# Bandwidth Estimation Problem & Solutions in IEEE 802.11 based Ad Hoc Networks

Neeraj Gupta
Department of Computer Science Engineering
Hindu College Of Engineering
Sonepat, INDIA

C.S. RAI
USICT, GGSIPU
Delhi, INDIA

***Abstract***— **With the rise in multimedia applications in ad hoc networks it is necessary to ensure the quality of service support from network. The routers which may be mobile nodes in ad hoc networks should be able to evaluate the resources available in the network, prior to offering guarantees on delay, bandwidth or any other metric. Estimating the available bandwidth is often required before performing admission control, flows management, congestion control or routing based on bandwidth constraints so that before any new flow is admitted the existing flow does not degrade. Lot of work in terms of various tools and techniques has been proposed to evaluate the available bandwidth in last decade; no consensus has yet been arrived. We present a comprehensive review on the various state of art work proposed carried out in this area**

***Keywords-*** *Ad hoc networks; collisions; contention count; backoff*

## I. Introduction

Among different wireless technologies, an emerging class of autonomous, self-deployable, self-organizing class of mobile networks popularly known as ad hoc networks has been area of interest for research community. Such networks are characterized by non-specialized routers for routing purpose. . Initially developed for militarily communication and disaster recovery, the rising popularity of multimedia applications has led to commercial usage of these networks. Quality of Service (QoS) in such networks has thus become an unavoidable task.

One of the fundamental resources in wireless communication is bandwidth. The network performance can be enhanced by estimating available bandwidth. As compared to wired network, wireless networks have significantly lower capacity. The realized throughput of wireless network link is often much less than the transmission rate. The difference can be accounted for reasons like congestion, hidden terminal problem, effect of neighbour interference and noise in the channel. The channel is shared among various nodes. It is necessary to keep track of the number of potential emitters on the sender side and number of potential scramblers on the receiver side. The collection of such information helps in determining the resource utilization before admitting any new flow. The problem for estimating the available bandwidth can be defined as maximum throughput that is available between two nodes, sender and receiver, so that they do not disturb any ongoing flow in network. The solution becomes trickier in case nodes are mobile. The mobility issue leads to change of links between the nodes and hence the utilization of resource changes dynamically.

IEEE 802.11 Distributed Coordination Function (DCF) CSMA/CA is most widely used MAC protocol used for estimating the available bandwidth in ad hoc networks. Since a lot of literature is available on IEEE 802.11 DCF, we assume that readers are comfortable with this protocol. In the current paper we review various work addressing the available bandwidth estimation problem. The main contribution of this paper is to present the efforts that have been made to improve the accuracy of estimation techniques.

We have also address the fundamental difficulties with these approaches so that solution to the problem can be re-invented all over again keeping in consideration the fundamental problem with available bandwidth estimation in 802.11 based ad hoc networks. The rest of paper is organized as follows: Section II presents the related terminology. Section III presents classification of bandwidth estimation techniques. Section IV, Section V and Section VI deals in detail with various estimation approaches. Finally, section VII concludes the paper.

## II. Related Terminology

Applications are usually concerned with different bandwidth related metrics. Various network related metrics, techniques, taxonomy and terms are often imprecisely applied for measurement purposes, such as capacity, available bandwidth, bulk transfer capacity and achievable throughput. Therefore differentiating these concepts is important for the developing, evaluating and applying bandwidth estimation tools.

Capacity of the medium can be defined as maximum possible bandwidth that a link or end-to-end path can deliver regardless of other flow present in the network [1]. In case of 802.11, link-layer technologies do not operate with a constant transmission rate. The achievable capacity depends upon the network size, traffic patterns and detailed local radio interaction. Ad hoc routing requires the spatial reuse of the medium to transmit the packets. The nodes need to cooperate in order to forward the packets from source to destination. This forwarding affects the raw capacity of the nodes. The fixed overheads introduced by the protocols at different layers, such as control packets and protocol header,

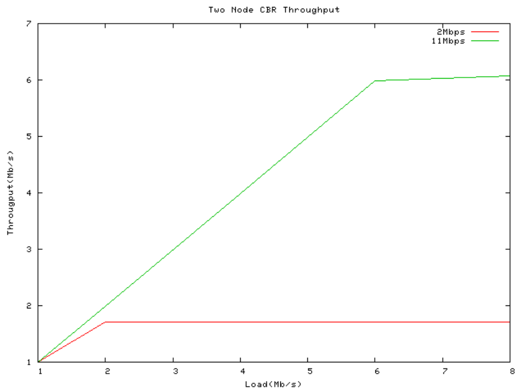


Figure 1: Achievable Throughput for 2 node scenario having 2Mbps and 11Mbps capacity

the maximum achievable throughput are much less than the raw medium capacity [2]. Assuming that source is L path length away from destination, it has been shown that capacity available to each node, λ, is bounded by

$$\lambda < (C / n) / (L / r) \qquad (1)$$

where C is capacity of the network, n is number of nodes and r is fixed radio transmission range.

The term bandwidth means the maximum amount of information that can be transmitted along a channel. In other words, it is the data rate that a network link or a network path can transfer. The said definition is true for specific period of time interval. The term throughput, on other hand, relates to amount of data transferred in one direction over a link divided by time taken to transfer it. The value of throughput thus measured is never constant but varies over time. Achievable throughput is extremely application specific, and thereby represents the throughput that an application might achieve in specified setting. Achievable throughput can be used as a guideline for local application configurations to fully utilize the available bandwidth without interfering with other traffic. The result of simulation on NS2 shows that maximum achievable throughput obtained varies to 1.7Mbps and 6.5Mbps for 2 Mbps and 11 Mbps capacity respectively as shown in figure 1.

Estimating the residual bandwidth is often required before performing the admission control, congestion control or routing based on bandwidth constraint. The available bandwidth between two neighbouring nodes can be defined as maximum throughput that can be transmitted between two peers without disrupting an already ongoing flow in the network. The residual bandwidth available in network is dependent not only on link capacity but also on traffic load and is time varying metric. The most common way to calculate the available bandwidth is to find out the utilization fraction of capacity, u, of the channel

$$A_i = (1 - u_i)\, C_i \qquad (2)$$

In the above equation $A_i$ is available bandwidth at hop i of end to end link over a certain interval. This utilization factor is often taken in terms of busyness of the channel. The node can be busy either due to transmission, reception or neighbour interference. In case of multihop ad hoc networks the value is determined as minimum available bandwidth among all H hops which can be represented mathematically as under:

$$A = min_{i=1,..,H} A_i \qquad (3)$$

The above equation states that available bandwidth on the path is equal to the minimum link available bandwidth on the path, i.e. the path from source to destination located H hops away.

## III. CLASSIFICATION OF BANDWIDTH ESTIMATION TECHNIQUES

A lot of work has been done in the area of bandwidth estimation. However, there is still no consensus on the way of precisely measuring the available bandwidth in ad hoc networks especially multi-hop ad hoc networks. The present work done in this area can be divided into three broad categories as shown in figure 2. The details of three estimation models are treated separately in sections to follow hereafter

## IV. ANALYTICAL MODELS

Analytical models helps in providing the quantitative analysis of the protocols, helping us to predict the result set if the network parameters are changed. This is not possible with the either active or passive estimation approach. There have been few analytical models proposed in late which models around the operation of DCF in ad hoc networks each with their own set of assumptions.

In our knowledge one of first pioneer work in this area was presented by Binanchi [3]. The author developed analytical model using two dimensional Markov chain which provide the closed form expression for calculation of throughput for 802.11 DCF at MAC layer. Each station is modeled by pair of integer (i, k) where i represents backoff stage and k represents the contention window size. The value of i is initially 0 representing first attempt. This value is incremented every time there is unsuccessful transmission or packet suffers a collision. The value of k is maximum at the $m^{th}$ stage. The model iterates in $m^{th}$ stage until the packet is successfully transmitted. The value of contention window, k, is uniformly chosen between $[0, W_i - 1]$ where W represents the value of backoff. Assuming, for every transmission attempt regardless of number of retransmission the collision probability is constant and independent of contention window. The expression for saturation throughput, S is represented as:

$$S = (P_s \,.\, P_{tr} \,.\, L) / (P_s . P_{tr} . T_s + P_{tr} . (1 - P_s) T_c + (1 - P_{tr}) T_{id}) \qquad (4)$$

where $P_{tr} = 1 - (1 - \pi)^N$ is the probability there is at least one transmission in considered slot time; L is average packet payload size; $P_s = ( N.\pi.( 1-\pi)^{N-1}) / ( 1- (1 - \pi)^N )$ is the probability of successful transmission; $T_{id}$ is the duration of idle time; $T_c$ is average time spent in collision; $T_s$ is the average time needed to transmit a packet of size L; π is channel access probability of node; N is number of nodes in network.

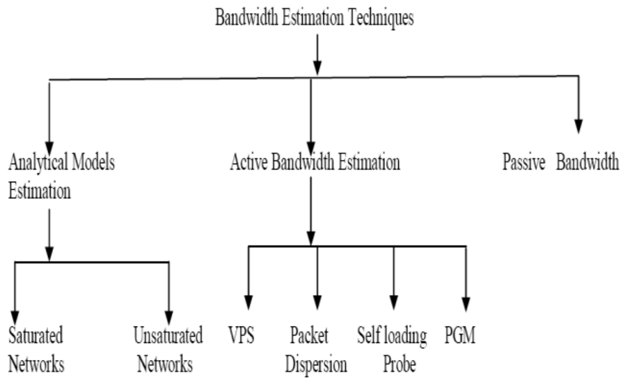


Figure 2: Classification of various available bandwidth estimation techniques.

The main assumptions of this work were 1. Ideal channel was assumed 2. Collision probability was assumed to be independent of the number of retransmissions. 3. Stations were in saturated condition i.e. they always have packets to transmit 4. Network is homogeneous with finite number of terminals. If the above assumptions are true, the model gives the accurate results. However, the assumptions are not necessarily true in real wireless networks. This seminal work opens the way for other analytical models to follow.

It has been noted that network does not work in saturated condition but in unsaturated condition where traffic is always in on-off mode. Internet, voice communication can be cited as some of the examples. In [4] authors extended the Binanchi model for unsaturated traffic conditions. For the stations which have transmitted the packet but has none waiting in buffer, it enters into post backoff stage. Allowing the stations to have different data rate, heterogeneous network, the normalized throughput of the system is represented in equation (5)

$$S = \sum_{i=1}^{n} S_i \quad ; \text{where } S_i = P_{Si}\, L_i \,/\, E_s \qquad (5)$$

where $S_i$ is throughput of source node i; $P_{Si}$ is probability that station i successfully transmits; $L_i$ is the expected time spent transmitting payload data for source i; $E_s$ is expected time spent per state. The basic assumption of fixed collision probability irrespective of its history is retained.

According to the IEEE 802.11 MAC standard after a certain number of retransmission attempts the contention window ceases to expand exponentially and after more attempts few its value is reset and the packet is dropped. In [3] [4], however, packets continue to iterative until it is successfully transmitted. This assumption is dropped in [5] [6] along with the introduction of ideal state and post backoff stage.

The assumption of ideal channel was dropped in work by [6]. The work presented the throughput calculation based on the Markov chain model in non-saturated condition in presence of the channel induced errors and channel capture effect over a Rayleigh fading channel. It was observed that that throughput is a linear function of packet rate. After certain critical rate throughput enters the saturated conditions.

A pioneering work by Zhao [7] [8] addresses intraflow contention and synchronization problems. The bandwidth of the node is consumed by its neighbours. These neighbours can be in the area where no direct communication is possible with each other. Whenever these nodes start emitting the packets they contribute to the intraflow contention problem. The work in [7] provides analytical modeling to the problem while considering the effects of channel bit rate, hidden-node collisions, and neighbouring interference. The problem of synchronization can be stated as the availability of idle medium on both sides for total transmission time in order to avoid collision. In case, the idle period of sender and receiver do not overlap at all, the available bandwidth will be evaluated to null. Some authors presume the airtime synchronization to occur naturally. However, the idle channel time period can neither be naturally synchronized nor they are independent of each other. For better estimation, it is necessary to differentiate the busy state (transmitting and receiving) from sense busy state. Based on the above idea, authors proposed IAB [8], which considers the natural dependence between medium states that, is sensed by two adjacent nodes.

## V. ACTIVE BANDWIDTH ESTIMATION TECHNIQUES

These estimation techniques were based on the probe packets which are injected into network to estimate parameters related to bandwidth estimation. Such techniques developed initially for wired networks were modified to suit the wireless environment. However these techniques suffer from lot of drawbacks. The details can be referenced from [33]

### A) Variable Packet Size (VPS) Probing

VPS allows measuring the capacity along end-to-end path for each hop. The concept was first introduced by Bellovin [9] and implemented in pathchar [10] by Jacobson in 1997. The concept was further refined in clink [11], pchar [12], and ACCSIG [13] improved VPS and implemented it in several ways. This technique is based on measuring round trip time (RTT) for each hop in network. The RTT was measured approximately by three delay components: serialization delay, propagation delay and queuing delay. The key assumptions while carrying out the analysis are

- The one way delay of packet is increased along each hop of a path.
- By injecting multiple packets of the same size to each hop of the network, at least one packet will not encounter any queuing delay.
- Propagation delays are independent of the packet size and constant for each hop.

Some of the key advantages VPS model offered are: firstly there is no need of any special software to be installed on either side of the network. Secondly The capacity for each hop along the entire network path can be measured and it helps in reducing the effects of cross traffic. However there are several limitations of this technique. VPS tool relies on a ICMP it is necessary to ensure its implementation at each router along the measured network path. Second, this technique measures bandwidth in a single direction, from the local host to the remote end host. Whenever large numbers of probing packets are injected, network suffers from stress and interference along the path. [22].

B) Packets Dispersion

A packet dispersion technique injects packet pairs or packet train probes to measure the end-to-end capacity of a network path. The concept of packet pair dispersion techniques were first introduced in [14, 15, 16]. Several other tools and techniques refined the measurement process such as bprobe/cprobe [17], nettimer [18, 19], sprobe [20] and pathrate [21, 22].

It is based on sending two packets of same size back-to-back in the network. Once the packet pair passes through the narrow link the time dispersion between two packets can related to the narrow link capacity. The concept is illustrated in figure 3. Packet train dispersion is extension of the above concept, in which multiple back-to-back probing packets are sent across the network. One of the key assumptions of these techniques is absence of cross-traffic during probing interval. The most important assumption of packet dispersion techniques is that there is no crossing traffic during the packet pair probing.

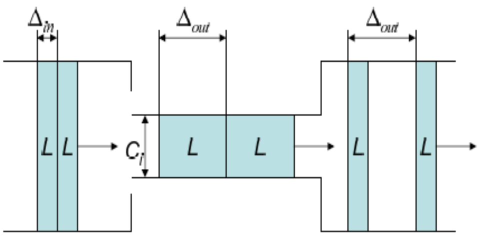


Figure 3: Packets Dispersion

When packets of size L with initial dispersion $D_{in}$ go through the link of capacity $C_i$, the dispersion after the link $D_{out}$ becomes

$$D_{out} = max\,(D_{in}, L / C_i) \qquad (6)$$

After the packets go through each link along an H hop end-to-end path, the final dispersion $D_R$ at the receiver is:

$$D_R = L / min_{i=1,....,H}\, C_i = L / C \qquad (7)$$

where C is the end-to-end capacity. Thus the path capacity can be estimated from $C = L / D_R$.

Although this technique is faster as compared to other estimation techniques in terms of faster measurement time and induce less stress on the network path. However, in presence of cross traffic the accuracy is significantly degraded [13]. Another disadvantage is tools needs to be executed on both sides of network path.

C) Self-loading Probe

The two techniques discussed above helps in measurement of capacity in the network. Self-loading techniques, including Self-loading Periodic Streams (SLoPS) [23] and Train of Packet Pairs (TOPP) [24, 25], are used to measure the available bandwidth of the end-to- end network path. Some of the key tools that implements a variety of self-Loading techniques, such as pathload [23], Packet Transmission Rate (PTR) [26] and pathChirp [27].

It works on the concept of sending the probe packets at multiple rates in the network. If the available bandwidth is less than probing packet at tight link, the probe packets queued at the tight link of router leading to increase in the delay on the receiver side. On the other hand, if the probing rate is lower than available bandwidth at the tight link, the probing packets will go through the tight link without causing an increased delay. The available bandwidth is obtained at tight link by analyzing the packet delay at receiver side. The estimation is made at the turning point probing rate at which queuing delay starts increasing. The probing rate can be managed in several ways say it can linearly increasing probing rate, exponentially probing rate and so on.

The key assumption in case of SLoPS is presence FIFO queue at all routers along the path. It also assumes that cross traffic changes slowly and is constant during measurement duration [26]. The disadvantages of this technique are self-induced congestion and long time required to convert the measurements into available bandwidth estimates.

D) Probe Gap Model (PGM)

The concept similar to packet dispersion probing is probe gap model. However, PGM measures the available bandwidth instead of the end-to-end capacity. The concept is based on estimating the cross traffic at the tight link. It assumes the presence of only single bottleneck which is both narrow and tight link for that path. It is further assumed that queue is not empty between two packets in probing packet pair and the capacity at the bottleneck link is known and constant.

## VI. PASSIVE BANDWIDTH ESTIMATION TECHNIQUES

With the problems and drawbacks of the active bandwidth estimation techniques in wireless scenarios the research shifted towards the passive methods for estimating available bandwidth. The sensing based approach/ listen method/passive methods are more suitable to wireless networks. Here nodes utilize the 802.11 MAC physical carrier sensing or virtual carrier sensing to determine free and busy time. The MAC detects the channel as idle when following criteria holds:

- Network Allocation Vector (NAV) is less than current time.
- Receiver state is idle
- Send state is idle.

Although the method is straight forward, the problem starts once the route is broken the corresponding sender will never know whether any node has changed its position until a new data transmission begins.

The above problem is tackled by researcher in form of the HELLO packets, used by most of routing protocols. These HELLO packets are emitted periodically and can be utilized for exchanging the local information. The few advantages we can derive are:

- They help in maintaining list of one hop neighbours.
- They help in exchanging the bandwidth information up to two hops.
- They avoid sending any other control messages for decimating the information.

It is important to understand the difference between transmission range, interference range and carrier sensing rage while studying the passive methods [28]. Since the medium is wireless it is shared by all nodes. In [29], BRUIT protocol was proposed. The authors take into consideration the fact that the carrier sense range is twice the transmission range. It was seen that even if two nodes are not able to communicate with each other they still contend the resources of each other. To address this issue information related to bandwidth is shared with all its neighbours. Such information can be propagated to two hop distance through HELLO packet. Each node performs the admission control based on information thus collected. The carrier sense range is assumed to be two hops which may not be true in real scenarios.

Using the same assumption of two hop neighborhood [30] the local available bandwidth at node is estimated by the monitoring idle channel time of medium. It was realized that nodes lying in the carries sense range can also contend for the bandwidth thus affecting any on-going flow, leading to Intra flow contention problem. It is important to calculate number of nodes in the carrier sensing range. The problem is popularly termed as contention count (CC). To calculate the contention count at any node, it must identify its c-neighbours. Given the total number of c-neighbours and route of flow, CC is determined as number of common nodes between the two. Thus we have

$$N_{cc} = \begin{cases} |(Route - Dest) \cap S_n| & ;if\ node \notin R \\ |(Route - Dest) \cap S_n| + 1 & ;if\ node \in R \end{cases} \quad (8)$$

where $N_{cc}$ is contention count at a particular node, $S_n$ is set of c-neighbours, and Route and Dest are set of all nodes from emitter to receiver and destination node respectively. To obtain bandwidth at c-neighbors (contending nodes), three approaches were proposed. In the first method bandwidth related information is exchanged by broadcasting the HELLO packets which is limited to two hops only (CACP multihop). Second approach makes use of the higher transmission power for packets containing the bandwidth information (CACP Power). Such an arrangement has high probability of interfering with the data transmission of other nodes thus disrupting the traffic. In last passive approach proposed the sensitivity of node is decreased to value lower than CS_Threshold. The above technique is likely to be affected by the noise and interference present in the channel.

The idea behind the AAC [31] was to reduce the overhead induced by the control message, use of routing metrics for calculation of the contention count and pausing of any existing flow when there is degradation in QoS due to mobility. Each node calculates its available bandwidth by monitoring the channel using the carrier sensing techniques for idle/busy periods. Depending upon the medium occupancy for the time period defined, each node can calculate the available bandwidth which is termed as "serviceable bandwidth". In order to reduce the control message overheads the HELLO message is extended such that it aggregates the available bandwidth of all its nodes in carrier sense range. The minimum available bandwidth from aggregated data becomes the node's own available bandwidth. In order to solve the intra-flow contention problem it is necessary to identify the contention count of the node. The AAC uniquely solve this problem with the help of hop counts provided by RREQ (Route Request) and RREP (Route reply) messages.

$$CC = min\ (h_{rreq},\ h_{max}) + min\ (h_{rrep},\ h_{max}) + K \quad (9)$$

In the above equation $h_{rreq}$ is hop count of route request, $h_{rrep}$ is hop count of route reply, $h_{max}$ represents maximum distance between sender and carrier sense neighbour and K = 0 when destination node is inside the interference range otherwise K = 1. The node carrier sense range is defined in terms of the number of hops, $h_{max}$. The value of $h_{max}$ varies between 2 and 3 depending upon the network node density referred to as roughness of path. However, this theory holds that all nodes have ideal circular propagation range. It is also assumed that the sender and receiver are perfectly synchronized. This lack of synchronization leads to over estimation of real available bandwidth.

Finally ABE technique proposed in [32]. The work is motivated by carrier sense capability, time lost due to collisions with its effect on backoff period and idle period synchronization. Assuming the carrier sense range is limited to two hops each node monitors its idle time, thus, calculating its upper bound of bandwidth available. The information is then sent to neighbours using the HELLO packets. Among many other contributions the authors addresses the problem of synchronization between the sender and receiver. Synchronization is related to idle time overlap between the sender and receiver. If either of them is busy the data packet will not be transmitted successfully. Assuming surrounding medium occupancy to be uniform randomly distributed a probabilistic mechanism was proposed to address this effect. In order to evaluate the collision probability authors relied on HELLO packets often used by routing algorithms. If number of packets is limited, the approach can be considered as non-intrusive. Every node can estimate the number of HELLO packets it should receive during a certain period (usually defined by routing algorithms such as AODV). The collision probability of these packets can be calculated as the ratio of the number of HELLO packets received to the expected number of HELLO packet that should have been received in that time interval. Since the size of HELLO packets can be small or big in comparison with data packets we can interpolate the data using Lagrange interpolating polynomial. The collisions leads to exponentially increase of contention window leading to loss of the bandwidth since the backoff time cannot be utilized for either transmission or reception. The authors evaluated the influence of contention window, which depends upon the success or failure of transmission, affecting bandwidth consumed in process. The available bandwidth between the two neighbouring node (s, r) can be estimated by the following equation:

$$E_{final}(b_{(s,r)}) = (1-K).(1-p).E(b_{(s,r)}) \quad (10)$$

Where the $E(b_{(s,r)})$ is the available bandwidth on the link (s, r) evaluated by monitoring the radio channel and combining the emitter and receiver's values in a probabilistic manner, p is the collision probability measured on the received HELLO packets and rescaled to the appropriate packet size and K is the proportion of the bandwidth lost due to back off scheme computed due to p.

There are certain drawbacks in the above approach. We need to run the experiment in advance to get our Lagrange coefficients. Lagrange interpolating polynomial does not possess the permanence property. Also as stated by authors the HELLO packets can be affected due to congestion related issues leading to the underestimation of available bandwidth.

## VII. CONCLUSION

The estimation of available bandwidth is challenging task due to inherent nature of the wireless medium. In this paper, we have presented with the various aspects in which the problem of the available bandwidth has been approached. Each of the techniques discussed has its own set of drawbacks. No clear consensus has been reached which provides the accurate estimation of the available bandwidth. The paper provides the ground for search of strategy which helps in reinventing the solution, taking into the consideration the fundamentals difficulties.

## REFERENCES

[1] R.S. Prasad, M. Murray, C. Dovrolis, and K.C. Claffy, "Bandwidth Estimation: Metrics, Measurement Techniques, and Tools," IEEE Network, November-December 2003.

[2] Jinyang Li, Charles Blake, Douglas S. J. De Couto, Hu Imm Lee, Robert Morris, Capacity of Ad Hoc Networks ,Proceedings of the 7th annual international conference on Mobile Computing and Networking, ACM, 2001.

[3] G. Bianchi, 'Performance Analysis of the IEEE 802.11 Distributed Coordination Function," IEEE Journals on Selected Areas in Communication, vol. 18, no. 3, March 2000

[4] D. Malone, Ken Duffy and D. Leith, "Modeling the 802.11 Distributed Coordination Function in Nonsaturated Heterogeneous Conditions," IEEE/ACM Transactions on Networking, vol. 15, no. 1, February 2007.

[5] G. Prakash and P. Thangaraj, "Non-Saturation Throughput Analysis of IEEE802.11 Distributed Coordination Function,' European Journal of Scientific Research, Vol. 51, 2011

[6] F. Daneshgaran, M. Laddomada, F. Mesiti and M.Mondin, "Unsaturated Throughput Analysis of IEEE 802.11 in Presence of Non Ideal Transmission Channel and Capture Effects," IEEE Transactions on Wireless Communication, 2008

[7] H. Zhao, S. Wang , Yong Xi and Jibo Wei, "Modeling Intra-Flow Contention Problem in IEEE 802.11 Wireless Multi-hop Networks," IEEE Communication Letters, vol. 14, no.1 , January 2010

[8] H. Zhao and E. Garcia-Palacios, "Rethinking available bandwidth estimation in 802.11- based ad hoc networks," IEEE Electronics Letters, Vol. 45 No. 4, 12th February 2009

[9] Steven M. Bellovin, A Best-Case Network Performance Model, Tech. Rep., ATT Research, Feb. 1992.

[10] Van Jacobson, "pathchar: A Tool to Infer Characteristics of Internet Paths," Apr. 1997, Online at: ftp://ftp.ee.lbl.gov/pathchar/.

[11] Allen B. Downey, 'Using Pathchar to Estimate Internet Link Characteristics," SIGCOMM '99: Proceedings of ACM Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications, Cambridge, MA, USA, Sept. 1999, pp. 222–223.

[12] Bruce Mah, "pchar: a Tool for Measuring Internet Path Characteristics," Feb. 1999, Online at: http://www.kitchenlab.org/www/bmah/Software/pchar/.

[13] A. Pasztor and D. Veitch, "Active Probing using Packet Quartets," IMW '02: Proceedings of the ACM SIGCOMM Internet Measurement Workshop, Marseille, France, Nov. 2002.

[14] V. Jacobson, "Congestion Avoidance and Control," SIGCOMM '88: Proceedings of ACM Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications, Stanford, CA, USA, Aug. 1988.

[15] Srinivasan Keshav, "A Control-Theoretic Approach to Flow Control," SIGCOMM '91: Proceedings of ACM Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications, Sept. 1991.

[16] Jean-Chrysotome Bolot, "End-to-end Packet Delay and Loss Behavior in the Internet," SIGCOMM '93: Proceedings of ACM Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications, San Francisco, CA, USA, Sept. 1993, pp. 289–298.

[17] Robert L. Carter and Mark E. Crovella, "Measuring Bottleneck Link Speed in Packet-Switched Networks, Performance Evaluation," vol. 27, no. 8, pp. 297–318, Oct. 1996.

[18] Kevin Lai and Mary Baker, "Measuring Bandwidth," Proceedings of IEEE Conference on Computer Communications (INFOCOM), New York, NY, USA, Apr. 1999,pp. 235–245.

[19] Kevin Lai and Mary Baker, "Measuring Link Bandwidths Using A Deterministic Model of Packet Delay," SIGCOMM '00: Proceedings of ACM Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications, Stockholm, Sweden, Aug. 2000, pp. 283–294.

[20] Stefan Saroiu, P. Krishna Gummadi, and Steven D. Gribble, "SProbe: A Fast Technique for Measuring Bottleneck Bandwidth in Uncooperative Environments," Aug. 2001, Online at: http://sprobe.cs.washington.edu.

[21] Constantinos Dovrolis, Parmesh Ramanathan, and David Moore, "What do Packet Dispersion Techniques Measure?," Proceedings of IEEE Conference on Computer Communications (INFOCOM), Anchorage, Alaska, USA, Apr. 2001

[22] Constantinos Dovrolis, Parameswaran Ramanathan, and David Moore, "Packet- Dispersion Techniques and a Capacity-Estimation Methodology," IEEE/ACM Transactions on Networking, vol. 12, no. 6, pp. 963–977, Dec. 2004.

[23] Manish Jain and Constantinos Dovrolis, "End-to-End Available Bandwidth: Measurement Methodology, Dynamics, and Relation with TCP Throughput," IEEE/ACM Transactions in Networking, no. 295-308, Aug. 2003.

[24] Bob Melander, Mats Bjorkman, and Per Gunningberg, "A New End-to-End Probing and Analysis Method for Estimating Bandwidth Bottlenecks," IEEE GLOBECOM–Global Internet Symposium, San Francisco, CA, USA, Nov. 2000, pp. 415–420

[25] Bob Melander, Mats Bjorkman, and Per Gunningberg, "Regression-Based Available Bandwidth Measurements," International Symposium on Performance Evaluation of Computer and Telecommunications Systems, July 2002.

[26] Ningning Hu and Peter Steenkiste, "Evaluation and Characterization of Available Bandwidth Probing Techniques," IEEE Journal on Selected Areas in Communications, vol. 21, no. 6, Aug. 2003.

[27] V. Riberio, R. Riedi, R. Baraniuk, J.Navratil, L.Cottrell, "pathChirp: Efficient Available Bandwidth Estimation for Network Paths," Proceedings of Passive and Active Measurements (PAM) Workshop, La Jolla, CA, USA, April 2003

[28] Jing Deng, Ben Liang and Parmod K. Varshney, "Tuning the Carrier Sense Range of IEEE 802.11 MAC," IEEE Communication Society, Globecom, 2004

[29] C.Chaudet and I.G. Lasssous, "BRuIT- Bandwidth Reservation under Interference Influence," Proc. European Wireless(EW' 02), Feb. 2002.

[30] Y. Yang and R. Kravets, "Contention Aware Admission Control for Ad Hoc Networks," IEEE Transaction Mobile Computing, vol. 4, July-August 2005, pp 363-377

[31] de Renesse, R., Friderikos, V. and Aghvami,A.H., "Cross-layer cooperation for accurate admission control decision in mobile ad hoc networks," IET Communication, 2007, pp 577-586

[32] Cheikh Sarr, Claude Chaudet, G. Chellius, I.G. Lassous, "Bandwidth Estimation for IEEE 802.11 Based Ad Hoc Networks," IEEE Transaction on mobile computing , Vol. 7 No. 10, October 2008.

[33] Mingzhe Li, "Using Bnadiwth Estimation to Optimize Buffer and Rate Selection for Straming Multimedia over IEEE 802.11 Wireless Network," Dissertationfor Doctorate of Philosphy, Worcester Polytechnic Institute, December 2006