On the Characterization, Evaluation and Analysis of Performance of Delay-Tolerant Networks

Deepak N A, Divya Jyothi P, Sahana Bhat, Senduralakshmi P, Sindhura R
Dr. Ananth A G, Shreelakshmi K
Department of Telecommunications & PG Studies,
RV College of Engineering, Bangalore – 59
Karnataka, INDIA.

***Abstract*–The Internet Protocol Suite, although widely used in almost every application is ill-suited for use in communication systems characterized by unpredictable link reliability, intermittent network connectivity, very high round trip times (RTTs) and wide variations in data rates (also asymmetric). Challenges exist in the transfer of data between networks where the availability of an end-to-end path between the source and the destination may be absent. These issues are overcome by the use of Delay-Tolerant Networking (DTN) Architectures and Protocols. This paper presents the performance evaluation and analysis of such networks. The performance of DTN Bundling protocol is measured utilizing a variety of metrics under different network conditions and scenarios, thus providing a comprehensive characterization of such networks.**

***Keywords*–Delay-Tolerant Networks (DTN), Bundling Protocol, Internet Protocol Suite.**

I. INTRODUCTION

The Internet plays a vital role in the interconnection of different communication devices geographically. It does this by using a packet switched service model where the data is sent through standardized network specific layers, so that it can span networks operating on different technologies. The use of Internet service models are governed by the following set of assumptions. Firstly, that a continuous end-to-end link exists between source and the destination nodes, short RTTs between any pair of nodes, low error rates and finally, the availability of reliable links. However, emerging network scenarios pose significant challenges to the above set of assumptions. The use of conventional Internet protocol suite in mobile systems, ad-hoc networks or interplanetary networks is not feasible as such networks are characterized by contacts which can be opportunistic, predictable or in some cases, periodic or scheduled. In satellite networks, the bandwidth is extremely low and the data rates are asymmetric (high uplink rates and low downlink rates). In the above mentioned network scenarios, performance of Internet protocol suite degrades. These issues are overcome by the use of Delay-Tolerant Networks, which make use of a store and forward technique and is an abstraction of Electronic mail. A number of DTN architectures are available [3][5], which facilitate reliable data transfer in extreme communication environments.

II. SIMULATION MODEL

The simulations performed utilize the network topology described in the figure 2.1. This topology is chosen to provide a stable and consistent environment for analysis and evaluation of the DTN Bundling protocol. The simulation model provides support for important DTN functions described in the DTN Bundling protocol specifications [7]. Custody transfer is supported by the simulation model.

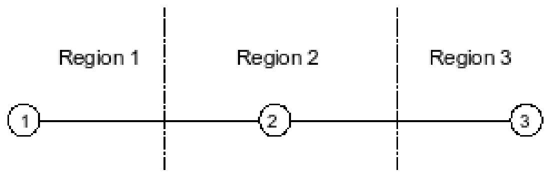

Fig 2.1: Simulation Network Topology.

Performance comparison for a few metrics is made with a similar setup operating on Internet protocol suite of TCP/IP. These basically characterize the performance of DTN Bundling protocol in networks with continuous connectivity. To provide for a fair platform for comparison with TCP networks, continuous connectivity is assumed and all network parameters like link bandwidths, delay, error rates, data transfer rates, topology and traffic loads are modeled on the same lines.

A Network Topology and Dynamics:

The network consists of three nodes and two duplex links between them. The links are of 1Mbps each with a delay of 1ms. Each node has a DTN Agent associated with it which is responsible for addressing, bundle storage, bundle transfers and associated administrative tasks like handling of various status reports.

B Routing Configuration:

The Simulation model uses a wired network setup with a static routing table. Since there are only two links, the performance metrics can be measured with a greater degree of accuracy as the network is unaffected by stray traffic. The routing table has to be updated every time a new route is required so as to notify the agent to keep track of the link usage. Two types of routing decisions are made in this regard. Firstly, to route bundles within the same region, wherein the underlying routing mechanism of the network is used. In the second case, to route a bundle to a different region, the agent finds the best matching link for that destination which is currently available. This is done using the link status information and the specified route metrics.

C Custody Transfer:

Custodial transfer denotes the commitment of a node to retaining a copy of the bundle possibly re-forwarding the bundle when the necessity to do so is determined. This means that the nodes becomes the custodian of the bundles and is responsible for their reliable transfer until the custody is released. When a node accepts custody, it updates the current custodian information and generates an acknowledgment. When a node having requested custody transfer, does not receive an acknowledgment, waits for an amount of time specified by the retransmission timer and then begins the retransmission of the original bundle again.

D Traffic Generation and Data Payload:

The traffic in the simulated network is generated through the use of a constant bit rate generator. The traffic generator generates, constantly, data of size 100 bytes. The data rate is set at 24kbps. This traffic generator is placed at the first node, generating bundles destined for the third node. The second node acts merely as a router with storage capabilities. Each Message Transmission Unit (MTU) is set at 1500 bytes. The bundle retransmission timers are set at 0.5 seconds and the bundle expiration time is set at 300 seconds.

E Status Reports:

The simulation environment provides support for generation of various status reports including: requesting custodial transfer, requesting end-to-end return receipt, requesting bundle reception reporting, requesting bundle forwarding reporting and requesting bundle custody transfer reports. The status reports generate additional overhead on the network as they require additional processing. The priority and expiration times of the bundles carrying the various status reports are set to the same value as that of the bundle for which they were generated.

III. Performance Metrics

Communication Network Metrology forms an important aspect of performance evaluation, analysis and characterization of Delay-Tolerant Networks. The simulations performed generate large trace files, which have to be processed using various data processing techniques to extract useful information and map various performance parameters.

The network measurements can be performed either actively or passively. The network simulation tool does not provide active measurement support, as the nodes are simulated locally (Active measurements can be performed in a real network with the use of ns-2 for traffic insertion and use of the tools emulation capabilities).

Passive techniques however utilize logs and observe traffic flows. In the current scenario, the measurement techniques utilize trace files generated from the simulations. Passive measurements are done at two levels [4]:

i. A microscopic level performed on each packet flowing across a measurement point.
ii. A macroscopic level performed on flows using necessary aggregation rules to match packets to flows. Examples of collected data are the number of flows per unit of time, flow bit rate, etc.

The passive techniques used here are suitable for various metric measurements like traffic measurements, although the amount of data logged can become quite inhibiting when simulations are performed for a long time. The main metrics that are used for performance analysis are Delivery Ratio, Load Handling, Bulk Transfer Capacity, Delay Variation, Link Error Rates and Link Availability.

A Delivery Ratio:

Delivery Ratio is an important metric used to characterize the DTN Bundling Protocol. Delivery Ratio is a measure of the amount of data sent towards the destination to the amount of data received at the destination. However, note that Delivery Ratio only provides a measure of percentage of data that was reliably transmitted and not the measure of the amount of data.

B Delay Variation:

Delay Variation is a key metric which characterizes the suitability of a network for specific applications. The IP Performance Metric Working Group (IPPM)[11] defines the one-way delay for a type-P packet as follows:

Consider two network hosts, SRC and DST. For a real number dT, the "Type-P-One-way-Delay" from SRC to DST at T is dT means that SRC sent the first bit of a Type-P packet to DST at wire-time T and that DST received the last bit of that packet at wire-time T + dT.

C Bulk Transfer Capacity (BTC)[12]:

Bulk Transfer Capacity or Bulk Transport Capacity represents the achievable throughput on an end-to-end path. [12] defines BTC as follows:

Bulk-Transport-Capacity is a measure of a network's ability to transfer significant quantities of data with a single congestion-

aware transport connection. The intuitive definition is the expected long time average data rate of a single ideal implementation over the path in question.

BTC = data_sent/elapsed_time 3.1

IV. LINK ERROR MODELS

Error models simulate link-level errors or loss by either marking the packet's error flag or dumping the packet to a drop target. In simulations, errors can be generated from a simple model such as the packet error rate, or from a more complicated statistical and empirical model. Different Link Error models used in the performance analysis are Uniform, Exponential, HyperExponential, Normal, LogNormal, Weibull, Pareto and Lomax distributions. The use of these distributions is discussed below:

A Uniform Distribution:

Generate '*U*' from *Uniform*(*0, 1*). Then,

$$X = a + U * (b - a) \sim Uniform(a,b) \quad ......4.2$$

is the pseudo-random number from the *Uniform(a, b).*

B Exponential Distribution:

The PDF of Exponential Distribution exceeding a threshold value *'a'* is given by:

$$f(x \mid a,b) = \frac{1}{b}\exp\left(-\left(\frac{x-a}{b}\right)\right), x > a, b > 0 \quad ...4.3$$

For a given '*a*' and '*b*', generate '*U*' from *Uniform*(*0, 1*). Set '*x*' as

$$x = a - b * \ln(U) \quad ....4.4$$

is the pseudo-random number from *Exponential(a, b).*

C Normal & LogNormal Distribution:

Choose *'U_1'* and *'U_2'* from *Uniform*(*0, 1*). Set pseudo-random numbers 'X_1' and 'X_2' as:

$$X_1 = \cos(2\pi\pi_1)\sqrt{-2\ln(U_2)}$$
$$X_2 = \sin(2\pi\pi_1)\sqrt{2\ln(U_2)} \quad ....4.5$$

For LogNormal, generate *'z'* from *Normal(0, 1)*

$$y = z * \sigma + \mu$$
$$x = \exp(y) \quad ....4.6$$

is the pseudo-random number from the LogNormal Distribution.

D Pareto Distribution:

The PDF of Pareto distribution with parameters '*a*' and '*b*' is given by:

$$f(x \mid a,b) = \frac{ba^b}{x^{b+1}}, x \geq a, a > 0, b > 0 \quad ......4.7$$

For a given '*a*' and '*b*', generate '*U*' from *Uniform*(*0, 1*). Set '*x*' as

$$x = \frac{a}{(1-U)(1-b)} \quad ....4.8$$

'*x*' is the pseudo-random number from *Pareto*(*a*, *b*).

E Weibull Distribution:

Let '*Y*' be the standard exponential random variable with PDF given by:

$$f(y) = e^{-y}, y > 0 \quad ....4.9$$

Define *'X'* as:

$$X = bY^{1/c} + m, b > 0, c > 0 \quad ....4.10$$

where *'X'* is the Weibull Distribution with shape parameter *'c'*, scale parameter *'b'* and location parameter *'m'*.

Its PDF is given by:

$$f(x \mid b,c,m) = \frac{c}{b}\left(\frac{x-m}{b}\right)^{c-1}\exp\left\{-\left[\frac{x-m}{b}\right]^c\right\},$$
$$x > m, b > 0, c > 0 \quad .....4.11$$

For a given *'m', 'b'* and *'c'*, generate *'U'* from *Uniform*(*0, 1*),

$$x = m + b(-\ln(1-U)) * (1/c) \quad ....4.12$$

is the pseudo-random number from *Weibull*(*b*, *c*, *m*).

V. SIMULATION RESULTS

This section presents the simulation results for different metrics. The delivery ratio behavior of DTN and TCP networks with varying link error models is discussed here. The results are as shown in figures 4.1 to 4.7. For all simulations, the MTU of the network is 1500 bytes and each bundle carries a payload of 100 bytes. The data load is set to 24 kilobytes per second. In each simulation run, the error rates of the corresponding error models are varied in increments of 10% from no error to an error rate of 90%.

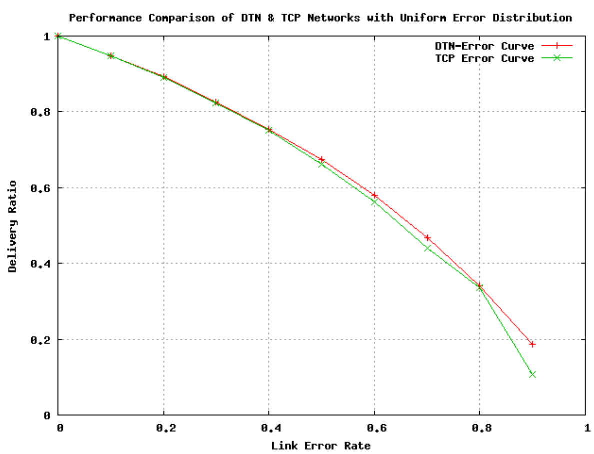

Fig 4.1: Delivery Ratio vs Link Error Rates (Uniform Distribution)

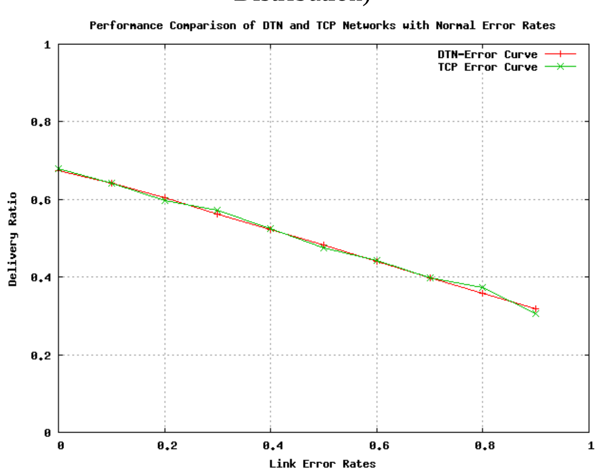

Fig 4.2: Delivery Ratio vs Link Error Rates (Normal Distribution)

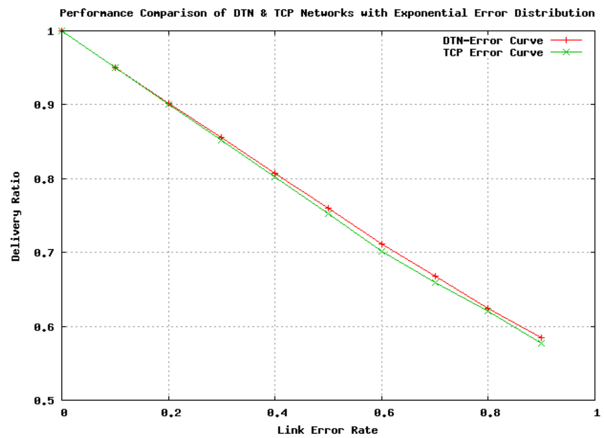

Fig 4.3: Delivery Ratio vs Link Error Rates (Exponential Distribution)

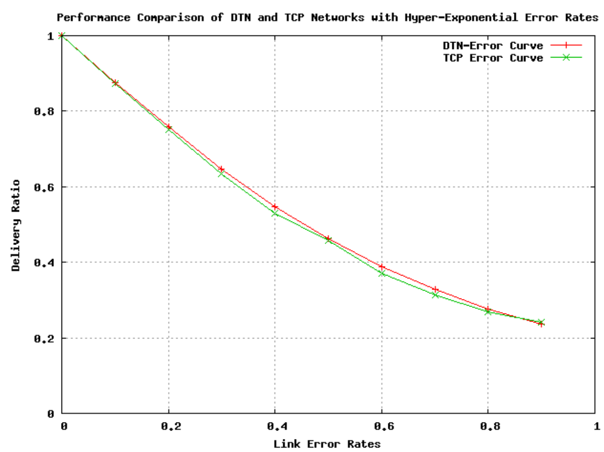

Fig 4.4: Delivery Ratio vs Link Error Rates (HyperExponential Distribution)

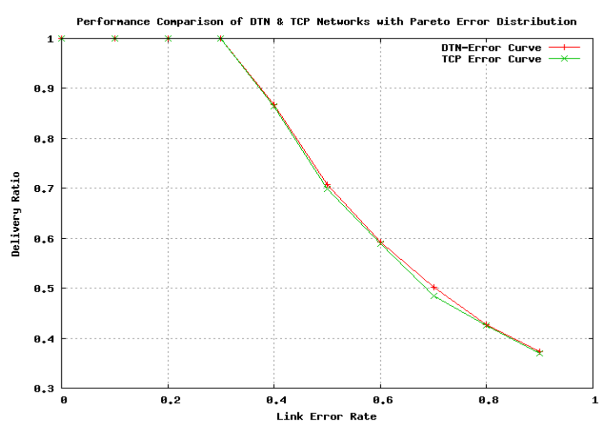

Fig 4.5: Delivery Ratio vs Link Error Rates (Pareto Distribution)

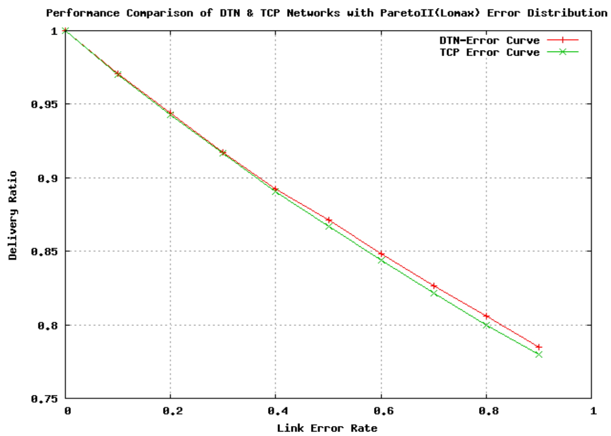

Fig 4.6: Delivery Ratio vs Link Error Rates (Lomax Distribution)

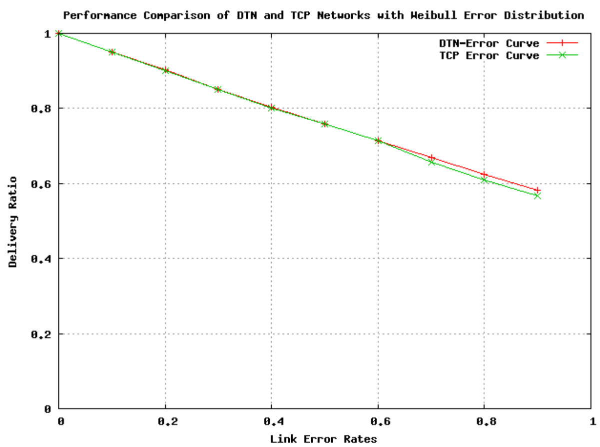

Fig 4.7: Delivery Ratio vs Link Error Rates (Weibull Distribution)

Figure 4.8 presents a comparison of Delivery Ratios of DTN and TCP networks for a *two-state* error model. Figure 4.9 shows the comparison of Delivery Ratios of DTN and TCP networks for a *multi-state* error model. In the case of *two-state* error model, two different state error models are considered and state transition between the two states is decided by two different and independent timing parameters.

The multi-*state* error model is similar to the two-*state* error model, but with multiple states and multiple transitions decided by various independent timing parameters. The multi-state error models implement time-based error state transitions. Transitions to the next error state occur at the end of the duration of the current state. The next error state is then selected using the transition state matrix. A *multi-state* error model with the following parameters is used in the simulation. The model consists of three states, with the following state transition matrix:

State_Transition_Matrix = {{0.9 0.1 0.0} {0.05 0.9 0.05} {0.05 0.15 0.8}} 4.13

The state transition type being *packet*, and the start state referenced by state 1.

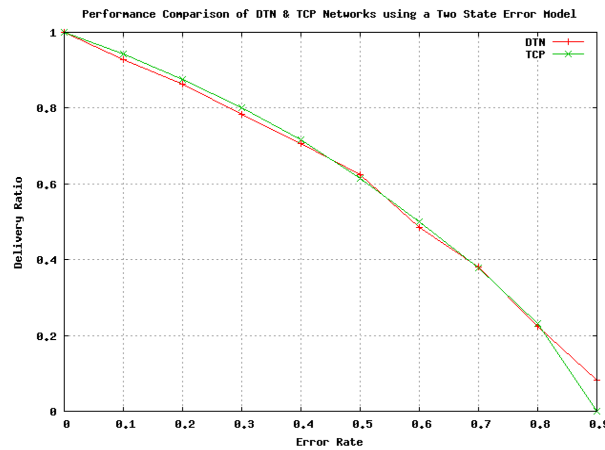

Fig 4.8: Delivery Ratio vs Link Error Rates for a Two-State Error Model

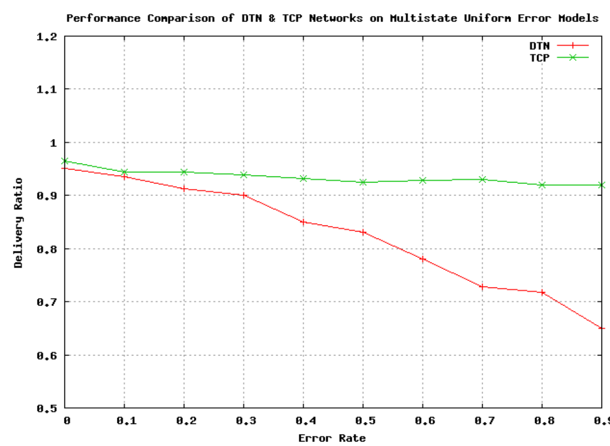

Fig 4.9: Delivery Ratio vs Link Error Rates for a Multi-State Error Model

The figure 4.10 shows a plot of Bulk Transfer Capacity vs. Link Error rates. The measurements are performed for a simulation time of 10,000 seconds. An interesting characteristic of DTN Bundling Protocol is seen here. The data transfer rate of the traffic source (Constant Bit-Rate Generator) is set at 8 times the data load of 3000 bytes, i.e. a data rate of 24kbps. This is reflected in the figure 4.10 when there is no error in the network. As the link error rate increases, the ability of the DTN Bundling Protocol to transmit data also increases. The data transfer rate increases to slightly more than double the initial transfer rate of 24kbps to about 49.8kbps. Thus the DTN Bundling Protocol is sending bundles to reach the destination reliably by utilizing an increase in data transfer rate to compensate for the increasing link error rates.

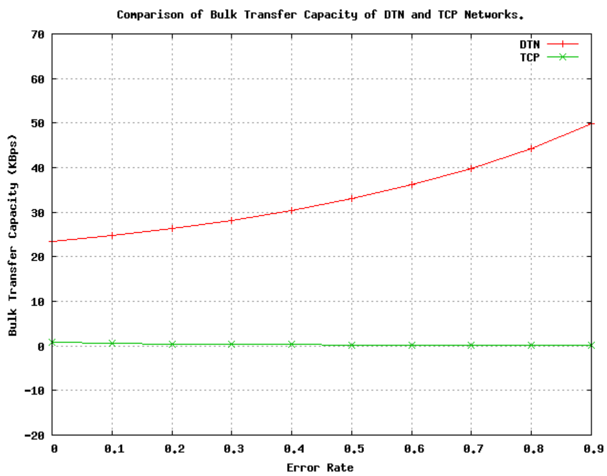

Fig 4.10: BTC vs Link Error Rates

The figure 4.11 represents a plot of Delivery Ratio vs Link Availability. Both plots are obtained with the custody transfer enabled. Two Link failure models are used to control the availability of the links. Also the failures are introduced in the second link in the three node network, so as to observe the effects of custodial transfer in the network. The two link failure models are exponential model and deterministic model.

The exponential on/off model takes four parameters: [start time], up interval, down interval, [finish time]. Start time is set to 0.0s, i.e. the start of the simulation, finish time defaults to the end of the simulation. Up interval and down interval specify the mean of the exponential distribution defining the time that the node or link will be up and down respectively.

The simulations are run for 400 seconds each. Delivery Ratio is computed from the trace files and plotted against a varying link availability (10% to 100% availability). It is to be noted that when simulation is run incorporating a deterministic link failure model, the delivery ratio is 100% and is independent of the induced link failures. However, with the use of an exponential link failure model, delivery ratio decreases with increasing link failures.

The Figures 4.12 and 4.13 present the load handling capability in DTN and TCP networks. The simulations are performed for 10,000 seconds. In both cases, DTN Networks display an important characteristic of being capable of transmitting significantly more data than TCP networks.

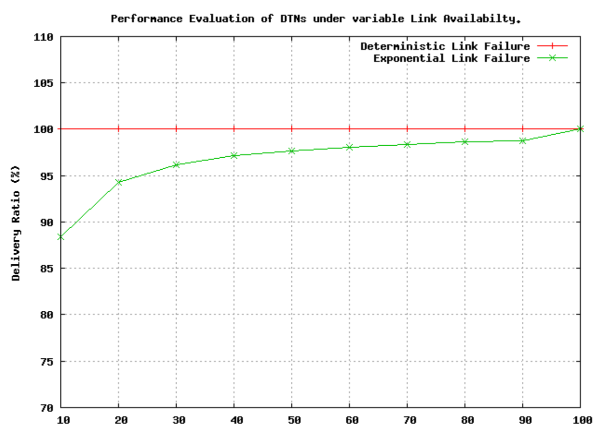

Fig 4.11: Delivery Ratio vs Link Availability

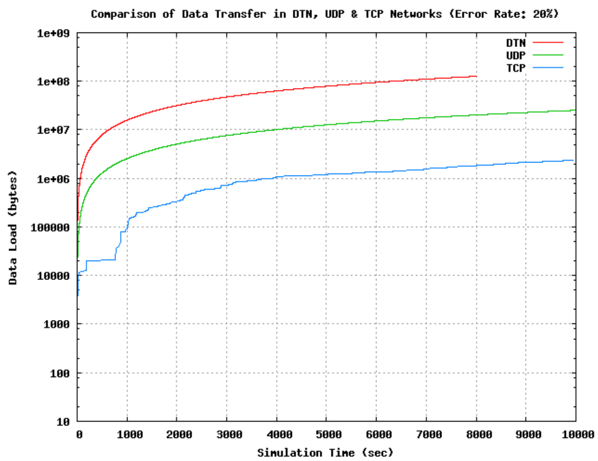

Fig 4.12: Load Handling

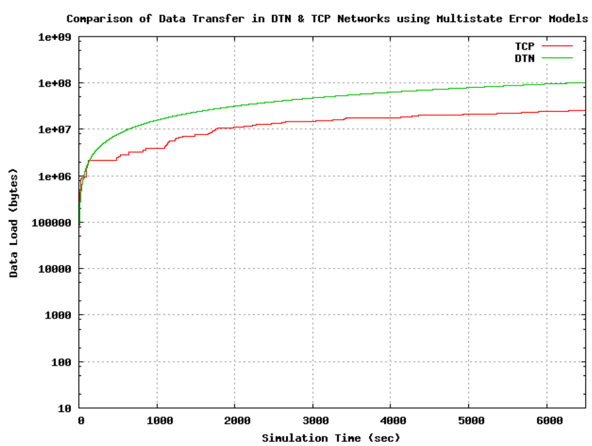

Fig 4.13: Load Handling (Multi-State Model)

VI. Conclusions

This paper presents the performance of DTN networks. Two significant results regarding BTC and load handling were obtained from the simulations. From figure 4.10 we see that DTN Bundling Protocol performs significantly better than TCP networks. As the error rates increase, there is an increase in the transmission rate in the case of DTN Bundling Protocol. Subsequently, the Bulk Transfer Capacity also increases. In the case of Delivery Ratio, both networks have similar performance, but note that delivery ratio is only a measure of the percentage of data reliably reaching the destination and not the amount of data. It was observed that for a given simulation time, DTN Bundling Protocol was able to transmit more data than TCP. This is further made clear by observing the DTN Bundling Protocol Load Handling shown in figures 4.12 and 4.13.

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