Modeling TCP throughput on Ad hoc Wireless Networks

Jaiwant Virk
{Jaiwant@ieee.org}
Dec 2002

***Abstract**: Many different models of TCP have been proposed over wired links but not much effort has been put into mathematical modeling of flow control behavior of TCP in the mobile Ad hoc networks. TCP has serious drawbacks in a wireless link due to its non differentiating nature of packets lost due to congestion or transmission loss. I have tried to model this behavior of regular TCP throughput with respect to loss rate and window size.*

1. **Introduction**

Ad hoc networks are rapidly deployable multi hop networks that route through each other to reach a destination. Communication is relayed in chains of router nodes when the nodes are not in direct connection with each other. All nodes are assumed to route the packets for the peers. The routes are in constant flux due to change of topology inducing a change in route reconstruction.

Most Ad hoc nodes may face a number of constraints ranging from the common shared bandwidth to power, high BER and security.

WLAN networks may operate in Access point mode and Independent Infrastructure mode. The Latter will be of interest to us for the simulation part..

Independent Mode is a peer-to-peer setup for communication, using other nodes to find a path to the destination using some specific routing protocols and then maintaining the connection.

TCP Congestion control behavior uses AIMD [9], linear additive increase and exponential decrease in the window size or the number of packets sent based on the loss of packets lost due to congestion on the link.

However wireless scenario has a lot of medium specific problems. The packets may be lost due to a variety of reasons like congestion at the router node, transmission loss due to path loss, mobility of nodes. These may lead to high BER, change in topology, rerouting and delay associated with it. Another problem may be Power Consumption due to retransmission. As we would see later that power control is an important factor in general in the Ad Hoc networks which has led to development of power aware protocols like PAMAS[10], [11].

The method of congestion detection is when the sender receives Triple duplicate ACK and Time out notification. Depending on these the Congestion window is increased or decreased. Moreover on a time out the window size goes into an exponential back-off.

This is a serious drawback in the wireless networks. Unless there is a mechanism [13] such as ECN [12] or RED to distinguish between congestion loss and transmission loss the exponential back-off creates extra delay.

2. **Previous Work**

From Previous research its been proven that TCP performs quite badly in Wireless networks for a variety of reasons. Most of the TCP wireless models and protocols for improvements have been suggested for Cellular networks or wireless networks with access point mode. These studies have led to the development of Split Connection, End-to-End, Link Level Notification and Explicit Congestion Notification.
Some of the Protocols that may be relevant in the Pure Ad Hoc scenario worth noting Are:
Split connection – Split Connection is relevant only in Overlay or Cellular Networks involving two different versions running on the wired and the wireless part of the network. Some of them are MTCP, ITCP, and M-TCP [12].

End-to-End – In this approach the sender and receiver adapt to the packet loss. Some of the solutions are Selective ACK [3], Fast Retransmit, and TCP-New Reno [6] and ATCP[16].

Link Level Retransmission – These Protocols implement their own link level retransmission techniques at the wireless links in addition to the TCP retransmission. Snoop Protocol [7], TCP –Aware, Delayed Duplicate ACK [8] fall under this category.

Explicit Notification –ECN, TCP-F explicitly notify the cause of the loss to the sender.
As far as Modeling is concerned the most notable one are [1] and [2]. There have been numerous ways to model the TCP behavior based on different distribution method or analysis notably the Markov analysis and Queuing theory.

3. **Model**

For the modeling the assumption is of a single sender to destination over an Ad hoc network. The Path taken by the packets may include multiple hops over similar nodes with a fixed processing speed. It's also assumed that during the relay, the SIR remains the same for all the nodes and all paths. It's not a simple assumption to make but to formulate the model these variables have to be constant to reduce the complexity.

T

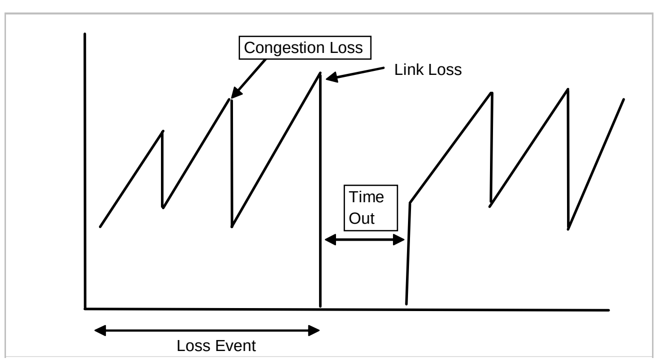

Figure 1: Window Size adjustment over time

As stated earlier the packet loss may occur due to the congestion or a link loss. The loss process is modeled as an occurrence between two timeout outs. The loss notification events arrive as a Poisson distribution. The time out is not included in the throughput calculation as there is no transmission during that period and therefore would not contribute towards it, although the average throughput over a period of time must include time out.

In general, in Ad hoc wireless networks it is observed that

Throughput= f (Loss rate, No. of hops, Window size, Packet Size, Power, mobility)

Loss rate = *f* (Loss on congestion, transmission loss)

Window Size =*f* (RTT)

RTT =*f* (No. of hops)

A Simple Model: This approach is based on the throughput formula developed by [4]

This model bases that throughput is dependent on the of probability of packet loss

$R= (1/RTT)* (1.22/\sqrt{P})$

Where P is the loss probability of the packet and RTT is the return Trip Time.

Since Probability of loosing a packet

$$P (L) = P (A_k) + P (B_k)$$

Where A_k and B_k are losses due to Congestion and Transmission respectively

Therefore substituting

$$R= (1/RTT)* (1.22/\sqrt{(P(Ak)+P(Bk)})$$

Since there in no way for the sender to know or judge the exact probability of any of these events we can perhaps assign them some weights given by ữ based on the condition of the network.

$$R= (1/RTT)* (1.22/\sqrt{(\tilde{ư}P (Ak) + (1-\tilde{ư}) P (Bk))} \qquad \text{.....(1)}$$

Fixed point model: In this Model the packet loss is seen in terms of network side view , i.e. packet loss notification arrivals are studied instead of giving a probability of loss to each packet sent out[1]. Packets arrive as a Poisson stream to the sender, and accordingly the window size is adjusted.

These loss are bundled together as a loss cycle L_k separated by a Time Out.. TO is not included I the equation as the each TO may mean node out of range (assuming the randomacity of the network. Or it also may mean that there is no routing node in between. So a time out is connection out when no packets are sent out assuming there is no buffering of packets or delayed ACK mechanism.

Slow start may be done away in modeling as the aim of the model is to Emulate the Throughput at any particular time, whereas the Slow start returns back to normal linear increase after a few RTTs.

The window size of the transmission depends on the reception of the ACK from the previous packet (there may be a case where there may be a single ACK for more than 1 packets[3]). The Window size of W_{n+1} depends on the W_n depending on the ACK arrival time i.e. RTT [4].

The Window size Increases linearly and Decreases multiplicatively (AIMD) [5]. The equation developed here will be formed on the basis of this principle.

Before Calculating Approximate Window Size we discussed the type of window size losses in the wireless domain.. As stated earlier the loss event consists of both type of losses at different times.
The Fixed Model is based on the coupling nature of the throughput and loss rate.
R =f (Congestion loss, Transmission loss)
C = f (R)
R is the throughput, C is the Congestion or general loss rate .

The Window size equation as in [1] ,except the TO part of the equation which is not being considered here is

$$W_{n+1}(t)= 1/T – 0.5(W_n) dNtd$$

Where Wn_{+1} is the current window size ,
T = Number of packets sent between the
Wn = Window size before arrival of losses and
dt/T indicates the additive increase and the second part is the multiplicative decrease when an Error ACK like a triple duplicate ACK is received at time *t.*
On the basis of above equation a Modified differential equation can be formed as follows

$$dW= dt/RTT – \alpha W * L_{AK} + \beta W * L_{BK} \quad .....(2)$$

Where α is the decrease rate of the window, which is normally 0.5,
And β is some constant rate which may be assigned to the transmission loss arrival.
By choice the value of β can range from 1 to -1, so there's a choice in change of window size. L_{AK} and L_{BK} are the rate of arrival of losses due to Congestion and Transmission respectively.

Taking expectation of both sides

$$E[dW] = E[dt/RTT] – E [\alpha W * L_{AK}] + E[\beta W * L_{BK}]$$
$$dE[W]/dt = 1/RTT – \alpha L_{AK} E[W] + \beta L_{BK} E[W]$$
$$E[W](t) = 1/RTT – (\alpha L_{AK} + \beta L_{BK})E[W]$$
$$E[W] = (1/RTT) / (\alpha L_{AK} + \beta L_{BK}) + Ce^{-(\alpha LAK + \beta BAK)}$$

For a steady State (t → ∞)

$$R = 1/RTT^2 * 1/ (\alpha L_{AK} + \beta L_{BK}) \quad .....(3)$$

The throughput R is described in terms of Loss rate and RTT here. Therefore the equation is a fixed point solution of throughput and loss rate which depend on each other.

Effect of Mobility, Number of hops and Power on throughput

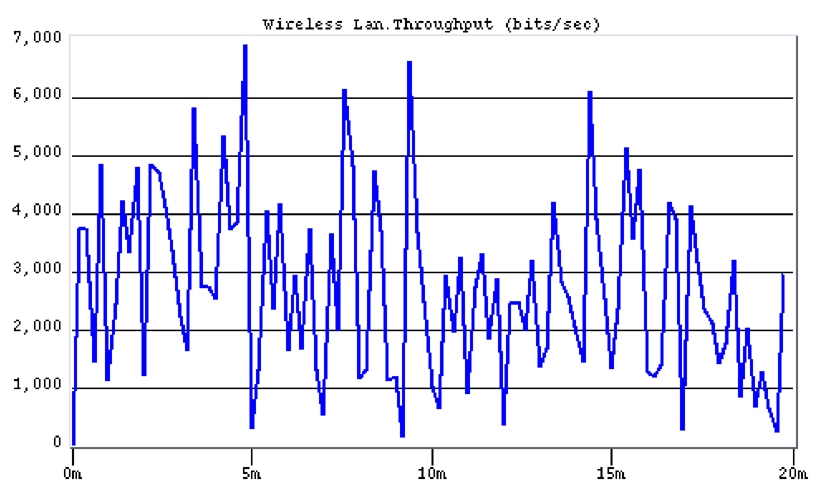

Figure 2. Effect of Mobility on throughput , when the two nodes are moving in a random manner.

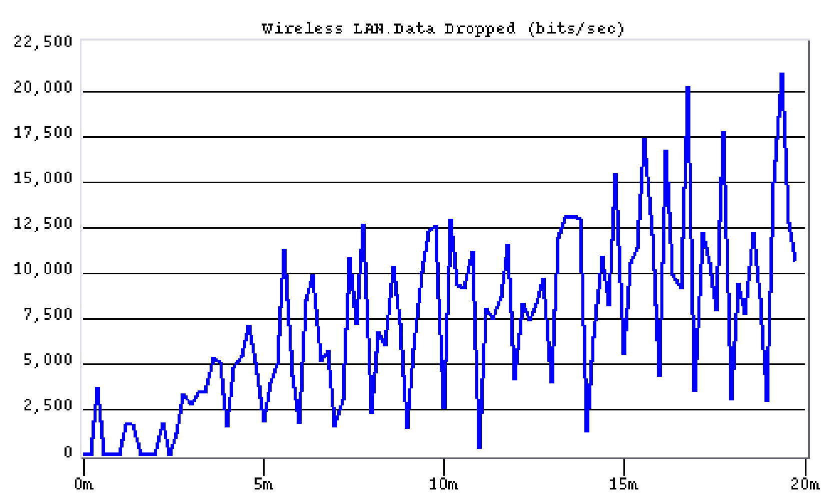

Figure 3. Increase in Delay induced by the mobility of the nodes.

A Simulation of the Mobility and its effect on throughput is shown in Figure 2. The increase in mobility gradually decreases the throughput of the connection as we see that the Random movement of the Nodes is visible in the spikes and then a downward movement as the distance between nodes increases. The delay caused due to the increased mobility and rerouting rises sharply over time as seen in figure 3. The number of hops in the connection also decreases the throughput exponentially as seen in figure 4. The largest drop seems to at the second hop and then it levels off. This could be explained on the concept of pipelining which is explained in detail in [15].

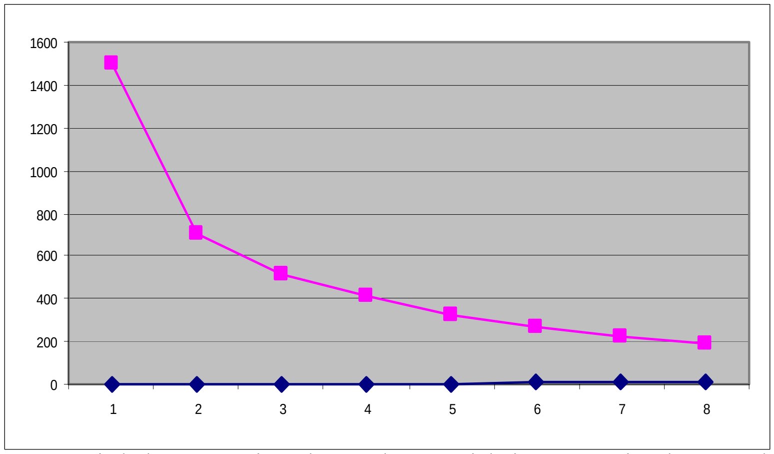

Figure 4. Exponential decrease in Throughput with increase in the number of hops

The power constraint is one of the biggest challenges facing the mobile ad hoc's(MANET) . As stated earlier the power efficient MAC layer protocols are being developed to overcome this constraint. Retransmission can consume a lot of power

4. Approximate Model:

From the above graphs its clear that mobility and hop counts are important in shaping the throughput.. Th following is a model which considers the throughput in terms of Mobility and Hop counts .

The Approximate model proposes a formula for the calculation or prediction of the throughput given the parameters .

$R \propto 1/$ mobility, $1/$ number of hops

Modifying the equation (3)

$$R = 1/RTT^2 * 1/(\alpha L_{AK} + \beta L_{BK}) * 1/M * 1/H$$

Where M= mobility constant
H= number of hops

The H (hop information can be extracted from the routing layer, which most routing protocols in Ad Hoc networks may carry.

The mobility constant can be derived from some careful simulations based on different configurations and network conditions.

This approximate model can used to predict the throughput in the MANET scenario given the appropriate parameters. This model is not a full representation of the idea but a general observation which can be refined by some simulations.

5. **ECN Model**

Early Congestion Notification can be an effective tool to differentiate the loss type[13]. This solves a big problem facing the wireless networks. The formulated equation (2) would also adapt to the model may change if we use an ECN in the following way.
Since we get a notification of packet loss and the cause, we may get either a congestion loss or a transmission loss. If the cause is a transmission loss , the packet is simple retransmitted. In case of a congestion loss, the equation is the same as the same as (2).
For Congestion Loss:

$$dW = dt/RTT - \alpha W(t) * L_{AK} + \beta W(t) * L_{BK}$$

For Transmission Loss.

$$dW = W(t)$$

The Window size does not increase in this case, as a safety measure because an increase in window might further lead to more losses. So for a transmission loss the Sender would just retransmit the packet without increasing or decreasing the window size.

6. **Improvement in TCP**

Some method which may be very effective in dealing with waste of power and bandwidth due to retransmission are as follows.

Slow start which may start from a window size greater than one, This may help save some time in adjusting to the window size without having to waste time in slow start.
Mitigation of BER can be tackled to some extent by FEC. Though this is applied on the Link layer,
Also automatic repeat request can be used where FEC would mean carrying extra bits in the header.
The role of ECN has already been discussed in the previous section. More detail can be read at [13].

7. **Conclusion**

Multiple Parameters and non predictive nature of the medium make it a complex problem to solve. However an effective Link layer and ECN coordination can overcome the problem to some extent. So far no work has been done in modeling the Throughput equation in terms of number of hops and power of transmission, which I have only touched and not solved it. The Equations are very general in nature and can be modified. The results of all of the equations must be compared to the real conditions by simulation to judge the TCP emulation vis-à-vis other models using some of the Link layer properties for retransmissions.

References:

[1] V. Mishra, W. Gong and D. Towsley, "Stochastic Differential Equation Modeling and Analysis of TCP-Windowsize Behavior".

[2] E Altman, K. Avrachenkov, C. Barakat, " A stochastic model of TCP\IP with stationary random losses".

[3] RFC -2018, " TCP Selective Acknowledgement Options".

[4] J. Padhye, V. Firoiu, D. Towsley and J. Kurose , " Modeling TCP throughput: A simple model and its empirical validation", ACM Sigcomm, Sept 1998.

[5] TCP RFC 2581

[6] RFC- 2582, " The New Reno Modification to TCP's Fast Recovery Algorithm".

[7] H Balakrishna, R. Katz. Et al "Improving TCP/IP performance over wireless networks".
[8] N. Vaidya and M. Mehta – "Delayed duplicate Acknowledgements: A TCP-unaware approach to improve performance of TCP over Wireless" , Feb 1999
[9] S Floyd, M. Handley, J. Padhye, " A Comparison of Equation-Based and AIMD Congestion Control", ACIRI
[10] S. Singh and C. Raghavendra, "PAMAS: Power Aware Multi-Access Protocol with signaling for Ad hoc Networks". SIGCOMM , July 1998
[11] J. Liu and S. Singh, "ATCP: TCP for Mobile Ad Hoc Networks," *IEEE* Journal on selected areas in Communications, July 2001
[12] K. Brown, S. Singh, " M-TCP:TCP for Cellular networks" July 1997.
[13] S. Floyd, "TCP and explicit congestion notification," *ACM Comput. Communication Oct .1994*
[14] K. Chandran, S. Raghunathan, S. Venkatesan, and R. Prakash, "A feedback-based scheme for improving TCP performance in *ad hoc* wireless networks".
[15] R. Bagrodia, M. Gerla, K. Tng, " TCP performance in wireless Multi-Hop Networks", 1999.
[16] Jian Liu, Suresh Singh, "ATCP: TCP for Mobile Ad Hoc Networks", IEEE Journal July2001.