Analysis of the Sliding Window Protocol over Multiple Hops for Fault-Tolerant Networks

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Abstract—The Sliding Window Protocol has long been established as an important network protocol in the ISO-OSI protocol stack. However the protocol cannot prevent the possibility of severe network degradation due to link failures. The paper explores a scenario when this might occur and proposes a solution to the problem using existing protocols and techniques. We analyze the behavior of the network at the Data Link Layer and use stochastic process modeling and the theory of blocking networks to identify parts of the protocol that might reduce the probability of backpressure from degrading the performance of the network at one of its lowest layers. Concurrent to the development of the mathematical models, we have created a tool to simulate and test the operation of the Sliding Window Protocol over multiple machines that are sequentially connected. The results we arrived at by using both the formal and empirical approaches are also described.

Index Terms—Fault-tolerant networks, sliding window protocol, multi-hop networks, stochastic process, backpressure, blocking networks, data link layer.

1 INTRODUCTION

The Sliding Window Protocol is an established protocol in the ISO-OSI protocol stack. Although the Selective Repeat Sliding Window Protocol is most commonly used because of its superior network bandwidth utilization and thus operating efficiency, our analysis focuses on the Go Back N version of the protocol. The functions of the data link layer are: providing a well-defined service interface to the network layer, determining how the bits of the physical layer are grouped into frames, dealing with transmission errors, and regulating the flow of frames. If the link between a transmitting node, node P, and a receiving node, node Q, is faulty, that is to say, the link has a low probability of transmission or a high probability of error, then frames sent on the link from the sender window to node Q might not be accepted at the receiving window. In this case, the Sliding Window Protocol will retry the transmission. At the same time, in a linear multi-hop network, node P is receiving frames from some other node, node O, that is eventually destined for node Q. This data might arrive correctly at node P but cannot be transmitted to node Q until all the earlier data frames have been successfully transmitted from node P. The window of the Sliding Window Protocol (henceforth referred to as, window) and the Network Layer buffer (henceforth referred to as, buffer) will eventually become full and no more data will be accepted at node P. Due to Node P being blocked, Node O cannot transmit any data to it and consequently its own buffer and windows begin to fill up. In this manner, backpressure propagates in a direction opposite to the flow of data and can become a severe problem by degrading the performance of the network. It is interesting to note at this juncture that backpressure need not be caused due to congestion or permanent link failures. A faulty link between nodes that has a low probability of successful frame data transmission, a small window size and a small buffer size that can easily fill up are all factors that can begin the phenomenon of backpressure. Therefore, through our study, we attempt to discover the relationships between these factors and their optimal values in different situations that will cause the steady-state probability of the network to be high.

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2 THE MATHEMATICAL MODEL

For the purpose of derivation, let us take the case of one intermediate node between the sender and the receiver. This brings into focus 4 Data Link Layer windows; the single windows (send or receive) at the sender and the destination and the 2 windows for receiving and transmitting frames at the intermediate node. In addition to these, we also bring into consideration the behavior of the network layer's buffer at the intermediate node. Thus in all we analyze 5 Markov chains models and 2 transmission media.

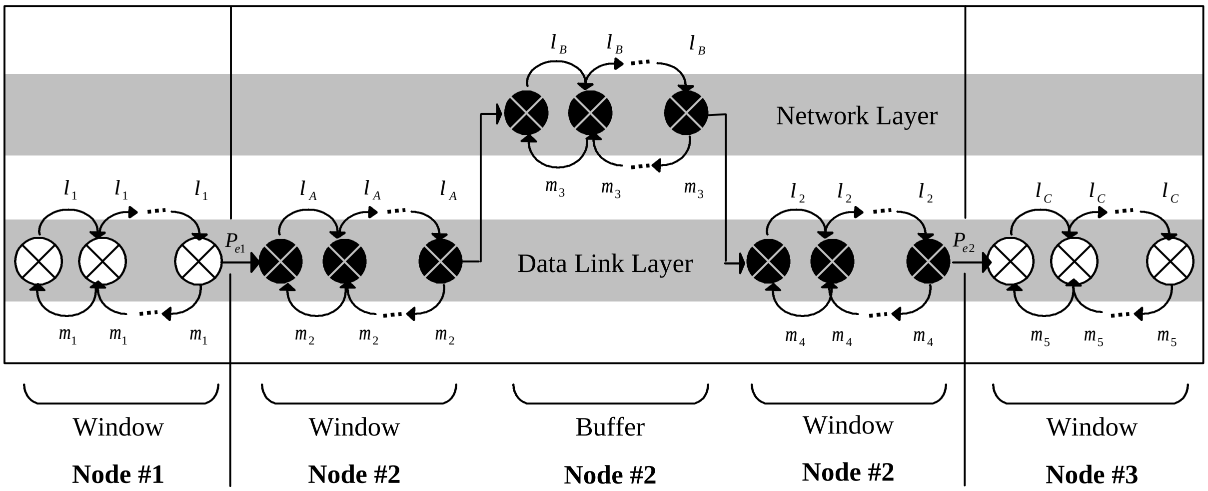

Figure 1: Markov Chain model of transmission of frames and packets over a multi-hop network.

The transitions between the states of a particular Markov chain is a constant l_i or a m_i for the arrival rate or service rate respectively. The number of states in the Markov chains above are assumed to be *W+1* for the Window chains and *B+1* for the Buffer chain, where *W* is the window size of the Sliding Window Protocol in the Data Link Layer and *B* is the Buffer size of the Network Layer's buffer. The probability that a frame is transmitted across a link between the transmitting window and a receiving window is P_{ei} . The states of the Markov chain models in Figure 1 indicate the number of frames or packets sent or received at the layer under consideration.

Let us consider a constant Poisson arrival rate of l_1 at the Data Link Layer of the sender node. Since frames will be received at the receiving window with the probability of successful transmission as P_{e1} , the service rate of the Markov chain model,

$$m_1 = P_{e1} \qquad \textbf{(1.1)}$$

Now let us analyze the receiving window of Node #2.
The arrival rate of frames,

$$l_A = l_1 P_{e1} \qquad \textbf{(1.2)}$$

As soon as the window is full all the frames are passed on to the network buffer. Therefore, the service rate is a constant 1.

The next Markov chain in sequence is the model of the Network Layer's buffer. The buffer has been modeled as an M/M/1 queue system. The transitions in this chain can be assumed to occur in constant time, but only when the window at the Data Link Layer is full and able to send the packets to the Network Layer. This means that once the last state in the Markov Chain of the receiving window is reached, as many packets that can be accommodated in the Network Layer buffer will be taken from the window in a constant time. The only unknown value being the probability that the receiving window is full. We denote this probability at the i^{th} window chain as,

$$P_{wi} = (l_i P_{ei})^W \quad \textbf{(1.3)}$$

where W is the window size, l_i is the arrival rate of frames and P_{ei} is the transmission probability for frames to reach this i^{th} window chain.

Put simply, this implies that the probability of the window being full (or receiving all the transmitted frames correctly), is the product of the probabilities that it went through each state in the chain.

The service of packets at this level is done through the routing algorithm. Let l_2 denote the Poisson service rate of the packets in the Network Layer.
The transitions of the transmitting Sliding Window Protocol model will also be l_2. Therefore, we get,

$$m_3 = l_2 \quad \textbf{(1.4)}$$

The analysis of the remaining chains will be similar to the models obtained from the window of the sender up to the model of the buffer in the network layer.

3 MODELING BACKPRESSURE

In order to successfully model backpressure, we use the theory of blocking networks. If we can identify those states in the above model that are blocking, we should be able to find the probability that blocking occurs. The figure below indicates the blocking states with a filled circle.

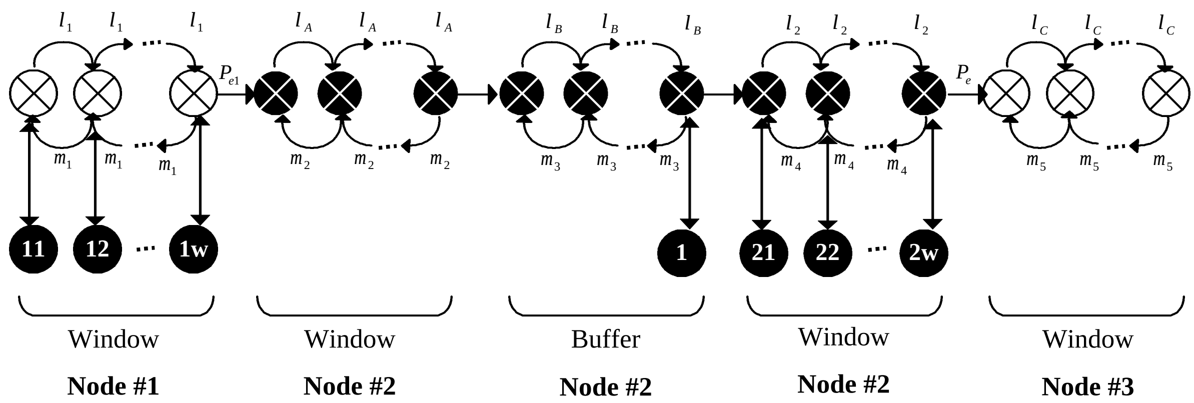

Figure 2: Markov Chain model with blocking states.

Let us analyze the blocking states:

1. The states numbered: *21*, *22* and *2w* will occur in the case of an erroneous transmission between the sending window of Node #2 and the receiving window of Node #3.
2. The state numbered *1* can result from prolonged blocking at the sending window of Node #2 due to some transmission problems so that the Network Layer's buffer fills up with packets from Node #1 and then blocks due to finite storage.
3. The states numbered: *11*, *12* and *1w* will occur for the same reasons that states *21*, *22* and *2w* occur, except that the transmission line in consideration now is that between Node #1 and Node # 2. These states might also occur due to backpressure from Node #2 as a result of the Buffer on Node #2 being blocked.

At this juncture, we would like to point out that the above model can be extended for ‘n’ intermediate nodes. The expressions are always in a generic form and need not be changed. The pattern: send window to receive window to buffer to send window can be assumed to repeat as many times until one reaches the destination.

Thus the states *21*, *22* and *2w* occur for the same reasons that the states *11*, *12* and *1w* occur.
One approach that might have crossed the reader's mind is the existence of another blocking state to denote the blocking of the receiving window on Node #2. This state would be redundant and by considering the receiving node and buffer on Node #2 as one continuous chain, we have captured all possibilities in state *1*.

It is deductive from the model above that the blocking states begin to occur in a direction opposite to the flow of information, resulting in a possibly catastrophic backpressure.
By finding the probability that the network begins this suicidal plunge we can try to find ways of preventing this from happening.

The steady-state probability of the network is denoted as, P_b and is given by the following relation:

$$P_s = \max \left\{ \begin{array}{l} \left[1 - \min(l_1 P_{e1},\ l_2 P_{e2}, \ldots ,\ l_{N-1} P_{eN-1}) \ \right], \\ \prod_{i=1}^{N-1} (P_{Bi} P_{Wi}), \\ \max\left[\max(P_{B1} P_{W1}, 1 - l_1 P_{e1}), \quad \max(P_{B2} P_{W2}, 1 - l_1 P_{e1}), \ldots , \max(P_{BN-1} P_{WN-1}, 1 - l_{N-1} P_{eN-1}) \right] \end{array} \right\}$$

…………………………..**(1.5)**

Here every term has its usual meaning. The probability that the Network Layer buffer is blocked is given by,

$$P_{Bi} = \frac{P_{Wi}}{K} \quad \text{……………………………………………………}\textbf{(1.6)}$$

where K is the ratio of buffer size to window size.
Also, in the above relation for P_b, N indicates the number of nodes in the network including the original sender and the destination.

It is clear that increasing the steady-state probability by varying the parameters of the relation increase the fault tolerance of the network system. Also at this juncture, we would like to emphasize that the above relation has the 3 variables:

1. Buffer size *(B)*
2. Window size *(W)*, and
3. Probability of error in transmission (1- P_{ei}).

4 RESULTS

Some results and observations from the mathematical model are given in this section. The various parameters that were taken into consideration for studying the nature of the model are:

- Window size (W)
- Arrival Rate as a Poisson distribution (l_i)
- Transmission Probabilities (P_{ei})
- Number of nodes (N)
- Buffer Size (B)
- Probability of window being full (P_w)
- Probability of buffer being full (P_b)
- Steady state probability (P_s)

It was observed that as the error probability increases the network degrades faster or steady state probability reduces. Another observation made was that higher the probability that window and buffer get full lesser is the steady-state probability. Additionally it was observed that the buffer and window sizes are inversely proportional to the probability that buffer and window gets full respectively. Figure 3,4,5 show these results graphically.

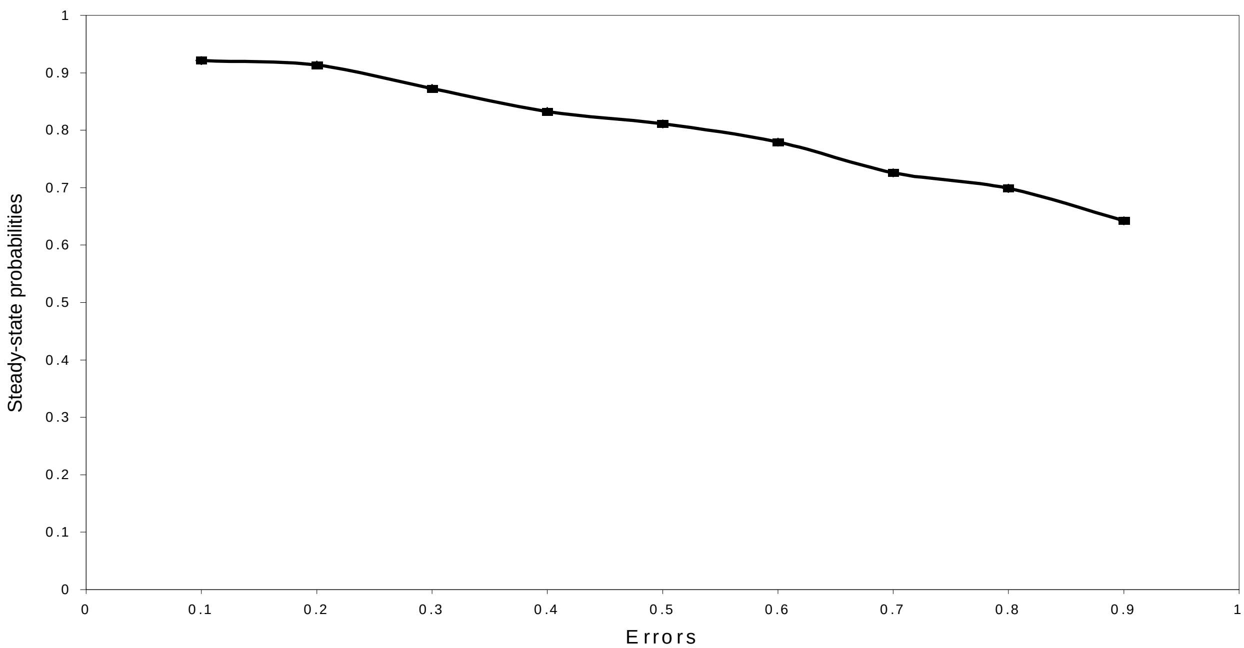

Figure 3: Relationship between probability of error and steady-state probability.

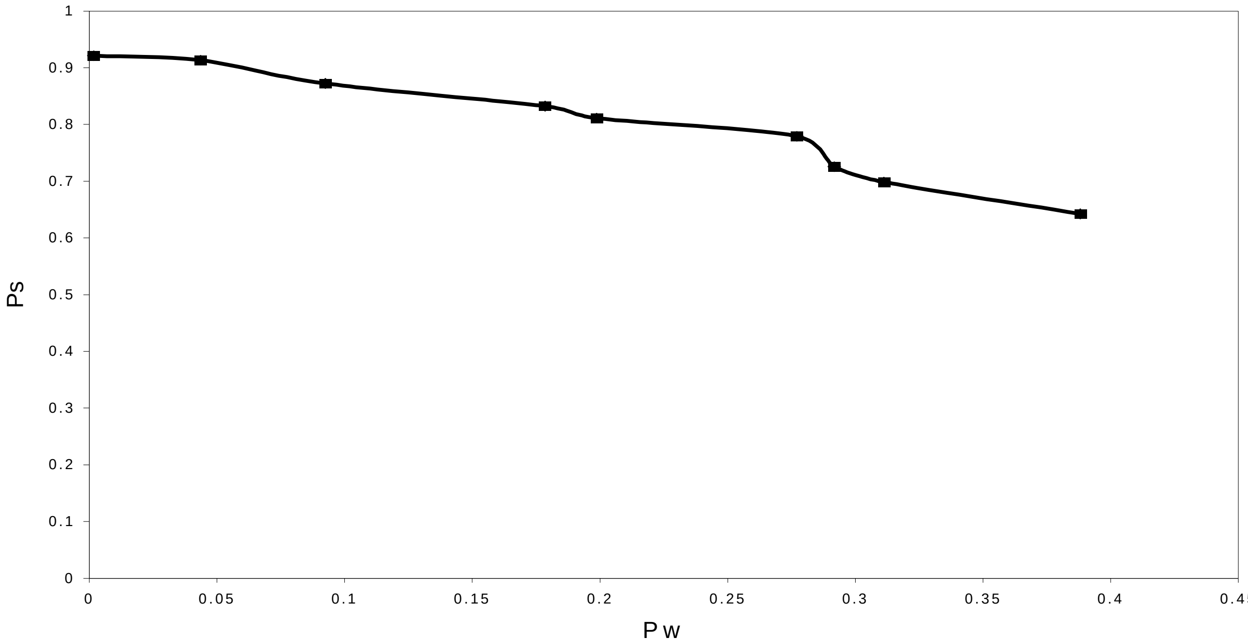

Figure 4: Relationship between the probability of window being full and the steady-state probability.

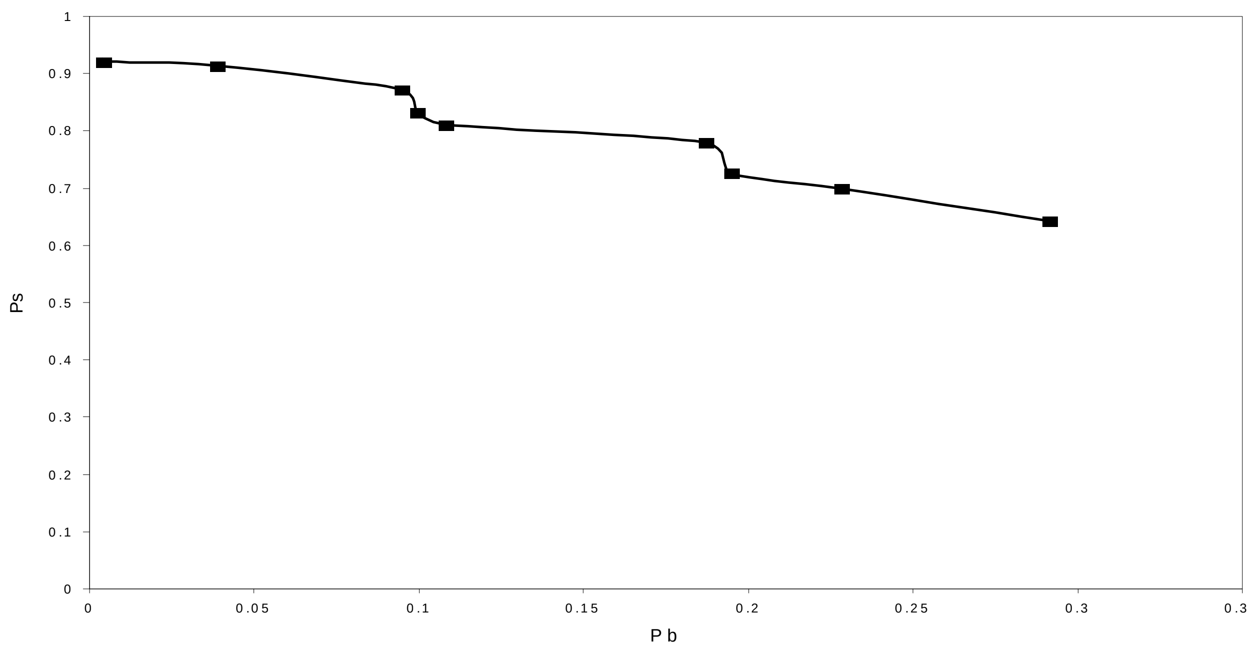

Figure 5: Relationship between the probability that the buffer is full and the steady-state probability.

5 SIMULATION

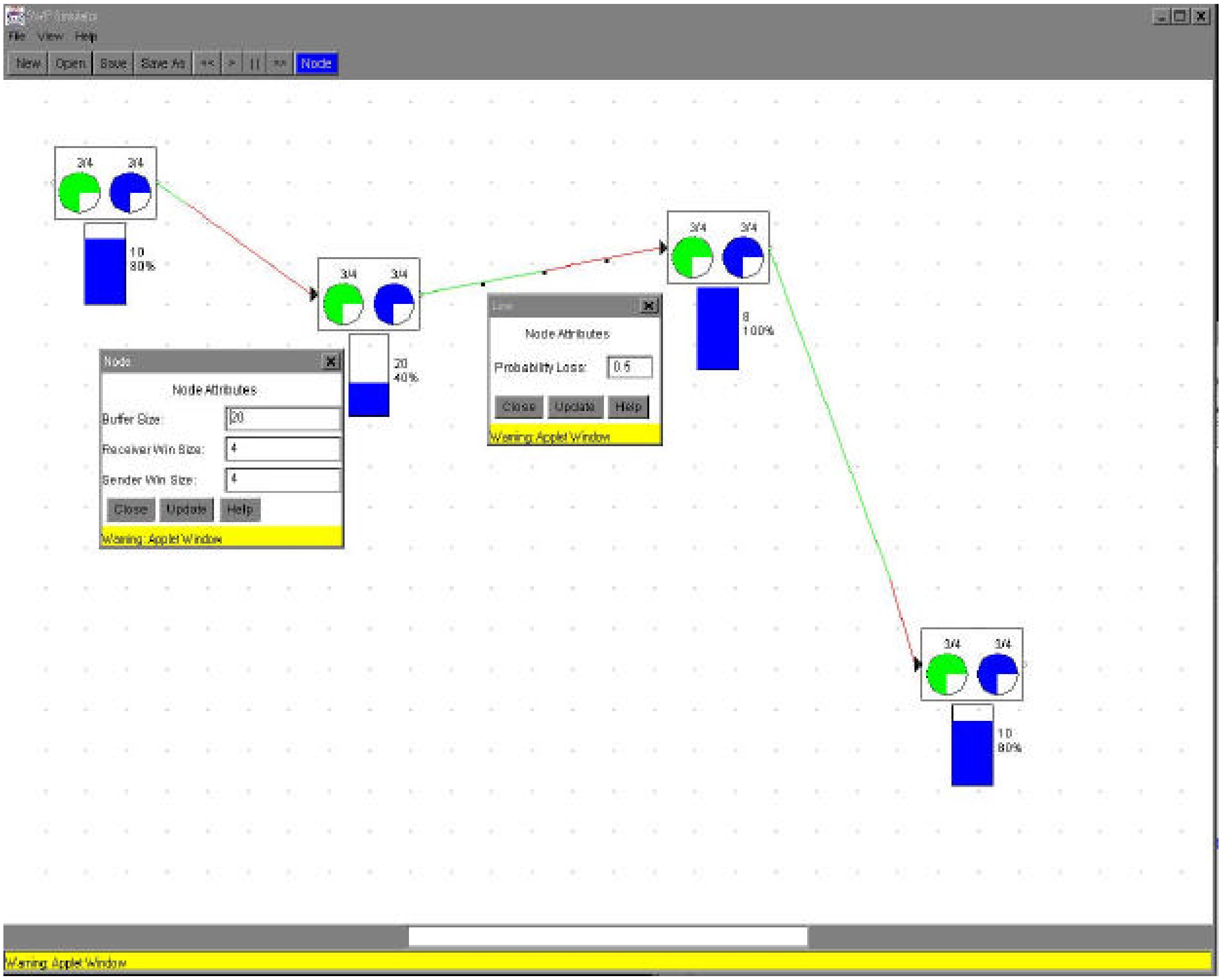

Figure 6: Applet interface to the front-end that simulates the behavior of the network.

The simulation tool can be accessed over the Internet as a Java Applet. The user can interactively create a network and run it to observe Sliding Window Protocol. At run time the user is allowed to modify the various parameters of the node like: Window size, buffer size and line error probability. This is done by double clicking on the node or line whereby a dialog pops-up and allows the parameters to be changed. The snapshot of the simulation above shows 4 nodes that are linearly connected. Each node has a sender and a receiver window. The receiver window is blue and the sender window is green. The line error probability is indicated with red. The network layer's buffer and the percentage of it being full is indicated by the rectangle below the send and receive windows of each node.

6 OBSERVATION FROM MODEL

We maintained the steady state probability of the network (P_s) at the critical value of 0.5. Keeping the Window size (W) constant, we found out the minimum value of the Buffer (B). In another test-run, we kept B constant we found minimum values for W.

P_s	P_e	W	B
0.5	0.1	2	0.4
0.5	0.5	2	2
0.5	0.9	2	3.6
0.5	0.1	4	0.8
0.5	0.5	4	4
0.5	0.9	4	7.2
0.5	0.1	5	1
0.5	0.5	5	5
0.5	0.9	5	9
0.5	0.1	20	4
0.5	0.5	4	4
0.5	0.9	2.22	4
0.5	0.1	40	8
0.5	0.5	8	8
0.5	0.9	4.44	8
0.5	0.1	50	10
0.5	0.5	10	10
0.5	0.9	5.56	10

7 CONCLUSION

We analyzed the effect of Backpressure at the Data Link Layer. The variables involved in the Sliding Window Protocol directly and indirectly can change the way the network behaves over faults. Our Mathematical model enables us to determine the minimum values for the Window and Buffer given an expected steady-state probability and line-error probability. The line-error probability tends to dominate the steady-state behavior of the network more than the Buffer and the Window sizes.

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