

## Chapter 7. Results

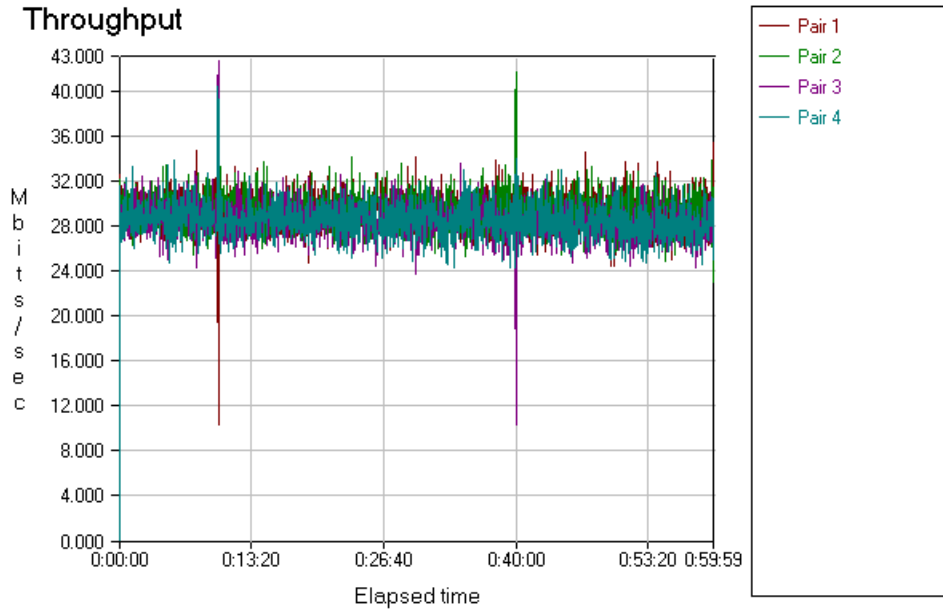
Network performance was evaluated for each of the four test templates described in Chapter 6 based on the values for throughput, transaction rate, and response time for Tests 1 and 2, and throughput, percent bytes lost and number of datagrams lost between the endpoints for Tests 3 and 4. Each performance metric was measured and evaluated for different optical power levels. Finally, the Bit Error Rate (BER) characterization of the fiber links, including the attenuators, was evaluated and the results are presented at the end of this chapter in Section 7.5.

### 7.1. Test 1 Results

This section gives a typical trace of a particular metric for scripts *filercvltest1* and *filesndltest1* running over TCP, from one test run at a certain power level, and then a graph representing all the average values obtained at different optical power levels.

#### 7.1.1. Test 1 Throughput

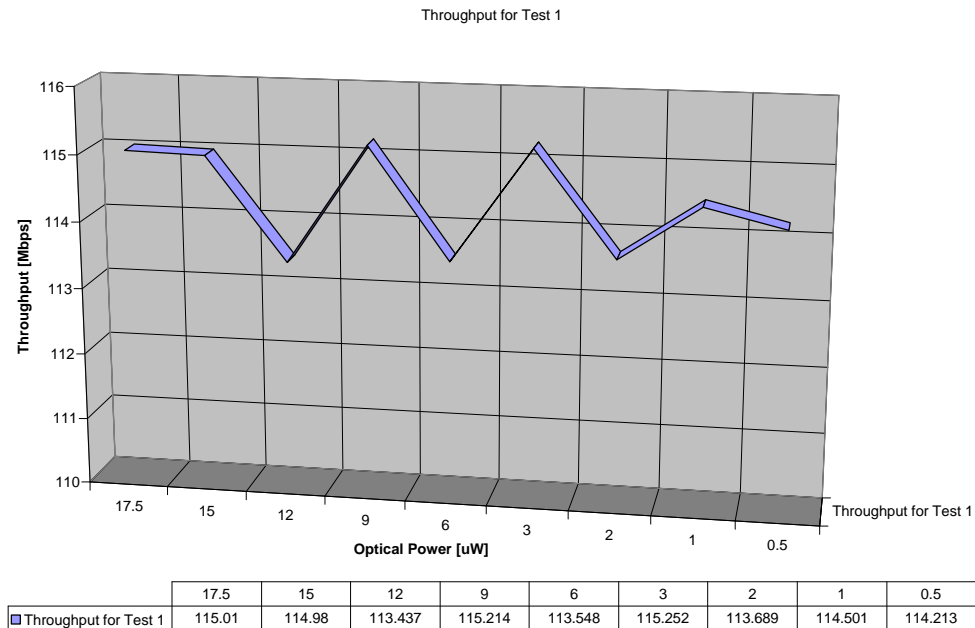
The typical trace for the overall throughput of all four pairs over the one-hour test duration is shown in Figure 7.1. Pairs one and two, running the same *filercvltest1* script, averaged about 29 Mbps each; pairs 3 and 4, which ran *filesndltest1*, achieved about 28 Mbps. The average overall throughput for all four pairs at this particular optical power level was 115.010 Mbps.



*Figure 7.1 Test 1 Throughput at 17.5 mW of Optical Power*

The same test run was repeated eight more times at different settings of the attenuators, and these values are given in Figure 7.2. From the figure, it can be observed that the average throughput has a peculiar periodic shape over most of the operating power region. The strange oscillation in throughput may be related to two main attributes of this test setup: 1) the removal occurs soon after the light from the transmitter in the ATM port launches light into the fiber, 2) there is a particular way that the attenuators remove optical power from the link.

The first factor has to do with the nature of light propagation through a multimode fiber. Light from a Light Emitting Diode (LED) is coupled into a relatively large core of the multimode fiber (62.5  $\mu\text{m}$  diameter versus 9  $\mu\text{m}$  for a singlemode fiber), where it excites a large number of different modes of propagation. These modes are the Bessel functions, which are the multiple solutions of Maxwell's equation for a cylindrical waveguide.



*Figure 7.2 Test 1 Average Throughput for Different Optical Power Levels*

The particular Bessel functions or modes that propagate through the fiber are decided based on the value of the boundary conditions or the actual size of the core of the fiber. Thus, the size of a singlemode fiber is designed to allow only one mode of propagation, while the larger size of multimode fiber allows for optical power, or a signal, to be transported through the fiber over a large number of different modes. The normalized propagation constant corresponding to a certain mode describes how the mode propagates through the fiber, as well as which modes die out fast. In addition to certain modes dying out fast, the peculiarities of the fiber will cause certain modes to couple into the cladding of the fiber and certain ones to completely couple out of the fiber. Generally, when the length of the fiber is sufficient, a cleansing of “dying” or “leaving” modes occurs, as well as an averaging of the “surviving” modes. However, the short distance associated with fibers replacing existing copper cabling in today’s

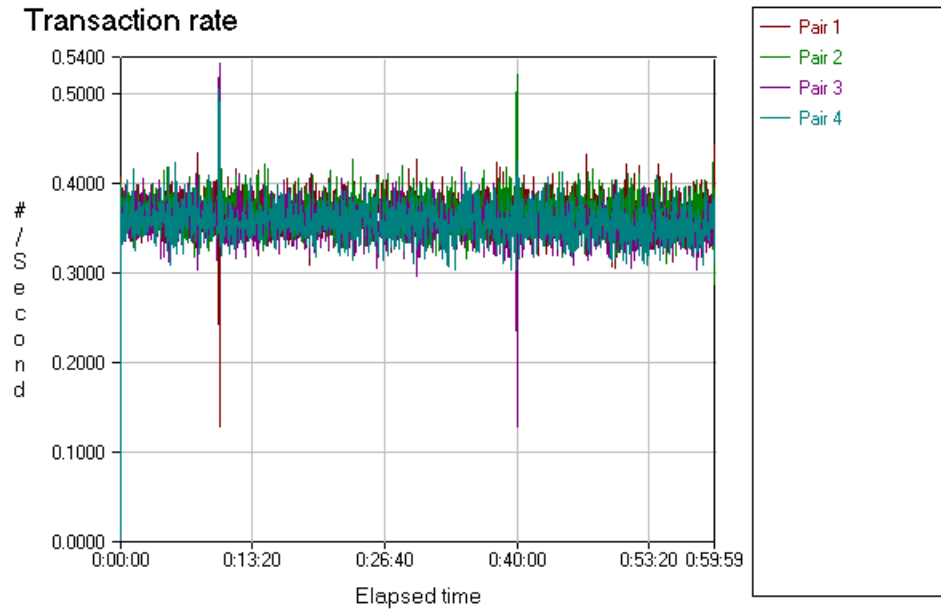
LANs, and especially the fibers used in this particular test (all fiber links were either 1m or 2 m in length), are not long enough to provide for mode “ironing.”

The second factor, coupled with the different propagating modes in the first few meters of the fiber, is the attenuators used for this setup. The attenuators remove optical power from the fiber by misaligning the fibers, as described in Chapter 5, Section 5.2.7. Unfortunately, with only 1 m of fiber between the attenuators and the LED, the attenuators also act as very powerful mode filters. Although multimode fibers, modal filters and modal as well as other types of noise in fibers, have been studied extensively during the 80’s and the 90’s, characterizing the light propagation through multimode fiber remains a pretty difficult task. The task becomes even more difficult when attempting to study the light during its initial period of propagation through the multimode fiber.

Since there is a great possibility that certain modes are selectively dropped while certain ones may be reflected back from the interface, these two factors may have to do with the oscillations in performance. The overall trend of decreasing throughput, especially below the 3  $\mu$ W power level has to do, as expected, with lower optical power level, which decreases the signal-to-noise ratio and ultimately increases the BER.

### **7.1.2. Test 1 Transaction Rate**

The typical trace for the transaction rate of all four pairs over the one-hour test duration is shown in Figure 7.3. The transaction rate provides information on how fast transactions between the two endpoints take place. The units are in number of transactions per second.



*Figure 7.3 Test 1 Transaction Rate at 17.5 mW of Optical Power*

Pairs 1 and 2 achieved around 0.36 transactions per second, whereas pairs 3 and 4 achieved about 0.35 transactions per second. The overall transaction rate average for this power level was around 1.44.

Transaction rate values at different settings of the attenuators are given in Figure 7.4. As expected, the shape of the transaction rate graph closely resembles the throughput graph, both in its oscillatory variations over the evaluated power range and in the overall-decreasing trend below the 3  $\mu$ W level.

Transaction Rate for Test 1

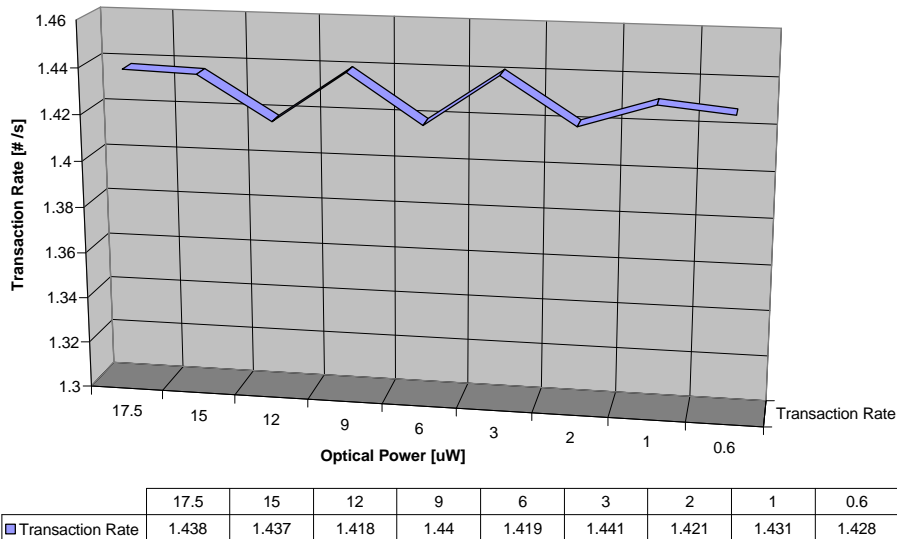


Figure 7.4 Test 1 Transaction Rate for Different Optical Power Levels

### 7.1.3. Test 1 Response Time

The response time of all four pairs over the one-hour test duration is presented in Figure 7.5. Response time is an inverse variable from the transaction rate, and it provides information on the length of time it takes to complete a transaction. Pairs 1 and 2 needed around 2.74 seconds per transaction, whereas Pairs 3 and 4 needed about 2.82 seconds per transaction. The overall response time average for this power level was around 2.78.

Response time values at different optical power levels are given in Figure 7.6. The graph clearly shows that the response time parameter is the inverse of the transaction rate. It also shows that the time it takes to complete a transaction increases at lower power levels, again especially below 3 $\mu$ W of power.

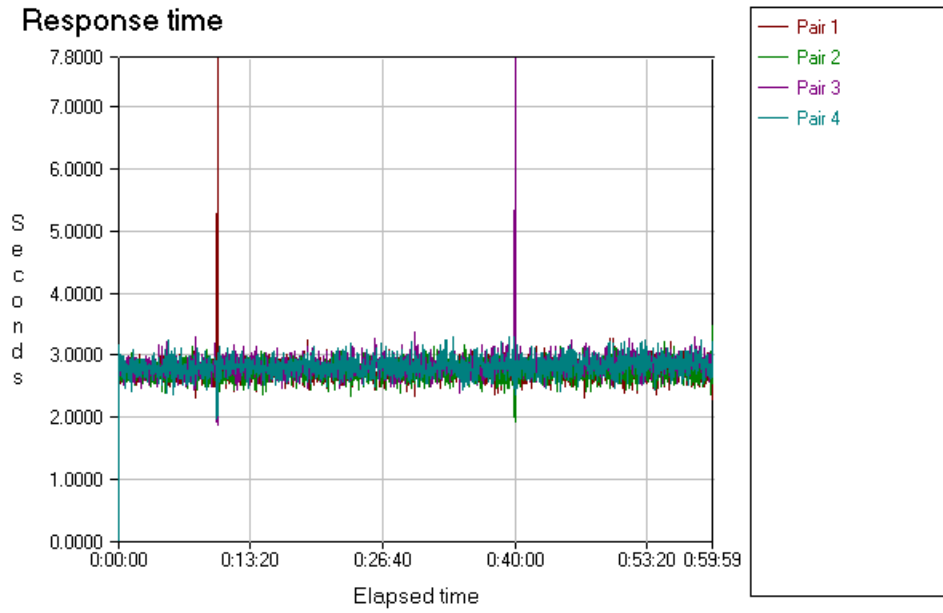


Figure 7.5 Test 1 Response Time at 17.5 mW of Optical Power

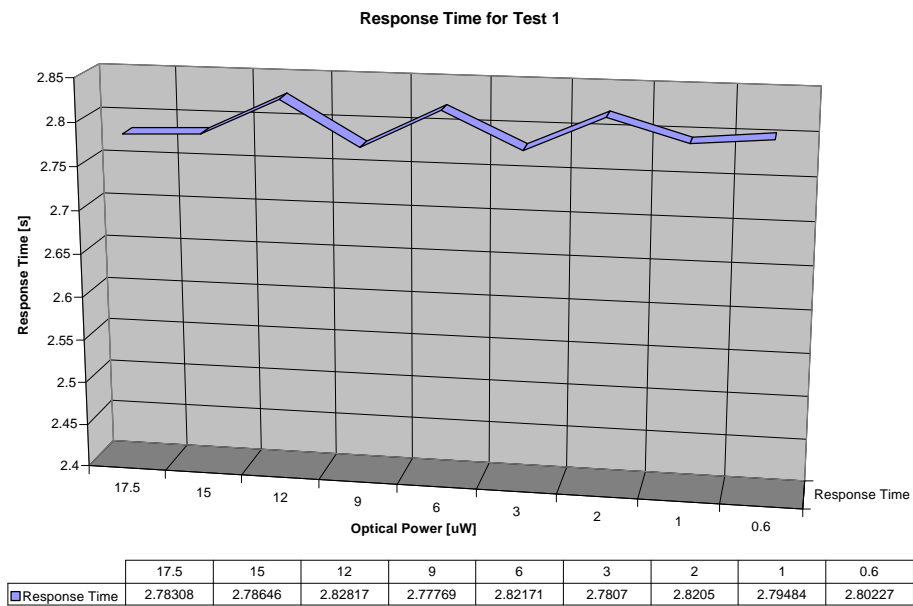


Figure 7.6 Test 1 Response Time for Different Optical Power Levels

## 7.2. Test 2 Results

This section gives a typical trace of a particular metric for *ftpputtest2*, *httpgifttest2* and *httptexttest2* scripts running over TCP. One test was run at a certain power level, and then the graph was generated showing the average values obtained at different optical power levels.

### 7.2.1. Test 2 Throughput

The typical trace for the overall throughput of all four pairs over the one-hour test duration is shown in Figure 7.7. Pair 1 running the *ftpputtest2* script achieved about 34.9 Mbps; pair 2 running the script *httpgifttest2* achieved about 36.9 Mbps; and pair 3 running the *httptexttest2* achieved about 36.6 Mbps of average throughput at 17.5  $\mu$ W of optical power.

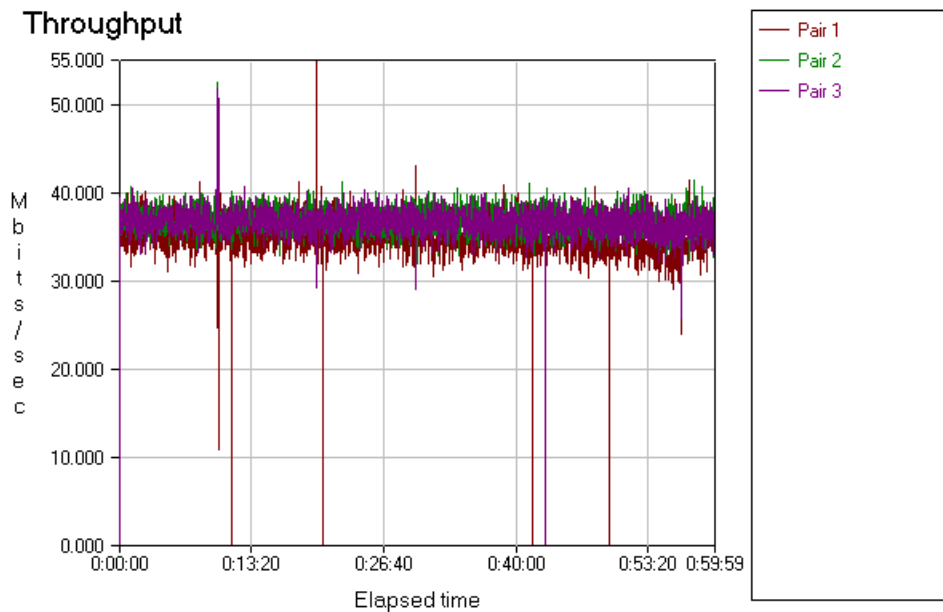
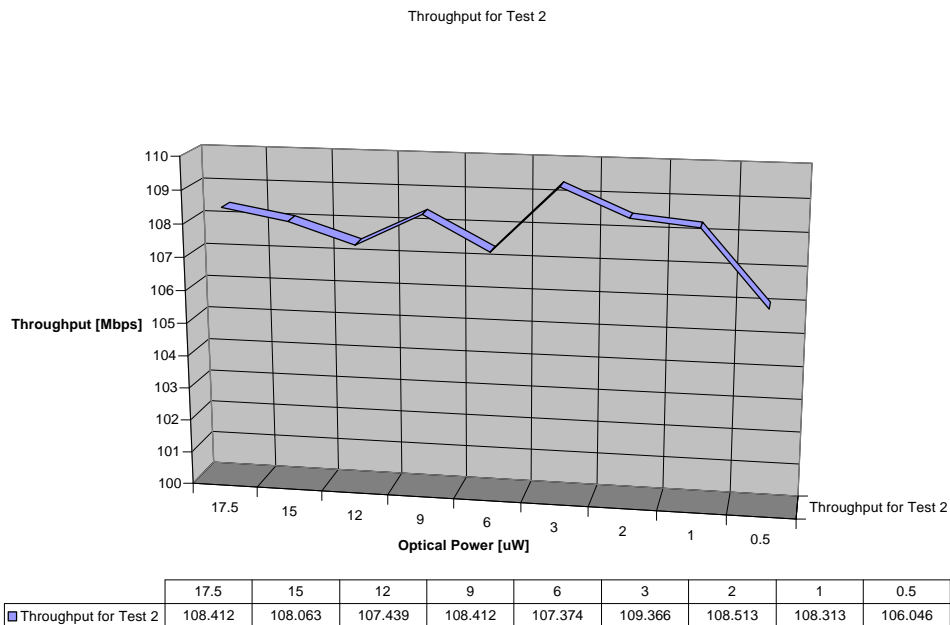


Figure 7.7 Test 2 Throughput at 17.5 mW of Optical Power



The same test run was repeated eight times at different settings of the attenuators and these values are given in Figure 7.8. From the figure, it can be observed that the average throughput also has a peculiar periodic shape over most of the operating power region.

The graph is somewhat similar to the throughput in Test 1 and its shape may also be attributed to the same two reasons mentioned for Test 1. The possibility of constructive and destructive interference of the modes, which may be dropped or reflected, may have caused oscillations in performance. Again, the overall trend of decreasing throughput, especially below the 3  $\mu\text{W}$  power level has to do, as expected, with lower optical power level which decreases the signal-to-noise ratio and ultimately increases the BER.

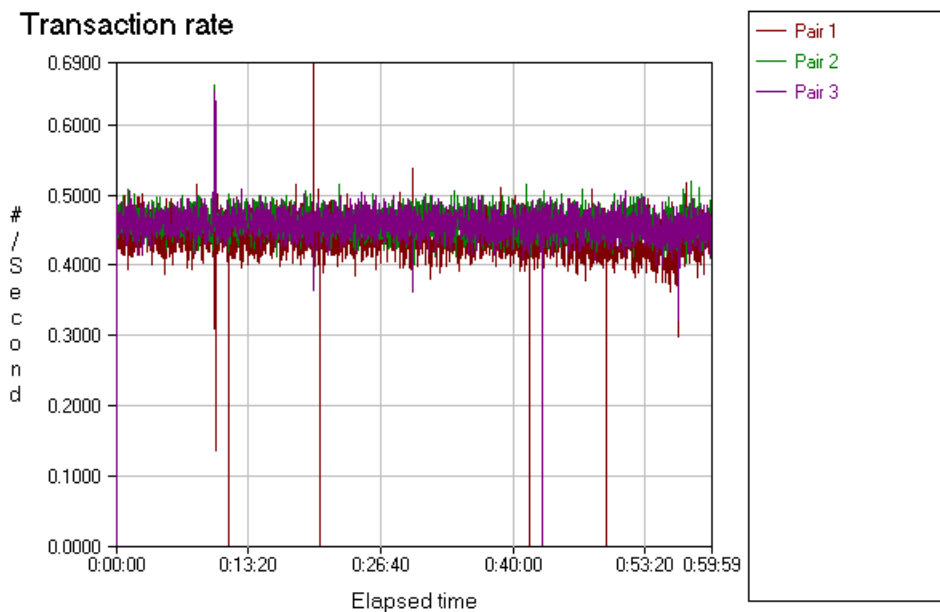


*Figure 7.8 Test 2 Average Throughput for Different Optical Power Levels*

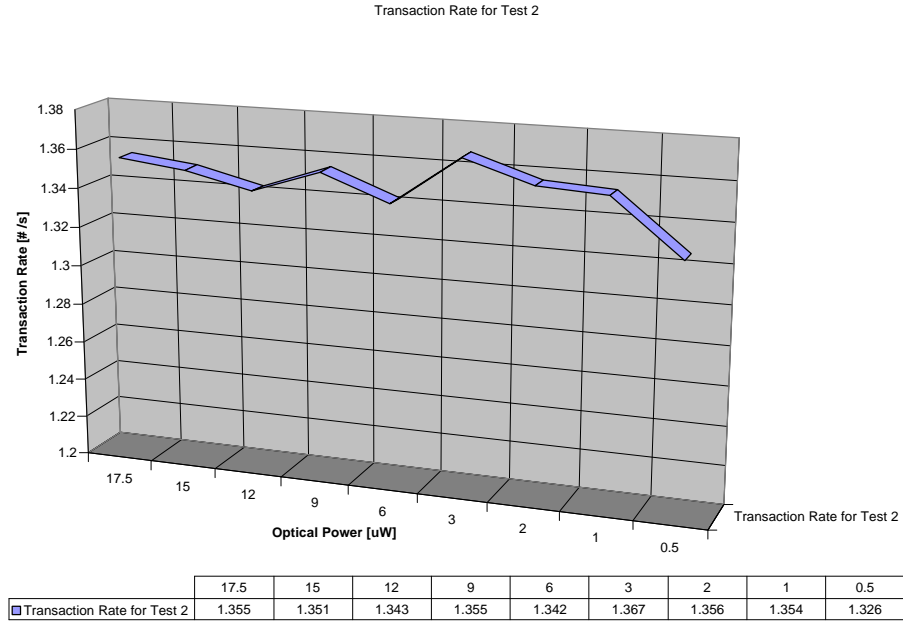
### 7.2.2. Test 2 Transaction Rate

A one-run trace of the Test 2 transaction rate is shown in Figure 7.9. Pair 1 had achieved around 0.44 transactions per second; pair 2 had achieved slightly above 0.46; and pair 3 had achieved slightly below 0.46 transactions per second. The overall transaction rate average for this power level was around 1.35.

Transaction rate values at different settings of the attenuators are given in Figure 7.10, from which a close resemblance to the throughput graph can be seen.



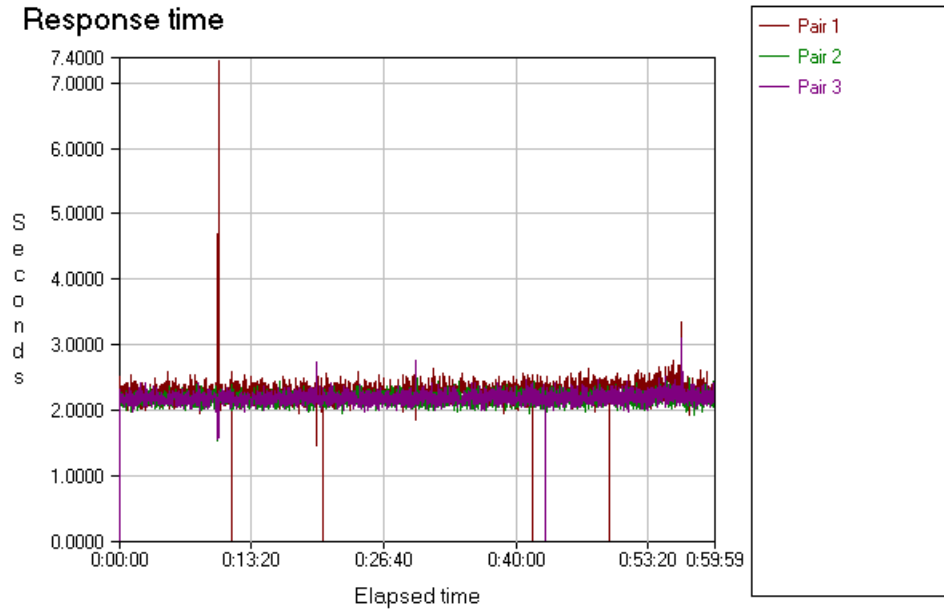
*Figure 7.9 Test 2 Transaction Rate at 17.5 mW of Optical Power*



*Figure 7.10 Test 2 Transaction Rate for Different Optical Power Levels*

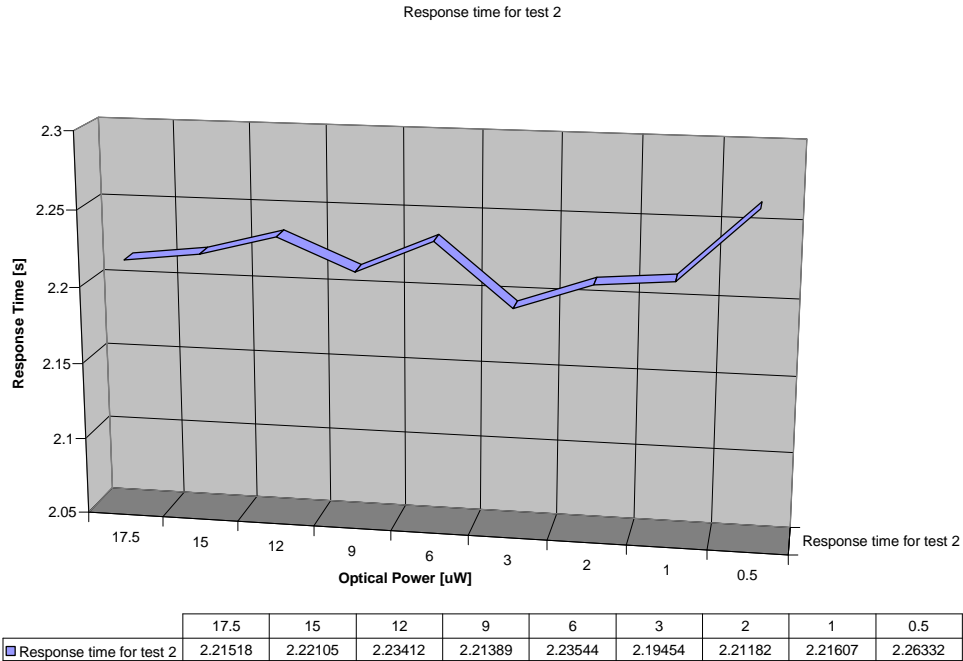
### 7.2.3. Test 2 Response Time

The response time of all three pairs is shown in Figure 7.11. Pair 1 required about 2.29 seconds per transaction, whereas pairs 2 and 3 needed about 2.18 seconds per transaction. The overall response time average for this power level was around 2.22 seconds per transaction.



*Figure 7.11 Test 2 Response Time at 17.5 mW of Optical Power*

Response time values at different optical power levels are given in Figure 7.12. As was the case for Test 1, the response time graph is the opposite of the transaction rate graph. The time it takes to complete a transaction increases at lower power levels, again especially below the 3  $\mu$ W of optical power level.



*Figure 7.12 Test 2 Response Time for Different Optical Power Levels*

### 7.3. Test 3 Results

Test three was initially designed only to show that the soft failures may not be having as much of an effect on network performance if the link is underutilized. The overall throughput achieved with this test was much lower than any of the other three. As suspected, throughput was not affected by the link deterioration, and therefore it was unnecessary to take as many data points.

Test 3 consisted of 10 pairs running different multimedia scripts as described in Chapter 6, Section 6.4.3, and the test used UDP as the network protocol.

### 7.3.1. Test 3 Throughput

In Test 3, Pairs 2, 3, 4 and 5 were running scripts *netmtgvttest3*, *netshowutest3*, *realaudtest3*, and *realmedtest3*, respectively, and achieved throughput between 2.3 Mbps and 3.7 Mbps. Pair 1, running *netmtgatest3* and Pairs 6, 7, 8, 9 and 10 all running *voipstest3*, achieved only around 0.3 Mbps of average throughput. These traces of individual pairs are displayed in Figure 7.13.

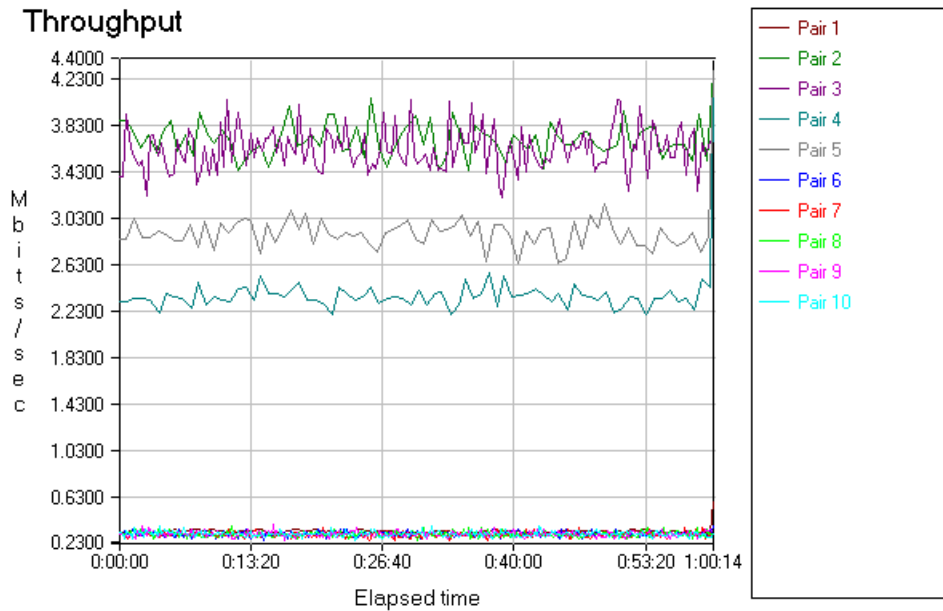
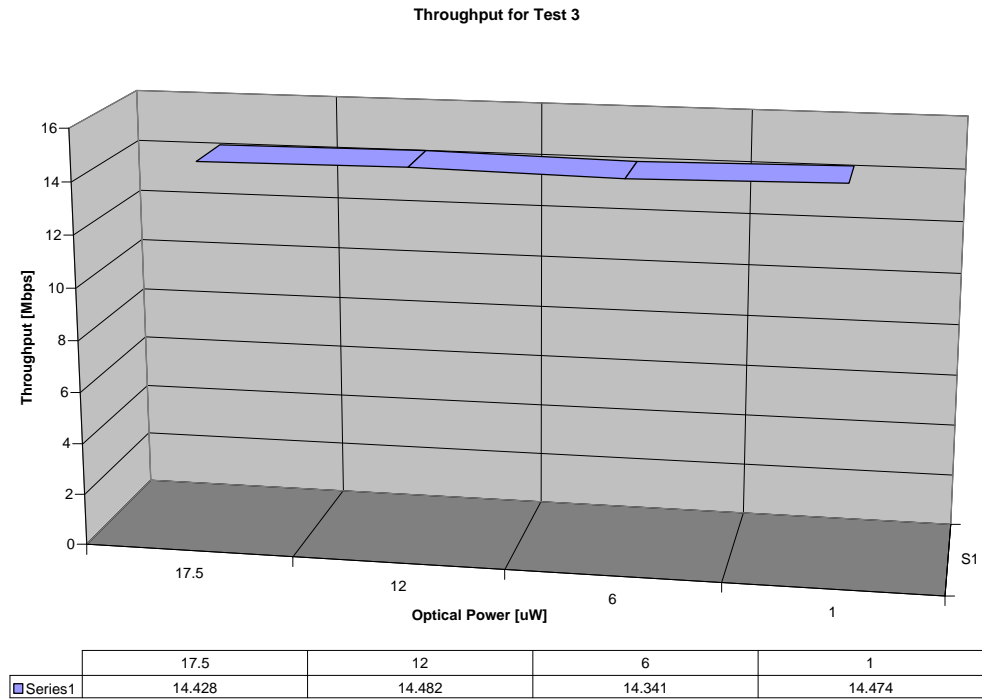


Figure 7.13 Test 3 Throughput at 17.5 mW of Optical Power

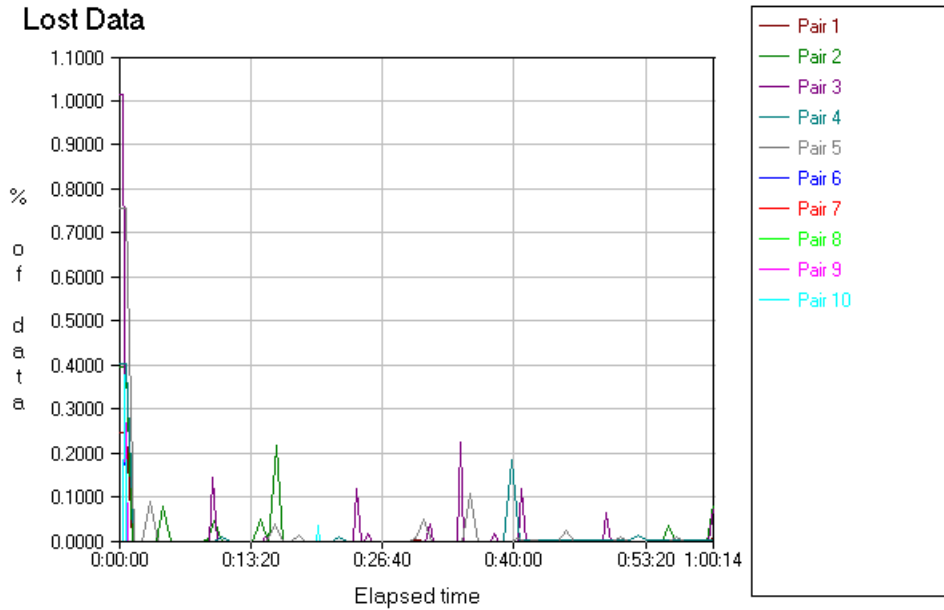
The graph of all the average values obtained at different optical power levels is presented in Figure 7.14, and as expected, does not show significant throughput change over the wide operating region of different power levels.



*Figure 7.14 Test 3 Average Throughput for Different Optical Power Levels*

### 7.3.2. Test 3 Lost Data

The trace showing percent of data lost during the one-hour test at 17.5  $\mu$ W power level for each individual pair can be found in Figure 7.15. It is not surprising that Pairs 2, 3, 4 and 5, which had achieved the highest throughput, also had the highest percentage of data lost.

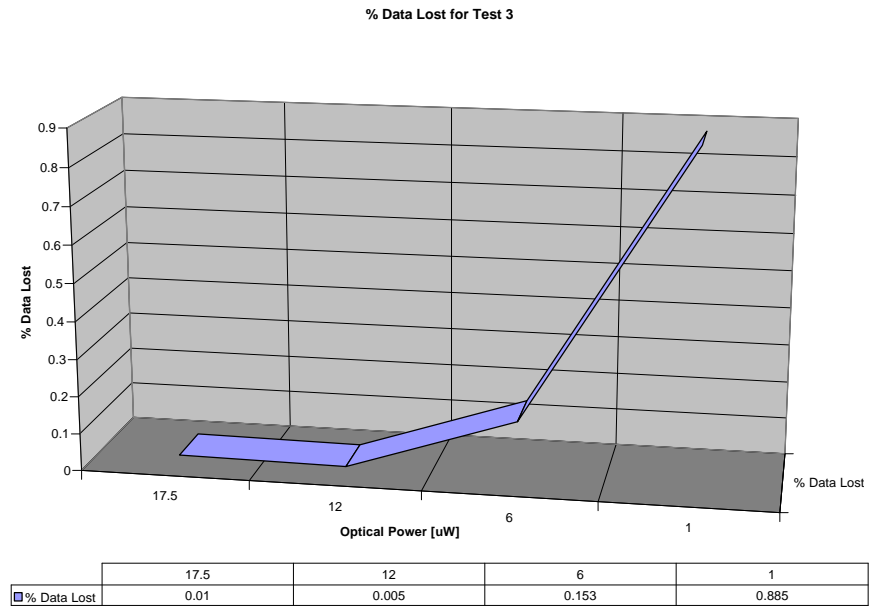


*Figure 7.15 Test 3 Percentage of Lost Data at 17.5 mW of Optical Power*

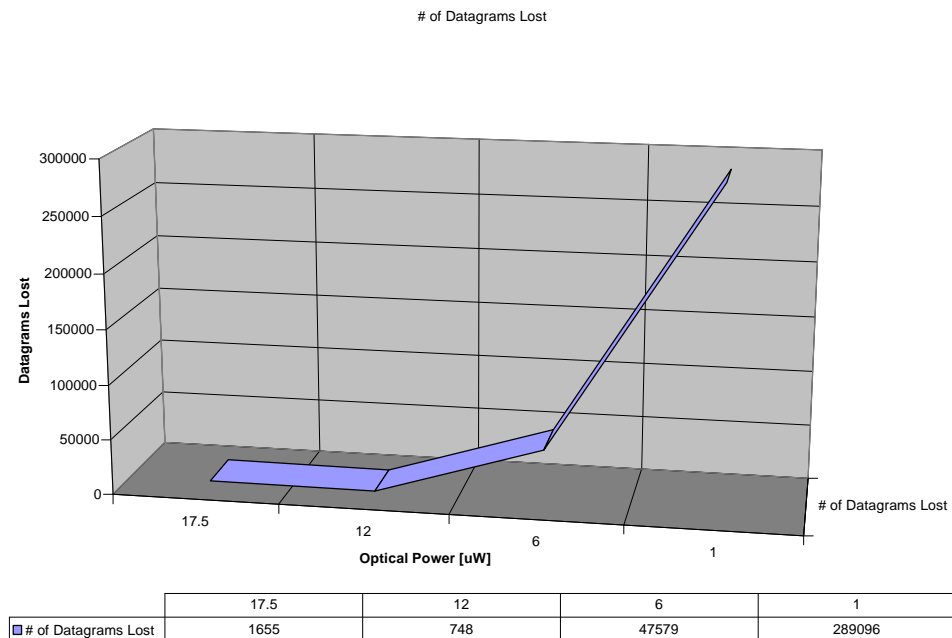
Although Test 3 was initially run only for its throughput values, which in itself showed no significant change and thus no influence of link degradation, a very interesting result came up when the lost data was analyzed and graphed: even though the throughput did not change, the lost data significantly increased as the link was deteriorated. This result shows that even though the throughput was unchanged, the amount of lost data was definitely influenced by the link deterioration.

Both, the percentage of lost data and the total number of datagrams lost over the different attenuation levels are shown in Figures 7.16 and 7.17 respectively.





*Figure 7.16 Percentage of Data Lost in Test 3 for Different Optical Power Levels*



*Figure 7.17 Number of Datagrams Lost in Test 3 for Different Optical Power Levels*

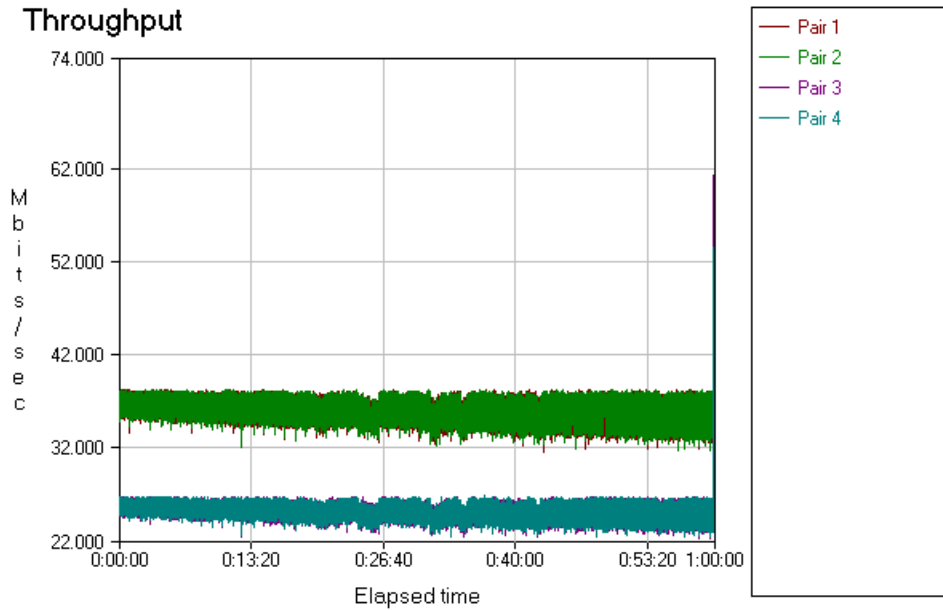
## 7.4. Test 4 Results

Test 4 achieved the highest throughput of all four tests and was run over UDP. However, Test 4 was unique in that some of the runs were not complete and that congestion was so bad that the connections timed out. The selective failures made the results for this test somewhat difficult to fully represent.

### 7.4.1. Test 4 Throughput

Pairs 1 and 2 of Test 4 were running *iptvvstress* scripts and achieved around 36.4 Mbps of average throughput each, and Pairs 3 and 4, which were running *iptvastress* scripts achieved about 25.4 Mbps each, for an overall average throughput of around 123 Mbps.

Figure 7.18 shows the trace for the overall throughput of all four pairs, which were successfully completed over the one-hour test duration. However, as this test was run over the increasingly degraded link there was a point where the test could not successfully finish due to the timeout error. The likely cause for the error (CHR0245), according to Chariot, is that the partner program encountered an error while running a test, but could not report the error on the connection being used for the tests. The most common example occurs if "validate data upon receipt" is specified, which it was for this test, and then the data at Endpoint 2 does not validate correctly during the test.



*Figure 7.18 Throughput of a Successfully Completed Test 4*

Essentially this error can occur when using IPX or UDP protocols. If there is a lot of traffic on the network, datagrams are lost. The endpoints will retransmit, but if things get congested enough to cause the loss of all retransmissions, the endpoints eventually time out. The first such significant error occurred at 9  $\mu$ W optical power level, and the trace of the four pairs is given in Figure 7.19.

In order to ascertain the initial result the same test was repeated at the 9  $\mu$ W level two more times. These traces are presented in Figures 7.20 and 7.21.

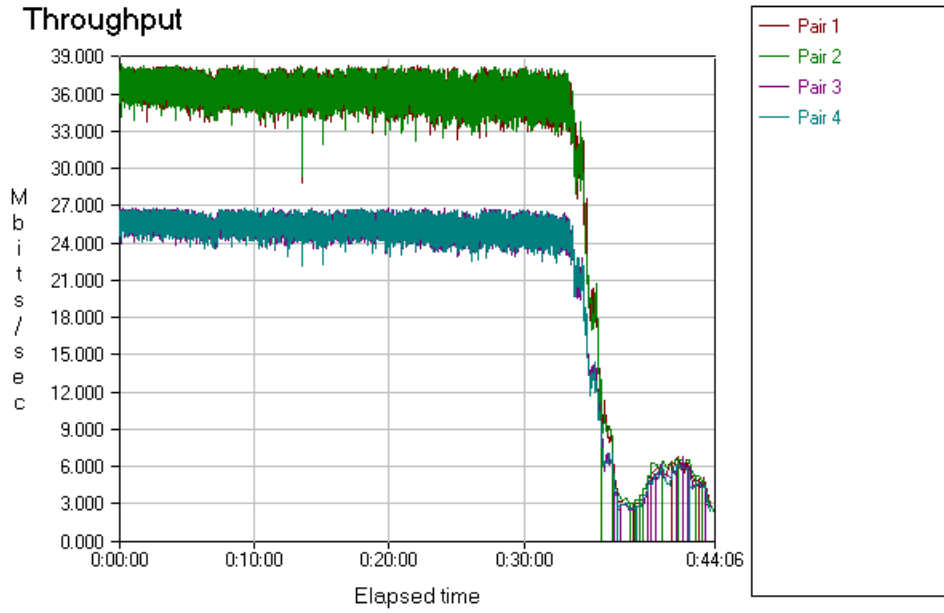


Figure 7.19 Throughput 1 of an Unsuccessfully Completed Test 4 at 9 mW Optical Power Level

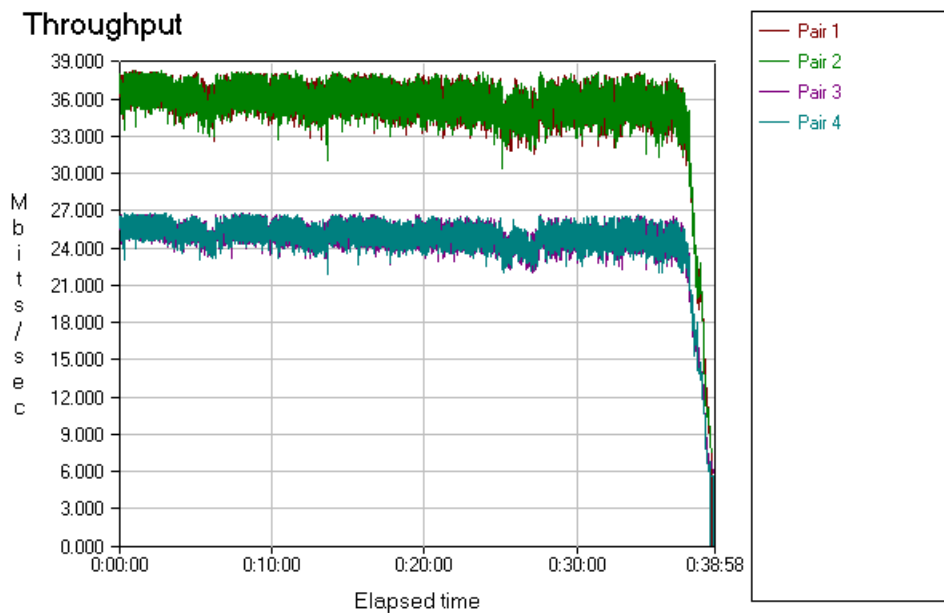
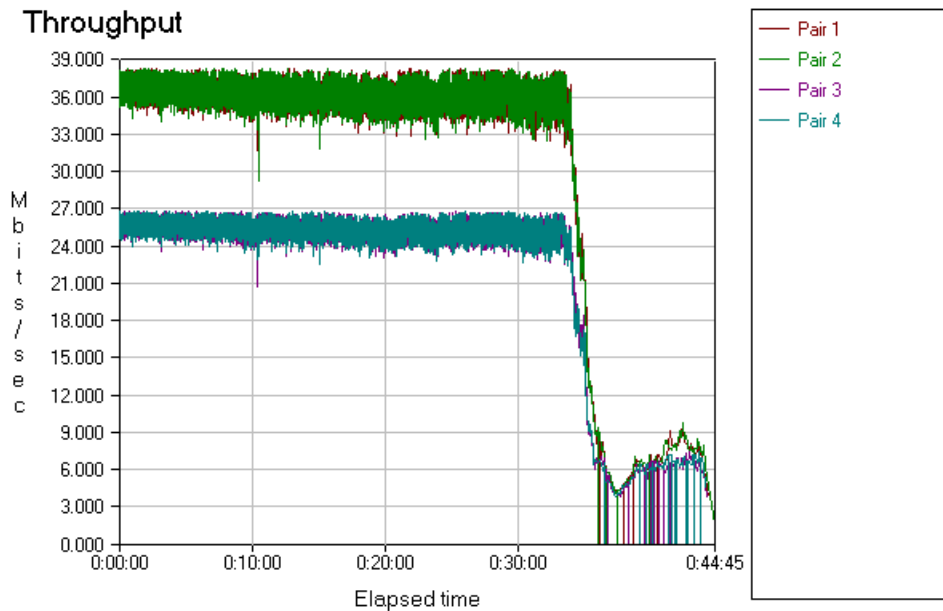


Figure 7.20 Throughput 2 of an Unsuccessfully Completed Test 4 at 9 mW Optical Power Level

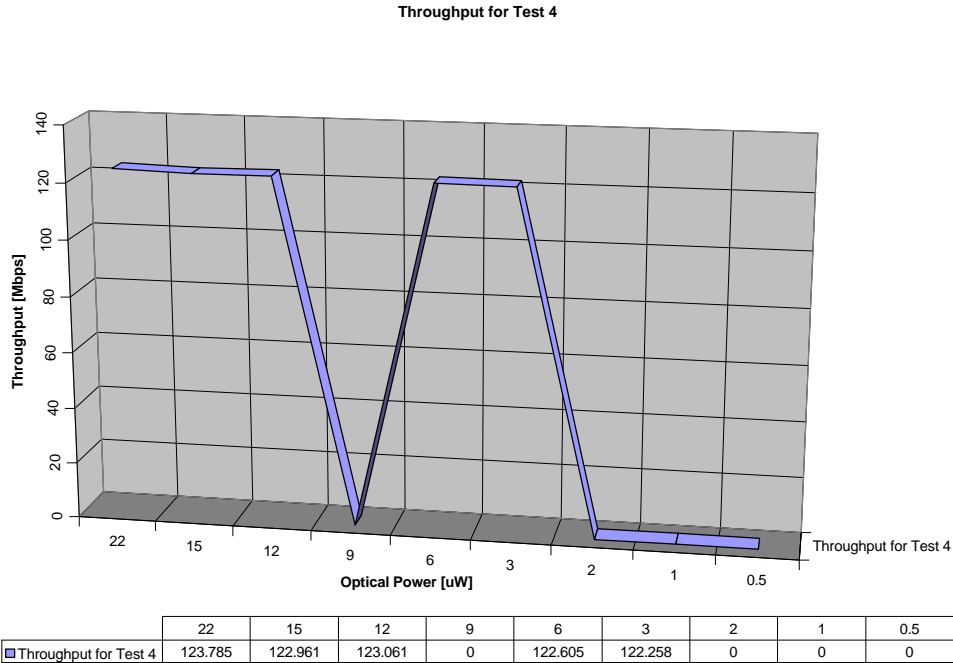
Although Throughput 1 and Throughput 3 are similar in that both were trying to recuperate from the congestion, all three tests experienced a significant decline in throughput around the 38<sup>th</sup> minute into the test.

The graph of all the average values obtained at different optical power levels is presented in Figure 7.22. The unsuccessfully completed runs are labeled as zero throughput, whereas the successful runs display the obtained values.



*Figure 7.21 Throughput 3 of an Unsuccessfully Completed Test 4 at 9 mW Optical Power Level*

One of the difficulties in painting a realistic picture about this test is the fact that not all errored tests failed at the same time. Somewhat strangely, it was the test at 9  $\mu$ W level that failed most quickly. The tests run at levels 2, 1 and 0.5  $\mu$ W completely failed at about the 48<sup>th</sup>, 54<sup>th</sup>, and 58<sup>th</sup> minutes respectively.

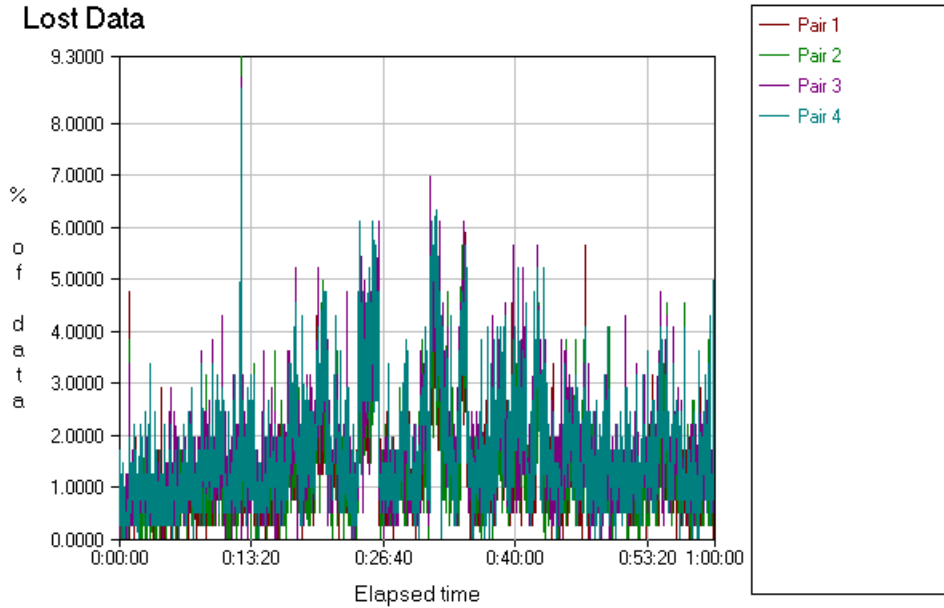


*Figure 7.22 Test 4 Average Throughput for Different Optical Power Levels*

### 7.4.2. Test 4 Lost Data

The trace showing percent of data lost for each individual pair during the one-hour test of a successfully completed Test 4 can be found in Figure 7.23. The graph shows that the amount of lost data is somewhat uniform over the duration of the test, and it mostly stayed under 5 % of total network traffic.

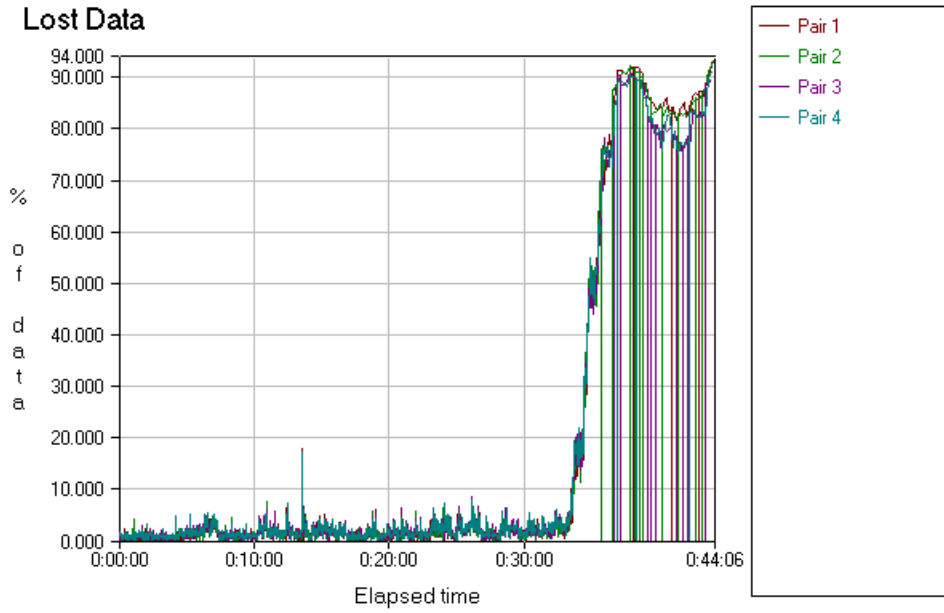
A somewhat unexpected detail is that the Pairs 1 and 2, which achieved higher throughput, had a smaller percentage of data lost than the Pairs 3 and 4, which achieved lower throughput. Pairs 1 and 2 lost about 1.31 % whereas Pairs 3 and 4 lost about 1.65 % of total data.



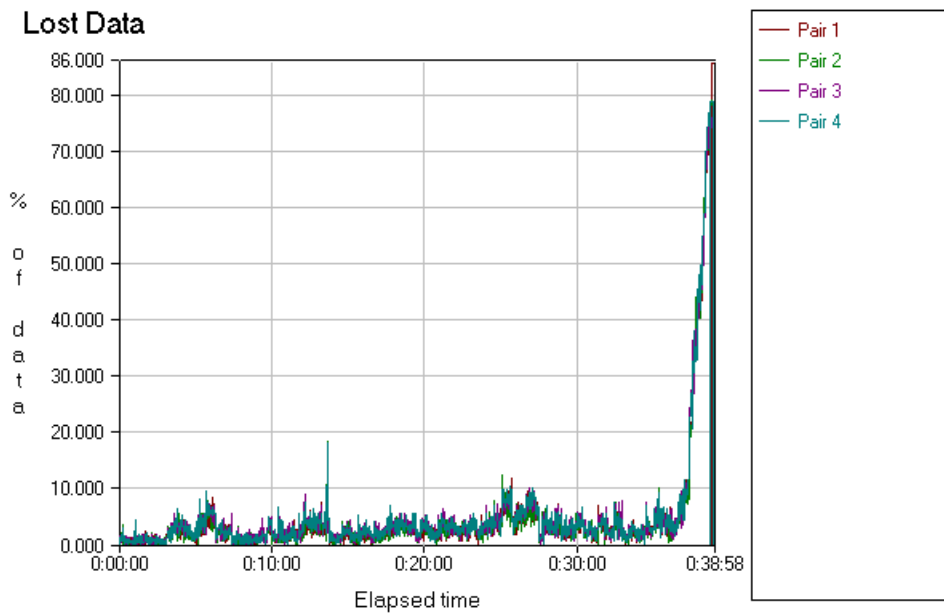
*Figure 7.23 Percentage of Lost Data of a Successfully Completed Test 4*

Figures 7.24, 7.25 and 7.26 show the percentage of lost data for the three failed tests, all at  $9 \mu\text{W}$  of optical power. These three graphs correspond to the throughput graphs of the same unsuccessfully completed tests presented in Figures 7.19, 7.20 and 7.21.

The higher throughput Pairs 1 and 2 of the two unsuccessfully completed tests, which had the “struggling” period of trying to recover from congestion are shown in Figures 7.24 and 7.26. They lost a higher percentage of data than Pairs 1 and 2 of the tests that failed quickly or didn’t fail at all.

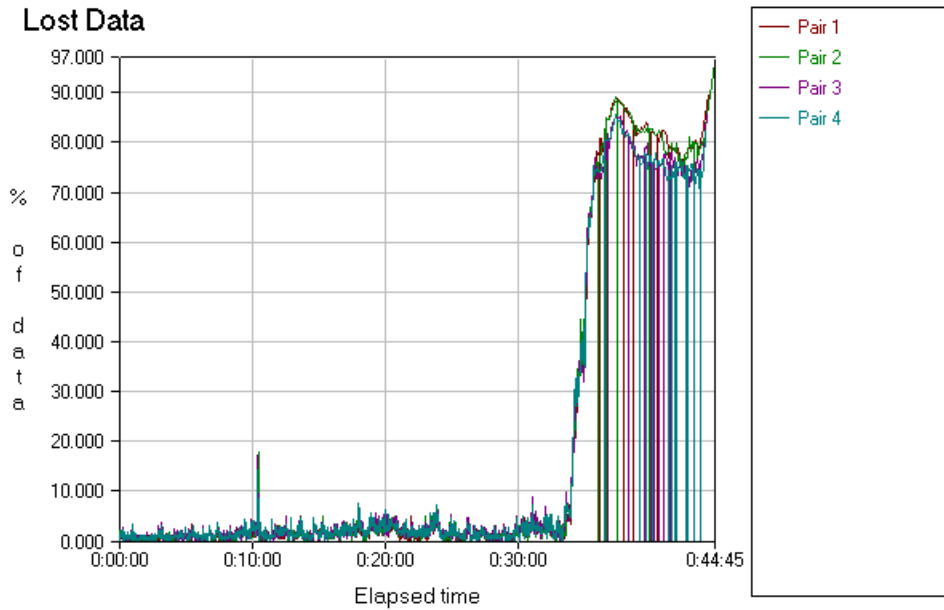


*Figure 7.24 Percentage 1 of Lost Data of an Unsuccessfully Completed Test 4 at 9 mW Optical Power Level*



*Figure 7.25 Percentage 2 of Lost Data of an Unsuccessfully Completed Test 4 at 9 mW Optical Power Level*





*Figure 7.26 Percentage 3 of Lost Data of an Unsuccessfully Completed Test 4 at 9 mW Optical Power Level*

The percentage of data lost in Test 4 over the full range of optical power levels is given in Figure 7.27. The values were collected at the moment the tests either failed or finished, and represent the percent of data lost until those moments occurred.

As evident by the test at optical power level of  $0.5 \mu\text{W}$ , which failed later in the test than the one at optical power level of  $1 \mu\text{W}$ , it is possible to have a lower percentage of data lost even though the total number of datagrams lost is higher. This can be seen by comparing the graph of percentage of data lost shown in Figure 7.27 with the graph showing total number of lost datagrams presented in Figure 7.28.

% of Data Lost for Test 4

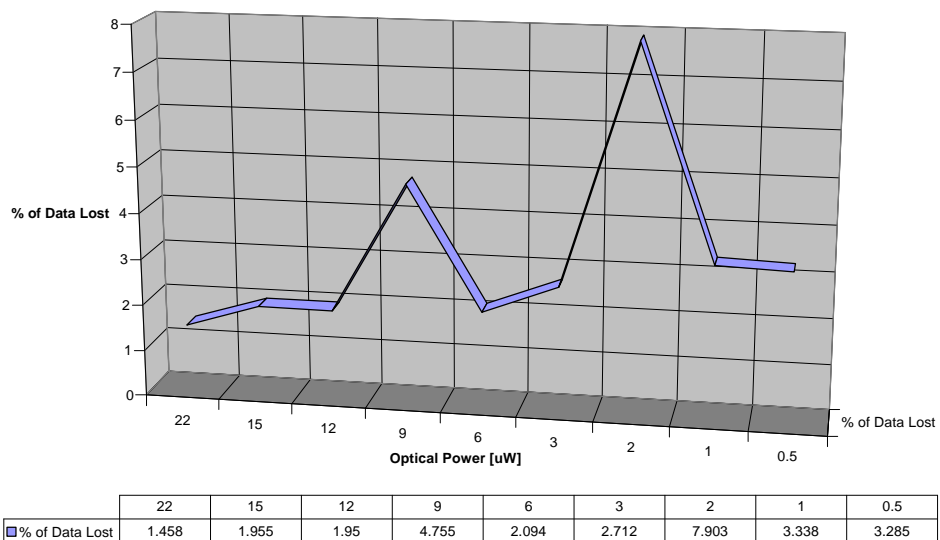


Figure 7.27 Percentage of Data Lost in Test 4 for Different Optical Power Levels

# of Datagrams Lost

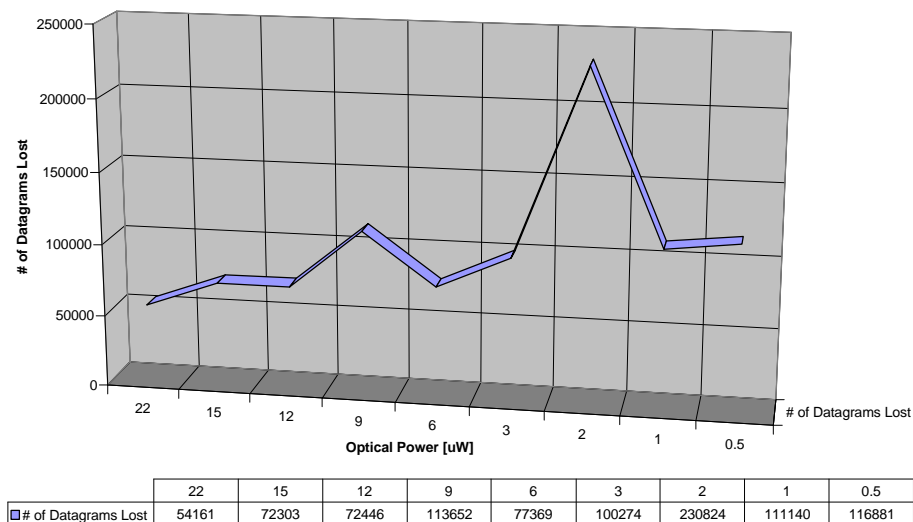


Figure 7.28 Number of Datagrams Lost in Test 4 for Different Optical Power Levels

## 7.5. Link Characterization

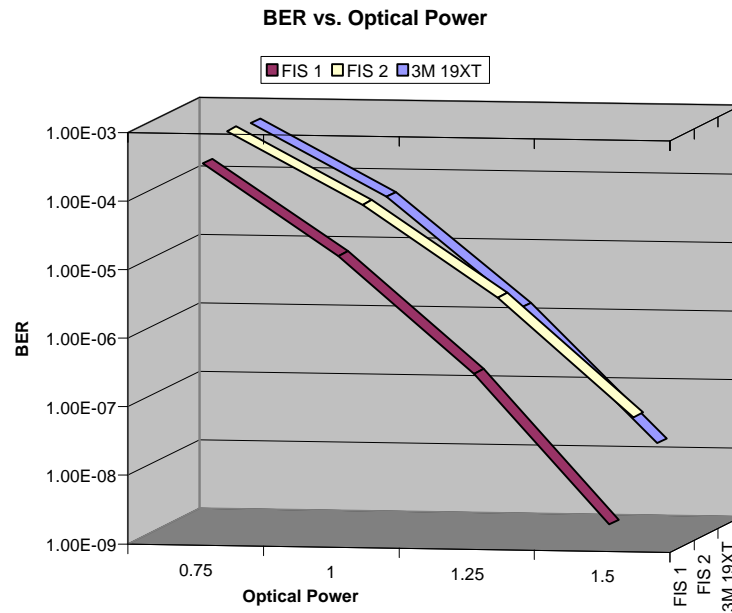
Due to the observation of a nonlinear relationship between the measured performance metrics and power levels, and due to propagation peculiarities associated with short fiber links coupled with the attenuator, which acts as a modal filter, it was deemed valuable to attempt to characterize the two attenuating links used in this research project.

To achieve this characterization a transmitter with an LED at 1300 nm and corresponding receiver circuitry were assembled in the laboratory of FORCE, Inc. However, by using a different transmitter/receiver pair than the one found in the ATM switches used for this research, the obtained BER values must not be assumed representative of the entire system used for network performance testing.

The BER measurements were also done in FORCE, Inc, using their BER testing system. The bit pattern from an HP70841B Pattern Generator was fed into the transmitter, which was then connected to the link with the attenuator. After measuring the optical power coming out of the fiber, the link was connected to the receiver. The signal from the receiver was fed into an HP70842B Error Detector, which was then connected to an HP54120B Digitizing Mainframe Oscilloscope displaying the errors, as well as the eye-pattern diagram.

The signal used for this characterization was a  $2^7-1$  pseudo-random bit sequence over  $10^{10}$  bits. Each run lasted 1 minute and 5 seconds, the time needed for transmitting  $10^{10}$  bits over a link with a bit rate of 155.52 Mbps. The characterization was done on both fiber attenuating links used in this project. Since they were made by/purchased from Fiber Instrument Sales, Inc., each link is labeled in the graph as FIS1 and FIS2. To get a better representation of the way

the attenuation occurs and the way the optical power is removed from a multimode fiber, the same BER tests were repeated with a 3M 19XT multimode attenuator which works by inserting a smoked mirror between the two fiber ends. The obtained results are presented in Figure 7.29.



	0.75	1	1.25	1.5
FIS 1	3.23E-04	1.56E-05	3.21E-07	2.18E-09
FIS 2	6.48E-04	5.87E-05	2.79E-06	5.36E-08
3M 19XT	5.72E-04	5.18E-05	1.34E-06	1.50E-08

*Figure 7.29 BER of the Link over Different Optical Power Levels*

Although the BER tests were performed over the entire range of attenuation levels as used in the research project for performance testing, there were no bit errors in the links for the 65 second duration until the power level dropped to 1.5  $\mu\text{W}$ . At the level below around 0.5  $\mu\text{W}$ , the BER was about 0.5.

This meant that the receiver used for BER testing was not as sensitive as the receivers in the test network's ATM switches.

Nevertheless, the graph in Figure 7.29 shows some surprising results. It can be observed that, even though the tendency of increasing the BER with decreased optical power is the same for all three links tested, they are not the same. The surprising result is that for the same optical power level two different attenuators had different BERs.

This result, coupled with the observation that the two links used for this research had significantly different BER curves, only adds to the initially stated difficulties of defining and quantizing the exact mechanisms at work in multimode fibers.