

Delay Analysis of Wireless Ad Hoc Networks: Single vs. Multiple Radio

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Abstract—Due to the self organizing characteristic of Ad Hoc network, it is difficult to adopt traditional delay measurement techniques in a multi hop Wireless Mesh network (WMN). This problem is much more complicated in multi-radio environment because of the mutual interferences that contribute significantly to the overall delay. We present an experimental methodology to obtain an estimate of average intra-node delay and inter-node delay for packets of variable payload size in both single radio and multi-radio environment without the constraint of clock synchronization between the nodes. Our results provide insights on comparing performances between single and multi-radio environment with some interesting findings like periodic nature for intra-node delay with oscillating frequency distribution. Finally our statistical analysis validates the linear relationship between end to end delay, intra-node delay and inter-node delay.

Index Terms—Intra node delay, inter node delay, wireless mesh networks, delay measurement

I. INTRODUCTION

IEEE 802.11 technology based Wireless Ad Hoc Networks are often considered as a viable alternative for providing broadband internet access and enable network connections in situations where it is impossible or difficult to set up infrastructure. Multi-hop Wireless Mesh Networks (WMNs) are also considered as means for achieving last mile internet connectivity on the go. Links in such networks are created in a self-organizing manner by participating nodes which relay data packets for other nodes. These types of self-organizing networks introduce several research challenges, among which the problem of determining an optimal route based on end to end delay estimation is prominent.

It is of immense importance to measure the performance parameters of Ad Hoc networks, especially the end to end delay which optimizes the overall network performance. Minimizing delay is also one of the vital conditions to ensure Quality of Service (QoS) requirements in these dynamic networks, which necessitates

proper estimations and realistic measurement techniques apart from network simulations. Unfortunately, the practical measurement of these wireless ad hoc networks has not received so much attention whereas a large number of studies have been devoted to system stability and throughput maximization.

In this paper, we focus on a practical implementation of intra-node as well as inter-node delay estimation in multi-hop mesh networks using a packet sniffer tool named Wireshark. We also show how the delay estimation varies on network load and connectivity. Finally we provided the performance comparison between single radio and multiple radio environments keeping the other network parameters constant.

In a nutshell, our prime achievements in this paper are as follows:

- (i) We successfully conducted the multihop ad hoc communication in windows platform with both single and multiple radios.
- (ii) We analyzed the total end to end delay as a linear summation of several delay components (intra-node delay, response time and air propagation delay). Also comparison between different experimental setups were illustrated with the use of these components.
- (iii) All the delay components were measured without time synchronization between the nodes

The rest of the paper is organized as follows: Section II describes the related works in the area of end to end delay measurement, section III describes our problem formulation with the network model and timing model. In section IV, we describe our experimental setup in both single radio as well as multi-radio environment and traffic generation. In section V, we present our results and analysis from the experiments. Finally we conclude in section VI.

II. RELATED WORKS

There are several classes of techniques discussed in the literature for determining end to end delay as well as one way delay. One class of technique, named internal measurement technique, adopts distributed method to deploy measurement agents on some internal nodes and calculate per hop delay by direct measurement. This information is then transferred to the central server node where the measurement data are processed and analyzed to optimize the overall network performance. The other class which is external network measurement technique (e.g. NT: Network Tomography technique) uses the measurement data sample of End-to-End to infer internal link performance parameters without the collaboration among internal nodes, which is also not concerned with network protocols. For this reason, some researchers [2,11,12,13] consider this technique apparently adaptable for quantifying link performance parameters in Ad Hoc network measurement.

For measuring one way delay, adding timestamp, sending probe packets and packet pair technique (PP) are three useful methodologies that are commonly practiced. With the first method, one could either add timestamps to each packet before it is sent and subtract the reception from the transmission time. If timestamps can be added to a packet directly before it is transmitted, this method allows determining the packet delay very easily and accurately without generating additional measurement overhead. The downside of this method is that the clocks of the stations have to be synchronized which is a challenge for any real-world implementation, as hardware clocks are in general neither synchronized nor equally fast. Clocks can be synchronized via the Network Time Protocol (NTP) or GPS, but both methods are more suitable for test bed setups than in a productive indoor environment.

The probing method does not need synchronized clocks, as the sender of a probe only need to record the time until the packet returns. Unfortunately, this method has several disadvantages: firstly it assumes that the receivers can response immediately to the probe packet which is not possible in real world. Our experimental measurements also prove this fact. Another major disadvantage is that it assumes the links are symmetric which gives unreliable measurement of one-way delay in wireless networks with asymmetric.

Packet Pair (PP) was a little bit sophisticated technique proposed by Keshav [9]. In this technique, two packets are sent directly after each other, the time dispersion

between the reception time of these two packets measure the transmission time. Two particular implementation of packet pair concept has been attempted by Kapoor et al.[8] and Sun et al. [10]. An experimental study using both RTT and PP for estimating the link quality has been presented by Draves et al. [14].

Motivated by the APHD mechanism [3], Staehle et al. in their implementation of TOM [1] addressed the problems of above techniques and made utilization of an IP option field to accumulate the per hop delay estimate. Unfortunately their model also had a flaw of unpredictability due to hardware abstraction layer. In our experiment we did not face this problem as we got the hardware timestamp from WinPcap driver integrated with Wireshark tool.

In brief, all the above methodologies refer to end to end delay or one way delay measurement problem. But the concern of measuring per hop delay still lacks efficient techniques. That is why our primary focus of this paper is on intra-node delay (sometimes referred to as internal node delay) within each intermediate node along the route from source to destination. The secondary goal is to estimate the air propagation delay between two consecutive nodes along the path or simply inter-node delay (hereafter referred to as airtime).

III. PROBLEM FORMULATION

A. Network Model

Our network model includes three wireless nodes: *Source node*, *Relay node* and *destination node*. The radio configuration of the *relay node* is varied depending on the operating mode, that is, the relay node operates either in single radio mode or multi radio mode. But in all cases, the *source node* and *destination node* is fixed to single radio mode. While operating in multiradio, the *relay node* is equipped with an external USB network interface card that belong to IEEE 802.11b/g category. All other internal on board NICs support IEEE 802.11a/b/g. The distance between the three nodes are kept constant throughout the experiment so that there is no impact of distance variation into the delay measurement.

Using the timing model described in the later subsection, an analytical dissection was done for the round trip delay. The three major delay components analyzed individually in our experiments are *Intra-Node delay*, *Inter-Node delay* and *Response time*. These terms are defined below:

1) *Intra-Node Delay*: The Intra-node delay can be simply viewed as the internal packet forwarding delay inside the relay node. Thus by this component we

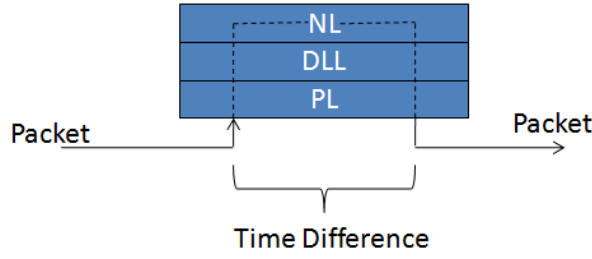


Fig. 1. Intra-node Delay

identified the delay period associated with packet header processing, route table lookup, queueing of packets to forwarding destination inside the relay node. Theoretically, this delay is equivalent to passing the packet through the bottom three layers. Figure 1 depicts the Intra-node delay diagrammatically.

2) *Inter-Node Delay*: This is the air propagation delay between two consecutive nodes along the path which is generally calculated by subtracting the reception timestamp of the receiver from the transmission timestamp of the sender. But as this mechanism requires the synchronization among the communicating stations, we designed an alternate technique (described in the timing model section) that can calculate the inter-node delay without synchronization between the clocks. In our experiment we also calculate the total *AirTime* by summing up the Inter-node delays for all hops along the round trip path for each packet.

3) *Response Time*: This delay incurs at the destination node where the packets are passed to the application layer and a reply packet is sent towards the source as acknowledgement packets. This delay is comparatively more significant than the intra-node delay due to the fact that it requires response from the application layer.

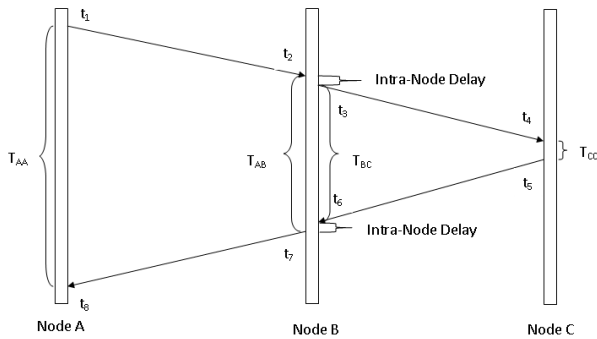


Fig. 2. Timing Model for Network Measurement

B. Timing Model

Figure 2 illustrates our timing model. For any successful packet transmission from node A to node C, traffic generator application of node A generates a packet specifying node C as destination and node A as source. Routing table of node A decides that all packets towards node C must be routed through intermediate node B. When packet is transmitted to the air, the WinPCAP driver associated with Wireshark attaches a timestamp t_1 with the packet which is captured by Wireshark. At Node B, when one of the radios receive the packet at timestamp t_2 , extracts the destination IP, looks at routing table to select route and sends it towards node C at timestamp t_3 . Node C receives the packet at timestamp t_4 and sends it to the application layer. The receiver application prepares an acknowledgement packet for the received data packet specifying node A as destination and node C as source. Routing table of node C routes the acknowledgement packet to node B which is transmitted at timestamp t_5 . Node B again receives acknowledgement from C at timestamp t_6 and extract the destination IP and forward to node A at timestamp t_7 . Node A receives acknowledgement at timestamp t_8 . Node A, B and C do not have synchronized clocks.

The timing model proposed in this paper (Figure 2), can estimate the delays without clock synchronization between the nodes. Timestamps t_1 and t_8 are synchronized as they are captured at node A, timestamps t_2 , t_3 , t_6 and t_7 are synchronized as they are captured at node B and timestamps t_4 and t_5 are synchronized as they were captured at node C. So response time of node C, T_{CC} , is simply the difference between timestamp t_4 and t_5 . Node B sends data at timestamp t_3 to node C and receives acknowledgement at timestamp t_6 from node C (difference between t_3 and t_6 is marked as T_{BC} .) Both data and acknowledgement propagation delay, $T_{B-C}^{(D+A)}$, between node B and node C is the difference of T_{BC} and T_{CC} . Node B receives data at timestamp t_2 from node A and sends acknowledgement at timestamp t_7 to node A (difference between t_2 and t_7 is marked as T_{AB}). So the Intranode delay for data $T_{IntraDelay}^D$ is the difference of t_3 and t_2 and Intranode delay for acknowledgement $T_{IntraDelay}^A$ is difference of t_7 and t_6 . The details equations for calculating the different delay components are provided below.

$$RTT = T_{A-B}^D + T_B^D + T_{B-C}^D + T_C^R + T_{C-B}^A + T_B^A + T_{B-A}^A \quad (1)$$

$$T_{AA} = t_8 - t_1 \quad (2)$$

$$T_{AB} = t_7 - t_2 \quad (3)$$

$$T_{A-B}^{(D+A)} = T_{AA} - T_{AB} \quad (4)$$

$$T_{BC} = t_6 - t_3 \quad (5)$$

$$T_{CC} = t_5 - t_4 \quad (6)$$

$$T_{B-C}^{(D+A)} = T_{BC} - T_{CC} \quad (7)$$

$$T_{IntraDelay}^D = t_3 - t_2 \quad (8)$$

$$T_{IntraDelay}^A = t_7 - t_6 \quad (9)$$

IV. EXPERIMENTAL SETUP

This section describes design and implementation of our experimental set up. We have used three Laptops as nodes, Wireshark to capture Ethernet protocol trace and traffic generator tools (Client/Server) to generate continuous traffic of variable packets size. We have done our experiment in Windows platform. We also used an external USB Radio to configure multi radio intermediate node. Data was collected with respect to 4 different scenarios.

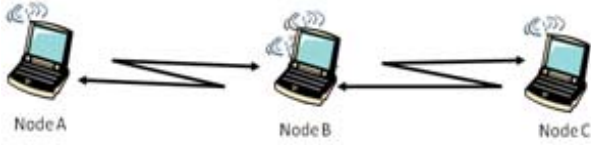


Fig. 3. Network setup

A. Single and Multiple radio environment

We created a mesh network between three laptops (Figure- 3). For single radio environment, the routing table of node A was modified and a new route with node C, static IP was created which redirected it to node B. We did exact same thing at node C and created a new route for node A via node B.

For the multiple-radio environments, node B has two radios R1, R2. It was connected to node A with radio R1 and connected to node C with radio R2. Two different peer to peer networks are created for the link between node A and node B and the link between node B and node C, respectively. The network between A and B has no idea about the network between B and C and vice versa. We modified routing table of A, added a new route for the ad hoc network B - C using radio R1 of node B as gateway. Routing table of node C was also modified and a new route was added to pass packets through B towards A using R2 radio of node B as gateway.

B. Traffic Generation

To impose traffic, we used an open source traffic generator tool. We also tested other applications like FTP, ICMP, RTP which were tested for special scenarios. For measurement of delay, we installed packet sniffer tool Wireshark in every node. We used unidirectional and bidirectional traffic to investigate the impact of the two-radio and two-channel scenario. For the one way traffic load, data transfers from Node A continuously with payload of (100, 500, 1000, 1500 and 2000 Bytes) to node C via node B. Then we transferred data between node A and node C via node B in double handshake mode. Node A and node C sent continuous traffic of (100, 500, 1000, 1500 and 2000 Bytes) payload simultaneously. In both scenario we captured Ethernet trace of couple of thousands packet transmission. Wireshark was running in all the nodes to capture trace from radio. In Node B, two Wireshark was active, one for Node A and another for Node C.

V. RESULTS AND ANALYSIS

In the following subsections, we present the analysis of two major components of round trip delay: Intra-Node Delay and Inter-Node delay.

A. Measurement of Intra-Node Delay (Relay Time)

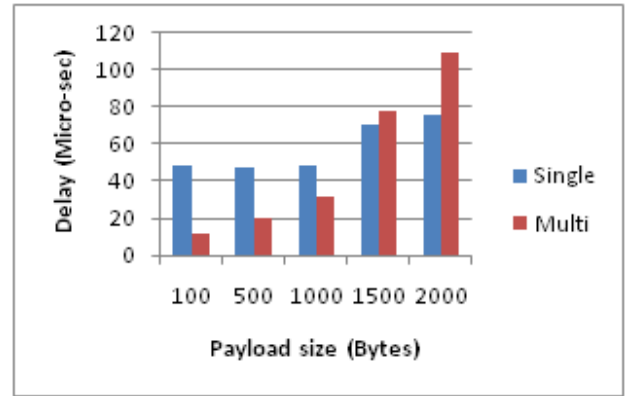


Fig. 4. Effect of packet size and number of radio

1) *Effect of packet size and number of radio:* The comparative analysis of data relay time between single radio and multiradio environment can be visualized from figure 4. Figure 5 shows the frequency distribution of Intranode delay for particular payload size of 500 bytes in a multiple radio environment.

From the graphs (Figures 4 and 5) below, it is evident that multi radio ad hoc network outperformed

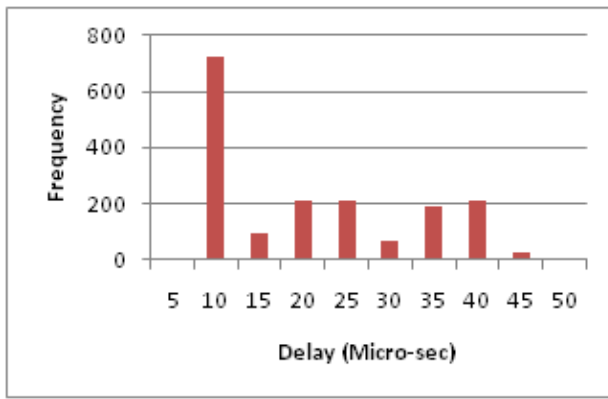


Fig. 5. Frequency Distribution for Intra-Node Delay

upto packet size 1000 byte but later single radio is the winner. This is the case where the processing time for fragmentation is taking place. Our hypothesis is, as for large packets in multi radio, fragmentation is a usual phenomenon (observed from Wireshark) and contributing more time in processing data and generation acknowledgement. But in the single radio this is not the case because fragmentation not take place (observed from Wireshark). There is also one more thought about the single radio, the total experimental set up was with one single network, the packet fragmentation was not mandatory in the physical level for ad hoc network, during packet transmission for upto 2000 byte packet size.

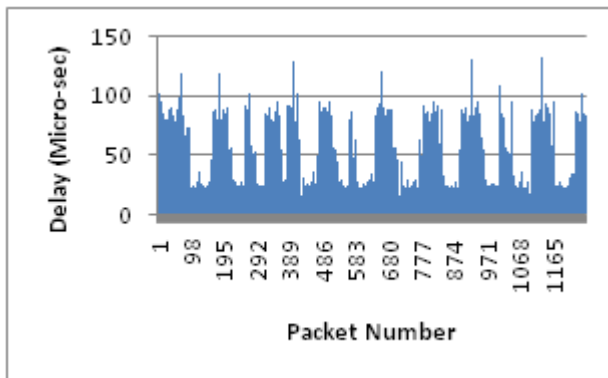


Fig. 6. Periodic Delay pattern for payload size 100

2) *Periodic pattern of Relay Time*: One of the most interesting findings from our experiments was to identify a periodic pattern of relay time in every setup irrespective of payload size or number of radios. The cause behind this phenomenon was possibly due to internal scheduling of operating system which may follow a

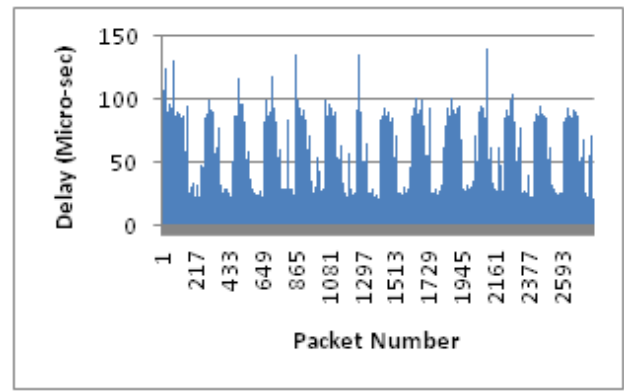


Fig. 7. Periodic Delay pattern for payload size 500

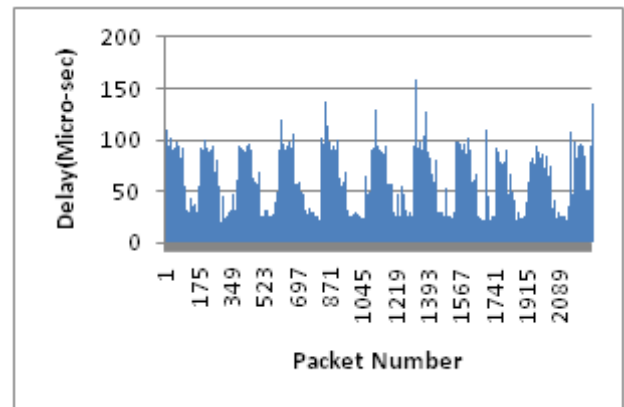


Fig. 8. Periodic Delay pattern for payload size 1000

periodic scheme for process scheduling. It can be clearly observed in Figures 6,7,8,9 that there is some kind of internal processing time of some applications engaging the CPU usage periodically and resulting the intermittent nature of the Relay-Time as mentioned before. It may be mentioned that the Relay-Time calculation and graphical representation was totally based on data relay, not based on acknowledgement relay. This is because of the fact that, acknowledgement packets are always of a fixed size even though the data payload was changed, which does not give the opportunity to measure the variation due to change of packet size.

3) *Frequency distribution of Relay Time*: We have measured the Intra-node delay (Relay Time) for both single radio and multiple radio environment by varying the payload size. In figures 10 and 11, we can find the frequency distribution of relay time for different payload size in both single radio and multiple radio environment. Quite interestingly, the single radio graphs take the shape of a damped oscillation where the skewness varies with

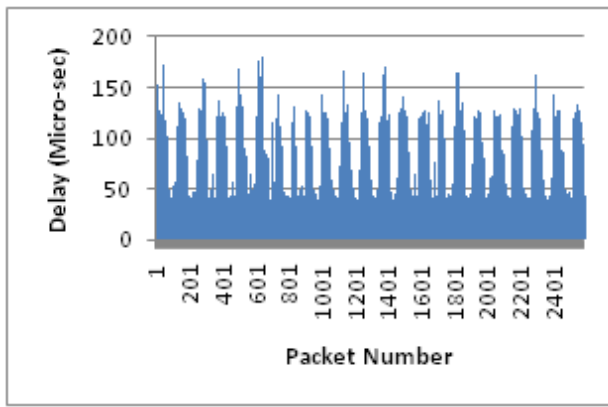


Fig. 9. Periodic Delay pattern for payload size 1500

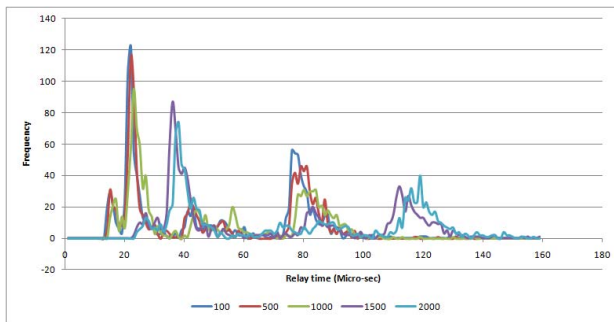


Fig. 10. Frequency Distribution for Relay Time (Single Radio)

the payload size. But in case of multiple radio, this was not noticed. Another major difference between the two figures is that, the mode of relay time for multiple radio has shifted leftwards compared to the single radio environment. This implies that, most of the packets in multiradio transmission take less time (about 9 micro-sec) compared to single radio environment (22 micro-sec). This scenario is also validated from the graph in Figure 4 which shows that the relay time for single radio is higher than multi-radio communication due to the flexibility of parallel transmission in the later case.

B. Measurement of Inter-Node Delay (AirTime)

We present the Inter-Node delay (AirTime) for different scenarios here. In order to measure the AirTime, first, the end to end time was collected from the Wireshark at Source Node A whereas the relay time was measured at node B and the response time was measured at node C. Then, after deducting the relay time and response time from the end to end delay the total Air time was found. Having a close observation in the relay time, it was observed that the internal process scheduling at

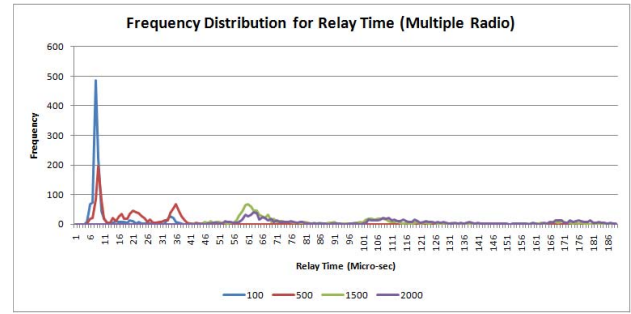


Fig. 11. Frequency Distribution for Relay Time (Multiple Radio)

the intermediate node B resulted a periodic nature for the relay time. With regards to the response time at destination Node C, note that this duration reflects the processing delay between receiving a data packet from the Node B and sending acknowledgement towards the source node A.

In addition, we show comparisons between the natures of packet transmission with single radio and multiple radio with respect to couple of points. In a multiple-radio ad hoc network, the packet transmission takes less time than a single-radio ad hoc network for all packet sizes. From Figure 12 it can be seen that multiple radio setup has outperformed the single radio setup, which is quite natural. The reasons behind this fact are that, in multiradio environment, a node can receive and transmit simultaneously, also the two different networks use different channels so that 802.11 carrier sensing and random access delay are eliminated. In all, the overall airTime associated with round trip delay is reduced. Figure 13 shows the frequency distribution histogram of AirTime for a particular setup.

C. Statistical Analysis of Delay Components

In order to identify the statistical correlations we performed multivariate linear regression analysis to model the relationships between end to end delay and other delay components. From the regression analysis, we validated that the end to end delay is linearly related to all the delay components through the values of regression co-efficients calculated to be 1. We can also verify from the correlation coefficients (Figure 14) that end to end (E2E) delay is 98% correlated with total AirTime. A general descriptive statistics (Figure 15) is also given for the overview of data. The descriptive statistics shows the mean, median, mode, standard deviations, variances, skewness etc. for each of the delay components.

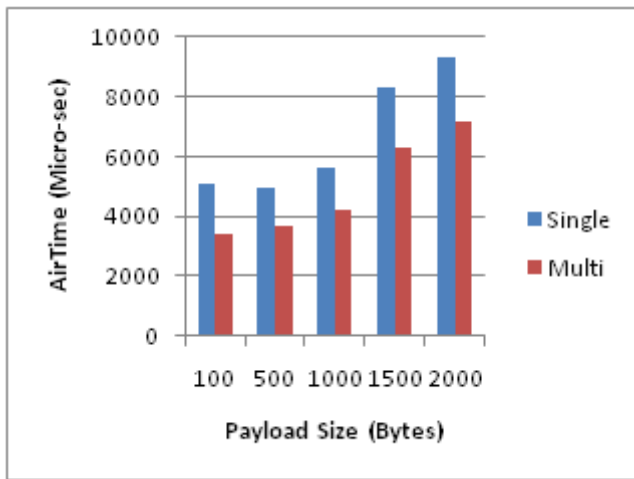


Fig. 12. Effect of packet size and number of radio

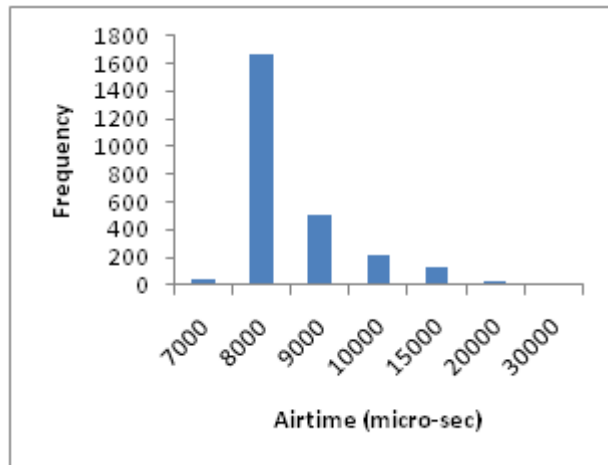


Fig. 13. Frequency Distribution for Air Propagation Delay

VI. CONCLUSION

In this paper, we presented a novel timing model and measurement methodology for the analysis of Intra-node delay and Inter-node delay in wireless ad hoc networks without the constraint of time synchronization among wireless devices. Our results show some interesting findings for intra-node delay analysis. For our future extension, we plan to investigate the feasibility of multi-radio deployment for real time multimedia applications by measuring the effect of jitter.

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	E2E	Data_Relay	Ack_Relay	Total-Relay	Response	AirTime
E2E	1					
Data_Relay	-0.002319614	1				
Ack_Relay	-0.004007915	0.874252184	1			
Relay	-0.003295873	0.965923521	0.970114339	1		
Response	0.195094366	0.008588875	0.013009168	0.011228674	1	
AirTime	0.981299445	-0.038401068	-0.041120174	-0.04111666	0.005913	1

Fig. 14. Correlation between Delay Components

	E2E	Data_Relay	Ack_Relay	Total-Relay	Response	AirTime
Mean	8656.942967	70.36454721	45.83044316	116.1949904	332.8458574	8207.902119
Standard Error	35.95493945	0.711256524	0.522577462	1.212106487	8.467037482	34.70960719
Median	8159	56	38	89	232	7742
Mode	7896	36	21	58	219	7278
Standard Deviation	1831.585695	36.23221994	26.62069295	61.74608929	431.320563	1768.147046
Sample Variance	3354706.156	1312.773762	708.6612934	3812.579543	186037.428	3126343.977
Kurtosis	57.7296419	-1.393657505	-1.313155267	-1.490529465	215.6565789	64.97756364
Skewness	6.115788567	0.36558812	0.471169531	0.382303724	11.40397393	6.559222543
Range	29812	158	122	224	11498	29684
Minimum	6867	22	13	39	204	6450
Maximum	36679	180	135	263	11702	36134
Sum	22464767	182596	118930	301526	863735	21299506
Count	2595	2595	2595	2595	2595	2595

Fig. 15. Descriptive statistics of Delay components

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