

Experience with ATM Switch Performance Testing

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Abstract

For users to be able to compare performance of different switches, it is important to have a common set of metrics. Examples of several such metrics and their measurements are presented in this paper. These measurements and metrics have impacted standardization efforts in this area. The key distinguishing feature of our effort is its emphasis on frame-level metrics (rather than cell-level metrics of the past). In particular, in this paper, we present definitions, methodologies, and measured results for frame latency, throughput, and maximum frame burst size (MFBS).

1. Introduction

Asynchronous Transfer Mode provides an elegant solution to the integration of services and allows for high levels of scalability. However, the performance of a given application may vary substantially with the switches used in the network. It is important that there be a standard set of metrics on which different switches can be compared. Without a standard set of definitions, each vendor would use their own definition of common metrics such as throughput and latency resulting in confusion in the market place. Avoiding such confusion will help buyers eventually leading to better sales resulting in the success of the ATM technology.

Therefore, in October 1995, we started an effort at the ATM Forum to develop a standard set of metrics for ATM switches. This paper presents some of the metrics that we proposed as a part of that effort [1, 3, 6]. One goal of this effort was that the metrics should be, as much as possible, representative of real network situations. Also they should be independent of switch architecture. We emphasized frame level metrics, because this level is more likely to influence the application performance. Cell-level metrics do not very often reflect the performance as experienced (or desired) by end users.

For example, a video user sending 30 frames/sec would like frames to be completely delivered every 33 ms and it does not matter whether the cells belonging to a frame arrive back-to-back or regularly spaced. Thus, it is the frame delay and its variation that matters, not cell delay.

A frame is defined here as the ATM Adaptation Layer (AAL) protocol data unit (PDU). One problem in measuring the frame delay in ATM networks is that when seen inside the network, the frames may be discontinuous with numerous gaps between the cells as well as cells of other frames. Note that the monitoring equipment, if placed inside the host, will be affected by the performance of the host and may not accurately reflect the performance of the switch. Thus, the test probes of the monitoring equipment should be placed at the entrance and the exit of the system to be measured, as in Figure 1.

Although we use the term "switch" throughout this paper, the discussion applies equally well to any network element (including switches, routers, multiplexers, inverse-multiplexers, wires, etc) or a network as whole.

In particular in this paper we will present measurement methodologies, results and analysis for frame latency, throughput and maximum frame burst size (MFBS)

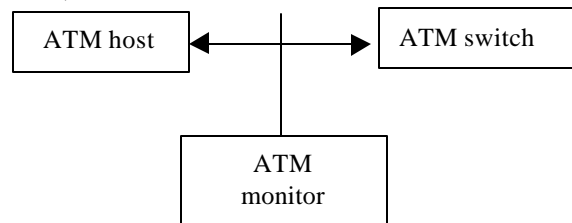


Figure 1. Measurement Point

2. MIMO frame latency

The delay of switch at the cell level is generally measured by FILO (first-bit in to the last-bit out) latency as indicated in Figure 2. Other alternative metrics such as FIFO (first-bit in to the first-bit out), LILO (last-bit in to

the last-bit out), and LIFO (last-bit in to the first-bit out) latencies can be easily obtained from the figure. A complete analysis of these metrics is given in [2, 3] where it is shown that unfortunately none of the four above metrics is appropriate for an ATM network. So LIFO may result in negative values, FIFO does not reflect the expansion and compression of gaps on output, and FILO is strongly influenced by the frame gap pattern. For this reason we have introduced a new metric to measure frame latency, called MIMO (Message In Message Out) [1, 2, 5, 7, 12]. Most ITU documents measure cell level delay using FILO metric. Therefore, we will use FILO for our discussion. FILO frame latency is shown in Figure 3.

Generally, the measured performance of a system depends upon the system as well as the workload. Some metrics are highly workload dependent while others are less dependent. A metric, which depends more on the system and less on the workload, is generally preferred particularly if the users are interested in comparing the systems and not the workloads. It turns out that the FILO frame latency as defined above has the undesirable property that it depends heavily on the workload.

To show the problem in its extreme case, consider the situation in Figure 3, where the two cells of the frame arrive two days apart. The switch delays each cell by 1 ms. But the FILO frame latency is 2 days plus 3 ms. It mostly reflects the arrival gap and is nowhere close to the actual delay introduced by the switch. In order to avoid this inconvenience, we have proposed a new metric called MIMO latency that measures the true contribution of the switch to the frame latency and is not affected by the arrival patterns (gaps) of the cells constituting the frame.

2.1. MIMO Latency Definition

We introduce the concept of an ideal switch that does the best possible processing of its frames. MIMO latency is calculated for any given arrival pattern as the FILO frame latency for the pattern through the ideal switch

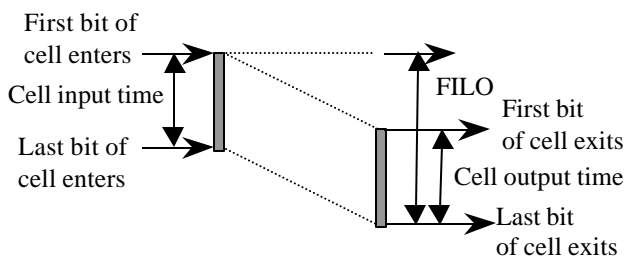


Figure 2. FILO latency at cell level

(FILO₀) subtracted from the measure FILO frame latency of the switch under test gives, i.e.:

$$\text{MIMO latency} = \text{FILO latency} - \text{FILO}_0 \quad (1)$$

For the example shown in Figure 3, FILO₀ is 2 days plus 2 ms and so MIMO latency is 1 ms. Notice that, MIMO latency reflects the switch behavior.

FILO₀ for a given frame is equal to the FILO latency of that frame passing through *an ideal switch*. An ideal switch is defined as a switch that handles incoming frames in such way that they are transmitted on the output link without any unnecessary time consumption, i.e. the best any switch can do. By definition, MIMO latency for an ideal switch is zero. Hence, an ideal switch can also be called a zero-delay switch.

The procedure for FILO₀ calculation is as follows:

- a. Initially FILO₀ = 0 and time t is measured from the arrival of the first bit of the first cell.
- b. For each cell with its first bit arriving at time t, update FILO₀ as follows:

$$\text{FILO}_0 = \max\{t, \text{FILO}_0\} + \max\{\text{CIT}, \text{COT}\}$$

where:

$$\text{CIT} = \text{cell input time} = 424 \text{ bits} / \text{Input Link Rate in bps}$$

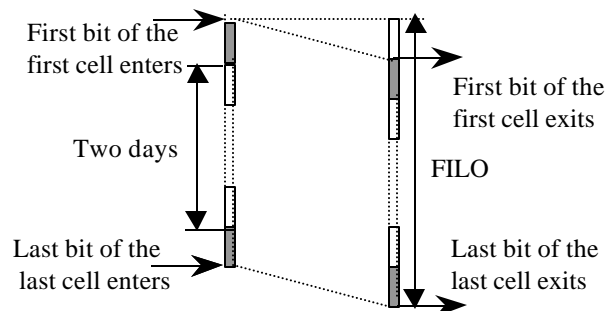
$$\text{COT} = \text{cell output time} = 424 \text{ bits} / \text{Output Link Rate in bps}$$

Note that MIMO latency, as a switch delay metric, accounts only for delays caused by node processing, such as switching, routing and queuing delays, and not by transmission delays introduced by communication links.

2.2. Frame Latency through an Ideal Switch

The concept of ideal switch is explored in this section. In particular it is shown how an ideal switch handles discontinuous frames in an ATM environment.

Figures 4 present two possible cases of a frame



$$\text{FILO} = 2 \text{ days and } 3 \text{ ms} = 172800000 \text{ ms}$$

Figure 3. FILO latency for the switch B that delays each cell by 1 ms

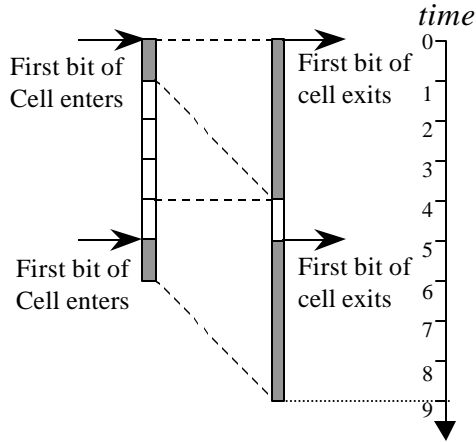


Figure 4a. No-Cell-Waiting Operation of an Ideal Switch for Input Rate > Output Rate

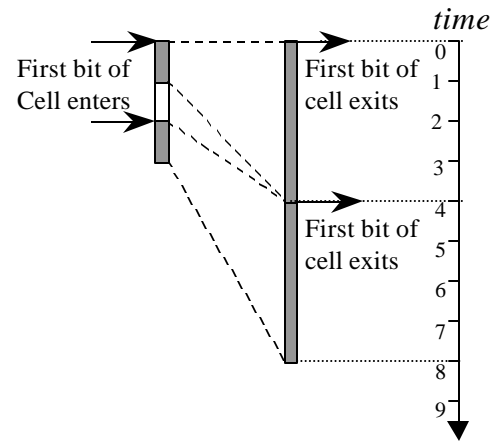


Figure 4b. Cell-Waiting Operation of an Ideal Switch for Input Rate > Output Rate

passing through an ideal switch with the input link rate higher than the output link rate. Figure 4a illustrates the case when cells of a frame do not have to wait. The given frame includes two cells and the input link rate is 4 times the output link rate. The two cells start arriving at time $t = 0$ and $t = 5$, respectively. An ideal switch will start transmitting the first cell at time $t = 0$ and finish at time $t = 4$. The second cell can be transmitted without waiting and the transmission is finished at $t = 9$. This is how long an ideal switch will take to transmit this frame. Hence, FILO latency of an ideal switch for this frame is 9 indicated as $FILO_0$.

Figure 4b shows the another possible case of a frame passing through an ideal switch with an input link rate higher than the output link rate when cells of a frame have to wait. As in Figure 4a, the given frame has two cells and the input link rate is 4 times the output link rate. However, the frame has a different gap pattern. The second cell arrives at time $t = 2$ and thus has to wait. An ideal switch will start transmitting the first cell at time $t = 0$ and finish at time $t = 4$. The second cell transmission starts at $t = 4$ and it is finished at $t = 8$. Hence, FILO latency of an ideal switch for this frame is 8, i.e. $FILO_0 = 8$. Thus, Figures 4 illustrate possibilities that an incoming cell can be transmitted immediately without waiting and that an incoming cell has to wait for previously received cells of the same frame to be transmitted.

In general, for a given discontinuous frame when the input link rate is higher than the output link rate, it is possible that some cells have to wait on previously received cells of the same frame, while some cells can be transmitted without waiting.

Also, notice that ideal switch on output decreases the size of each gap from input, with some gaps being completely removed.

Figure 5 illustrates the only possible case of a frame passing through an ideal switch with an input rate lower

than the output rate. Again, the frame includes two cells but the output link rate is now four times the input link rate. The two cells arrive at time $t = 0$ and $t = 5$, respectively. An ideal switch will start transmitting the first cell at time $t = 3$ (not at $t = 0$, in order to avoid an underrun), and finish at time $t = 4$. The second cell transmission starts at $t = 8$ and finishes at $t = 9$. This is how long an ideal switch will take to transmit this frame. Hence, the FILO latency of an ideal switch for this frame is 9, i.e. $FILO_0 = 9$.

Note that in the cases when the input rate is less than or equal to the output rate, a cell never has to wait for completion of transmissions of previously received cells. The $FILO_0$ in such cases is equal to the frame input time (first-bit-in to the last bit in) and MIMO latency becomes equal to the delay of the last bit of the last cell, i.e. LILO latency. Thus, when input link rate \leq output link rate, we have:

$$\text{MIMO latency} = \text{LILO latency} \quad (2)$$

2.3 Measurement Experiences

In this section we describe several measurements performed in our performance laboratory using a commercial available ATM monitor as a traffic generator as well as a traffic analyzer [4, 5, 8]. This monitor and, as far as we are aware all other similar systems, can provide measurement data on delays and inter-arrival times at the cell level.

The following two relations, which can be easily derived, are used later in this section for MIMO latency calculation:

$$\text{FILO latency} = \text{First cell to last cell inter-arrival time at the output} + \text{First cell transfer delay} \quad (3)$$

$$\text{LILO latency} = \text{Last cell transfer delay} - \text{Cell input time} \quad (4)$$

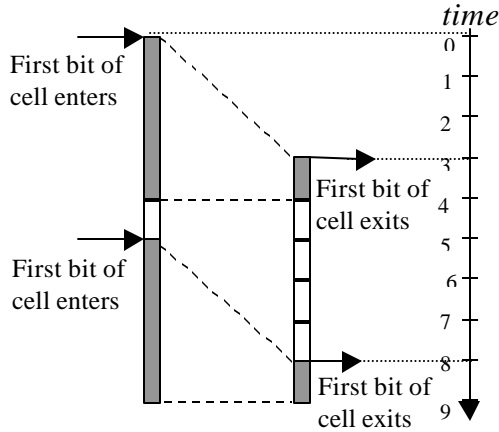


Figure 5. Operations of an Ideal Switch for Input Rate < Output Rate

2.3.1. Tests with Input Rate Higher Than Output Rate.

The test configuration for the MIMO latency measurements for the case with the input link rate higher than the output link rate, shown in Figure 6. It uses a 155 Mbps UTP-5 link between the monitor port 1 and the switch port A1 and a 25 Mbps link between the monitor port 2 and the switch port D1.

In this configurations:

- CIT = 2.83 μ s
- COT = 424[bits] / Output Link Rate = 424[bits] / 25.6 [Mbps] = 16.56 μ s

We performed all our tests with 32-cell frames. One of the measurements used contiguous frames, i.e. cells of the test frame were transmitted back-to-back. In the rest of the tests, we introduce identical gaps (unassigned cells or cells of other frames) between cells of the test frame.

Table 1 presents measurement results for eight test runs, from which MIMO latency is calculated. The first test uses a contiguous test frame on input. All other tests use discontinuous frames on input, with gaps between cells of the test frame, as indicated in the second column.

The third and fourth columns present measurement results for the first cell delay and inter-arrival time between the first and the last cells. The fifth column includes calculated values for $FILO_0$, as explained in Section 2.3, given a frame pattern on input. Here is how we calculate those values. For the first five tests, it can be found that each cell entering an ideal switch has to wait for transmission of the previously received cell to finish. Thus, on output we should have back-to-back cells, i.e. a contiguous frame. Therefore, we can calculate $FILO_0$ for 32-cell frames in all those cases as:

$$FILO_0 = 32 \times COT = 32 \times 16.56 = 530 \mu\text{s}$$

In the last three tests, the gaps on input are large enough that no cells have to wait on a previously received cell. In the case with 5-cell gaps, the first bit of the 32nd (last) cell arrives at an ideal switch at time t , where:

$$t = (CIT + 5\text{-cell gap}) \times 31 = 6 \text{ CIT} \times 31 = 526.4 \mu\text{s}$$

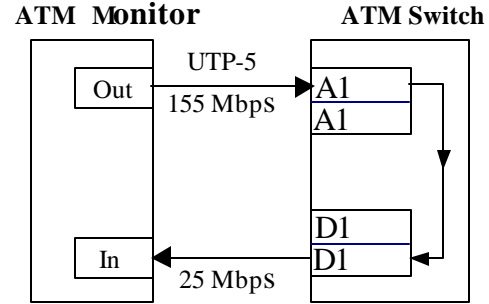


Figure 6. Test configuration for measurements of MIMO latency

and then

$$FILO_0 = t + COT = 526.4 + 16.5 = 542.9$$

Similarly in the cases with 6-cell gaps and 7-cell gaps, $FILO_0$ is calculated as 630.6 μ s and 718.4 μ s, respectively.

The sixth column shows $FILO$ latency calculated, according to the expression (3) as the sum of terms in the third and the fourth column. In the last column, according to the expression (1), MIMO latency values are obtained subtracting terms in the fifth column from terms in sixth column.

Note that the switch latency is higher in the first 5 tests due to cell queuing. In the last three tests, the gap between the cells is large and there is no queuing. MIMO latency clearly reflects this effect.

2.3.2. Tests with Input Link Rate Lower Than Output Link Rate.

We also performed tests using the configuration in Figure 6, but with the traffic flow in the opposite direction as indicated in the figure. Thus, this is the configuration with the input link rate lower than the output link rate. In this case, we have:

- CIT = cell input time = 16.56 μ s
- COT = cell output time = 2.83 μ s

We performed tests with 32-cell frames, with random idle periods between cells. Table 2 includes measurement data from two tests for which MIMO latency is also calculated. Since the input link rate is lower than the output link rate, both the expression (1) and the expression (2) can be used to calculate MIMO latency.

The results in Table 2 show clearly that MIMO latency reflects the switch behavior and is not affected by the arrival pattern. On the other hand, it is shown that $FILO$ latency is strongly affected by the arrival pattern. It can be observed that good agreement of MIMO latency values can be obtained using any of the two expressions for its calculation.

Test No.	Frame Pattern	1 st cell CTD	1 st cell to last cell inter-arrival time	FILO ₀	FILO latency (3)	MIMO Latency (1)
1	No gap	36.8	526.5	530.0	563.3	33.3
2	1-cell gaps	35.8	526.0	530.0	561.8	31.8
3	2-cell gaps	36.8	526.0	530.0	562.8	32.8
4	3-cell gaps	34.8	526.5	530.0	561.3	31.3
5	4-cell gaps	40.8	519.5	530.0	560.3	30.3
6	5-cell gaps	36.8	526.5	542.9	562.8	19.9
7	6-cell gaps	36.8	616.0	630.6	652.8	22.2
8	7-cell gaps	35.3	705.0	718.4	740.3	21.9

Table 1. MIMO measurement results for Input Rate Higher than Output Rate. All times are in ms

Last cell CTD	MIMO latency (2)	1 st cell CTD	1 st cell to last cell inter-arrival time	FILO ₀	FILO Latency	MIMO Latency(1)
32.0	15.44	31.0	535.0	550.0	566.0	16.0
32.5	15.94	33.0	1067.5	1082.6	1100.5	17.9

Table 2. MIMO measurement results for Input Link Rate Lower Than Output Link Rate. All times are in ms

3. Throughput

There are three frame-level throughput metrics that are of interest to a user:

- **Loss-less throughput** - It is the maximum rate at which none of the offered frames is dropped by the SUT.
- **Peak throughput** - It is the maximum rate at which the SUT operates regardless of frames dropped. The maximum rate can actually occur when the loss is not zero.
- **Full-load throughput** - It is the rate at which the SUT operates when the input links are loaded at 100% of their capacity.

A model graph of throughput vs. input rate is shown in Figure 7. Level X defines the loss-less throughput, level Y defines the peak throughput and level Z defines the full-load throughput.

The loss-less throughput is the highest load at which the count of the output frames equals the count of the input frames. The peak throughput is the maximum throughput that can be achieved in spite of the losses. The full-load throughput is the throughput of the system at 100% load on input links. Note that the peak throughput may equal the loss-less throughput in some cases.

Only frames that are received completely without errors are included in frame-level throughput computation. Partial frames and frames with CRC errors are not included.

3.1 Throughput measurement

In throughput measurements, we use an n-to-1 configuration as given in [1, 3, 5, 11], i.e. the case with n traffic sources generating frames through input links to one output link. However, since our monitor has only 4 ports, we are able to perform tests only with the 4-to-1 configuration. We also perform tests with 2-to-1 and 3-to-1 configurations, but the results are similar to those reported here for the 4-to-1 case.

The 4-to-1 configuration for throughput measurements is given in Figure 8. The configuration includes one ATM monitor and one ATM switch with two 155 Mbps UTP-5 links and two 155 Mbps OC-3c links. Four permanent virtual path connections (VPC) are established between the monitor ports. Note that the link between the monitor port 3 and the switch port B1 is used in one direction as the output link and in the another direction as one of the input links.

Four traffic sources generate, over VPC's, fixed length frames (106 cells) at identical rates with equally spaced frames. All frames are generated in simulated AAL 5 format.

A frame in simulated AAL 5 format is transmitted as 106 back-to back cells, with PT field in the ATM header set to 0 in the first 105 cells, while set to 1 in the last cell. Since we are interested not only in frame losses but also in cell losses to compare with, each cell payload includes a 16 bit cell sequence number and 10 bit CRC field. With such cells, undetected cell loss is unlikely.

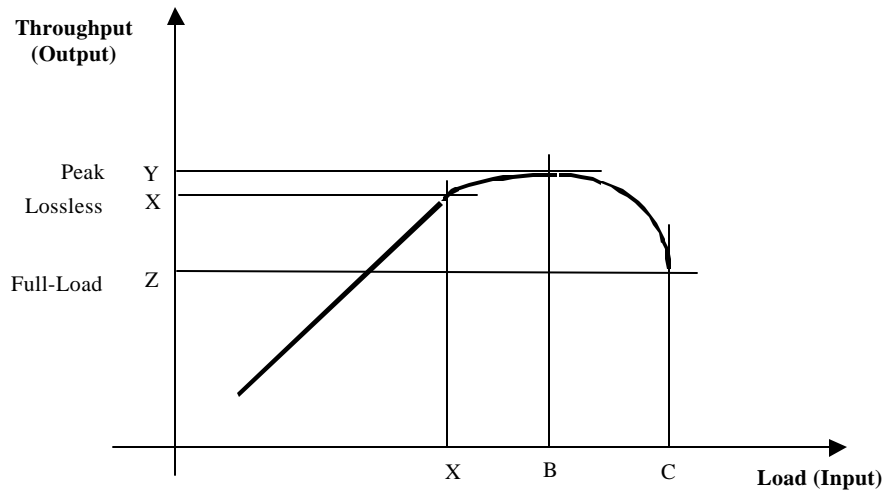


Figure 7. Peak, loss-less and full-load throughput

Metric	Input 1	Input 2	Input 3	Input 4	Mean
Cell Loss Ratio	0.00333	0.00381	0.00387	0.00278	0.00345
Frame Loss Ratio	0.288	0.283	0.204	0.283	0.265

Table 3: Total offered load = 100.32% of output link rate

Metric	Input 1	Input 2	Input 3	Input 4	Mean
Cell Loss Ratio	0.177	0.187	0.157	0.146	0.167
Frame Loss Ratio	0.817	0.784	0.736	0.820	0.789

Table 4. Total offered load = 120% of output link rate

Metric	Input 1	Input 2	Input 3	Input 4	Mean
Cell Loss Ratio	0.742	0.743	0.743	0.744	0.743
Frame Loss Ratio	1.0	1.0	1.0	1.0	1.0

Table 5: Total offered load = 400% of output link rate

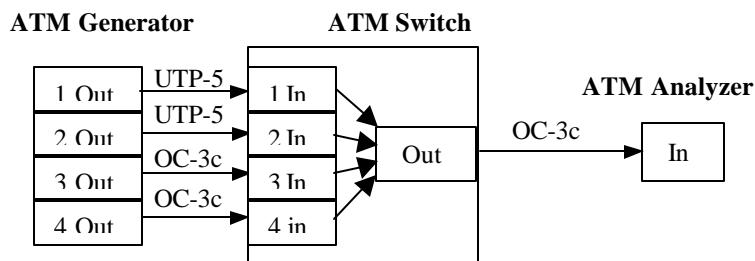


Figure 8: Throughput and MFBS measurement configuration

Changing the frame rate varies the input load. Each test run lasts 180 sec. Our measurements show that as long as the total input load is less than the output link rate, no loss of frames (or cells) is observed. For example, no loss is detected even when the load on each

input line is 24.94% of its rate resulting in a total load of 99.76% (=4x24.94) of the output link rate.

If the total input rate is even slightly higher than the output link rate, the frames are lost at a high rate.

Table 3 presents measurement results for the case when the total load is 100.32% (= 4x25.08%) of the output link rate. Measured results include cell loss ratio and frame loss ratio

From Table 3, it is observed that even with loads just slightly over the output link rate, the cell loss ratio is small but the frame loss ratio is high. The frame loss ratio is two orders of magnitude larger than the cell loss ratio. Note that frame loss rate varies between four traffic sources (within the range 20%-29%) resulting in some unfairness

From Table 4, it is seen that with an offered load of 20% over the output link rate, the frame loss ratio is considerable, and 73% to 82 % of input frames are lost

From Table 5, it is observed that with an offered load 300 % over the output link rate (full load per each input), all input frames are lost.

Although the manufacturer of the ATM switch we tested claims that Early Packet Discard is implemented, our tests did not show any improvements in frame loss rates with EPD on.

In conclusion, for the n-to-1 configurations, the loss less throughput for the switch under test is 155 Mbps (ie equal to the output link rate). Obviously, in this case the loss less throughput equals the peak throughput. Also, from the results presented in Table 5, we have found that for this particular ATM switch, the full load throughput for the n-to-1 configuration does not make sense, because even with EPD turned on practically all the frames are lost.

4. Maximum Frame Burst Size (MFBS)

Maximum Frame Burst Size (MFBS) is the maximum number of frames that each of source end systems can send at the peak rate through a system under test without incurring any loss. MFBS measures the data buffering capability of the SUT and its ability to handle back-to-back frames [1, 3, 10].

Many applications and transport layer protocol drivers often present a burst of frames to AAL for transmission. For such applications, Maximum Frame Burst Size provides a useful indication.

Traffic Configuration	64B frames	1518B frames	9188B frame	64kB frames
2-to-1	434,368 B	434,148 B	431, 836 B	393, 216 B
3-to-1	223, 168 B	223, 146 B	220,512 B	196,608 B
4-to-1	146, 368 B	145,728 B	137, 820 B	132, 072 B

Table 7 MFBS values for the each configuration and frame size.

This metric is particularly relevant to UBR service category since the UBR sources are always allowed to send a burst at peak rate. ABR sources may be throttled down to a lower rate if a switch runs out of buffer.

4.1. MFBS Measurement

Four virtual paths were set up inside the switch, for switching test traffic from four different input ports to a single output port as is shown in Figure 8. Two of the input ports were 155 Mbps UTP ports, the other two were 155 Mbps OC-3 ports. The first UTP port also served as the output port for the tests.

An ATM analyzer was used to generate the four traffic sources. Each source generator produced a burst of back-to-back cells, and was coordinated with the other generators to produce identical bursts starting at the same instant. The size of the bursts was increased until losses were observed.

The maximum sizes of the bursts that could be sent over each link without losses, the Maximum Cell Burst Size (MCBS), are summarized in Table 6. Burst sizes were adjusted with a 100 cell granularity, so the precision is +/- 50 cells. Although we repeated the experiments several times, the results were same. There was no variation.

Traffic Configuration	MCBS (per source)
2-to-1	9,050 cells
3-to-1	4,650 cells
4-to-1	3,050 cells

Table 6. Measured MCBS per source.

The MCBS is the largest length of back-to-back cells that all sources may send simultaneously without loss. The ratio of the measured values is as expected, indicating that the MCBS for all k-to-1 configurations (where k= 2, 3,..) can be predicted from any single MCBS measurement where k is given.

For example, in the 2-to-1 configuration, the results of this test imply the ability of the switch to buffer about 9,050 cells on that output port. That is, during each cell interval of the bursts, one cell can be transmitted by the switch, and one cell must be buffered. In the 3-to-1 configuration, one would expect the MCBS to be one-half of the MCBS from the 2-to-1 configuration. Whereas one cell can still be transmitted by the switch, it must now buffer two cells during each cell interval. Similarly, the 4-to-1 configuration would be expected to have a MCBS one-third of the 2-to-1 MCBS, as the switch must now buffer three cells during each cell interval. So given (measured) MCBS for k, MCBS for j can be calculated as:

$$MCBS_j = MCBS_k * (k-1)/(j-1)$$

The Maximum Frame Burst Size (MFBS) is the number of complete frames of a given size (including the AAL overhead) that can fit within the bounds of the MCBS. It is expressed as a total number of data octets. The MFBS values from this test (assuming no AAL overhead) are summarized in Table 7. Again, MFBS for various values of k and frame sizes can be computed from one test. Therefore, we conclude that it is not necessary to repeat the experiment for various values of k.

5. Conclusions

In this paper we defined the following frame level performance metrics: MIMO frame latency, throughput, and MFBS. MIMO latency, as a switch delay metric, accounts only for delays caused by node processing, and not by transmission delays introduced by communication links.

Three different types of throughputs, namely, lossless, peak, and full-load, were defined. Our measurements show that lossless throughput is very close peak throughput and that full-load throughput is generally close to zero.

MFBS measures the data buffering capability of the switch and its ability to handle back-to-back frames. A number of configurations were tested and it was shown that a 2-to-1 configuration is sufficient to evaluate the MFBS.

Methodologies to measure these metrics have also been developed. The experience presented in this paper has been the basis for our contributions to standardization bodies such as ATM Forum and ANSI [7].

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