feet for VDSL2 connections. ADSL and ADSL2 are the most widely deployed varieties of DSL providing access speeds up to 24 Mbps for ADSL2+. With less common VDSL2 connections maximally reaching throughputs in the range if 12 to 200 Mbps, depending on he transmission bands and bandwidths chosen.

2.2.2 Cable Type

Cable type and quality can vary depending on the geographic region and the age of the construction. Cable on the telephone pole is often different than cable within the home. Generally home cabling varies widely with many homes using low quality copper cables. This can be a heavy performance detractor for many DSL deployments.

DSL is almost exclusively run over non-shielded cables, which means it can be very susceptible to electrical noise within the environment, from other devices (such as electrical motors) or even other DSL lines. Future variants of DSL technologies, Gfast and upcoming MGFast are looking at using coaxial cable and Ethernet for higher maximal bandwidths.

In addition to the quality of cables, the topology of cables can also be an impactor to performance. Phone lines can often have bridged taps from older telephone connections spliced directly into the phone cable, this can cause reflection and negatively impact DSL performance.

2.3 DSL Performance Impactors

There are several factors that impact the performance of DSL connections. These have been heavily studied and modeled, and their presence has driven the development of DSL technology into creating ways to combat them. The major impactors are cable type/quality, crosstalk (NEXT, FEXT, Alien), and impulse noises (REIN, PEIN, SHINE).

As stated above, cable type can have a large impact on the type of possible performance, low quality cable can degrade performance when it is included in a connection. This can be a major source of crosstalk. There is little to be done about connections over bad cabling. Generally when cabling is the cause of an issue, the only approach is to replace the bad cabling involved in the setup with more modern, or possibly better installed cable, and to remove any impactors such as bridged taps.

2.3.1 Crosstalk

One of the most major and well studied forms of DSL performance impactors is crosstalk. Crosstalk can take many forms but there are at least three well studied forms of DSL crosstalk, NEXT (Near End crosstalk), FEXT (Far End crosstalk), and ATX (Alien crosstalk). All forms of crosstalk are unwanted coupling between signal paths.

NEXT crosstalk, is as the name implies, crosstalk on the Near End of the line. NEXT crosstalk is generally caused by badly twisted wire pairs in a connector. When the twist of the wire is insufficient, or a cable is poorly installed, power sent over one pair may be picked up by an adjacent pair, at the termination point, resulting in interference. When excessive NEXT crosstalk is found to be a performance impactor, generally cable termination points need to be re-wired to ensure sufficient twist is present in the cables and good connections are made.

FEXT crosstalk, or Far End crosstalk, is interference generated from the far end of the cable. This is generally from the presence of other DSL CPE's on the far end of the cable, often transmitting with different power levels or at different bandwidth. FEXT can be minimized through good practice in DSL configuration, and through use of DSL setting such as UPBO (Upstream Power Back Off) and DPBO (Downstream Power Back Off), this is sometimes referred to as Spectral management. Through the use of these settings, the interference between CPE on the same device can be minimized. In the newest VDSL2 chipsets, FEXT can be measured by the CPE and CO, cancelled using a newer DSL technology called Vectoring.

ATX is crosstalk from one cable to another. ATX crosstalk generally occurs when cables are in a *binder* or a set of cables all run together. Often alien crosstalk is cause by the coexistence of different types of DSL in a binder (e.g. VDSL2 and ADLS2plus), the solution is to generally divide the frequency of the technologies, that is to say, not transmit the VDSL2 line in the ADSL frequency.

2.3.2 Impulse Noise

Another type of impairment impacting DSL lines is known as noise. *Common Mode* noise is simply the coupling of other sources of electrical noise onto a transmitting DSL line. This can occur from electric motors, power adapters, heating systems, high voltage power lines, and other electronics. This is generally a cable routing issue, and care should be taken to run DSL cabling isolated from these sources.

When noise cannot be avoided, there are several ways a DSL line can adapt to avoid and correct the errors caused by noise inference. Configuration such a RFI notches and specialized PSD (Power Spectrum Density) parameters allow noisy areas, and the operation of other expected technologies to be avoided. In cases where these noises cannot be explicitly expected and avoided, other DSL functionality exists to repair or retransmit damaged frames, these being FEC (Foward Error Correction) + Interleaving and Retransmission (Detailed in the next section).

There are multiple types of impulse noise, the duration and characteristics of some of these noises have been separated into several models for ease of reproduction and identification; these types are REIN (Repetitive Impulse Noise), PEIN (Prolonged Electrical Impulse Noise), and SHINE (Single High Impulse Noise.) Many other models of Noise exist, but are not commonly used in DSL testing. In DSL deployments and thereby testing, the most common varieties are REIN and SHINE noise. These impulse noises cause packet corruptions triggering Retransmission events, or require the use of settings such as FEC + Interleaving, resulting in increases in latency for transmitted data and lowered user QoE.

REIN noise is repetitive impulses, all up to but not exceeding 1 ms in duration but having a constant frequency. REIN noise, in testing, is often desired to cause no bit errors and be completely corrected by a modem using FEC + Interleaving. In a CPE using Retransmission, it is expected that a REIN noise will cause Retransmission events, but will not result in a loss of sync.

SHINE noise is a single, longer duration impulse noise. Defined as being greater than 10 ms in latency, SHINE noise is very disruptive to the operation of a DSL line. DSL modems using FEC + Interleaving are much less likely to survive a SHINE event, and Retransmission may be a more appropriate tactic.

PEIN noise is a prolonged level of high noise. This type is less common in DSL testing and would be difficult to survive for any DSL device.

These types of Impulse noise are heavily impacting factors on DSL connections. Multiple techniques have been devised to mitigate the affects of these noises, including FEC + Interleaving and Retransmission.

2.4 Network Factors in DSL Connections

This section details the factors of DSL connections that have a direct impact on the network level performance of DSL connections. Though all parameters of a DSL connection have a potential impact on performance, some parts (specifically INP and Retransmission) have a much more direct impact on the performance of the network layer and their configuration can be highly impactful for a DSL line [2].

2.5 Error Detection and Correction

Since DSL lines are required to operate in noisy environments and over unshielded twisted pair cables, it becomes very likely that transmission will be affected by some form of noise. To mitigate the effects of this noise on performance, there are multiple different encoding and error detection and repair schemes employed by a DSL line [3].

2.5.1 Forward Error Correction (FEC)

Forward error correction sends additional, redundant data and error detection bits to both detect and be able to repair damaged transmissions. If a damaged frame is detected a receiving device can ideally repair it out of the redundant data, with limited effect on the connection. Since this excess redundant data is being sent along, the overall amount of useful data that is being sent is reduced. Checking these error codes also adds a significant fixed amount of latency for processing time, however may improve end user QoS in the event that transmissions are damaged and need to be resent. This technique combined with Interleaving is particularly effective when noise events are common and regular, such as REIN noise [3].

The typical method of FEC used in DSL, is called Reed-Solomon encoding [4]. As stated, Reed-Solomon encoding is able to encode data units with error checks and redundant data, then decode the data, error check, repair, and decode the data on the other side of a transmission. The level of redundant data encoded determines the amount of damaged data that can be repaired, and thereby the error tolerance. These data units encoded into Reed-Solomon encoding are referred to as *code-words* This method is also used for CDs/DVDs/QR Code and other fault tolerant systems. The level of redundant encoding in DSL is controlled by the INP parameter. The use of Reed-Solomon encoding is almost always combined with data interleaving, to spread out the code words [5].

2.5.2 Interleaving

In the most basic forms of DSL, all data was transmitted in order as it came in. This type of transmission is typically referred to as *Fast Mode* transmission. The downside of fast mode transmission comes with the onset of impulse noise events. As an impulse noise event hits the line, it corrupts the data that it hits. With fast mode transmission it is likely that the impulse will corrupt one or more frames of transmission, completely destroying them and causing them to be lost, and possible cause the line to drop sync.

To limit the effect of impulse noise on each frame, a technique called Interleaving can be employed. Interleaving is the process of taking the potential content of multiple frames of data, and dividing them into a number of pieces, then sending those pieces mixed together in frames.

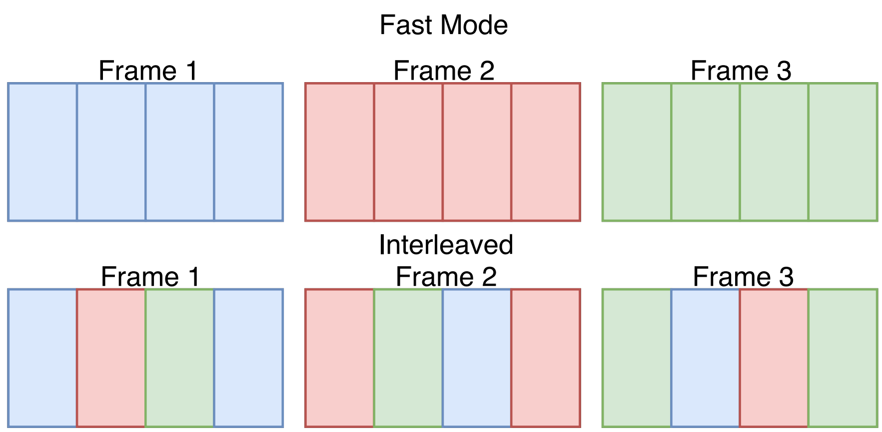

Figure 2.1: Interleaving

By performing this method of interleaving, the impact of an impulse noise on a single frame is minimized. Without interleaving, if an impulse noise hit frame one, it would destroy most of the content of that frame and with that most of the Reed-Solomon code-words that can be used to repair it. With interleaving, it would destroy a smaller amount of multiple frames, and less code-words; these small amounts of other frames can be then repaired and the code-words stored in the other frames [6].

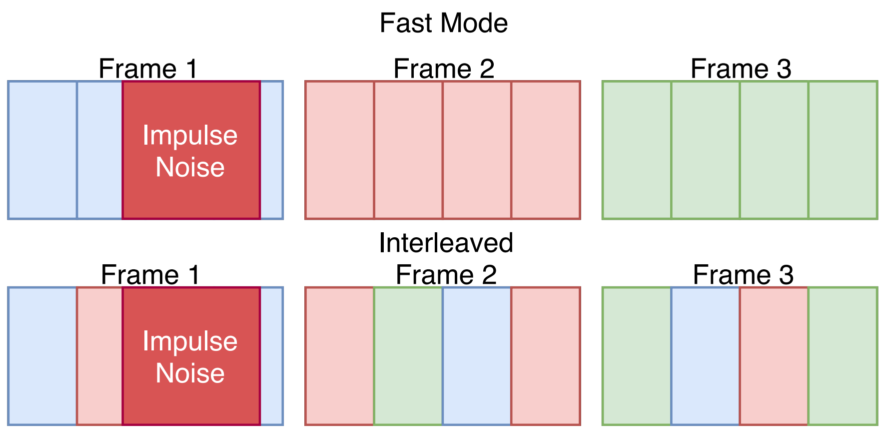

Figure 2.2: Interleaving under impulse event

2.5.2.1 Downsides of interleaving

Though interleaving is a very powerful technique for reducing the impact of noise events, there are significant downsides over fast mode. As data units are received in the DSL transceiver, there is additional time required to separate these into pieces, and reorder them interleaved. This process adds significant, direct latency to a DSL connection. This can make these connections unsuitable for applications such as VOIP, and often lines requiring VOIP are deployed in fast mode or make use of dual paths (one with fast mode, one with Interleaving) to operate properly. Interleaving was one of the significant factors enabled in this study to represent a typical DSL internet deployment.

This effect on latency can be seen in Figure 2.3. With fast mode the full content of Frame one is received at time t1, whereas with interleaving the full content of frame 1 is not received until time t3. This imposes a significant fixed latency increase. The amount of interleaving depth is defined by the DSLAM and determines the amount of division of frames. The example above uses an interleaving depth of 3, where values can range as high as 64. Latency also scales as the interleaving depth increases.

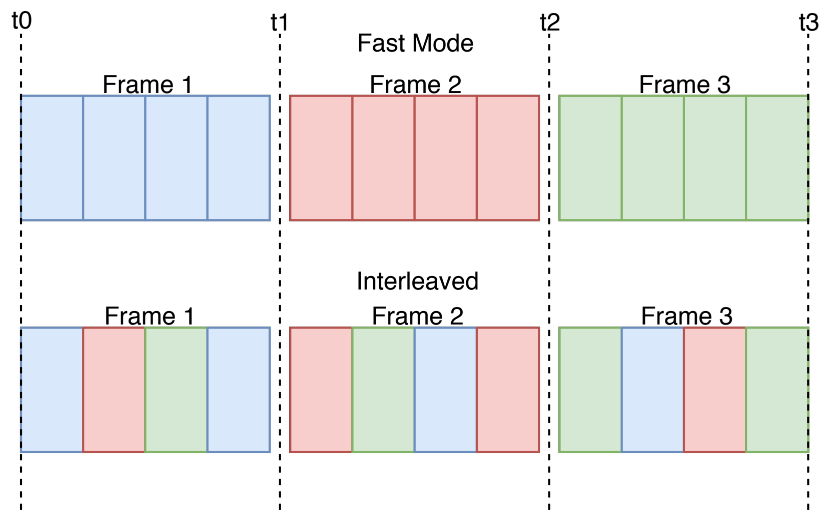

Figure 2.3: Latency affect from interleaving

2.5.2.2 FEC + Interleaving Settings

DSL defines a huge number of settings to control impulse noise protection settings. Depending on the level of expected noise on a line, or the use case of said line, these settings can be adapted to meet performance or stability goals.

Impulse Noise Protection Minimum (INP):
The INP parameter is defined in terms of DMT (Discrete Multi-Tone Symbols). DMT symbols are single unit data frames. The INP parameter is defined as the number of DMT symbols which can be completely corrected by the FEC systems, regardless of the amount of errors [4]. The INP setting is not a direct parameter by itself, but rather a guideline for the FEC system to perform under. Based on INP settings the Reed-Solomon encoding settings are determined. Values vary between 0 and 16 with 0 indicating that there is no minimum amount of symbols.

Interleaving Depth:
As defined above, the depth of interleaving is the amount of divisions of each data unit that is performed by the interleaver. Though this is a configurable parameter by a chipset, from the configuration level, interleaving depth is often determined based on Minimum INP value

and not directly configured.

Maximum Interleaving Delay:

The maximum interleaving delay defines the maximum amount of delay placed on the system by the interleaver between the two DSL interfaces (in one direction). If the interleaver is disabled (fast mode) the maximum delay between the DSL interfaces may not exceed 2 ms (in one direction). This value typically ranges between 2 and 63 ms.

2.5.3 Retransmission

Retransmission is a newer method for dealing with packet corruption due to impulse noise events. This is an optional setting, only supported in newer VDSL2 connections.

When Retransmission is enabled. a DSL transceiver's unit of data is referred to as a Data Transmission Unit (DTU) [2]. Retransmission works by attaching a frame check sequence (FCS), and sequence number, to a DTU and buffering DTU's before they are sent. If the FCS fails, or the receiver has missed a transmission (known via sequence number), a negative acknowledgement is sent indicating that the DTU needs Retransmission and the receiver awaits a Retransmission from the sender.

2.5.3.1 Impact of Retransmission on Network Performance

Retransmission has benefits in use over traditional FEC methods of noise protection in some scenarios, though they can be used in conjunction with each other. In some cases it may allow for lower or no interleaving to be used, while still having protection from impulse noise. This may lead to a direct increase in available data rate, and improved latency during low-noise periods.

Retransmission can also have notable downsides, meaning much higher peak latencies when packets are being frequently retransmitted, while having lower good case average latency when noise events are rare. There is also a large memory requirement to do downstream buffering within a DSLAM for each of its lines, meaning that all DSL hardware requires a physical upgrade to be able to do restransmission.

There is a balance to be struck, if noise events are expected to be very frequent on a line, Retransmission may be a worse option compared to FEC, if they are relatively infrequent, better data rate, latency, and there by better user QoS can be achieved without sacrificing line stability.

2.6 Impact of Noise Protection on Network Performance

All forms of DSL noise protection have some impact on latency, with FEC + Interleaving being more fixed, consistent impact on latency and Retransmission applying conditional impact on latency depending on line conditions. In a system where Noise is a factor, there is no method of noise protection that does not come at some cost.

The maximum cost of latency can depend on the configuration of these parameters; DSL provides many tools to allow operators to configure these on a case by case basis, but their use should be carefully considered and weighed based on deployment scenario.

DSL is, in part due to these technologies, a high latency technology that can have heavy effect on user QoE, especially with the increases in low latency video streaming and gaming service usage by end users. The various deployment scenarios tested in this study, experienced a wide range of average latency depending on the direction of traffic, and the presence of noise. This latency existing only in the last mile is additional to all other network latency and may have a heavy impact on user performance and QoE.

CHAPTER 3

DSL Measurements

3.1 Test Setup

To perform our study we decided to use equipment that is representative of the average case that may deployed in a customer home. All pieces of equipment were carefully chosen to minimize impact from potential interoperability issues.

3.1.1 Test Setup

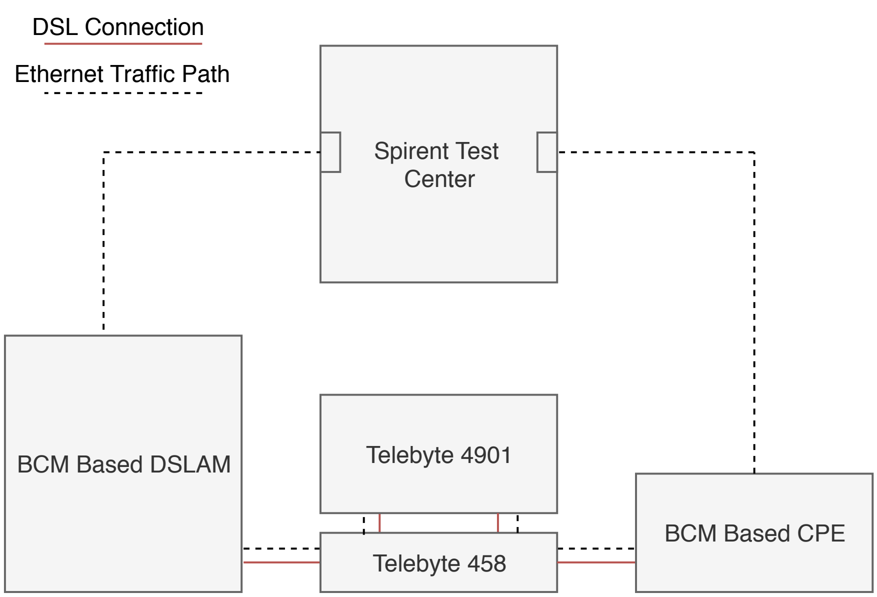

Figure 3.1: DSL Measurement Test Setup

3.1.1.1 DSLAM

The DSLAM chosen was using a Broadcom based chipset, model 65300, running version VDSL-5B 16l v10.09.80. This device was configured to bridge untagged traffic from a 1 Gbps copper (Ethernet) SFP in its network port to its DSL interface. Only the line under test was connected to the DSLAM at any time during testing. This device was chosen to represent an average DSLAM that would support newer VDSL2 technologies such as Retransmission.

3.1.1.2 CPE

The CPE was also a Broadcom based chipset model 63138, running version A2pvbH042u.d26q. This device was chosen to minimize any interoperability issues with no cross-vendor chipset. This device is available commercially and the version was the newest available at the time. This device was set to bridge traffic from its DSL interface though its gigabit Ethernet interface.

3.1.1.3 Traffic generator

The traffic generator chosen was a Spirent Test Center running version 4.75. Both the CPE and CO sides were connected via a one gigabit copper (Ethernet) SFP.

3.1.1.4 Noise Generator

The noise generator chosen to generate and inject both the fixed level white noise and impulse noises was a Telebyte 4901. The noise files chosen were generated as part of a library for Broadband Forum TR-114 and were modeled on real noise encountered in the field.

3.1.1.5 Loop Simulator

The loop simulator was a Telebyte 458-LM-A1-30-TR114 model loop simulator. This was modeling the 26 AWG cable model.

3.1.1.6 Cabling

All cabling used in this setup was Cat5e or better of less than 6 foot lengths, with the exception of the connection between the DSLAM and Spirent Test Center was a longer connection of Cat5e or better quality.

3.1.1.7 Switch

Some test cases involved a switch using port mirroring to capture Wireshark packet captures. This switch was a Cisco WS-C4948E enterprise grade switch. The switch was tested to add minimal delay to captures, less than 10 μs. The presence or absence of the switch does not have a significant effect on the measurements.

3.2 Traffic Details

For this project we chose to test with stateless Ethernet traffic, containing UDP (Unreliable Datagram Protocol) headers. Ethernet was chosen to remove the impact of stateful traffic protocols such as TCP potentially affecting the measurement of the DSL connection. For FEC cases traffic levels were tuned to a percentage of the NDR (net data rate), a value provided by the DSLAM. For Retransmission cases, traffic levels were tuned to ETR (Expected Throughput). Cases varied with level using either (0.5 * ETR/NDR) or (0.9 * ETR/NDR) traffic level, 50% and 90% respectively.

3.2.1 Traffic Used

For this testing we chose to use the standard IMIX (Internet Mix) traffic defined by the Spirent Test Center. The Test Center allows for configuration of this traffic, though none was done for this testing. The standard mix provided by the Spirent Test Center is broken down in Table 3.1.

This IMix distribution is commonly used for DSL testing and provides a challenging scenario for a DSL connection, due to the large proportion of small sized frames (meaning more frames per data rate.) This was chosen to give a more representative case, as real traffic will include variable sized frames.

IP Total Length (Bytes)	*Default Ethernet (Bytes)*	*Weight*	*Percentage*
48	66	7	57.33%
576	594	4	33.33%
1500	1518	1	8.33%

Table 3.1: Spirent IMix traffic distribution

3.2.2 Spirent Latency Measurement

The Spirent Test Center relies on a time stamping method to measure the latency between frames. This is included in the payload so it does not add any frame size. This includes a timestamp, sequence number, and stream ID [7]. The Spirent Test Center was measuring latency by appending these signatures on the outbound interfaces, and removing them upon reception, calculating the time in travel at that point. This method means that all measurements should be accurate and have minimal effect from any clock skew. This also means that all measurements are one way latency, and not round trip times.

3.2.3 Histograms

Following the initial decision to study latency as the focus of these experiments, methods for measuring latency accurately were looked into. We decided to leverage the Histogram feature of the Spirent Test Center. This feature allows a user to configure 16 buckets to group each packet in depending on their measured latency. These buckets were manually configured to provided good granularity on the measured latency, meaning no one bucket would have too high of a proportion of the measured traffic. It would be superior to measure the latency of each frame individually, however, the Spirent Test Center and other tools that were accessible did not provide any method to do so.

3.3 Setup and Test Procedure

Throughout the measurement campaign, a number of variations of the configuration were used. These were used to push the DSL line into various states, including many very stressed cases, providing insight into the functionality of each setting and its impact on latency performance.

It was initially determined that DSL in a unimpaired condition provided reliable and steady performance with little latency variation outside of the fixed level provided by the configuration. These cases were given less focus during the course of the study, with a more heavy focus placed on studying the more impaired conditions where higher latency would occur, and the error correction/mitigation technologies would be required for proper operation.

Many of the test cases chosen were intended to represent the worst cases a consumer DSL deployment may be able to encounter and survive.

3.3.1 Test Procedure

For all cases the test procedure was static, aside from configuration values:

- The loop simulator was set to the required value for that test case.
- The Noise generator was configured to inject -140 dBm/Hz White Noise, to minimize the impact of any background lab noise.
- The DSLAM was configured with the line disabled.
- The line was enabled, and the CPE allowed to train and remain stable for 60 seconds.
- The line was measured from the DSLAM and recorded, including performance counters.
- The traffic generator was configured to either 50% or 90% of the NDR reported by the DSLAM.

- Any impairment (REIN Noise) was played on the Noise Generator, remaining enabled through the test case.
- Test Traffic was enabled in the Spirent Test Center and passed through the setup.
- Test Traffic and Noise were played for 30 seconds.[1]
- Noise and traffic were ceased.
- Measurements were taken from the DSLAM (line batch, and performance counters) and results from the Spirent Test Center were saved.

3.3.2 DSL Profiles

For these experiments two differing profiles were used. Both were based on the same Broadband forum TR-114 profile. This profile was chosen to represent an average 8 MHz, North American DSL deployment profile [8]. The settings contained in this profile would be compatible across many deployment scenarios and over a range of loops. INP and Interleaving settings are typical for deployment profiles. The full settings of this profile are defined in Table 3.6 and Table 3.7

The only variation applied to that profile was the use of a typical Retransmission profile. The Retransmission profile applied was also of standard settings based on Broadband Forum TR-249 [9]. Full settings are defined in Table 3.2

[1]Experiments were performed with longer times to determine testing time. It was determined that 30 seconds was sufficient for accurate measurements.

R-17/2/41	
Parameter	*Setting*
INPMIN_REIN_RTX	2 symbols
INPMIN_SHINE_RTX	41 symbols
SHINERATIO_RTX	2%
LEFTR_THRESH	0.78
DELAYMAX_RTX	17 ms
DELAYMIN_RTX	0 (Off)

Table 3.2: R-17/2/41 Profile

3.4 Experiment Results

3.4.1 FEC Upstream and Downstream variation

As mentioned in Chapter 2, many of the settings requested by a DSL profile are suggestions or high level requirements for the behavior of a modem, and often actual settings may differ from the those requested in the profile.

For example, the default profile used for this experiment requests an identical Maximum Interleaver Delay of 8 ms, and a minimum INP of 2 symbols. When looking at the measurements recorded from the DSLAM, Actual Interleaver Delay is 5 ms for Downstream, and 8 ms for Upstream, with INP at 2 symbols for both sides. This results in the increased latency by a fixed amount on the upstream side when compared with the downstream side.

Even under the same configuration settings, actual values can differ from the requested values as the DSL chipsets attempt to optimize operation under the current conditions. This is seen with longer loops as the actual interleaver delay increases with no alteration to the configuration on the DSLAM.

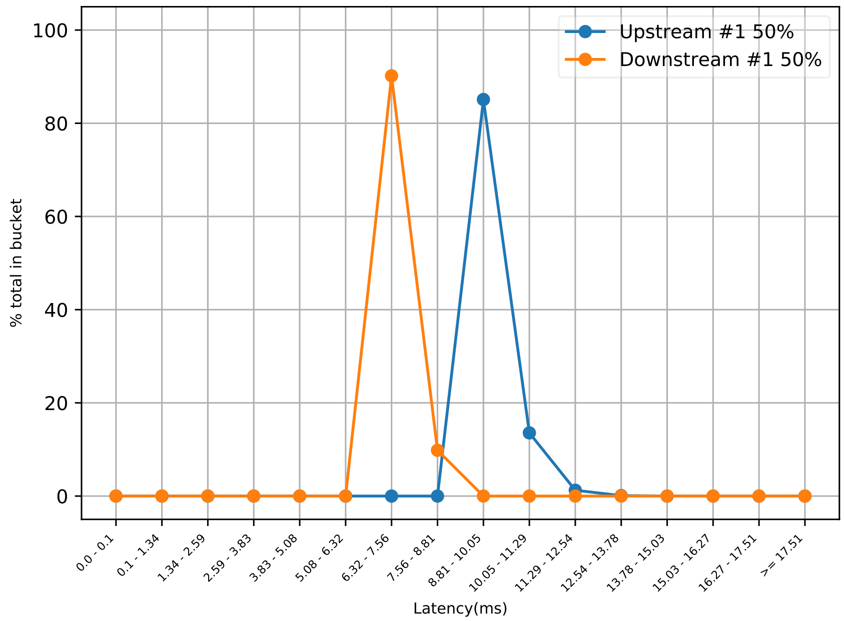

Figure 3.2: Upstream and Downstream latency variation, 50% traffic, FEC + Interleaving

3.4.2 50% traffic vs 90% traffic

One initial variation in test setup, was traffic level. Two differing traffic levels were tested, those being 50% of NDR/ETR (as reported by the DSLAM) and 90% of NDR/ETR. These variable traffic levels were tested across all configurations and noise impairments.

Cases using 90% traffic levels had more distributed latency, with higher peak and average latency measurements. This variation is likely due to the high volume of packets causing filled buffers within the transceivers. Both 50% and 90% measurements were continued through most of the campaign. It was suspected that 50% traffic levels may better indicate the real use case of a users connection, and 90% traffic was more accurate to model the worst case a connection might encounter. Performance in the Retransmission enabled cases looked similar to the FEC + Interleaving cases, but with lower overall latency.

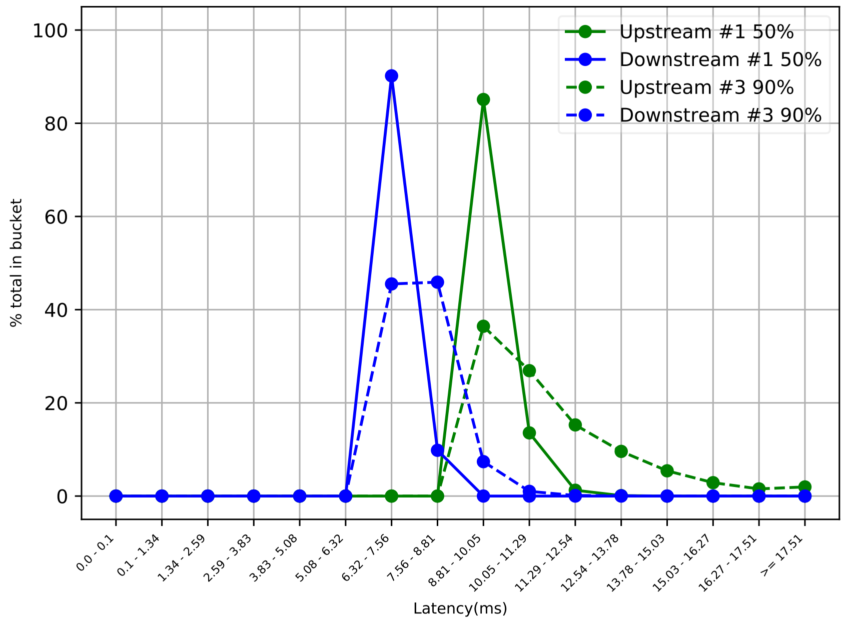

Figure 3.3: 50% Traffic vs 90% Traffic, FEC + Interleaving

Value	*US 50%*	*US 90%*	*DS 50%*	*DS 90%*
TX Count	88,664	150,585	269,652	486,082
RX Count	88,664	150,585	269,652	456,082
Dropped Count	0	0	0	0
Avg Latency (ms)	9.69	11.30	7.29	7.82
Min Latency (ms)	9.12	9.15	6.86	6.94
Max Latency (ms)	13.94	25.18	8.91	14.48

Table 3.3: Comparison of 50% to 90% traffic level, FEC + Interleaving

3.4.3 Impulse Noise

For impulse noise, three levels of interference were tested. These three levels being white noise only (control), 100 µs REIN, and 1 ms REIN. As is expected, all of these levels of interference resulted in packet destruction and longer latency (in Retransmission cases). It was determined that only the Retransmission settings used had the correct amount of protection required to survive REIN noises as long as 1 ms. It is possible with more interleaving and higher minimum INP, the FEC + Interleaving case could survive 1 ms REIN as well.

3.4.3.1 Retransmission vs FEC + Interleaving

Perhaps the most major difference in configuration attempted in this study, was the inclusion and removal of Retransmission. When Retransmission is applied, the line was found to enable no additional protections (meaning it was running in fast mode). This resulted in lower latency, and often higher data rates, under good conditions (as no interleaving was present.) This would provide a notable performance increase to a customer using this connection.

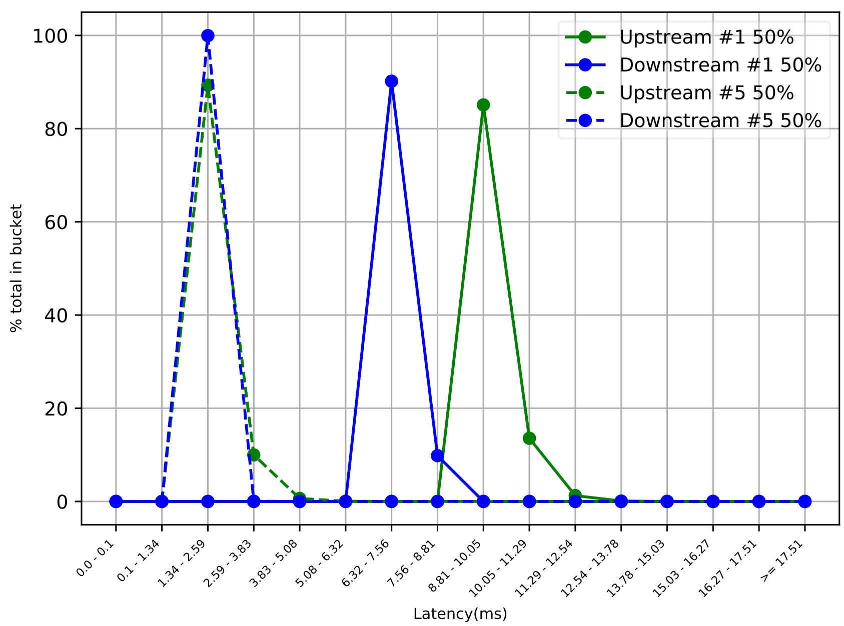

Figure 3.4: FEC (#1) vs Retransmission(#5), 50% traffic

During impulse noise cases, clear differences between Retransmission and FEC approaches became apparent. With FEC + Interleaving, under the 100 µs length REIN events, some packets may be lost, but the overall latency performance was not significantly affected. Any REIN noise longer than 100 µs would cause a drop in line sync, as the protection was inadequate to repair the frames damaged by the REIN event. This is typical of FEC + Interleaving, as the additional latency and overhead required to repair the damaged frames, was present at configuration time; meaning that no additional latency is incurred during noise events. This configuration would be more ideal for a connection experiencing common

REIN events.

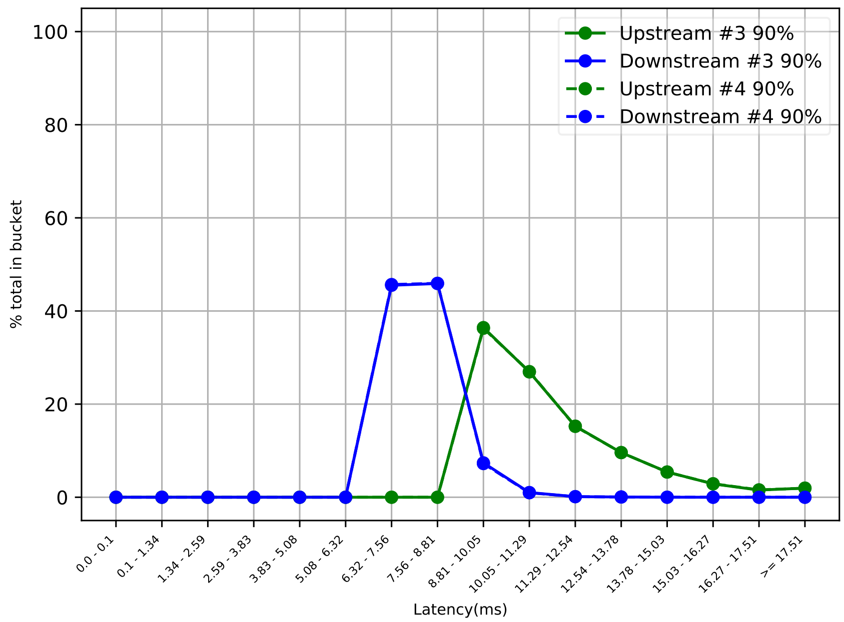

Figure 3.5: FEC Control (#3) vs 100us REIN (#4) (Lines are overlapping)

As the Retransmission equipped line saw REIN noise events, increased latency was seen as packets were re-transmitted. Both 100 µs and 1 ms REIN events were found to be survivable for the Retransmission equipped line, though significant packet drop was observed under 1 ms events, in addition to very high latency.

Both of these technologies demonstrate a different approach to noise protection. With FEC + Interleaving the line is correcting forward of the event occurring, and the latency and bandwidth cost is paid up-front and is a consistent and fixed cost. With Retransmission the cost of protection is paid as the events occur and improved latency can be seen during the quiet periods. This study also observed significantly higher peak latency under the Retransmission case, even under equivalent noise events (25 ms vs 35 ms for the 100 µs case).

It is also notable that in several cases, Retransmission resulted in a higher data rate, as less redundant data was encoded on the line, so more original data was able to be passed between the devices. This aligns the throughput performance closer to that of a fast mode line in good scenarios, which would provide improved performance for many low latency services a customer may use, without sacrificing the ability to remain online during noise events.

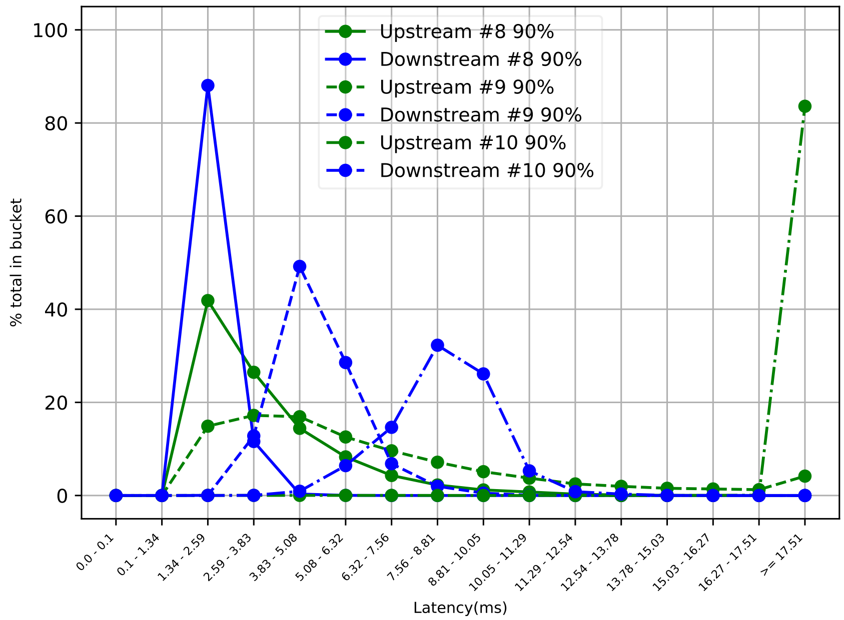

Figure 3.6: Retransmission, 90% traffic, Control(#8), 100 μs REIN (#9), 1 ms REIN (#10)

3.4.4 Long Loop Cases

The final variation of the experiment was based around lower data-rates. The intention was to replicate scenarios present in subscriber networks where a home may be located further away from a DSLAM, resulting in lower achievable rates. Two loop configuration settings were determined for use in this scenario, one with approximately 15 Mbps downstream speeds, and approximately 8 Mbps downstream speeds. To achieve these rates, loops of approximately 5,750 ft were used for the 15 Mbps case, and loops between 7,300 to 7,500 ft were used tor the 8 Mbps case. The intention of these settings was to provide an indication of what a customer could expect over a connection under reasonable access speeds.

In all scenarios with longer loop lengths, more variable latency was observed. Each link, regardless of profile configuration, was observed to have higher overall latency, and a bi-modal upstream latency. Following the conclusion of this study, we determined that the very long latency packets (resulting in much of the data outside the measurement range, may have been anomalous, and perhaps the result of a configuration issue in those test cases. This was observed consistently during the course of this study, and more research may be required to fully characterize the behavior of DSL under long loop scenarios, and to look into the presence of these very long latency packets. Data outside of these very high values appears to be accurate to actual performance.

3.4.4.1 FEC + Interleaving

For the DSL connection running FEC + Interleaving, the line was observed to train with a higher level of interleaving delay (8 ms downstream, 7 ms upstream) when compared to the short loop cases. This resulted in a fixed amount higher latency than the short loop case. Long loop cases were initially observed to experience significantly latency values compared to their short loop counter parts, as well a larger variance.

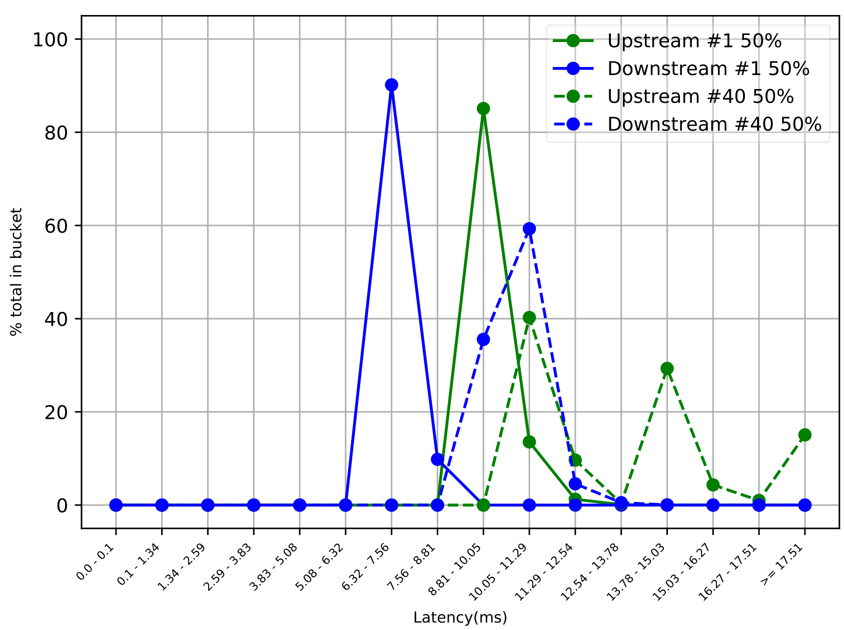

Figure 3.7: FEC + Interleaving, 50% traffic, Control(#1), 5350 ft loop (#40)

	Short Loop US	*Long Loop US*	*Short Loop DS*	*Long Loop DS*
Avg. Latency (ms)	11.30	14.60	7.82	10.30
Min Latency (ms)	9.15	10.30	6.95	9.65
Max Latency (ms)	25.18	62.60	14.50	15.14

Table 3.4: Comparison of 90% traffic, FEC + Interleaving short loop vs Long Loop performance indicators

3.4.4.2 Retransmission

For the Retransmission enabled case, similar performance to the FEC case was observed. Higher latency overall, as well as a bi-modality in the upstream direction, and more variable latency. Latency performance again was much more variable between frames (higher jitter). As suggested above, the presence of these very long values, may have been anomalous behavior and not indicative of the behavior of all devices under these conditions.

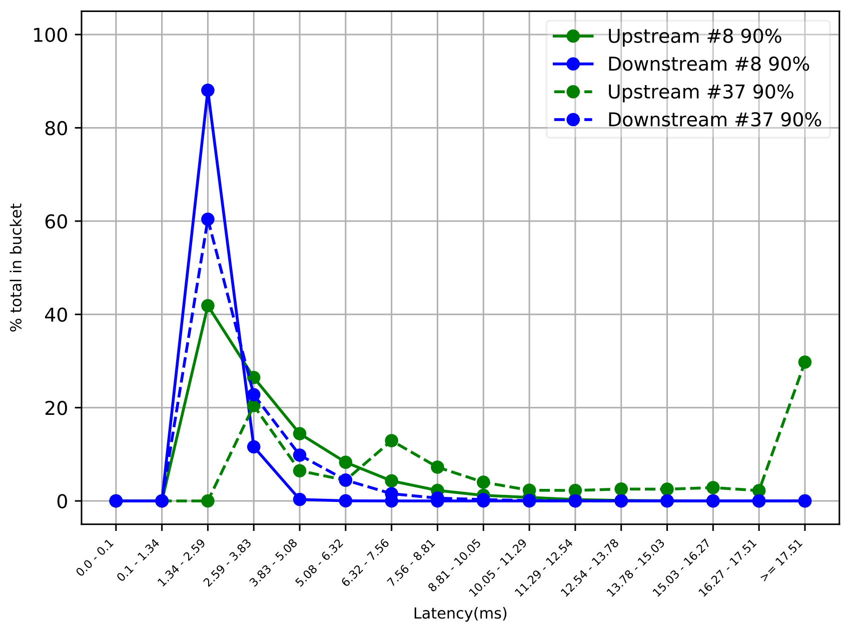

Figure 3.8: Retransmission, 50% traffic, Control(#1), 5,350 ft loop (#40)

	Short Loop US	*Long Loop US*	*Short Loop DS*	*Long Loop DS*
Avg. Latency (ms)	3.54	16.60	2.11	2.79
Min Latency (ms)	1.60	2.72	1.41	1.42
Max Latency (ms)	16.05	110.73	6.076	11.66

Table 3.5: Comparison of 90% traffic, Retransmission short loop vs Long Loop performance indicators

3.4.4.3 Measurement Resolution

During the initial study of these cases, it was determined that the window sizing of the histogram was not adequate to measure the range of values present in these cases. Many of these cases were repeated with wider histogram windows, and varying histogram window between the upstream and downstream directions. Those repeated cases were ultimately used in the modeling of these connections.

The performance of all long loop cases was found to have higher latency than their low loop counterparts. To fully explain the behavior of these cases, a full mapping and study of the network performance of these lines under a variety of line conditions and loop lengths would need to be performed. The focus of the study would need to fully map the performance of lines under long loop conditions and determine if these long loop cases experience these very long latency packets.

3.4.4.4 Possible Issues with Long Loop Data

During a cursory re-examination of the data captured in this study, we determined that the very long latency experienced by both the FEC + Interleaving lines as well as the Retransmission lines in the long loop case study may have been anomalous. The behavior of the line with the exclusion of those long latency packets, (those located mostly in the final bucket), appears consistent with additional test cases run after the conclusion of this study. A full mapping of long loop cases providing an examination into this issues must be performed to provide insight into these issues.

A cursory look into long loop performance done after the initial study, suggests that the presence of a bi-modal upstream (likely due to variations in packet size), and overall lower latency with less extreme maximums is normal for long loops cases. A comparison of a 0 ft loop vs a 7,000 ft loop from additional data gathering efforts can be seen in Figure 3.9

This test case poses a similar performance to the initial Retransmission test cases, but does not experience the presence of long latency values outside of the measurement range.

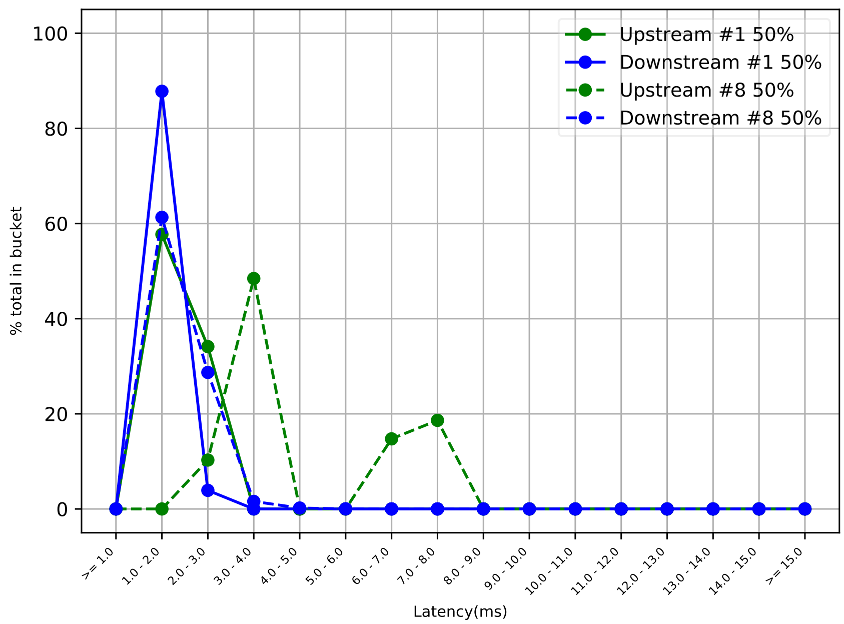

Figure 3.9: Retransmission, 50% traffic, 0 ft loop, 7,000 ft loop

3.5 Summary

One of the most major parts of this study was this DSL mapping procedure. Performing these experiments lead to the affirmation of many expectations (such a fixed latency on FEC configurations and more variable latency on Retransmission configurations.)

The very high levels of latency experienced by a variety of the connections, particularly the restransmission under REIN events, is indicative of possible serious issues that can be encountered in deployments worldwide. Many of these levels would be seriously impactful to customer experience on these connections.

One avenue for further study is a more complete mapping of how these variations on parameters (loop length, varying levels of interleaving,) affect latency. This study attempts only a cursory and partially representative investigation of some worst case scenarios, but does not attempt to represent the full range of possibilities a DSL connection can encounter.

In addition to that, a deep look into the performance of loop cases would be valuable to study the presence or absence of the very long latency values seen in the initial study.

Raw data and additional information for the experiments performed in this study are available at [10]

TR-114 AA8d_I_096_056	
DSL Parameter	Requested Value
xDSL Transmission System(s) Enabled	G993_2_A
VDSL2 Limit Mask (includes US0 mask)	Annex A, D-32
VDSL2 Profile	8d
Upstream PSD Mask (G.992.3/5 Annex J/M)	0
Max SNRM Upstream (dB)	31
Upshift SNRM Upstream (dB)	30
Target SNRM Upstream (dB)	6
Downshift SNRM Upstream (dB)	1
Min SNRM Upstream (dB)	0
Upshift Time Upstream (seconds)	60
Downshift Time Upstream (seconds)	60
Max SNRM Downstream (dB)	31
Upshift SNRM Downstream (dB)	30
Target SNRM Downstream (dB)	6
Downshift SNRM Downstream (dB)	1
Min SNRM Downstream (dB)	0
Upshift Time Downstream (seconds)	60
Downshift Time Downstream (seconds)	60
Maximum Nominal Transmit Power Upstream (dBm)	14.5
Maximum Nominal Transmit Power Downstream (dBm)	14.5

Table 3.6: TR-114 AA8d_I_096_056 Profile, Part 1/2

TR-114 AA8d_I_096_056	
DSL Parameter	Requested Value
Rate Mode (Manual, At-Init, Dynamic)	At-Init
Min Rate Upstream (kbps)	128
Max Rate Upstream (kbps)	56,000
Min INP Upstream (symbols)	2
Max Interleaving Delay Upstream (ms)	8
Min Rate Downstream (kbps)	256
Max Rate Downstream (kbps)	96,000
Min INP Downstream (symbols)	2
Max Interleaving Delay Downstream (ms)	8
ForceINP (true/faluse)	TRUE
Minimum Reserved Overhead bit-rate (kbps)	16
Trellis Coding Enabled (true/false)	TRUE
Bit-swapping Enabled (true/false)	TRUE
UPBO Disabled (true/false)	FALSE
Force Electrical Length (true/false)	FALSE
UPBO A-value US0	40
UPBO B-value US0	0
UPBO A-value US1	53
UPBO B-value US1	21.2
UPBO A-value US2	54
UPBO B-value US2	18.7
UPBO A-value US3	54
UPBO B-value US3	18.7
DPBO Disabled (true/false)	TRUE

Table 3.7: TR-114 AA8d_I_096_056 Profile, Part 2/2

CHAPTER 4

NetEm Models

4.1 What is NetEm

According to the NetEm web page, *NetEm is an enhancement of the Linux traffic control facilities that allow to add delay, packet loss duplication and more other characteristics to packets outgoing from a selected network interface* [11]. Essentially it is a tool to allow for basic simulation of network connections by traffic shaping through Ethernet ports on a Linux machine.

4.2 NetEm Capabilities

NetEm supports a number of parameters in both simple and more complex formats. It has support for fixed and dynamic delay, packet loss, packet duplication, and packet corruption. The most complex parameter is delay, supporting three modes, fixed, random variation, and variation according to an input distribution. Delay can be used to model latency. The simplest commands allow a fixed delay percentage to be set.

```
tc qdisc add dev eth0 root netem delay 100ms
```

This adds a fixed delay to each packet of 100 ms. Either random variation, or random variation with a simulated correlation to the delay distribution can also be specified. While this adds some realism, the distribution mode of operation was most important for the purposes of this study.

Outside of specifying the delay values and variations, a distribution argument can also be included. There are a few predefined distributions (uniform, normal, pareto, and paretonormal.) This can be useful and rely on the other delay arguments to center themselves. For example when using the following command:

```
tc qdisc change dev eth0 root netem delay 100 ms 20 ms distribution normal
```

This follows a normal distribution with a mean at 100 ms and a random variation (jitter) per packet of 20 ms. When the distribution argument is not specified, it defaults to normal, and all packets would range between 80 ms and 120 ms.

NetEm also allows for custom distribution files to be specified. The *maketable* program defined in iproute2, allows a user to generate these distribution files. The input file to this program is simply a flat list of measurement values. For example:

If a few packets are measured at 10 ms, 12 ms, 13 ms, 14 ms, the input file would be a file containing 10, 12, 13, 14. (Separated by new lines, not commas.)

This would be passed as input to the `iproute` *maketable* program which would generate a distribution based around the occurrence of these numbers. This can handle a large volume of measurements and produce a fairly accurate distribution based around the exact measurements provided. The table is generally a set of negative or positive numbers, allowing the distribution to still follow the passed in mean and standard deviation.

In addition to delay based features NetEm supports a full range of other networking properties. Packet loss can be specified as a simple percentage argument, or a percentage with an additional correlation value to simulate multiple packet losses due to some event.

NetEm can also specify packet corruption, reordering, and duplication events on a simple percentage and with a similar correlation value.

4.3 What to model in DSL

When modeling a network connection, a few parameters are considered, packet loss, duplication, reordering, as well as latency and bandwidth.

When packet loss is considered, DSL is a generally reliable connection, any packet sent will be either recovered or resent if it is lost (depending on FEC + Interleaving versus Retransmission support). Serious packet loss only occurs in the most stressed situations (such as heavy REIN), and when a link is overrated (more traffic being sent than a line can support.) Though packet delivery is reliable, latency may be variable under these conditions depending on the type of noise protection being used. Duplication and reordering events are also not seen in a typical DSL connection.

Packet corruption is a normal part of DSL. It happens frequently but the aim of Retransmission and FEC is to correct these packet corruptions and replace or resend any corrupted data. The frequency of these corruptions is dependent on line conditions (presence of noise, cabling issues). These corruptions are present in our measurements of the DSL line, but would not be seen from a network perspective (they are corrected by the DSL), so no additional simulation is necessary by NetEm.

Throughput is one key parameter in modeling a DSL connection. In a DSL connection the throughput, in the form of upstream/downstream net data rate, is either a directly configured parameter by a service provider, or a deterministic quality based on line condition, distance from the termination point, and electrical bandwidth profile. This is generally a tightly controllable parameter for a DSL connection, and less focus can be given to modeling this as it should be fairly consistent based on loop length, noise condition, and SNR parameters.

Likely the most key part of the network performance of a DSL connection, and the one directly modeled by this study, is the latency of the connection. DSL due to the interleaving or Retransmission of data, and the potential latency of long loops, has increased latency over other access technologies. The study of latency data under both FEC + Interleaving, and

Retransmission was chosen as the direct target for modeling, due to its potential impact on end user QoE and highly variable performance in the DSL measurements.

4.4 Modeling DSL with NetEm

From the measurements gathered during the DSL measurement campaign, it was determined early on that modeling DSL connections as a whole with a single model was not feasible due to the highly variable nature of the latency distributions measured. Instead, the target was to create a number of models and NetEm profiles based around different measured DSL connection conditions. This would allow the end user of the models to test under a variety of conditions with the best possible accuracy.

It was also determined that data rate could be simply modeled by using a fixed limit. Each model was measured at a certain data rate during the DSL testing, but the model could be simply set to that limit with a simple NetEm command, no more sophisticated modeling was required. DSL in most connections provides a fairly steady data rate with little fluctuation, depending on the features enabled on a line.

The modeling of the latency of a connection was a more involved task. The distribution of the latency varied highly depending on the conditions of the line and the overall length of the cabling, or presence of noise. Generally, in a well behaved connection free of any impairment, (added noise corrupting packets and causing either Retransmissions or FEC events), latency was relatively consistent. In these cases latency followed a very tight normal distribution around a fixed value. This can be seen in the DSL measurements.

A higher focus was given to highly impaired cases, such as those experiencing significant REIN noises. During the measurement campaign it was found that these cases would often result in very high and highly variable latency, and would be very disruptive to any service running over these connections. The connections were targeted for the majority of the modeling effort.

Initial attempts to model these cases using the in-built parameters of NetEm, and default distribution models were fruitless, and it was quickly determined that custom distribution files would be required.

Given the limitation of measurement tools used, only histograms of latency values could be gathered in the DSL campaign. These histogram buckets (16 total, on each side of a connection), were tuned as close as possible to provide the best resolution for each particular test case's latency distribution. Since the input of the NetEm table generator is raw numbers, some effort was required to convert the bucket sizes and counts to actual number values.

To accomplish the task of converting buckets to raw values, a simple script was implemented in Python to create raw data files. This script worked naively and placed the average value of the upper and lower bound of each particular bucket serially into a file. This raw file was able to be input into the iproute2 table creator which resulted in a distribution file. Both an upstream and downstream distribution file was created for each set of NetEm models. The mean and standard deviation of the values in the buckets were also calculated and those values used as additional parameters into the NetEm model.

These models were then turned into a set of commands for an interface. These commands, with their corespondent files, would allow a typical linux server bridging traffic from one interface to another, to apply the commands via NetEm to their interfaces and shape the traffic, resulting in similar impact on the traffic to the DSL link it was simulating. Each model had four commands.

```
1. tc qdisc change dev enp3s0f0 root handle 1:0 netem delay 7062us 370us 0\%
        distribution no_rtx_control_1DOWN
2. tc qdisc change dev enp3s0f1 root handle 1:0 netem delay 9631us 509us 0\%
        distribution no_rtx_control_1UP
3. tc qdisc change dev enp3s0f0 parent 1:1 pfifo limit 1000
4. tc qdisc change dev enp3s0f1 parent 1:1 pfifo limit 1000
```

Command 1, is the shaping command for the downstream side of the connection, interface enp3s0f0 in our experimental setup. The "`handle 1:0`" connection creates a logical handle for this configuration to be applied to. The next part of the command "`delay 7062us 370us 8%`" referes to the delay parameters, being mean (7062 μs), standard deviation (370 μs), and co-dependancy factor (correlation between each frame and its previous frames.) which for our purposes was 0%. The final part of the command "`distribution no_rtx_control_1DOWN`" is specifying to use a custom distribution file, name "`no_rtx_control_1DOWN`". Command 2 is identical to command one, but for the upstream interface.

Commands 3 and 4 are to specify that NetEm use pfifo queuing, with a 1000 packet limit to shape the traffic. This was to attempt to not only ensure a consistent queuing method was used, but to attempt to minimize packet reordering. Ultimately, this command was ineffectual in producing non-reordered traffic, but was left in to ensure that a consistent method was used.

Models of this style were created for every relevant link, and were tested and compared to their DSL counterpart.

CHAPTER 5

Model Results and Comparison

5.1 Test Setup

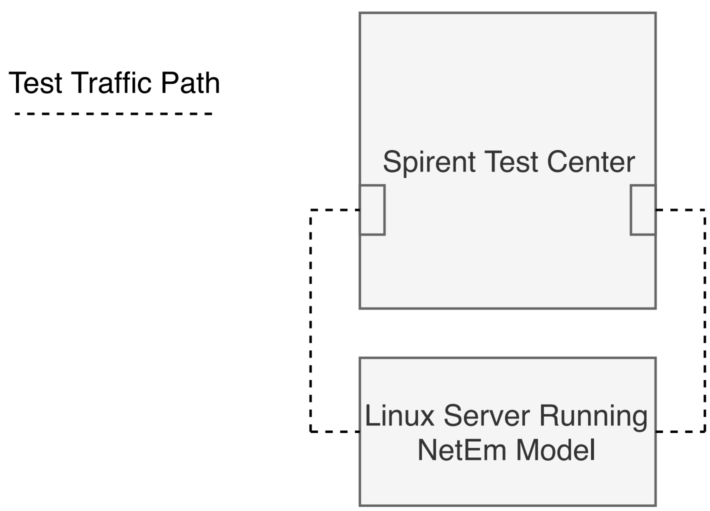

Figure 5.1: NetEm Measurement Test Setup

The NetEm experimental setup involved the same traffic generation hardware as the DSL setup, and the same level of traffic was run through each simulated link case. The hope of the experiment was that the network traffic would perform identically to the DSL it was simulating, returning a latency distribution across the histogram.

5.1.0.1 Hardware Setup

All NetEm tests were run on an Ubuntu based server, running Ubuntu 16.04.2 LTS. This server had an Intel Pentium(R) Dual-Core CPU E5300 running at 2.6 Ghz, 4 GB of DDR2 RAM. This machine was equipped with a Intel based 82576 chipset multi-port Ethernet adapter running over a PCI-E bus. Two of the Ethernet interfaces on this card were connected via bridging to simulate the DSL connection, with one port acting as the upstream, and the other as the downstream shaper. These interfaces were then connected to each of the Spirent Test Center ports and traffic passed through them. Some tests involved a network switch, which was measured and did not attribute significant impact to the measurements made.

5.2 Generated Models

As described in chapter 4, each NetEm model was four commands. Before testing the link, each of these commands were run on the server to configure the network ports, and a bridge was created between the two interfaces. Models were created for every test case that was identified as interesting, and those models were compared to the original measurements by running an identical traffic load.

```
1. tc qdisc change dev enp3s0f0 root handle 1:0 NetEm delay 7062us 370us 0\%
        distribution no_rtx_control_1DOWN
2. tc qdisc change dev enp3s0f1 root handle 1:0 NetEm delay 9631us 509us 0\%
        distribution no_rtx_control_1UP
3. tc qdisc change dev enp3s0f0 parent 1:1 pfifo limit 1000
4. tc qdisc change dev enp3s0f1 parent 1:1 pfifo limit 1000
```

5.3 Comparison to Measured DSL

Each model of note was generated and measured against the same traffic run over the initial DSL link. Measurements were gathered in a histogram with bucket sizes equivalent to those in the initial measurements. Ideally, this should result in an identical distribution to the original measured DSL.

5.3.1 Basic Cases

5.3.1.1 FEC + Interleaving

The most basic cases were measured under both traffic loads tested in the original experiment. The shape of the 50% traffic load cases was generally distributed into normal peaks with minimum values around the original interleaving delay parameters.

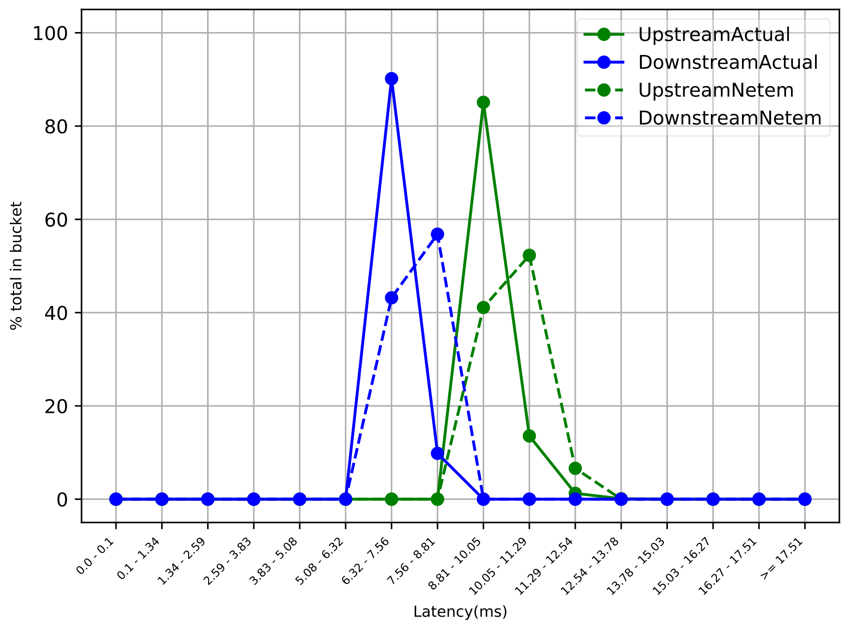

Figure 5.2: Case #1 (50% traffic load, FEC + Interleaving profile, compared to NetEm recipe)

Overall, the NetEm link saw a slight skew to higher latency over the original measurement of the DSL. This resulted in a higher maximum latency and more variability between the central buckets. This is likely due to the use of raw averages of bucket size to create the original distribution files, i.e., for bucket (6.32 ms - 7.56 ms), the file was filled with 6.94 values. This may result in a slight skew toward higher values. There is also some fixed effect on the NetEm latency from queuing and processing of data, resulting in slightly higher values across the board. Overall the match was close, and would not result in drastically different network performance for devices running over this link.

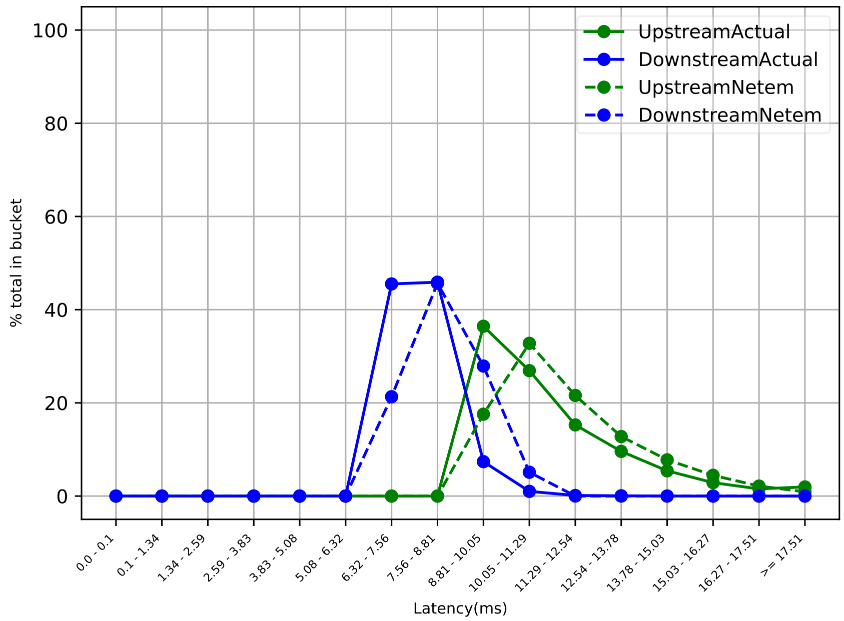

Figure 5.3: Case #3 (90% traffic load, FEC + Interleaving profile, compared to NetEm recipe)

Results for the 90% traffic case were very similar, with a similar skew toward higher values. The upstream model demonstrated this methods ability to replicate long tailed data, which is present in many of the data acquisitions.

5.3.1.2 Retransmission

Retransmission model results were similar to FEC, those shapes resulted in a lower overall latency when compared to FEC, but occasionally longer sloping tails for the packets that were being re-transmitted. For the basic 90% traffic case, the match showed again a similar skew toward higher values with a slight distribution between buckets.

5.3.2 Stressed Cases

This section details the performance of models replicating DSL links impacted by REIN noise events.

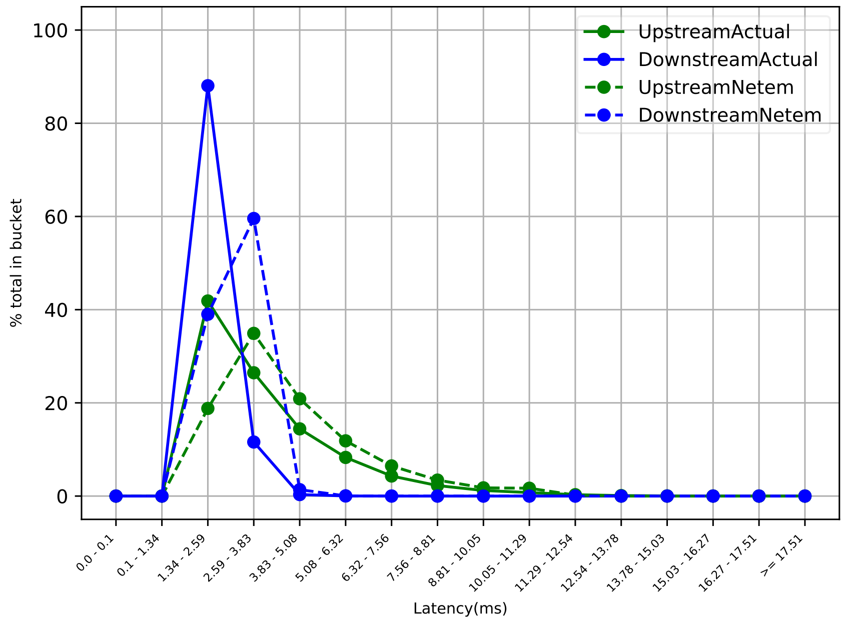

Figure 5.4: Case #8 (90% traffic load, Retransmission profile, compared to NetEm recipe)

5.3.2.1 FEC + Interleaving

When in the presence of impulse noise, the DSL links running FEC performed similarly to the links without any impulse noise. Any damaged frames were being repaired without any latency increase during transmission. The NetEm model performance in these cases was identical to the basic cases, as the DSL performance did not differ when under the impact of REIN noise.

5.3.2.2 Retransmission

Retransmission cases under the impact of REIN noise experienced a significant change in latency. Both an increased minimum and average latency and wider distribution of latency across the board. As seen in Figure 5.5, the NetEm model was accurately able to model these cases, with the wide curve in the upstream matching accurately, and the peak in the downstream matching closely as well. This model also experienced a slight skew toward higher values consistent with other models. Values in the last bucket ≥ 17.51 ms, were lower on the NetEm model. This is an artifact of the method used to create distribution files, further detail is given in the section on Model Issues 5.4.2

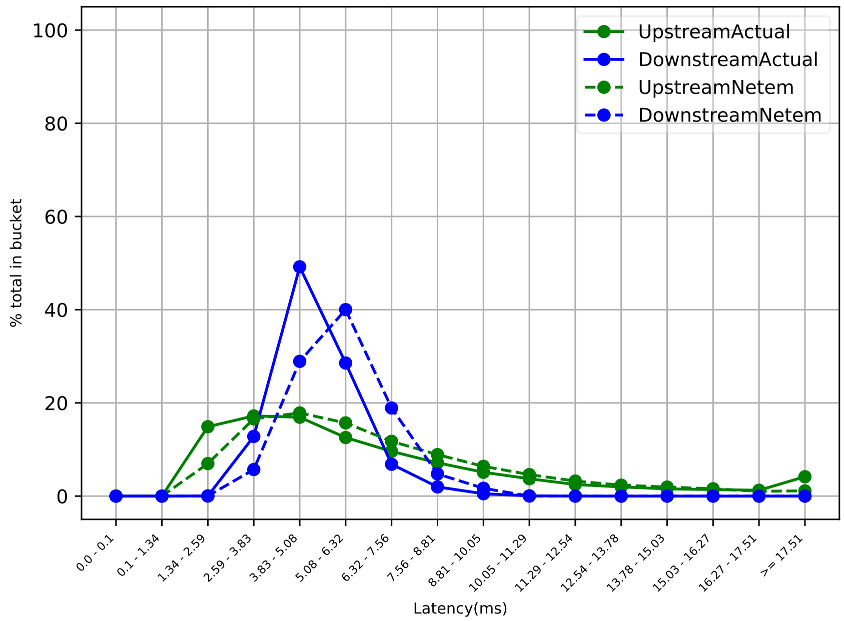

Figure 5.5: Case #9 (90% traffic load, Retransmission profile, 100 µs REIN, compared to NetEm recipe)

5.3.3 Long Loop Cases

In testing of the DSL, all cases trained on longer loops showed significantly more distributed latency values and higher variability (jitter) over their short loop counterparts. As described in chapter 3, the initial long loop case measurements contained a possibly anomalous long tail, with the presence of long latency packets, many of which fell outside of the measurement window. This data provided a modeling challenge, and although possibly incorrect for DSL, provides good insight into the limitations of the method used to model this data using NetEm.

5.3.3.1 FEC

For the FEC cases, running with a 50% traffic rate kept the majority of the values inside the measurement range (and limited the number of values in the last bucket). The upstream data resulted in a bi-modal distribution, suspected to be due to varying frame size. NetEm again had both its characteristic skew toward higher values, and its lack of last bucket values. The overall match was adequate to mirror similar performance to the DSL line. The presence of values in this last bucket, and NetEm's failure to match those values, increases the incidence of packets within the range modeled by NetEm, possibly contributing to the slightly higher values in the modeled range.

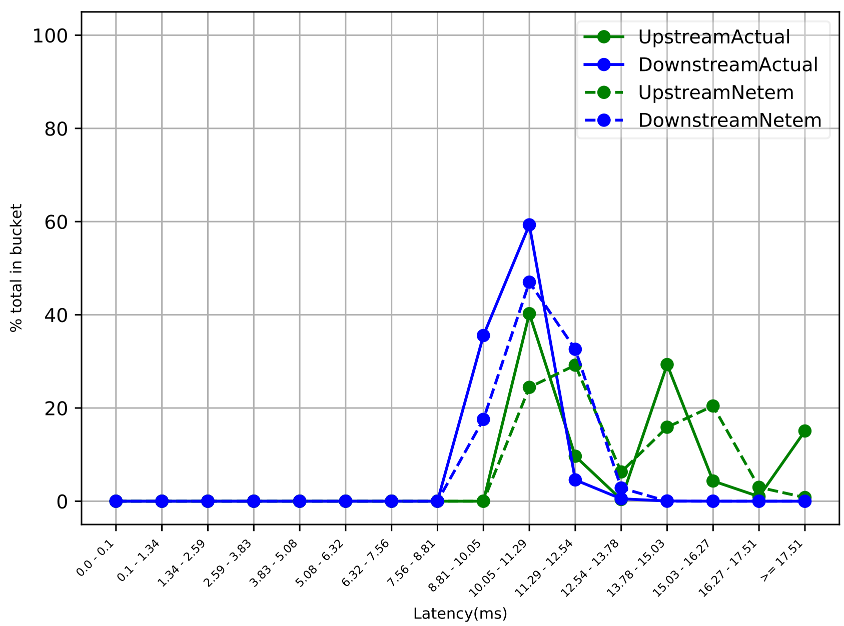

Figure 5.6: Case #40 (50% traffic load, FEC profile, compared to NetEm recipe)

With the 90% traffic rate additional traffic variability was seen. Particularly in the upstream, many values were pushed into the last bucket. This is both due to the high values seen in the initial test cases, and the actual values being outside of the measurement window as can be seen in Figure 5.7 This resulted in a good match of the downstream conditions by NetEm, but a somewhat inaccurate match of the upstream performance, as the outliers were not matched and more values were pushed into the other buckets. This could be improved by using a more accurate window of measurement for this case. This experiment was repeated widening the max window to 30 ms Figure 5.8, resulting in a better match, still a large amount of outliers were present, implying an even wider, or possibly shifted over window could be used.

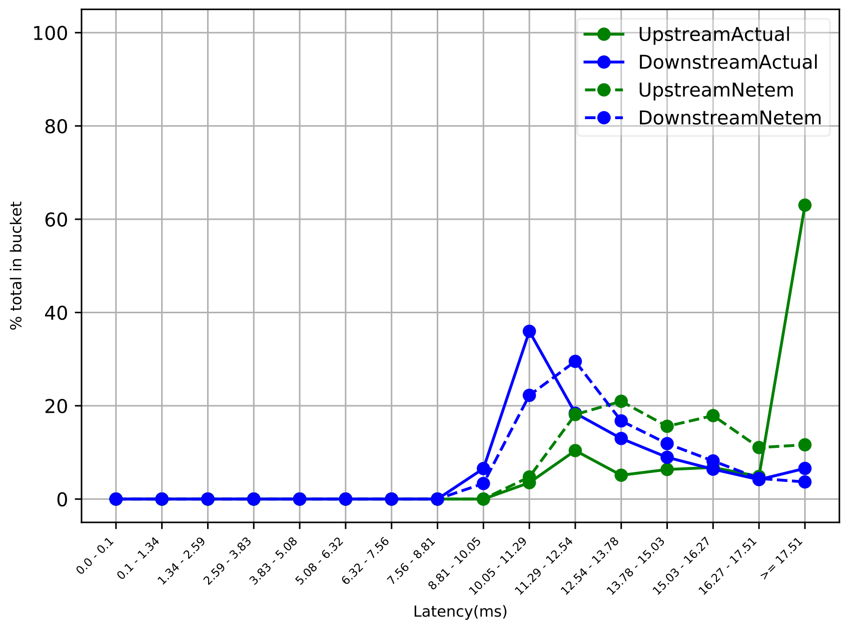

Figure 5.7: Case #35 (90% traffic load, FEC profile, 17.5 ms max bucket, compared to NetEm recipe)

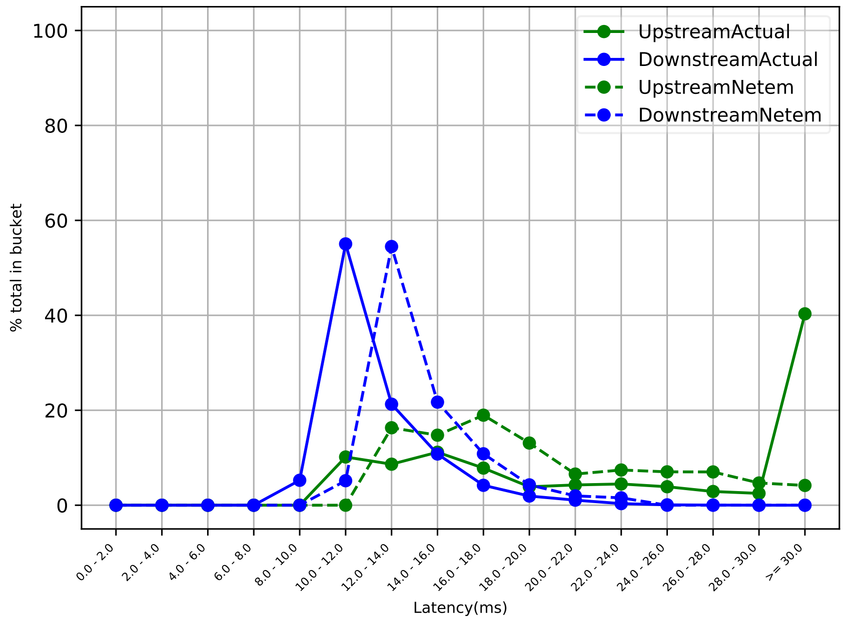

Figure 5.8: Case #50 (90% traffic load, FEC profile, 30 ms max bucket, compared to NetEm recipe)

5.3.3.2 Retransmission

For the Retransmission cases under longer loop testing, similarly variable latency was seen. These also suffered from similar NetEm matching issues with a lot of values present in the final bucket during the initial measurements. The Retransmission cases suffered the worst from the presence of possibly non-standard measured behavior generating very high values. Any REIN noise used in these test cases further increased maximal latency and compounded this issue. See Figure 5.9. Further experiments could be captured to attempt to remove the presence of these outliers.

Though the presence of these values in the last bucket is assumed to be non-typical behavior of DSL, the cases as measured provided an interesting modeling challenge. The values present were so highly distributed that adjustment of the measurement window to an adequate size to capture them, resulted in a loss of accuracy in the normal measurement range. This is a considerable limitation of the measurement tools used to study the latency.

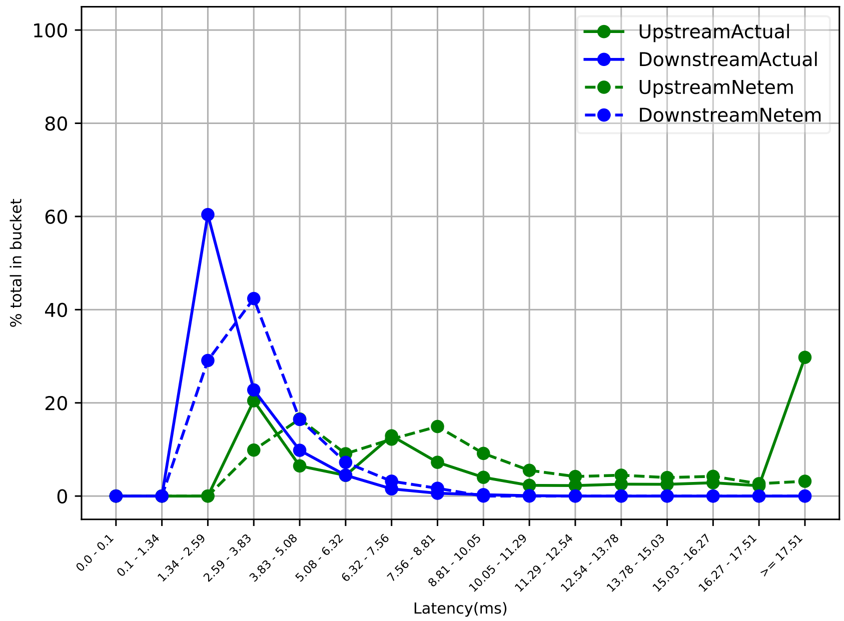

Figure 5.9: Case #37 (90% traffic load, Retransmission profile, compared to NetEm recipe)

5.4 Observations

This section attempts to detail and collect all of the observations of the models and their comparison to their original data cases, including deficiencies in the model and where improvements can be made for future study.

5.4.1 Model Performance

The original target of this modeling effort was to be able to simulate network performance of DSL lines with enough accuracy to test devices and applications and have an improved assurance of operational success over a DSL line. From that perspective, the modeling efforts were a success. Though many improvements could be made to further match DSL performance, the addition of our method's slight skew to latency would not have a significant impact on real devices, and in most cases, models are a more highly impaired case than the real DSL. This means if a device were able to survive the model, it could survive the real DSL.

5.4.2 Model Issues

This section details several issues that were found causing less than perfect matching between the measured DSL and its correspondent NetEm models.

5.4.2.1 Skew toward high values

Present in all of the cases was a slight skew toward higher values. This is likely a compound issue resulting from both fixed delay on the NetEm side (passing through NetEm imposes some delay), and from the way values were populated by the script. One 2011 study found that the latency imposed by NetEm was around 350 µs [12]. Other sources of this skew could likely be from the way values were filled by the script (only the average of the bucket size was represented, rather than variation between bucket sizes.) This may also result in some skew toward higher values.

5.4.2.2 Measurement accuracy

Due to the Spirent Test Center's limitations for capturing latency (a histogram of values with maximally 16 buckets), full measurement accuracy could not be obtained for the full range of values in every case, particularly those there a large percentage of values fell in the last bucket. When the actual latency was fairly consistent around a small range of values, very good accuracy could be provided for each of these values with the 16 buckets. When the latency became highly variable however, it became very difficult to get an accurate picture of the width of the latency variation without losing the concept of concentration around particular values. This became a significant difficulty for modeling the most stressed cases. The wider the histograms are made, the more accuracy lost for the actual values. It's possible that using a tool enabling even more accurate measurement of latency, that the modeling efforts could be improved, this would result in much more accurate models when passed into NetEm. If per-packet latency was obtainable, this method would result in near perfect models when correcting for NetEms inherent skew.

5.4.2.3 Outlier matching

Values at the upper end of the DSL measurements, measured in the less than or equal to 17.51 ms bucket, were not matched accurately represented. NetEm consistently produced lower values in the last bucket on all cases with a significant number of values in that container (outside the bounds of the configured histogram). This is a direct artifact of the way histogram values were converted to distribution files. As the python script read in the histogram values, and filled the initial output file with the average values of the buckets, for the last bucket it simply placed that number of 17.51 ms values into the output file. This of course leads to a tighter distribution around the measured values, and a lower amount of values beyond that measurement, as the real values of the DSL measurements were likely far outside of that 17.51 ms range. In cases with many values in this bucket, values in the central buckets were higher in the model than the DSL, and the last bucket value was much lower. This can be corrected by using a wider histogram range to capture the majority of these values in the central graph.

5.4.2.4 Packet Reordering

Perhaps the most major limitation of these models was the presence of packet reordering. Due to the design of NetEm's queuing (used to delay packets and create latency), packets were often re-ordered from their originally sent order. This was measured by the Spirent Test Center via its sequence counter. In all DSL test cases, packets were sent and received in order (with the exception of a very small number of packets in cases 8-10). This could have impact on higher layer protocols run over these simulated links. This study attempted to use NetEm's `pfifo` queuing setting to minimize the amount of re-ordering, but found that the majority of packets still arrived re-ordered.

5.4.3 Possible Improvements

Though the models were adequate for their intended purpose, many further experiments could be run and further improvements could be made to the models to correct for some of the deficiencies that were measured. This section is a breakdown of some potential next steps to be taken by further research.

5.4.3.1 Skew toward high values

Since the skew appears to be present in all models, some fixed correction based on NetEm's inherent additional latency could be made to the measurements. This could be as simple as subtracting a fixed value from each of the measurements to add a simple left adjustment. To get a better match to realistic latency, perhaps a more random generation of values between the bound of the buckets could be used to more accurately represent the variation between the buckets bounds.

5.4.3.2 Measurement accuracy

The models could be vastly improved by the use of a more granular tool to measure latency. The Spirent Test Center provides a limited visibility into the the latency values with its 16 buckets. Either the use of more buckets for measurement or a more granular view closer to per-packet latency would dramatically improve the accuracy of the model. Care should be taken here to select a tool that shares a similarly reliable and reproducible measurement of latency as the Spirent Test Center does.

5.4.3.3 Outlier matching

The deficiency of matching very variable data is directly related to measurement accuracy. With a more accurate picture of the true distribution of the latency, the tendency for NetEm to not represent the tail of the data would not be present. In all cases where the data fell entirely within measurement bounds the models matched accurately, in cases such as the

Retransmission on longer loops with REIN, accurate matches were nearly impossible due to the wide range of values present. This limitation is only due to the measurement accuracy available, improvements to that would help limit this effect.

5.4.3.4 Packet Reordering

The packet re-ordering, is based on NetEm's queuing policy. Any improvement of that issue would have to involve modifications to the NetEm code base to allow some sort of delay mechanism that did not remove the ordering of the packet. This would mean that the packets sent through the NetEm would be highly correlated to each other (though NetEm's correlation values did not result in any improvement.) The real issue is related to the fact that in DSL, events changing latency affect a set of related packets, where NetEm is applying random delay to match the distribution. Heavy modification and extension to NetEm would be required here.

5.5 Summary

For most cases of DSL that were measured, widely variable latency performance was seen. Experiments show that the NetEm models designed by this study provide a reasonable level of accuracy to most of the measured connection. Though some cases were difficult to model due to the difficult of measurement and limitations of the measurement equipment, the method of creation of models based on histogram values remains sound.

For more improvement on these models, tweaks can be made to the generation based off of the measured values, and a more complete and accurate measurement campaign can be performed to get a better idea of DSL across all scenarios.

CHAPTER 6

Conclusions

6.1 Results

This study initially took a look into identifying and measuring DSL under a number of normal operation conditions, and worse case scenarios. Detailed measurements of the latency on over 50 variations of the DSL connection under a variety of conditions were gathered. Following that a method was created for conversion of these detailed histogram measurements of latency into a distribution usable by NetEm to model the performance of a DSL connection.

On the subject of DSL measurements, the study was successful at identifying a number of key scenarios with highly variant performance. These included REIN noise being corrected by retransmission, and long loop cases. Any of these conditions being encountered in real deployment would represent some of the worst case scenarios technologies running over these connections, with highly variable latency distribution, including bi-modal latency patterns. Latency was identified as one of the key performance impactors of DSL connections. These detailed measurements provide an insight into the potential pain points of DSL connections and their possible latency distributions. Ultimately, DSL latency was shown to be highly variable, and less simple than initial expectations.

Following the measurement campaign the modeling efforts began, to give application and hardware developers and other testers a better toolkit to test over more realistic simulations of network latency. The majority of these models, and the method used for creating them, were very successful in matching DSL latency performance when measured against the original subject of their simulation, and should provide some better indication of performance over real links when compared to more simplistic modeling techniques. The technique defined in this paper and the method for studying latency and modeling it with NetEm, can be used and applied to other technologies and a library of simulations built up.

The subject of this research provides an interesting look into the world of latency performance of DSL connections, as well as providing useful output in the form of NetEm models that can be used to give a more complete and accurate to reality testing scenario for anyone looking to deploy technologies over live connections. Use of these models can give these interested parties a better indication of performance over these connections without the need for rare and expensive networking equipment to experiment on.

6.2 Future Work

Throughout the course of this study, many points where additional study can be looked into were identified. The details of possible further research are below. Raw data and additional information for the experiments performed in this study are available at [10]

6.2.1 Further DSL Studies

The most major continuation of the study is to further understand the impact of all DSL parameters on the network performance of the connection. This would require more variations of the conditions, configurations, and impairments. DSL contains a massive set of configurable settings, fully understanding the impact of all of them on latency would be a large project.

Of particular target for further study would be variations of the Retransmission settings, INP, interleaving delay, and variation on loop length. ADSL2plus, and other bandwidths of VDSL2, and even Gfast could be additionally interesting topics for study.

The intention of this study would be to create a more complete mapping of the impact of each setting and to create a better understanding of the bounds and possibilities of DSL connection latency.

6.2.2 Further Improvements to Modeling

The Model Results and Comparisons chapter details a number of possible improvements to the NetEm models. Performing any of these improvements and re-evaluating the models would be a good continuation of work.

The main deficiency of the models was related to measurement accuracy. Either the use or creation of an improved tool with a better ability to measure latency across a wider range would greatly improve the models. Additional tweaks to the conversion from measurements to NetEm distribution files may also improve the fit.

This modeling technique could also be applied to other sets of measurements for different connection types such as 802.11, DOCSIS, or Gfast.

6.2.3 Testing of Models with other Protocols

Though this study focused solely on replicating the performance of Ethernet frames over the simulated connection, one interesting course of study would be to use higher level protocols such as TCP, and test their performance over these simulated links.

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APPENDIX A

GLOSSARY

ADSL Asynchronous Digital Subscriber Line

ATX Alien Crosstalk

AWG American Wire Gauge

CO Central Office

CPE Customer Premise Equipment

CRC Cyclical Redundancy Check

DSL Digital Subscriber Line

DSLAM Digital Subscriber Line Access Multiplexer

DTU Data transmission unit

ETR Estimated throughput

FCS Frame check sequence

FEC Forward Error Correction

FEXT Far End Crosstalk

IMIX Internet Mix

INP Impulse Noise Protection

NDR Net data rate

NEXT Near End Crosstalk

PEIN Prolonged Electrical Impluse noise

PSD Power Spectrum Density

QoE Quality of Experience

QoS Quality of Service

REIN Repetitive Impulse noise

SHINE Single High Impulse noise

TCP Transmission Control Protocol

UDP Unreliable datagram protocol

VDSL Very high-bitrate Digital Subscriber Line

APPENDIX B

Test Cases

Table B.1 through Table B.4 summarize all parameters tested, and test conditions used during the course of this study. The numbers are used as reference in any graphs contained in this document and in the reference materials available on the web page specified in [10].

Test Case #	*Loop Length*	*Configured DSLAM Profile*	*Trained Line Rates (Mbps)*	*Traffic Rates (Mbps)*	*Traffic Level*	*Notes*
1	1000 ft	TR-114 AA8d_I_096_056_no_rtx	51.279M/11.360M	25.63M/5.68M	50%	50% no impulse/baseline
2	1000 ft	TR-114 AA8d_I_096_056_no_rtx	51.279M/11.360M	25.63M/5.68M	50%	100us REIN
3	1000 ft	TR-114 AA8d_I_096_056_no_rtx	51.279M/11.360M	46.151M/10.224M	90%	90% no impulse/baseline
4	1000 ft	TR-114 AA8d_I_096_056_no_rtx	51.279M/11.360M	46.151M/10.224M	90%	100us REIN
5	1000 ft	TR-114 AA8d_I_096_056_rtx	56.212M/12.224M	28.106M/6.112M	50%	50% no impulse/baseline
6	1000 ft	TR-114 AA8d_I_096_056_rtx	56.212M/12.224M	28.106M/6.112M	50%	50% 100us REIN
7	1000 ft	TR-114 AA8d_I_096_056_rtx	56.212M/12.224M	28.106M/6.112M	50%	50% 1ms REIN
8	1000 ft	TR-114 AA8d_I_096_056_rtx	56.212M/12.224M	50.59M/11M	90%	90% no impulse/baseline
9	1000 ft	TR-114 AA8d_I_096_056_rtx	56.212M/12.224M	50.59M/11M	90%	90% 100us REIN
10	1000 ft	TR-114 AA8d_I_096_056_rtx	56.212M/12.224M	50.59M/11M	90%	90% 1ms REIN
11	1000 ft	TR-114 AA8d_I_096_056_no_rtx	51.279M/11.360M	25.63M/5.68M	50%	50% no impulse/baseline
12	1000 ft	TR-114 AA8d_I_096_056_no_rtx	51.279M/11.360M	25.63M/5.68M	50%	100us REIN
13	1000 ft	TR-114 AA8d_I_096_056_no_rtx	51.279M/11.360M	46.151M/10.224M	90%	90% no impulse/baseline
14	1000 ft	TR-114 AA8d_I_096_056_no_rtx	51.279M/11.360M	46.151M/10.224M	90%	100us REIN
15	1000 ft	TR-114 AA8d_I_096_056_rtx	56.212M/12.224M	28.106M/6.112M	50%	50% no impulse/baseline

Table B.1: Test Cases 1/4

Test Case #	*Loop Length*	*Configured DSLAM Profile*	*Trained Line Rates (Mbps)*	*Traffic Rates (Mbps)*	*Traffic Level*	*Notes*
16	1000 ft	TR-114 AA8d_I_096_056_rtx	56.212M/12.224M	28.106M/6.112M	50%	50% 100us REIN
17	1000 ft	TR-114 AA8d_I_096_056_rtx	56.212M/12.224M	28.106M/6.112M	50%	50% 1ms REIN
18	1000 ft	TR-114 AA8d_I_096_056_rtx	56.212M/12.224M	50.59M/11M	90%	90% no impulse/baseline
19	1000 ft	TR-114 AA8d_I_096_056_rtx	56.212M/12.224M	50.59M/11M	90%	90% 100us REIN
20	1000 ft	TR-114 AA8d_I_096_056_rtx	56.212M/12.224M	50.59M/11M	90%	90% 1ms REIN
21	1000 ft	TR-114 AA8d_I_096_056_no_rtx	50.625M/11.372M	25.3M/5.68M	50%	50% no impulse/baseline
22	1000 ft	TR-114 AA8d_I_096_056_no_rtx	50.625M/11.372M	25.3M/5.68M	50%	50% 100us REIN
23	1000 ft	TR-114 AA8d_I_096_056_rtx	51.404M/11.004M	25.702M/5.502M	50%	50% no impulse/baseline
24	1000 ft	TR-114 AA8d_I_096_056_rtx	51.404M/11.004M	25.702M/5.502M	50%	50% 100us REIN
25	1000 ft	TR-114 AA8d_I_096_056_rtx	51.404M/11.004M	25.702M/5.502M	50%	50% 1ms REIN
26	1000 ft	TR-114 AA8d_I_096_056_rtx	51.394M/11.011M	46.254M/9.909M	90%	90% no impulse/baseline
27	1000 ft	TR-114 AA8d_I_096_056_rtx	51.394M/11.011M	46.254M/9.909M	90%	90% 100us REIN
28	1000 ft	TR-114 AA8d_I_096_056_rtx	51.404M/11.004M	46.263M/9.903M	90%	90% 1ms REIN
29	1000 ft	TR-114 AA8d_I_096_056_rtx	75.227M/11.876M	67.704M/10.688M	90%	no impulse

Table B.2: Test Cases 2/4

Test Case #	*Loop Length*	*Configured DSLAM Profile*	*Trained Line Rates (Mbps)*	*Traffic Rates (Mbps)*	*Traffic Level*	*Notes*
30	1000 ft	TR-114 AA8d_I_096_056_rtx	75.227M/11.876M	67.704M/10.688M	90%	90% 1ms REIN
31	2000 ft	TR-114 AA8d_I_096_056_rtx	65.610M/6.789M	67.704M/10.688M	90%	no impulse
32	2000 ft	TR-114 AA8d_I_096_056_rtx	65.610M/6.789M	67.704M/10.688M	90%	90% 1ms REIN
33	3000 ft	TR-114 AA8d_I_096_056_rtx	40.398M/1.043M	67.704M/10.688M	90%	no impulse
34	3000 ft	TR-114 AA8d_I_096_056_rtx	40.398M/1.043M	67.704M/10.688M	90%	90% 1ms REIN
35	5350 ft	TR-114 AA8d_I_096_056_no_rtx	15.603M/1.204M	14.042M/1.083M	90%	Baseline
36	5350 ft	TR-114 AA8d_I_096_056_no_rtx	15.603M/1.204M	14.042M/1.083M	90%	100us rein
37	5350 ft	TR-114 AA8d_I_096_056_rtx	15.103M/0.964M	13.592M/0.867M	90%	Baseline
38	5350 ft	TR-114 AA8d_I_096_056_rtx	15.103M/0.964M	13.592M/0.867M	90%	100us rein
39	5350 ft	TR-114 AA8d_I_096_056_rtx	15.103M/0.964M	13.592M/0.867M	90%	1ms rein
40	5350 ft	TR-114 AA8d_I_096_056_no_rtx	15.603M/1.204M	7.801M/0.602M	50%	Baseline
41	5350 ft	TR-114 AA8d_I_096_056_no_rtx	15.603M/1.204M	7.801M/0.602M	50%	100us rein
42	5350 ft	TR-114 AA8d_I_096_056_rtx	15.103M/0.964M	7.551M/0.482M	50%	Baseline
43	5350 ft	TR-114 AA8d_I_096_056_rtx	15.103M/0.964M	7.551M/0.482M	50%	100us rein
44	5350 ft	TR-114 AA8d_I_096_056_rtx	15.103M/0.964M	7.551M/0.482M	50%	1ms rein
45	7300 ft	TR-114 AA8d_I_096_056_no_rtx	8.215M/1.202M	7.393M/1.081M	90%	Baseline

Table B.3: Test Cases 3/4

Test Case #	*Loop Length*	*Configured DSLAM Profile*	*Trained Line Rates (Mbps)*	*Traffic Rates (Mbps)*	*Traffic Level*	*Notes*
46	7300 ft	TR-114 AA8d_I_096_056_no_rtx	8.215M/1.202M	7.393M/1.081M	90%	100us rein
47	7300 ft	TR-114 AA8d_I_096_056_rtx	7.763M/0.948M	6.986M/0.853M	90%	Baseline
48	7300 ft	TR-114 AA8d_I_096_056_rtx	7.763M/0.948M	6.986M/0.853M	90%	100us rein
49	7300 ft	TR-114 AA8d_I_096_056_rtx	7.763M/0.948M	6.986M/0.853M	90%	1ms rein
50	5750 ft	TR-114 AA8d_I_096_056_no_rtx	15.325M/1.227M	13.792M/1.104M	90%	Baseline
51	5750 ft	TR-114 AA8d_I_096_056_no_rtx	15.325M/1.227M	13.792M/1.104M	90%	100us rein
52	7500 ft	TR-114 AA8d_I_096_056_no_rtx	8.633M/1.198M	7.769M/1.078M	90%	Baseline
53	7500 ft	TR-114 AA8d_I_096_056_no_rtx	8.633M/1.198M	7.769M/1.078M	90%	100us rein
54	5750 ft	TR-114 AA8d_I_096_056_no_rtx	14.322M/1.227M	12.898M/1.104M	90%	Baseline
55	5750 ft	TR-114 AA8d_I_096_056_no_rtx	14.322M/1.227M	12.898M/1.104M	90%	100us rein
56	7500 ft	TR-114 AA8d_I_096_056_no_rtx	8.523M/1.198M	7.670M/1.078M	90%	Baseline
57	7500 ft	TR-114 AA8d_I_096_056_no_rtx	8.523M/1.198M	7.670M/1.078M	90%	100us rein

Table B.4: Test Cases 4/4