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ESTIMATION OF MAXIMUM ACHIEVABLE END-TO-END THROUGHPUT IN IEEE 802.11 BASED WIRELESS MESH NETWORKS

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ESTIMATION OF MAXIMUM ACHIEVABLE END-TO-END THROUGHPUT IN IEEE 802.11 BASED WIRELESS MESH NETWORKS

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Master of Science
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by
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ABSTRACT

Wireless mesh networks can be quickly deployed in various situations to provide temporary to permanent wireless network coverage. To assess the feasibility and reliability of a given end-to-end communication need, it is essential for communication end points to accurately estimate their achievable end-to-end throughput. Several capacity, end-to-end throughput, and available bandwidth estimation techniques have been studied in the past for wired and wireless networks. The contention among wireless nodes arising due to the IEEE 802.11 medium access control protocol's channel access mechanism renders the estimation of such network attributes challenging in multi-hop networks. This thesis evaluates Adhoc Probe, one state-of-the-art capacity estimation approach for ad hoc wireless networks and shows that it in fact measures achievable throughput instead of capacity and its estimated achievable throughput is not realizable. An analysis of end-to-end delays of the injected probe packets is presented to show the effects of medium access contention and network queuing on the delays and estimated achievable throughput subject to different network traffic patterns and multi-hop collisions. Based on the observations, an alternative less intrusive delay distribution based achievable throughput estimation solution is proposed. With ns-2 simulations, the scheme was shown to accurately estimate the achievable throughput under various topologies and cross traffic conditions.

DEDICATION

This thesis is dedicated to my family and friends who have been very supportive and encouraging in every phase of my life.

ACKNOWLEDGMENTS

I would like to thank my advisor Dr. Kuang-Ching Wang for his valuable time and support throughout the course of my study at Clemson University. The guidance and insightful inputs provided by him during our discussions immensely helped me in my research progress. I would like to thank him for having given me an opportunity to be a part of his research group. It has been an enriching learning experience.

I would also like to thank all the faculty members and colleagues of the wireless communication group at Clemson University for their help and encouragement.

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CHAPTER 1

INTRODUCTION

Wireless networks have gained increasing popularity because of their ability to allow the components of a system to stay connected. However, wireless mesh networks (WMNs) have emerged as a key technology for next-generation wireless networking [1]. Mesh networks are self configuring, self managing, and self healing [25]. When a mesh node powers up, it broadcasts and listens to identification messages from neighbor nodes and a network is thus self formed. Their dynamic reconfiguration ability ensures that failure of a particular link to a node does not lead to node isolation. Mesh networks can cover a wider geographical area without having to establish additional backhaul communication links, resulting in a cost effective technology. Hence WMNs have been accepted as a fast, low-cost, and easily extensible solution for providing network connectivity and coverage to distributed users in a wide area [4] [23]. The ease of maintenance, robustness, and reliability of these networks makes them suitable for varied applications.

Efficient deployment and operation of a network depends on the ability of the network to provide reliable service to its users. For instance, a video streaming application requires its minimum share of bandwidth at any instant of time to deliver acceptable quality multimedia content. On the other hand, in case of networks deployed for military communications it is required that the network successfully delivers time critical and delay sensitive information. It is imperative that such application specific requirements be handled by a wireless network. To assure such reliable and timely end-to-end communication, it is essential for the communication end points to acquire accurate estimates of the network metrics such as path capacity, achievable throughput and available bandwidth of a link or a path. Estimation of the end-to-end network characteristics help in network error diagnosis, usage monitoring, and resource allocation.

Path capacity, achievable throughput, and available bandwidth are metrics that have been easily confused and at times used interchangeably in past studies. In general networking terminology, path capacity is usually measured as an inherent attribute of the network that does not depend on the traffic pattern it carries. It is defined as the minimum of the transmission rates of all links in the path [6], while achievable throughput is always measured as the maximum amount of data that can be relayed by the network within a unit time. Available bandwidth of a network is the rate of additional traffic that can be relayed from a node without causing degradation of service to other ongoing flows in the network [8]. In wireless networks, however, the traffic-independent assumption of capacity becomes a source of inaccuracy. For example, in [21], the Adhoc Probe protocol estimates the path capacity by sending a few probe packet pairs and chooses one pair with the least one way delay (OWD) to estimate capacity with minimal impacts due to traffic and topology dependent delays; nevertheless, by doing so the paper also admits that the estimated capacity may not match the “real throughput” achievable by pushing real UDP traffic in such networks as done in [11]. Though the Adhoc Probe claims to estimate the capacity of a path, it is shown that the estimated value depends on the physical and MAC layer overheads and is closer to the achievable throughput of the path.

In [21], the authors stated that it would be difficult to measure achievable throughput in wireless networks without incurring intrusive probing traffic in the network. The focus of this thesis is thus to explore the feasibility of finding a light-weight probing mechanism that can accurately estimate the achievable throughput in a wireless mesh network with light to heavy traffic loads.

The path capacity and achievable throughput and available bandwidth estimation problem has been more extensively studied in the past for wired networks [6-7] [11] [15] [22]. These estimation techniques can be largely categorized as active and passive methods. With active methods, probe packets are sent in the network at regular intervals and the network attributes are estimated based on the probe arrival pattern and dispersion between the probe packets at the destination. With passive methods, ongoing data traffic along network paths are monitored for estimations. Passive estimation techniques perform better in scenarios focused on monitoring local information and its accuracy depends on a recent activity in the network and hence this technique will not provide best results in a network path that has been idle over a period of time. This study focuses on active probing methods that can be used for proactive network monitoring, flow admission control, and bandwidth allocation.

The nature of the multi-hop wireless networks renders the application of the same techniques much more challenging. The data transmissions from a wireless node interfere with transmissions from other nodes within its transmission and carrier sensing range [18] leading to multiple collisions among the contending nodes. These factors alter the dispersion between the probe packets and hence affect the accuracy of the estimations.

This thesis studies the limitations of Adhoc Probe technique and proposes an alternate delay distribution based approach to estimate the end-to-end achievable throughput of the path for a multi-hop wireless network. It begins with a survey of various active and passive network characteristics estimation methods for wired and wireless networks. Then, with ns-2 simulations [26], the Adhoc Probe method is shown to consistently over-estimate the achievable throughput with real injected UDP packets, especially under high load conditions. The end-to-end delay distributions of the UDP packets are analyzed to show that the actual achievable throughput is determined by the queueing and medium access delays. Furthermore, we show that such delays can be actively “triggered” by injecting probe packet trains at properly chosen intervals. The triggered delays can then be measured and used to accurately estimate the achievable end-to-end throughput.

The rest of the thesis is organized as follows. Chapter 2 reviews the IEEE 802.11 medium access control protocol scheme and presents a background on the dispersion-based estimation techniques. Chapter 3 illustrates the previous studies and Chapter 4 discusses the limitations of the Adhoc Probe method and analyses the improvement opportunities. Chapter 5 describes the problem statement, network model, and alternate delay distribution based solution. The simulation studies are presented in Chapter 6 and the thesis concludes in Chapter 7 with recommendations for future work.

CHAPTER 2

BACKGROUND

2.1 *IEEE 802.11 Medium Access Control Protocol – Distributed Coordination Function Mode*

The knowledge of the operations of 802.11 medium access control protocol helps in the understanding of the time required for a packet transmission in a wireless ad hoc network. In 802.11 protocols, the fundamental channel access mechanism is based on the Distributed Coordination Function (DCF) mode [3] [24]. It is a decentralized algorithm and does not require a single node to monitor or coordinate the channel access scheme. The two techniques employed by the DCF mode are the basic access mechanism and the RTS/CTS method. The basic access method involves the transmission of ACK packets from the destination node after the reception of the packet from the source node. In the case of RTS/CTS mechanism, the source node first sends the Request To Send (RTS) packet and waits for the Clear To Send (CTS) packet from the destination node. This is followed by the actual data transmission and the reception of the ACK packet from the destination.

The random channel access in 802.11 networks is based on the Carrier Sense Multiple Access Collision Avoidance (CSMA/CA) scheme. When a data packet is ready to be sent, the protocol senses the channel for ongoing transmissions. If the channel is observed as free for a particular period of time called Distributed Inter Frame Size

(DIFS), the DCF mode initializes the back-off counter and waits till the counter becomes zero before attempting transmission. The packet is transmitted when the counter reaches zero. Upon successful transmission, the next packet is chosen from the queue. The packet transmission may fail, if a collision is encountered with any other packets in the network and a back-off counter is chosen at random from a uniform distribution of [0, CW] where CW is the size of the contention window. The back-off value increases exponentially with increasing collisions. A maximum of M transmissions are attempted before the packet is discarded. According to the DCF channel access mechanism [8], single hop channel occupation duration of a data packet can be expressed as

$$T_{occup} = 4T_{plcp} + T_{difs} + T_{backoff} + T_{rts} + T_{cts} + L/B + T_{ack} + 3T_{sifs} \qquad (1)$$

where T_{plcp} is the time taken by physical layer PLCP header, T_{difs} and T_{sifs} corresponds to the short and DCF inter-frame spacing, $T_{backoff}$ represents the back-off period, T_{rts} and T_{cts} and T_{ack} represent the RTS, CTS, and ACK packet transmission times, L/B is the actual transmission time of the data packet of size L bytes in a channel with rate B bps.

2.2 *Dispersion Between Successive Packets in the Network*

The dispersion between two packets in a network is defined as the time between the reception of the last bit of the first packet and the last bit of the second packet [6] [14]. When two packets are sent back-to-back by a source node, the packets are separated by a time corresponding to the capacity of the bottle neck link of the path. Hence dispersion between the packets can be used in the measurement of end-to-end achievable throughput of a path. Consider packets of known size P bits, transmitted back-to-back in a network and a dispersion of T seconds is observed between the packets at the destination node. The path capacity of the network, C bps is in general estimated using the following equation

$$C = P / T \tag{2}$$

It is observed that the presence of cross traffic in the network alters the dispersion between the packets and leads to either an expansion or a compression in the dispersion based on the nature of the interference [6] [13]. An expansion in the dispersion results in the under estimation while a compression results in the over estimation of the throughput of the network path. In [6] the authors show that the measured dispersion between the probes sent over a wired network follows a multimodal distribution. The dispersion corresponding to the path capacity is called the *capacity mode*. The capacity under estimation resulting from the interference with the cross traffic is called *sub-capacity dispersion range* and the over estimation caused due to the first packet of a pair being queued long enough is called *post-narrow capacity mode*. The authors illustrate that the capacity estimations of a network should consider the queueing strategies employed in the network to obtain accurate estimates of the network characteristics.

2.3 *Active vs. Passive Estimation*

The throughput estimation techniques can be broadly classified into active and passive estimation methods. The passive non-intrusive estimations do not involve the transmission of additional probe packets into the network and instead depend on the existing data transmissions along the network path. Passive estimations are usually a time based mechanism [10] [14] and involve the calculation of the channel access time associated with a data transmission. In IEEE 802.11 based networks, the communication from one node consumes the bandwidth of the other nodes present in its transmission or the career sensing range due to shared medium access mechanisms [3]. The information carried by the MAC layer headers are used in the estimation of the achievable throughput for a particular node. In [14] the information carried by the network allocation vector (NAV) or the duration field in the MAC header is used in throughput estimations.

The active throughput estimation techniques on the other hand involve sending additional special packets called probe packets into the network [11] [12] [15] [17] [22]. The sending rate of the probe packet is chosen so that the number of probe samples are large enough to capture the dynamics of the network and yet the rate is not so large to avoid creating congestion from the probe packets. The packet pair technique involves the transmission of two back-to-back packets at any instant of time. The spacing between the packets at the receiver is used to estimate the path capacity and achievable throughput of the network. Similarly larger number of probes packets called a probe train is used to estimate the network metrics in conditions where two packets would not suffice. The length of the probe train is the number of back-to-back packets that injected in to the network. The probe packets are time stamped at the sender before transmission. The reception time stamp of the packets is again observed at the destination. The delay and dispersion associated with a packet transmission is calculated based on these timestamps

CHAPTER 3

RELATED WORK

Several researchers have studied the path capacity and achievable throughput and bandwidth estimation problem in wired as well as wireless networks. The earlier works on capacity estimation in wired networks are based primarily on the Pathchar and the Pathload estimation techniques. Pathchar [7] is a delay based capacity estimation tool while Pathload [12] is based on the dispersion measurements. These works examine the packet pair and packet train techniques and analyze the effects of varying the probe packet sizes on the dispersion measurement in the presence and absence of cross traffic in the network. The Packet pair based approach is shown to be a good choice for capacity estimation in wired networks. Experiments were carried out with live internet traffic and measurements were recorded to validate the claim and the proposed solutions. The Initial Gap Increase (IGI) algorithm described in [11] identifies a gap model to understand the interaction of probe packets and the cross traffic in the network. Conditions are identified under which the packet pair gap can be used to accurately characterize the competing traffic. The relation between the measured dispersion and the cross traffic intensity is explained based on the queuing periods the probe packets fall into where a queuing period is defined as a time segment during which the queue is not empty. The algorithm iteratively increases the initial gap between the probe packets until the turning point is reached. Turning point is the point where the initial gap equals the bottle neck link gap and the probe packets interleave with the cross traffic. The dispersion measurements at this region give accurate estimations of cross traffic throughput. Recent capacity estimation techniques for wired networks employ a combination of both delay and dispersion based mechanisms [15] [19]. In [15] the authors propose a tool CapProbe for estimating the capacity of the bottleneck link of the path based on the round trip measurements. The round trip time of the probe samples are monitored to filter out the dispersion sample to be used in the capacity estimation.

Throughput estimations in a mixed network topology consisting of wired nodes and last hop wireless networks are based on the increasing the mean probing rate at the source node. In [13], the bandwidth estimation techniques are studied for last hop IEEE 802.11 based wireless networks. The experiments show that the measured available bandwidth and the link capacity vary with the probe packet size and the cross traffic intensity in the network. This is based on an iterative algorithm which increases the rate of the probe packets until the point that the network becomes congested. The dispersion between the packets is used to measure the probe rate at the destination node. The ratio of the transmitted probe rate to the measured rate is calculated. A graphical methodology is used to estimate the available bandwidth based on the slope of the curve. Although the proposed technique accurately measures the bandwidth for a last hop wireless network, this method of increasing the probing rate is very intrusive and will result in multiple collisions and packet drops when adopted for a multi-hop wireless network.

Analytical approaches, experimental test bed based approaches and simulation studies can be employed to estimate the capacity and throughput of a path in a multi-hop wireless network. In [16], the authors analyze the 802.11 MAC interactions with ad hoc forwarding and its effect on network topology and the achieved throughput. They show that in order for the total capacity to scale up with network size, the average distance between the end-to-end source and destination nodes must remain small as the network grows. In [9] the authors propose a methodology to compute the maximum end-to-end achievable throughput of a given flow in a multi-hop wireless network based on the contention graph. The graph represents the interference from both neighbor and hidden nodes. The channel idle probability and the collision probability of a node are derived to yield a set of fixed point equations for the individual link capacities. The end-to-end throughput is obtained from the individual link capacities.

An experimental test bed based throughput estimation study is presented in [8] for multi-hop mesh networks with emphasis on admission control for quality of service routing. The algorithm is based on assigning different priorities to the probe packets using the IEEE 802.11e standard. The first packet is assigned the highest priority compared to all the other data packets in the network and the second probe packet is generated with the lowest priority. The dispersion of the probe packets reflects the on-going data traffic rate in the network and is used to estimate the available bandwidth of the path. A simulation study on the packet pair based estimation technique for ad hoc networks is presented in [21]. Adhoc Probe is a technique to measure the path capacity in the absence of competing traffic. It is based on the combination of delay and dispersion based techniques similar to [15]. OWD measurements are used instead of round trip times to account for the asymmetry in wireless channels. Probing packet pairs of fixed sizes are sent back-to-back from the sender to the receiver. The sending time is stamped on every packet by the sender. The OWD is measured at the receiver as the difference between the reception time and the sending time stamp and capacity estimation is performed at the receiver using Eq. 2. The algorithm is based on the theory that among all the injected probe packets, the probe sample corresponding to the minimum OWD sum is the pair that has not been interrupted by the cross traffic in the network and will yield an accurate estimate. Hence the dispersion of the pair with minimum OWD is used in the capacity estimations.

Among the capacity, throughput, and bandwidth estimation techniques illustrated above, in [8] and [21] are discussions of the active probing based estimation techniques for wireless multi-hop networks. A packet pair based approach is described in [8] to estimate the available bandwidth of the path. As discussed above, the algorithm involves assigning different priorities to individual probe packets and is based on the IEEE 802.11e standard. The practical implementation of this solution in existing off-the-shelf devices requires the support for 802.11e, hence this makes this approach less interoperable. On the other hand, we will show that our delay distribution based approach can be adopted with ease.

Though Adhoc Probe claims to measure the path capacity, it is in fact the achievable throughput that is estimated by the algorithm. This can be seen from the results in [21]. The measured path capacity is shown to vary with the probe packet sizes and the overload resulting from RTS/CTS data exchange indicating that the network attribute estimated is the achievable throughput of a path when a packet of fixed size is transmitted from the source to the destination. The accuracy of the throughput estimated by Adhoc Probe is analyzed is this thesis by observing the end-to-end delays of the probe packets. It is shown that medium access control contention and queuing behavior of the network affects the throughput estimation and Adhoc Probe always over estimates the achievable throughput of the path. Chapter 3 illustrates these limitations in depth and discusses the reasons for throughput over estimation with possible improvement opportunities.

CHAPTER 4

LIMITATIONS OF ADHOC PROBE AND OPPORTUNITIES FOR IMPROVEMENT

4.1 *Adhoc Probe Estimation*

The Adhoc Probe algorithm is a packet pair based technique to estimate the path capacity of wireless network. Given an empty multi-hop wireless network, probe pairs are transmitted back-to-back into the network from a source node to the destination node. The sender time stamps the packets before transmission. The receiver extracts the sender timestamps and records the reception time of the probes. The one way delay of a probe packet is calculated by the receiver as the difference between the reception time of the packet and the sender’s timestamp. The sum of the one way delays of both the packets of a probe pair is referred to as the delay sum. The probe samples are filtered to identify the packet pair with minimum delay sum. The dispersion of this packet pair is used in Eq. 2 to calculate the path capacity. The estimated value was observed to be closer to the achievable throughput of the path. Adhoc probe sends probing packets with the packet size of P bytes at 2*P*R bytes/seconds where R is the number of packet pairs generated per second.

The correctness and accuracy of this algorithm can be validated by employing a network flooding based approach. This method involves estimation of the achievable end-to-end throughput of a path by flooding a network with data packets and by measuring the throughput achieved at the destination node. UDP packets with constant or exponential inter-arrival times are generated by the source node at an input rate equal to the maximum achievable throughput estimated by the Adhoc Probe algorithm and the achieved throughput is measured as the amount of data received at the destination node per unit time.

Adhoc Probe and the flooding approach were implemented in ns-2 and simulations were carried out for a single linear multi-hop network with a single source. Fig. [4.1-4.6] shows the achievable throughput estimated by Adhoc Probe and measured by flooding the network using data packets with constant and exponential inter-arrival times. The simulations were performed for channel bandwidths of 2 Mbps and 11 Mbps to verify the consistency of the results. The Adhoc Probe simulations were repeated for variable probe packet sizes. It is observed from the results presented that the estimated achievable throughput depends on the probe packet sizes. This behavior is attributed to the physical and MAC layer overheads associated with the probe packet. Simulations using flooding approach were also repeated for variable size data packets.

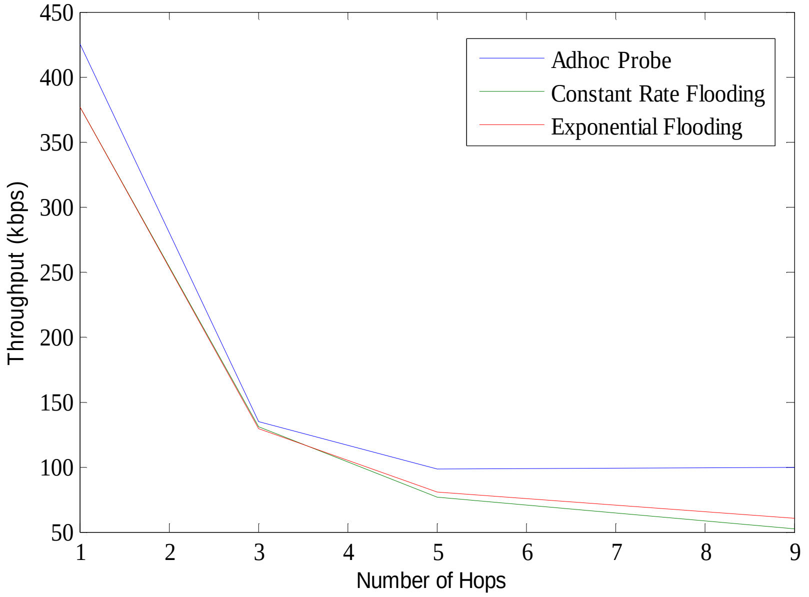

Figure 4.1: Throughput Measurements of a 2Mbps Channel for Packet Size of 100 Bytes

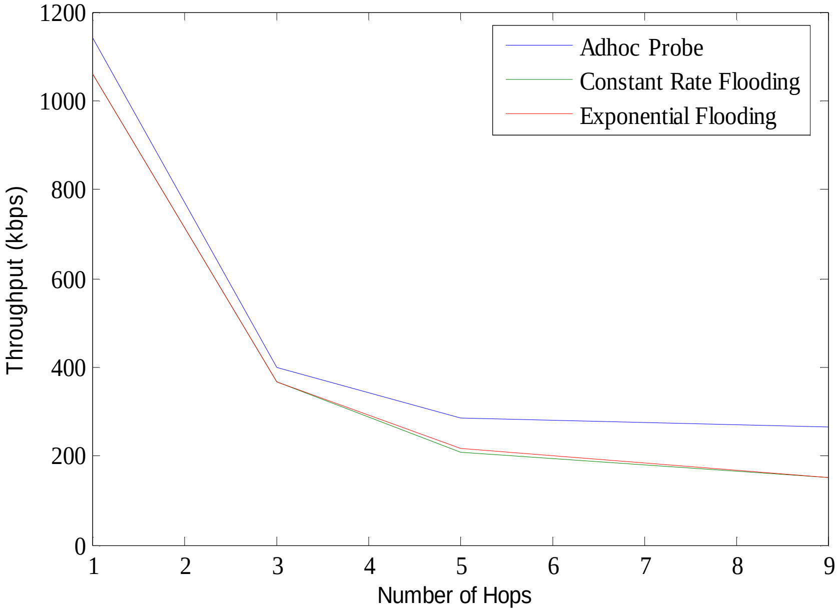

Figure 4.2: Throughput Measurements of a 2Mbps Channel for Packet Size of 500 Bytes

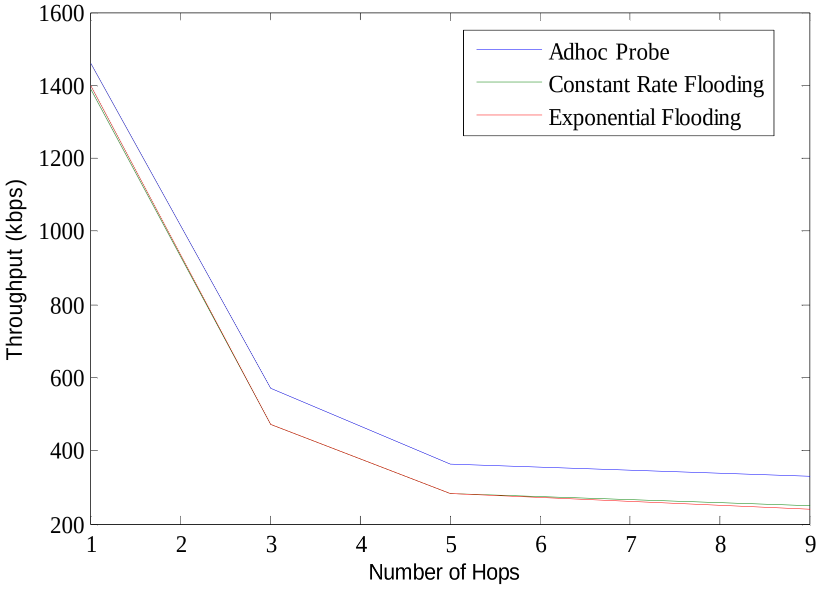

Figure 4.3: Throughput Measurements of a 2 Mbps Channel for Packet Size of 1000 Bytes

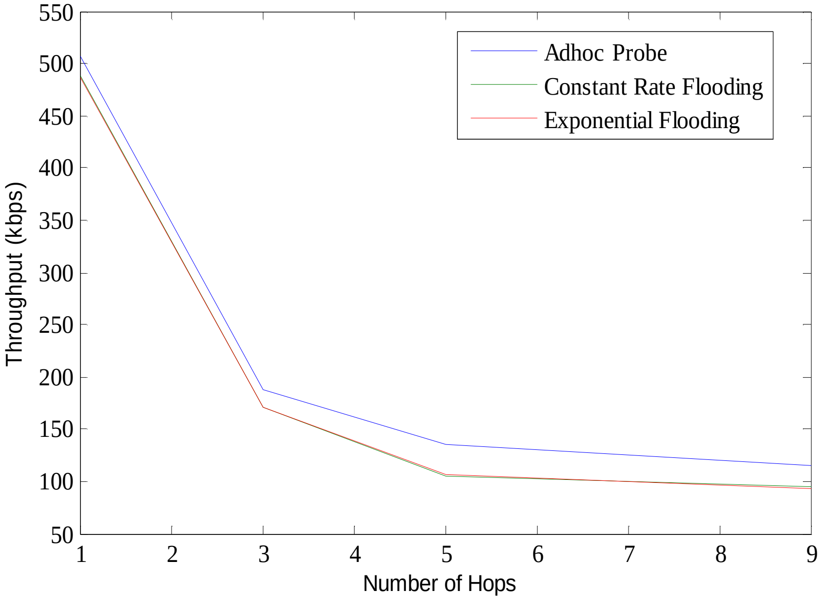

Figure 4.4: Throughput Measurements of an 11 Mbps Channel for Packet Size of 100 Bytes

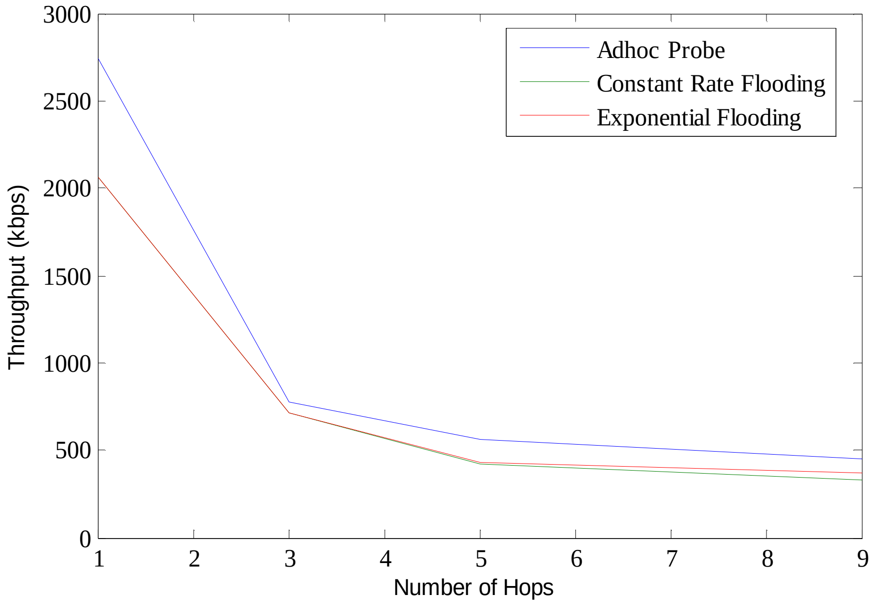

Figure 4.5: Throughput Measurements of an 11 Mbps Channel for a Packet Size of 500 Bytes

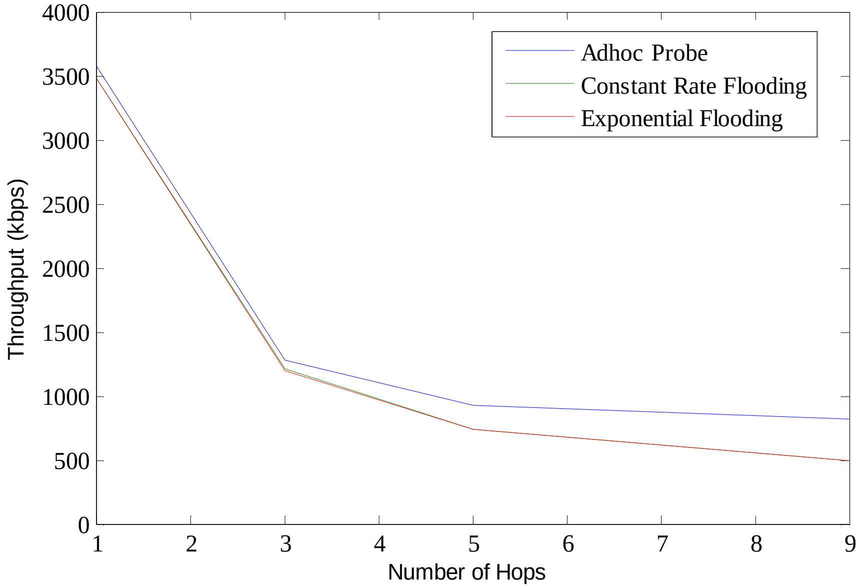

Figure 4.6: Throughput Measurements of an 11 Mbps Channel for a Packet Size of 1000 Bytes

It is observed from the graphs that for a given multi-hop wireless network with no additional competing traffic, the maximum achievable end-to-end throughput of a path measured by the flooding approach is always lower than the throughput estimated by the Adhoc Probe algorithm. UDP packets are transmitted by the source node at the input rate estimated as the achievable throughput by Adhoc Probe and the average fraction of packet loss were measured at the destination node as shown in Table 4.1 and 4.2. These losses become very significant in long run under steady state conditions and affect the reliability of the network.

Table 4.1: Average Loss Rate of 500 Byte Data Packets Transmitted on a 2 Mbps Channel

Number of Hops	Data Rate / Throughput Estimated by Adhoc Probe (bps)	Average Loss Rate
1	1.14M	.0166
3	400k	.009
5	285k	.141
9	266.6k	.414

Table 4.2: Average Loss Rate of 500 Byte Data Packets Transmitted an 11 Mbps Channel

Number of Hops	Data Rate / Throughput estimated by Adhoc Probe (bps)	Average Loss Rate
1	2.73M	.019
3	776.7k	.211
5	563.4k	.225
9	451.46k	.259

4.2 *Reasons for Throughput Overestimation*

The discrepancy in the throughput estimated by the approach adopted by Adhoc Probe is attributed to the queuing behavior associated with the data packets in the network. The probe sample with minimum one way delay corresponds to the packet pair that has not been interrupted and queued long in the network. On the other hand, it was observed from the flooding based approach discussed in the previous section that the average dispersion of the UDP packets is higher than the dispersion corresponding to the packet pair with minimum OWD implying that most of the packets are queued in the network. Hence the dispersion used by Adhoc Probe to calculate the throughput does not reflect the overall behavior of the network and results in inaccurate throughput estimates. This phenomenon is illustrated in this section for specific scenarios. The delay distribution of the probe packets showing the dispersion of the probe samples are presented in Fig. [4.7- 4.12] for Adhoc Probe and the flooding based approach with constant inter arrival time for 500 byte sized probe packets. The dispersion of 100 packets presented in Fig. 4.8 for a flooding based approach are from different time periods as compared to the Adhoc Probe method.

Consider the case of a single hop wireless network with no additional cross traffic along the path.

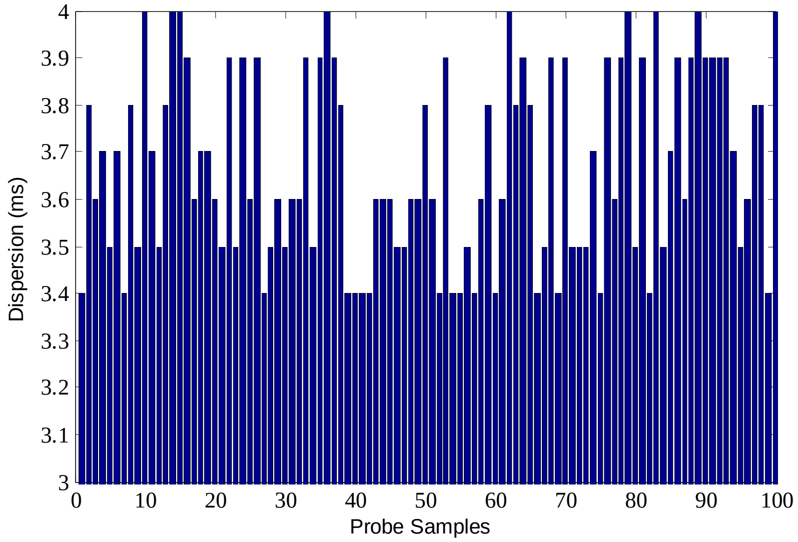

Figure 4.7: Dispersion of Probe packets in a Single Hop Network using Adhoc Probe

Dispersion corresponding to the packet pair with minimum one way delay = 3.5 ms

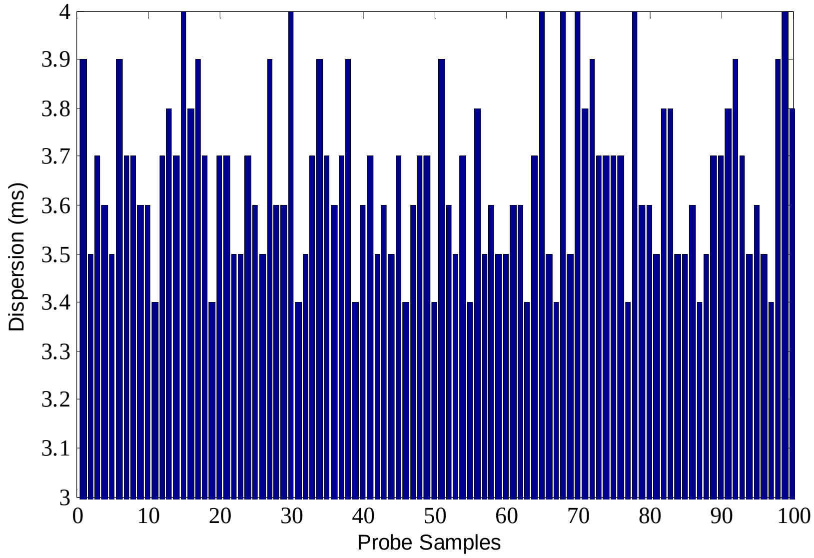

Figure 4.8: Dispersion of Probe packets in a Single Hop Network using Flooding Approach

Average Dispersion of all Probe Packets = 3.73 ms

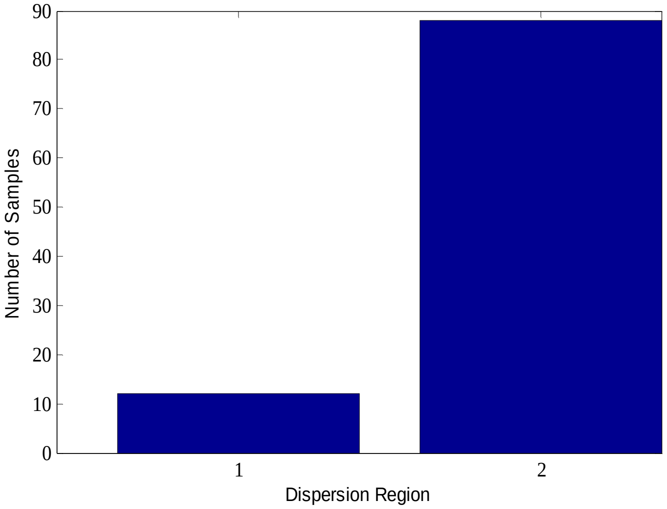

Figure 4.9: Delay Distribution of Probe packets for a Single Hop Network

Region 1 – Probe samples with dispersion less than 3.5 ms

Region 2 – Probe samples with dispersion greater than 3.5 ms

Based on the Adhoc Probe throughput estimation technique, the packet pair corresponding to the minimum one way delay has a dispersion value of 3.5 ms. The delay distribution of the flooding approach in Fig. 4.8, shows an average dispersion value of 3.73 ms experienced by the packets which is greater than the minimum dispersion used by Adhoc Probe in throughput estimation. Fig. 4.9, shows that an average of 88% of the probe packets transmitted on the network experience dispersion greater than 3.5 ms.

The difference in the dispersion values is more prominent in a multi-hop network. Consider the case of a 5-hop network with no additional cross traffic along the path.

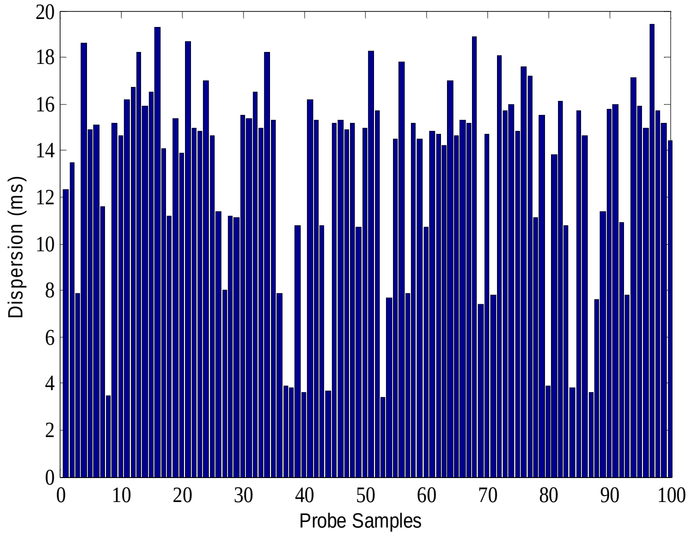

Figure 4.10: Dispersion of Probe packets in a 5-Hop Network using Adhoc Probe

Dispersion corresponding to probe pair with minimum one way delay = 14.1 ms

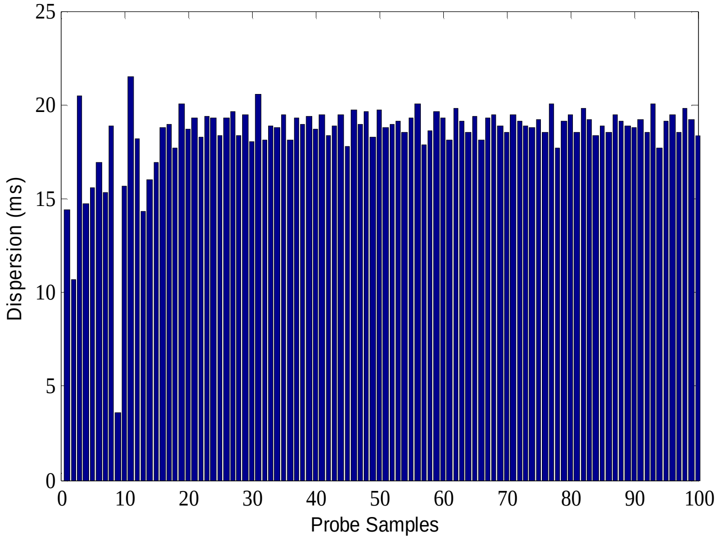

Figure 4.11: Dispersion of Probe packets in a 5-Hop Network using Flooding Approach

Average Dispersion of all Probe Packets = 19.04 ms

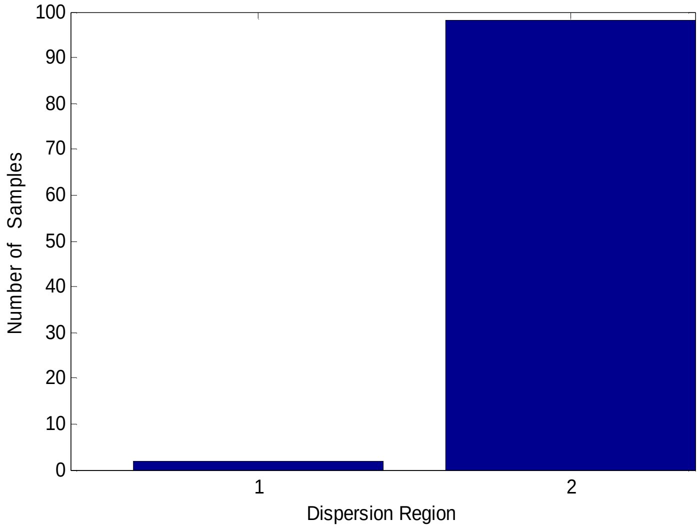

Figure 4.12: Delay Distribution of Probe packets for 5-Hop Network

Region 1 – Probe samples with dispersion less than 14.1 ms

Region 2 – Probe samples with dispersion greater than 14.1 ms

Fig. 4.12 shows that 98% of the probe packets have dispersion greater than the dispersion used by Adhoc Probe in the throughput estimation. The average dispersion value for the flooding approach is 19.04 ms as shown in Fig. 4.11. An example calculation estimating the throughput of the path from the observed dispersion value according to Eq. 2 is shown below.

Average dispersion observed for a 5-hop network using Flooding Approach = 19.04 ms.

*Achievable Throughput of the path = (500*8)/19.04 ms for 500 Byte probe packet.*

Throughput = 210 kbps.

This value is consistent with the throughput measured by flooding based approach.

The effect of queuing behavior of the probe packets on the measured dispersion value can be explained with the transmission and reception timestamps of the probe packets at individual nodes. In the 5-hop network discussed in this section, the dispersion used by Adhoc Probe in throughput estimations is 14.1 ms and the flooding based approach uses an average dispersion value of 19.04 ms to calculate the maximum achievable throughput of the path. Timestamps were recorded for each probe packet when they arrive at a node, i.e., the received timestamp, and when they were sent by a node, i.e., the sent time stamp. Based on these timestamps, the queuing delay of probe packet at each node is calculated as the difference between the sent time stamp and the received time stamp. Tables 4.3 and 4.4 shows the queuing delays of the first and second packet of the probe pair at each node.

Table 4.3: Queuing Delays of the First Packet of the Probe Pair at each Node

Node	Queuing Delay with Adhoc Probe (ms)	Queuing Delay with Flooding Approach (ms)
1	1.2	4.7
2	1.2	1.5
3	1.6	1.1
4	1.6	1.1

Table 4.4: Queuing Delays of the Second Packet of the Probe Pair at each Node

Node	Queuing Delay with Adhoc Probe (ms)	Queuing Delay with Flooding Approach (ms)
1	2.3	21.4
2	1	1.3
3	1.1	1.1
4	0.9	1.5

The observations reflect that the queuing delay of most of the probe packets at individual nodes is less than 2 ms for Adhoc Probe and Flooding based approach. However, in the case of flooding approach the probe packets experience a greater delay at node 1. The first packet of the probe is queued at node 1 for 4.7 ms and the second packet of the probe suffers a significantly higher queuing delay of 21.4 ms. This larger delay experienced by the second packet of the probe pair clearly increases the dispersion of the probe sample in flooding approach.

The key contribution of this section is that for a multi-hop wireless network, the achievable end-to-end throughput of a path cannot be accurately estimated from the dispersion of the packet pair with minimum delay. The queuing behavior associated with the network should be taken into consideration while designing the network metrics estimation techniques.

4.3 *Improvement Opportunities*

The previous section illustrates that when a network path is flooded, the measured average dispersion of the probe samples gives the achievable end-to-end throughput of a path. In this section we study the possibility of reproducing the queuing behavior similar to the flooding approach using a less intrusive packet train based technique. The method involves an iterative transmission of probe samples of increasing probe train lengths from source to destination. The delay distribution of the probe packets are monitored for all the iterations to identify the presence of a dispersion peak that will accurately estimate the maximum achievable end-to-end throughput of the path when used in Eq. 2. Consider the example of a 5-hop network discussed in the previous section. The four iterations discussed below were carried out by changing the probe train length while keeping the other parameters related to the dispersion of the packets such as probing rate, interval between the transmission of the probe samples and size of the data packets fixed.

Iteration 1

Samples of two back-to-back probe packets are injected in to the network and the distribution of the dispersion of probes packets is shown in Fig. 4.13.

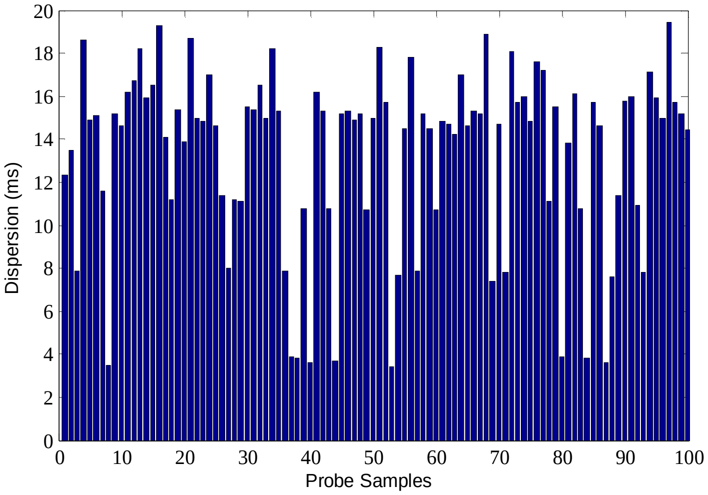

Figure 4.13(a): Packet Pair Based Dispersion Samples

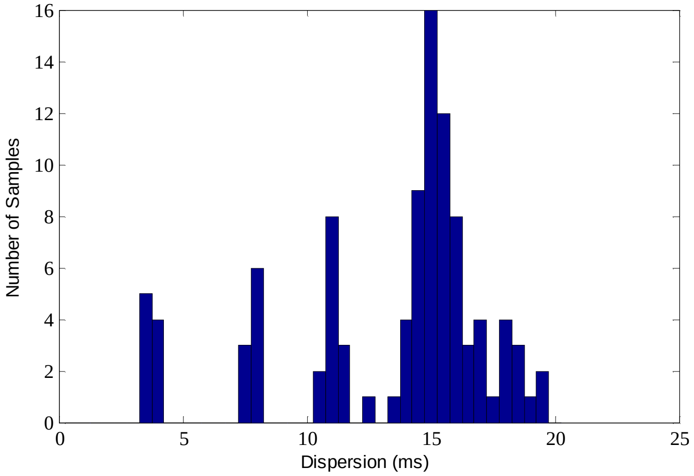

Figure 4.13(b): Packet Pair Based Delay Distribution

Fig. 4.13(a) shows the dispersion of all the probe samples in a 5-hop network and the presence of peaks among the dispersion of the probe samples is shown in Fig. 4.13(b). The bin size for the distribution is chosen based on the required resolution. Further statistical analysis is needed to understand the dependency of the presented results on the chosen bin size. The dominant dispersion corresponds to the highest peak observed from the graph and occurs due to the queuing of the second packet of the probe pair resulting in an expansion of the dispersion. The dominant dispersion thus has an average value of 15.5 ms. It was earlier observed from the flooding based approach that the average dispersion of 19.04 ms accurately estimates the achievable throughput of a 5-hop network. Hence the dominant dispersion induced by the packet pair technique does not reflect the maximum achievable end-to-end throughput of the path.

Iteration 2

Samples of probe train of 3 back-to-back packets are sent in to the network. The observed delay distribution in Fig. 4.14(b) shows the highest peak with an average of 17.5 ms. This value does not accurately estimate the achievable throughput of the path but provides a significant improvement over the packet pair technique.

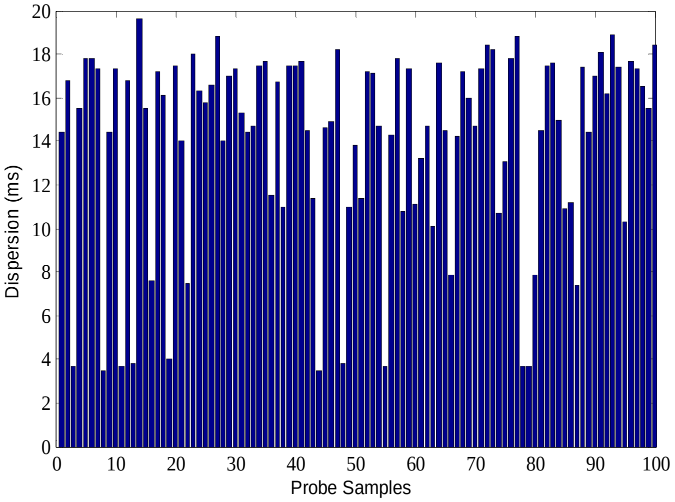

Figure 4.14(a): Dispersion Samples of Probe Train with 3 packets

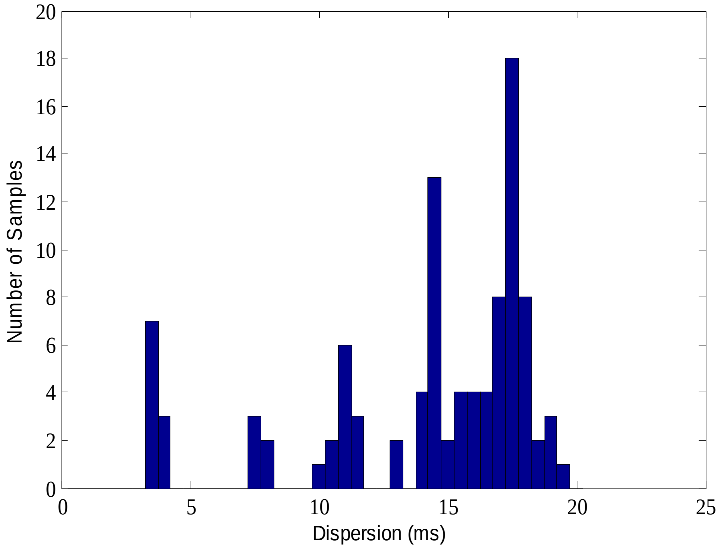

Figure 4.14(b): Delay Distribution of Probe Train with 3 packets

Iteration 3

Consider a probe train with 4 back-to-back packets sent into the network. Fig. 4.15(a) shows the dispersion of the probe samples. The delay distribution of the probe samples in Fig. 4.15(b) show a dominant dispersion with an average of 18.3 ms which gives a closer though not accurate estimate of the achievable throughput using Eq. 2 compared to a probe train with 3 packets.

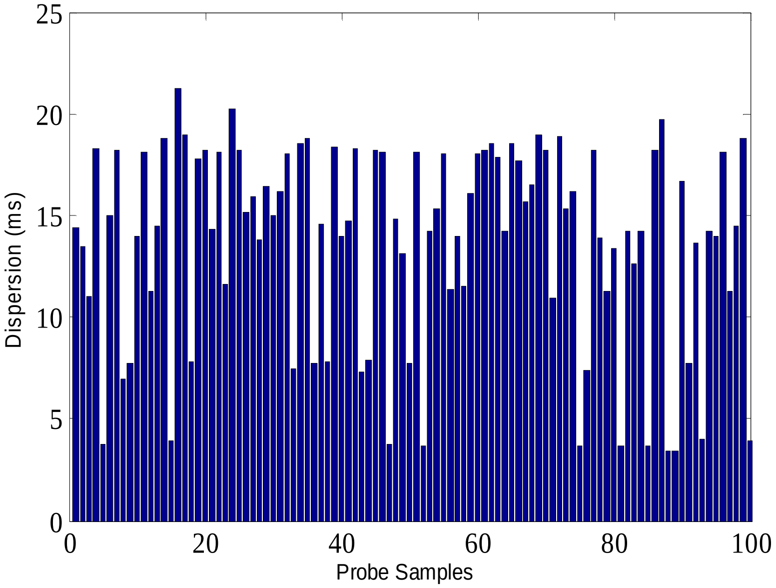

Figure 4.15(a): Dispersion Samples of Probe Train with 4 Packets

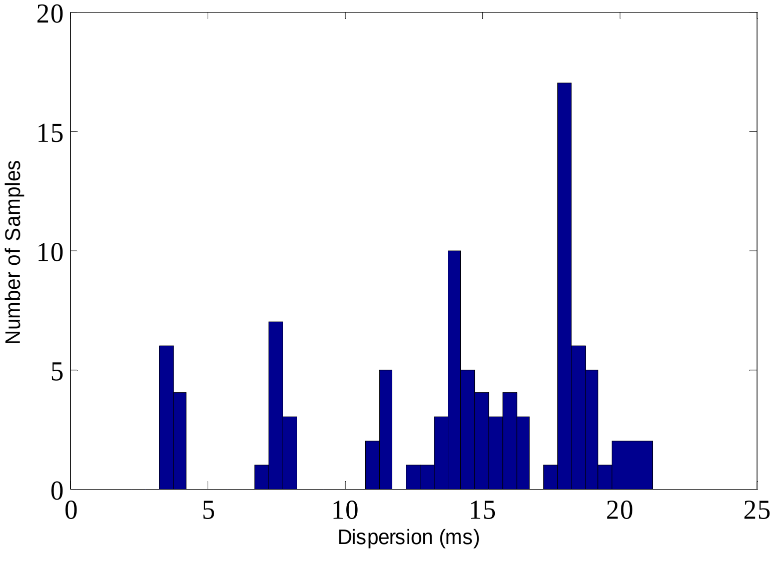

Figure 4.15(b): Delay Distribution of Probe Train with 4 Packets

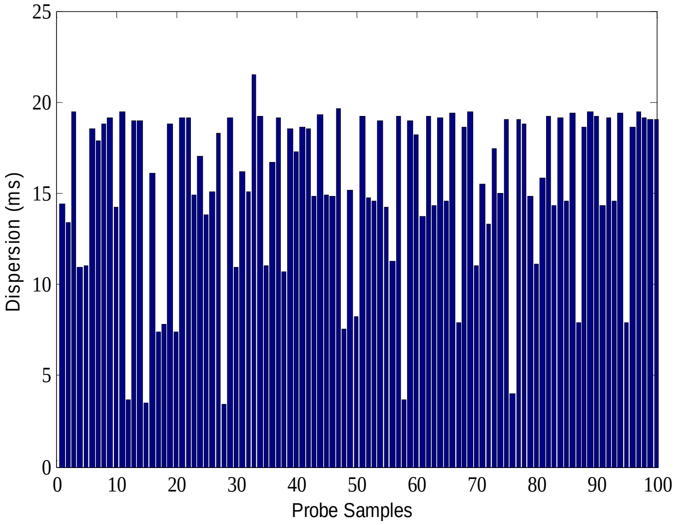

Figure 4.16(a): Delay Samples of Probe Train with 5 Packets

Iteration 4

The dispersion of the probe samples is shown in Fig. 4.16(a) and the delay distribution of probe train of 5 back-to-back packets is shown in Fig. 4.16(b).

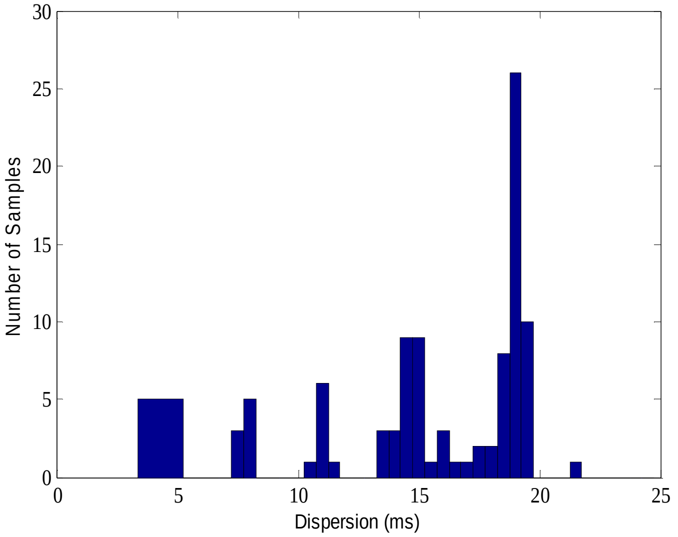

Figure 4.16(b): Delay Distribution of Probe Train with 5 Packets

The dominant dispersion as seen from Fig. 4.16(b) has an average dispersion of 19.04 ms. This value equals the average dispersion value measured based on the flooding approach for a 5-hop network and results in the accurate estimation of achievable throughput of the path and is therefore referred to as the achievable throughput dispersion.

A queuing behavior similar to that of the flooding based approach can therefore be induced with the help of a less intrusive probing pattern. For the proposed maximum achievable end-to-end throughput estimation method’s purpose, the achievable throughput dispersion is always defined as the highest peak’s dispersion value which is dominant among the probe packets injected in to the network.

CHAPTER 5

DELAY DISTRIBUTION BASED ACHIEVABLE THROUGHPUT ESTIMATION

5.1 *Problem Statement*

This research studies the problem of probe based estimation of maximum achievable end-to-end throughput in a WMN with different traffic loads. Specifically, a probing method with very limited probe traffic is developed to reproduce the queuing and medium contention behavior along a network path similar to the real flooding UDP traffic, such that the probes' delay distribution contains a peak that corresponds to the maximum achievable end-to-end throughput of the path. The proposed solution is less intrusive and accurately estimates the achievable throughput of the path irrespective of the cross traffic conditions.

5.2 *Network Model*

The network model consists of the IEEE 802.11 based wireless users or stations distributed in a fashion that establishes mesh connectivity with each other. Each station helps in relaying traffic from neighbor nodes to the respective destination nodes. The distance between the wireless nodes is such that every node is at least in the transmission range of one of the nodes. The communication between the nodes is considered to be omni-directional. The medium access control layer interactions are based on the IEEE

802.11 RTS/CTS Distributed Coordination Function (DCF) mode. The CSMA/CA protocol aids the random access mechanism with an exponential collision back-off algorithm. The carrier sensing range of the wireless nodes is twice the transmission range. The nodes identify and communicate with each other using an ad hoc mesh routing protocol.

5.3 *Delay Distribution Based Achievable Throughput Estimation Technique*

Given an ad hoc multi-hop wireless mesh network with varying traffic loads, an accurate and less intrusive, variable length packet train based solution is presented in this thesis for estimating the maximum achievable end-to-end throughput of the path. Consider K groups of N probe packets sent back-to-back every S seconds. The value of N determines the length of the probe train. The probe packets are time stamped at the sender before transmission. The time stamp is extracted at the receiver and dispersion between the probe samples is calculated as the difference between the reception times of the first and the next probe packet. The delay distribution of the probe samples is analyzed to identify the presence of a peak corresponding to the achievable throughput dispersion along the network path. The average of the dispersion values of the probe samples belonging to this peak is used to estimate the maximum achievable throughput C bps according to Eq. 3.

$$C = P / D \tag{3}$$

where P corresponds to the probe packet size in bits and D is the average dispersion of probe samples in seconds associated with the achievable throughput dispersion. Note its similarity with Eq. 2 in Ch. 2.

The performance of the estimation technique depends on the protocol parameters K, N and S. The number of probe samples K and the probe train length N must be chosen based on the network topology and the number of hops in the estimation path. Higher the number of hops, greater is the length of the probe train. The value of N should be large enough to reproduce the queuing behavior of the flooding approach and at the same time should not result in network congestion. The interval between the probe trains is defined as the time between the transmission of the first packet of consecutive trains and is given by Eq. 4

$$S = N * P / R \tag{4}$$

where R is the mean probing rate in bits per second. The probing interval S should be significantly greater than the per hop latency to avoid collisions among the probe packets.

CHAPTER 6

SIMULATION STUDIES

The proposed maximum achievable end-to-end throughput estimation method was studied using network simulator, ns-2.31[26]. Multi-hop wireless mesh networks based on IEEE 802.11 were simulated. IEEE 802.11 protocol parameters used in the simulations are listed in Table 6.1.

Table 6.1 IEEE 802.11 Parameters

Parameter	Value
Slot time	20us
SIFS	10us
DIFS	50us
CWmin	31
CWmax	1023
Retransmission limit	7
Propagation model	TwoRayGround
Channel Bandwidth	2 Mbps

6.1 *Network Topologies*

The network topology consists of IEEE 802.11 based wireless nodes distributed in linear and grid fashion as shown in Fig. 6.1 and 6.2 to form a variable hop mesh network. The nodes are placed at a distance of 200m from each other. The transmission range of the nodes was set to 250m and the career sensing range was set to 500m, twice the transmission range. The routing policy is based on Ad hoc On-Demand Distance Vector (AODV) protocol. A probe packet generation agent is attached to the source node and a receiver agent is attached to the destination node.

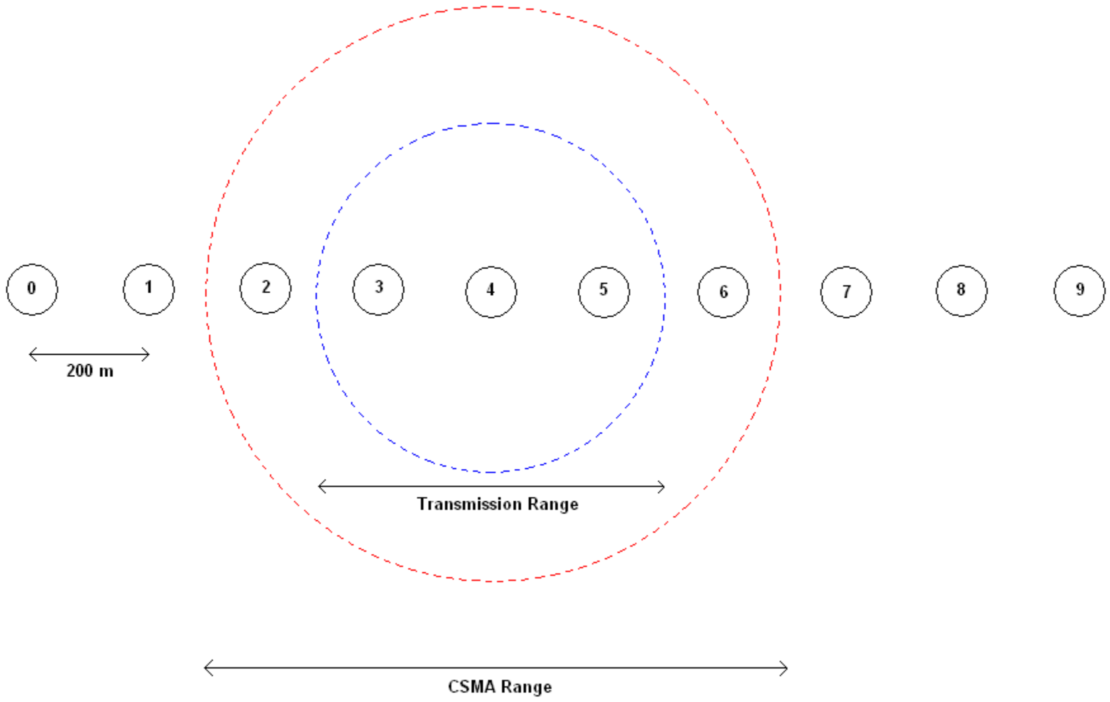

Figure 6.1: Linear Mesh Topology

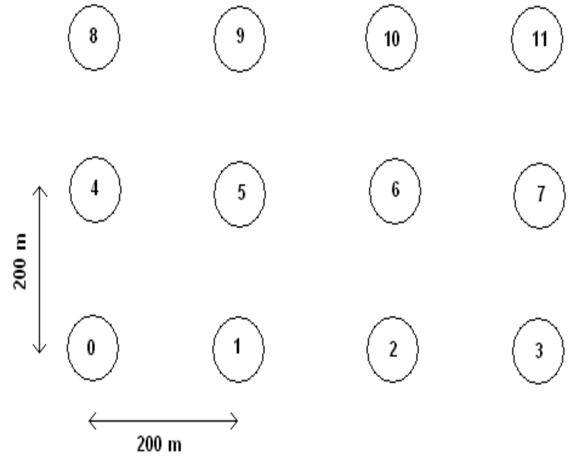

Figure 6.2: Grid Topology

6.2 *Simulation Parameters*

Packet pairs (PP) and packet trains are generated in ns-2 using a *constant bit rate* source generator by specifying the number of back-to-back packets injected into the network by the source node. The mean rate of the probe generator source is set by the rate parameter.

For the various simulation scenarios discussed in this section the buffer size of each node was unaltered and was to set to 50, the ns-2 default limit. Though the end-to-end delay of a packet in a network depends on the queuing delay, in this simulation we study the dispersion of the probes which is calculated as the difference between the reception times of the probes and does not change with the queuing delay. Hence the change in the buffer limit of a node will not affect the throughput estimations.

Simulations were carried out for a probe packet size of 500 bytes at a probing rate of 100 kbps. The interval between the probing for a packet pair based approach is

$$2*(500*8)/100000 = 80ms$$

according to Eq. 4 and is significantly greater than the per hop latency of the network.

6.3 *Linear Networks with No Cross Traffic*

Linear mesh network topology in Fig. 6.1 is considered with no additional cross traffic along the path. Probe packets of variable length are generated from source, node 0 to destination, based on the number of hops to estimate the achievable end-to-end throughput of the path. The simulations presented show that the injected probe train induces peaks in the probe packet dispersions and one of the peaks correspond to the achievable throughput dispersion which accurately estimates the end-to-end throughput of the path using Eq. 3.

6.3.1 *Single Hop Linear Network with No Cross Traffic*

A single hop wireless network with no additional competing traffic along the path is constructed with two nodes. The length of the probe train required to accurately estimate the end-to-end throughput depends on the number of hops in the path. Hence probe trains of length 2 are generated from node 0 to node 1 to estimate the maximum achievable throughput of a single hop network. The delay distribution of the probe samples shown in Fig. 6.3 indicate a peak corresponding to 3.7 ms. The average dispersion value of the probe samples forming the peak was measured to be 3.73 ms. It is observed that the dispersion of all the probe samples is distributed around the average value. The achievable throughput of the path estimated using Eq. 3 is thus

$$4000 / .00373 = 1.072 Mbps$$

This value is consistent with the achievable throughput estimated by the flooding approach discussed in Chapter 4. Hence the packet pair based throughput estimation technique results in an average dispersion value that accurately estimates the maximum achievable throughput of a path for a single hop network.

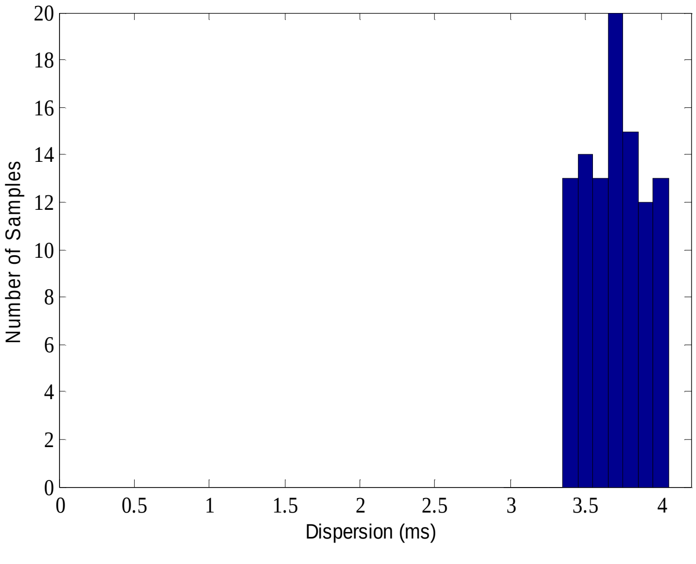

Figure 6.3: Delay Distribution of a Single Hop Network

6.3.2 *Three Hop Linear Network with No Cross Traffic*

Consider a 3-hop network with packet pairs generated from node 0 to node 3.The resulting average dispersion of the probe samples is found to be 8.09 ms. This does not reflect the behavior of the flooding approach and over estimates the throughput as 494.43 kbps according to Eq. 3. The length of the probe train is therefore increased to 3 to induce the dispersion peak similar to the flooding based approach. The delay distribution of the samples is shown in Fig. 6.4 for a probe train of length 3. The overall average dispersion of all the probe packets is observed to be 9.3 ms. The delay distribution shows a peak corresponding to the achievable throughput dispersion with an average value of 10.9 ms resembling the queuing behavior of the flooding technique.

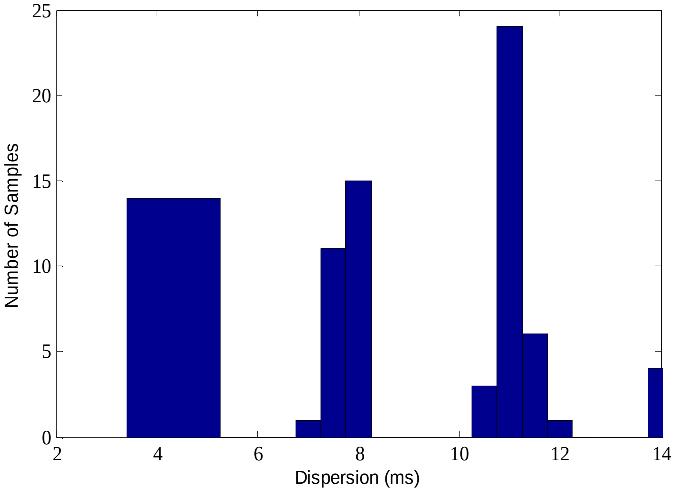

Figure 6.4: Delay Distribution of a 3-Hop Network

Average Distribution of all Samples = 9.3ms

The achievable end-to-end throughput of the path calculated using Eq. 3 is consistent with the throughput estimations shown in Fig. [4.1 - 4.3].

$$4000 / .00109 = 366.9 kbps$$

6.3.3 *Five Hop Linear Network with No Cross Traffic*

Packet trains with probe length of less than 5 packets were used to estimate the throughput of the path. It was found from the delay distribution that the dispersion values of the probe packets do not reflect the queuing and medium access control contention behavior of a heavy loaded network. The probe length was increased to 5 and the simulation was repeated. The resulting delay distribution is shown in Fig. 6.5.

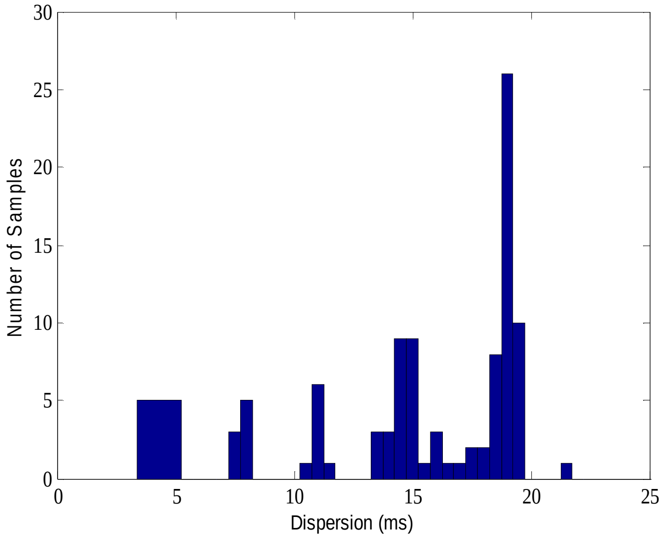

Figure 6.5: Delay Distribution of a 5-Hop Network

Overall Average Dispersion = 16.5 ms

The graph shows the presence of a dominant achievable throughput dispersion peak centered on an average dispersion value of 19.1 ms resulting in an achievable throughput of 210 kbps according to Eq. 3.

6.3.4 *Nine Hop Linear Network with No Cross Traffic*

Probe trains of 5 back-to-back packets sent at any instant of time provides an accurate estimate of the maximum achievable throughput of the path for a nine hop wireless network. The distribution of the dispersion of the probe packets is shown in Fig. 6.6.

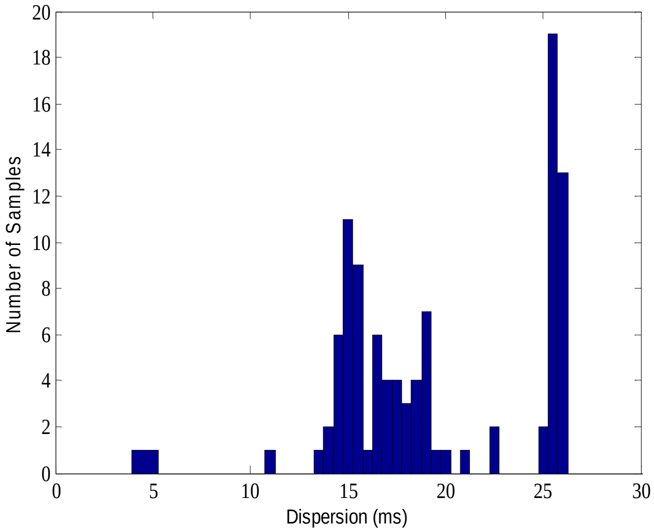

Figure 6.6: Delay Distribution of a 9-Hop Network

Overall Average Dispersion = 18.8 ms

The achievable throughput dispersion has an average value of 26 ms which estimates the throughput of the path as 153.84 kbps according to Eq. 3.

6.3.5 *Overall Observations*

For a variable hop mesh network, light weight probe trains injected into the network induce the achievable throughput dispersion which corresponds to the highest peak among the dispersion of probe samples. The solution is light weight as the number of probe samples injected is set to a constant value of 100 and does not involve infinite probing. Probe train of less than 5 back-to-back packets are sufficient to reproduce the medium access contention and network queuing behavior similar to flooding approach for wireless networks with less than 5 hops along the path. Simulations were repeated for increasing hops and the observed delay distributions showed a consistent highest peak reflecting the maximum achievable throughput of the path. Though the length of the probe train required to accurately estimating the end-to-end throughput increases with the number of hops, a probe length of 5 was verified to be a good choice for up to 15 hops in the path.

6.4 *Linear Network with Cross Traffic*

The performance of the proposed probe train based achievable throughput estimation technique was studied for networks with additional competing data flows present with the probe traffic. The data rate of the cross traffic in the simulation was chosen to be more than half the rate of the maximum achievable throughput estimated in order to increase the probability of the dispersion of the probe samples being affected by the presence of cross traffic. The simulations presented below show that the probe train of 2 back-to-back packets are sufficient to induce the queuing behavior similar to the flooding approach in networks with significant cross traffic. The analysis of the delay distribution identifies the existence of yet another distinct peak along with the achievable throughput dispersion. This peak is found to accurately estimate the available bandwidth of the path when used in Eq. 3.

6.4.1 *Single Hop Linear Network with Cross Traffic*

Consider a single hop network with constant bit rate traffic of 800 kbps flowing between node 0 and node1.It is illustrated from the previous sections that the maximum achievable end-to-end throughput of the path for a single hop wireless network with a channel bandwidth of 2 Mbps and data packet size of 500 Byes is 1.07 Mbps. In order to validate the packet train based throughput estimation technique in the presence of a competing traffic, probe trains of length 2 are generated from node 0 to node 1. The delay distribution of the probe samples is shown in Fig. 6.7.

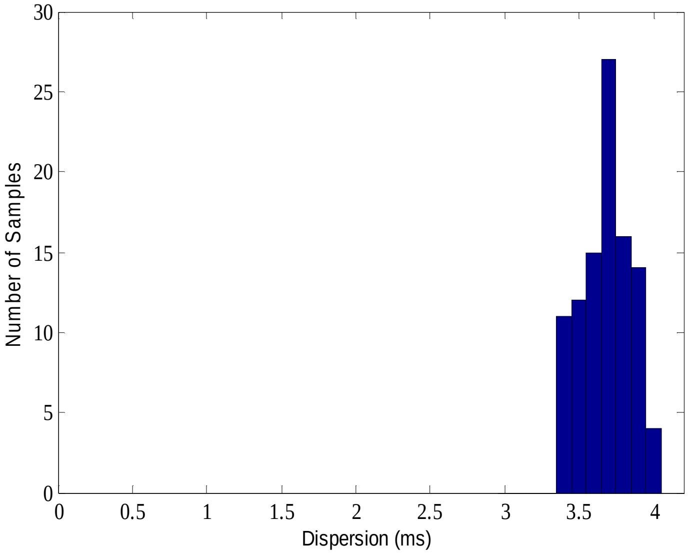

Figure 6.7: Delay Distribution of Single Hop Network with Cross Traffic of 800 kbps

The dispersion of the probe samples as seen from Fig. 6.7 are very similar to the distribution observed for a single hop network with no additional traffic along the network path. The dispersion corresponding to 3.7 ms is dominant and results in a consistent throughput value of 1.07 Mbps based on Eq. 3.

6.4.2 *Three Hop Linear Network with Cross Traffic*

A CBR traffic source of 200 kbps is generated between node 0 and node 3 and packet pairs are generated to probe the network to measure the end-to-end throughput of the path. The delay distribution of probe samples is shown in Fig. 6.8 .

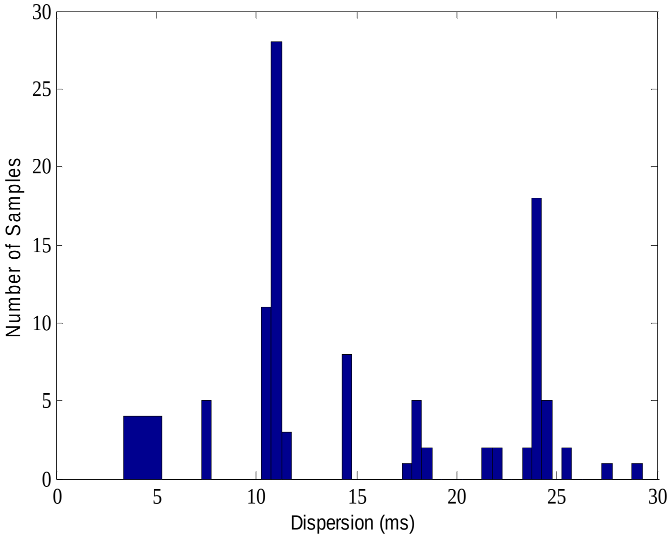

Figure 6.8: Delay Distribution for a 3-Hop Network with Cross Traffic of 200 kbps

The dominant dispersion with the highest peak corresponds to the average value of 11 ms. This value plugged into Eq. 3 gives the achievable end-to-end throughput of the path.

$$4000 / .011 = 363.63 kbps$$

Unlike the three hop network with no additional traffic, in this case the delay distribution shows another significant peak with an average value of 24 ms. This value plugged in Eq. 3 results in a throughput of

$$4000 / .024 = 166.66 kbps$$

Given a mean cross traffic rate of 200 kbps and the achievable end-to-end throughput of the path of 363.6 kbps the available bandwidth is calculated as

(363.63 – 200) kbps = 163.63 kbps according to the definition. These calculations show that the throughput estimated by the peak corresponding to an average value of 24 ms closely estimates the available bandwidth of the path.

6.4.3 *Five Hop Linear Network with Cross Traffic*

Consider a CBR source of 100 kbps transmitted from source node, node 0 to the destination node, node 5 of a 5-hop network. The delay distributions corresponding to the packet pairs in Fig. 6.9 identify the distinct dispersion peaks associated with the probe samples. The highest peak corresponds to an average value of 19.1 ms resulting in a maximum achievable throughput of 210 kbps using Eq. 3 and is consistent with the throughput estimated for a 5-hop network with no additional data traffic in the network path. The second largest dispersion peak has an average value of 36 ms and results in a throughput estimate of 111.11 kbps. The available bandwidth of the path is calculated as difference between the maximum achievable throughput and the cross traffic rate (210 – 100) kbps = 110 kbps which is estimated by the peak corresponding to the average value of 36 ms.

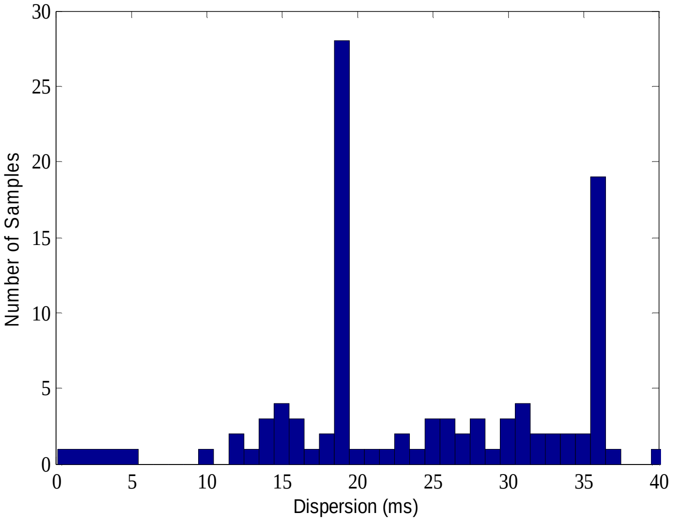

Figure 6.9: Delay Distribution of probe samples for a 5-hop Network with CBR traffic of 100 kbps

6.4.4 *Overall Observations*

It is observed from the simulation scenarios discussed above that packet pairs injected into the network induce two significant dispersion peaks. The peak associated with the largest dispersion value estimates the available bandwidth of a network path carrying cross traffic using Eq. 3. The calculations presented in this section verify the accuracy of the estimations.

6.5 *Grid Network with Cross Traffic*

The multi-hop grid topology shown in Fig. 6.2 demonstrates the throughput estimation problem in the presence of a data transmission along a path adjacent to the network path being probed. The presented scenarios explore the performance of the probe train based proposed estimation technique in situations when a distributed wireless mesh network has variable number of adjacent wireless users transmitting data at the instant when a specific path is being probed to estimate its maximum achievable end-to-end throughput.

6.5.1 *Single Cross Traffic Flow within the Transmission Range*

Consider a packet pair source at node 4 shown in Fig. 6.2 attempting to estimate the end-to-end throughput of the path from node 4 to node 7 consisting of 3 hops. Node 0 on the other hand present within the transmission range of node 4 generates CBR traffic of 200 kbps to the destination node 3. The distribution of the dispersion between the probes samples sent from node 4 to node 7 presented in Fig. 6.10 identifies two distinct dispersion peaks similar to the linear topology networks. The network path between node 4 and node 7 consists of 3 hops. The highest peak has an average value of 11 ms and accurately estimates the maximum achievable throughput of the path as 363.63 kbps according to Eq. 3. Note this value equals the throughput estimated for a 3-hop network without cross traffic. The presence of a cross traffic of 200 kbps within the transmission range induces yet another dispersion peak with an average value of 24 ms resulting in a throughput of 163.63 kbps. This is closer to the available bandwidth (maximum achievable throughput (363.63 kbps) – cross traffic rate (200 kbps)), 163.63 kbps of the path.

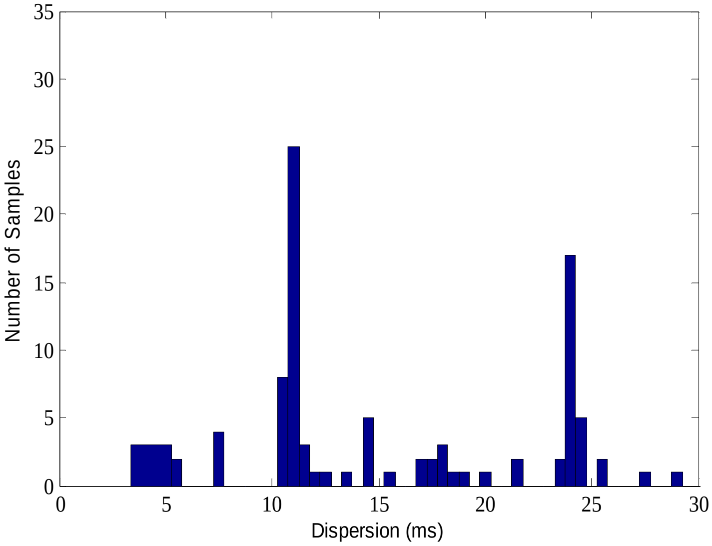

Figure 6.10: Delay Distribution of Probe Packets with a Single Cross Traffic Flow

6.5.2 *Two Cross Traffic Flows within the Transmission Range*

For the grid topology shown in Fig. 6.2, consider two CBR sources with average rate of 100 kbps each generated from node 0 to node 3 and node 8 to node11 respectively. Probe pairs are injected by node 4 to probe the network path from node 4 to node 7.This scenario studies the throughput estimation technique when two competing traffic flows present adjacent to the network path contend with the probe traffic. The total rate of competing cross traffic in this case in 200 kbps and the maximum achievable throughput of a 3-hop network with no cross traffic is 363.63 kbps based on the flooding approach.

The delay distribution of the probe samples in Fig. 6.11 indicate two significant dispersion peaks similar to other cross traffic scenarios discussed. The peak corresponding to an average value of 10.9 ms gives the maximum achievable end-to-end throughput in the absence of cross traffic and the peak with an average value of 24.1 ms gives the available bandwidth of the path with an aggregate cross traffic of 200 kbps.

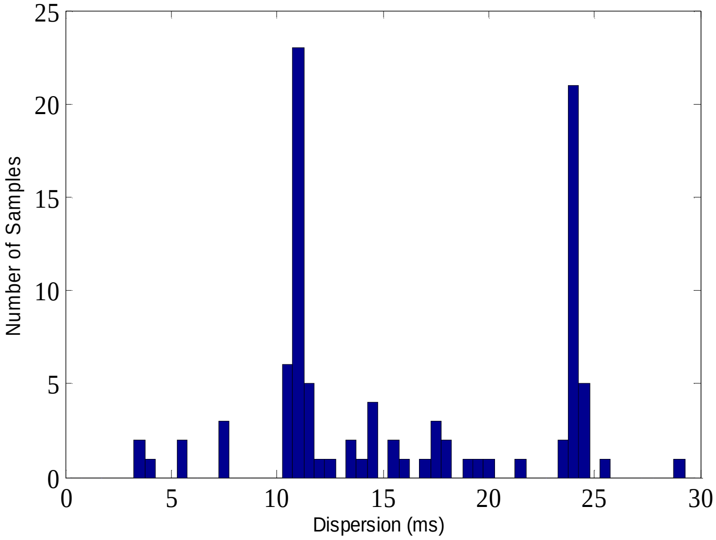

Figure 6.11: Delay Distribution of Probe Packets with Two Cross Traffic Flows

6.5.3 *Single Cross Traffic Flow outside the Transmission Range and within the Career Sensing Range*

Consider a CBR source of 200 kbps flowing from node 8 to node 11 and probe packets generated from node 0 to node 3.The grid topology is the same as Fig. 6.2. Each wireless node is placed at a distance of 200m from each other and transmission range of each node is 250m while the career sensing range is 500m. Thus the nodes 8 to 11 carrying cross traffic are present outside the transmission range and within the career sensing range of nodes 0 to 3. The delay distribution of the probe samples in Fig. 6.12 resembles the distribution of probes when a single cross traffic flow present within the transmission range contends with the probe packets as shown in Fig. 6.10 and accurately estimates the maximum achievable throughput as well as the available bandwidth of the path.

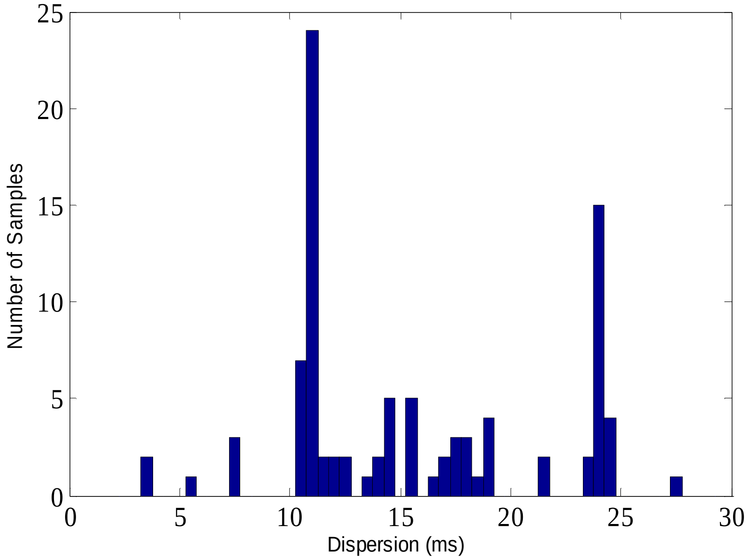

Figure 6.12: Delay Distribution of Probe packets with Single Cross Traffic Flow present outside the Transmission Range and within the Career Sensing Range

6.5.4 *Overall Observations*

For the grid topologies discussed in this section, it is observed that packet pairs are sufficient to induce the dispersion peaks corresponding to achievable throughput and available bandwidth of the path. When probe trains are injected in to the network with cross traffic present within the transmission or career sensing range of the probe packets, it induces significant dispersion peaks. One of the peaks is shown to accurately estimate the maximum achievable end-to-end throughput of the path realizable in the absence of cross traffic while the other peak corresponding to a larger dispersion value estimates the available bandwidth of the path. In the case of networks with cross traffic the peak with larger dispersion value thus estimates the available bandwidth of the path which is in fact more vital as it is not possible to achieve maximum throughput due to the presence of cross traffic.

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

This thesis illustrates the basic techniques and methods used to estimate the achievable end-to-end throughput of a multi-hop wireless network. The inherent challenges in the network characteristics estimation associated with wireless networks are explained and the performance of the Adhoc Probe algorithm is analyzed for its accuracy using a flooding based approach. Adhoc Probe is shown to always overestimate the maximum achievable throughput of the path. The delay distribution of the probe packets presented for single and multi-hop networks illustrate that the dispersion corresponding to the probe sample with minimum one way delay does not reflect the maximum achievable throughput of the path and further its is shown that when a network is flooded, the average dispersion of the probe samples is higher than the dispersion value used by Adhoc Probe and it accurately estimates the achievable throughput of the path.

An alternative light weight delay distribution based approach using probe trains of variable length is proposed in this thesis. The length of the probe train is chosen based on the number of hops in the network and it reproduces the medium access control contention and network queuing behavior of the flooding approach and induces the achievable throughput dispersion peak which accurately estimates the achievable throughput of the path. The simulation scenario considered in this thesis studies a multi-hop wireless network in the absence and presence of cross traffic and includes variable cross traffic rates and different network topologies and therefore is general enough to be applied to realistic WMN deployments. It is observed that for networks with competing cross traffic contending with the probe packets, two significant dispersion peaks each corresponding to the maximum achievable throughput and the available bandwidth of the path are induced by the injected probe packets.

The proposed achievable throughput estimation method requires the knowledge of the network topology and the number of hops present along the network path in order to efficiently choose the length of the probe train. In scenarios when the number of hops is not known, an iteration based method should be employed to identify the probe train length required to induce the achievable throughput dispersion peak. Further the dispersion analysis and calculations presented in this thesis assumes that at least 100 probe samples are injected into the network. The performance of the proposed method with lesser number probe samples is to be studied. The simulation results presented in this thesis focus on static wireless networks with wireless nodes being equidistant from each other and do not include the presence of mobile nodes in the scope. Future research direction can focus on the modifications required to the probing approach to accurately estimate the achievable throughput for networks with random topology. Further analysis of the presented probe train based approach is needed to study the dispersion of the probe samples in dynamically varying network topology conditions present in mobile ad hoc networks with constant and varying link capacities.

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