Statistical Analysis of the Impact of Routing in MANET Based on Real-Time Measurements

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Abstract - **Performance degradation due to routing overhead is a serious impediment to fulfilling quality of service (QoS) in Mobile Ad Hoc Networks (MANETs). Therefore, analyzing the performance impact of the routing overhead in a real-time environment becomes critical to developing efficient routing protocols and provisioning network performance. We develop a statistical-analytic approach to studying the impact of the routing overhead on delay and throughput in a real-time MANET testbed. The approach helps us in deriving statistical models of delay and throughput which, in turn, enables us to analyze the behavior of routing protocols beyond the scenarios configured in the testbed. In addition, we conduct a simple analysis of measuring network bandwidth consumed by the routing overhead in various environments. Although Optimized Link State Routing (OLSR) and Ad-hoc On-demand Distance Vector (AODV) routing protocols are studied as case studies in this paper, our approach and findings are applicable to other routing protocols as well.**

I. Introduction

A Mobile Ad Hoc Network (MANET) is characterized as a self-organizing system of mobile nodes requiring no centralized infrastructure for the network establishment. As a result, intermediate nodes in MANET act as routers in forwarding messages from nodes not in communication range of each other [13]. Therefore, routing protocols play an invaluable role for efficient data transmissions in MANETs. However, MANET routing protocols consume significant amount of the network bandwidth in response to the network variations due to nodes mobility which causes frequent communication failures. Therefore, to acquire acceptable network performance, it becomes inevitable to perform in-depth research on routing overhead in MANETs under various loads.

Measurements and statistical analysis are very important to explain and predict network performance observed in real world, contributing fundamental knowledge, problems and requirements for protocol design and evaluation in MANETs. However, Existing experimental works lack in providing analysis with statistical modeling and in providing quantitative measurements or comparison of routing overhead, making it impossible to predict the behavior of the routing protocols beyond the scenarios discussed in the existing simulation and experimental studies[5], [4], [12].

Due to few MANET deployments in the real world, research in this area has been mostly simulation based [1], [2], [3], [9], [10], [14]. As simulation studies assume some ideal conditions to approximate the realistic behavior, it is not possible sometimes to map the simulation results onto real-time networks. Thus, the statistical analysis based on real-time measurements is critical to verifying analytical models and simulation assumptions. To address these problems collectively, first we perform a real-time experimental study to measure the performance impact in terms of delay and throughput. Then, we derive statistical models to describe the performance impact caused by routing protocols. The statistical models enable us to analyze the behavior of the routing protocols beyond the scenarios configured in the testbed. In addition, by developing a simple analysis, we present realistic and quantitative measurements of the network bandwidth consumed by the routing overhead in various scenarios.

To achieve our objectives, we have established a real-time testbed with mobile nodes communicating in *ad-hoc* mode. Varied data streams and different the testbed topologies are used to generate several load conditions. To study proactive and reactive protocols collectively, we investigate OLSR and AODV protocols as case studies. In addition, the testbed spans various mobile devices consisting different hardware platforms, therefore we believe that our approach and findings are applicable to heterogeneous ad-hoc networks as well.

The rest of the paper is organized as follows. We explain details of the experimental testbed setup and the methodology to carry out experiments in Section II. Section III explains the performance impact caused by routing protocols, presents the statistical-analytic approach, and discusses the statistical models for delay and throughput for OLSR and AODV. Section IV analyzes the percentage network bandwidth consumed by the routing overhead generated by AODV and OLSR. Finally, Section V concludes the paper.

II. Experimental Testbed Setup

The testbed setup along with protocol stacks is shown in Fig 1 in which devices are used as mobile nodes (MNs).

A. Testbed Setup

The hardware and software specifications are:

- **Desktop MN** : Dell PC, Pentium IV 2.6 GHZ (RHL 9, kernel version 2.4.20).

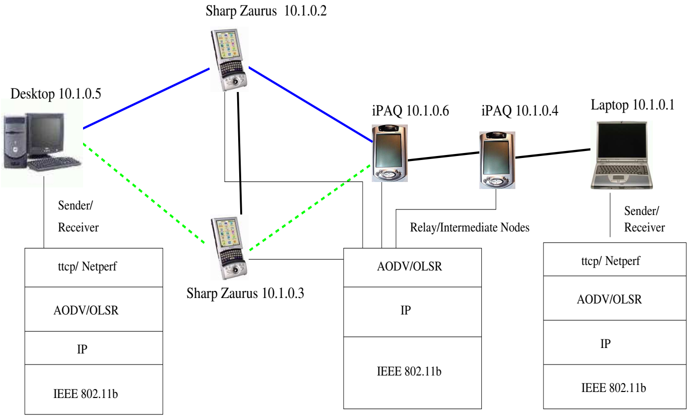

Fig. 1. Ad hoc Testbed Architecture.

- **MN iPAQ** : Intel StrongARM 206 MHx (Familiar Linux 0.6, kernel version 2.4.18-rmk3).
- **MN Sharp Zaurus** : Intel XScale 400 MHz (Linux Embedix kernel version 2.4.18-rmk7-pxa3-embedix).
- **MN Dell Laptop** : Celeron Processor 2.4GHZ (RHL 9, kernel version 2.4.20).
- **Wireless Cards** : Netgear MA 311 802.11b, Lucent Orinoco Gold 802.11b.
- **Kernel AODV** version 2.1 from NIST [7].
- **OLSR** version 0.4.5 [11].
- **IPtables** for filtering packet at MAC level.
- **Ethereal** network packet analyzer.
- **Netperf**, **floodping** and **ttcp** data transmission utilities.

B. Experimental Methodology

All experiments are performed in an indoor environment. MAC layer filtering is configured using `iptables` to achieve physical separation among mobile nodes. In addition, the transmission rate for each wireless card has been set to 11Mbps. To avoid interferences with campus network, wireless channel has been set to 10, whereas campus network uses wireless channel 1. Transmission of data streams consists of packets with sizes varying from 56 bytes to 1024 bytes, and total data size is varied from 56 kbytes to 1 Mbytes.

In our experiments, network topology is configured from 2 to 4 hops. At the destination node, statistics are collected using `ethereal` for performing various observations. Every experiment is repeated around 20 times and then average value from all the observations is calculated to minimize accidental errors. We studied different configurations consisting of various mobile devices acting as a source as well as a destination to eliminate any effects such as hardware platforms and OS related to a particular device. Therefore, we ensure that experimental results presented in the paper are applicable to heterogeneous ad-hoc networks as well.

III. Statistical Analysis of Experimental Results

Here, we discuss and interpret the experimental results obtained for OLSR and AODV. Using experimental measurements, the statistics analysis is conducted with non-linear regression methods to derive the statistical models.

A. Methodology of Statistical Analysis

MATLAB tool [8] provides various statistics to determine the best suitable models to approximate experimental data. Some of the statistics such as, *Weighted Sum of Squares Due to Error (WSSE)*, *R-square*, *Adjusted R-Square* and *Root Mean Squared Error (RMSE)* are used to determine the most appropriate models for the measurements.

- **Weighted Sum of Squares Due to Error (SSE) :** Let z_k be an experimental value, $\tilde{z_k}$ be the corresponding predicted value and w_k be the corresponding weight. Assume that there are n experimental values, then we define SSE as follows:
$$SSE = \sum_{k=1}^{n} w_k (z_k - \tilde{z_k})^2. \tag{1}$$
If SSE obtained is close to zero, then the corresponding statistical model is considered a suitable match.
- **Adjusted R-Square :** First, we define R-square which is the square of the correlations between experimental data and predicted data [8]. We express R-square in terms of *SST* which is *sum of squares about the mean value* of experimental data. Let $\overline{z_k}$ denote the mean value of the experimental data. Then *SST* and R-square (RS) are,
$$SST = \sum_{k=1}^{n} w_k (z_k - \overline{z_k})^2 \quad \text{and} \quad RS = 1 - \frac{SSE}{SST}. \tag{2}$$
Values for R-square statistic can vary between 0 and 1; those values close to 1 suggest smaller deviations between predicted and experimental values. Now, we define another measure, called *degree of freedom*, to describe adjusted R-square. *Degree of freedom* is defined as the difference between the number of predicted values and number of fitted coefficients obtained from experimental data. Formally, $f = n - m$, where f, n and m denote *degree of freedom*, number of predicted values, and number of fitted coefficients, respectively. Adjusted R-square, now, can be expressed formally as,
$$ARS = 1 - \frac{SSE(n-1)}{SST(f-1)}. \tag{3}$$
Adjusted R-square value close to 1 suggests a closer approximation for experimental data.
- **Root Mean Squared Error (RMSE) :** Mean squared error is defined as the ratio of SSE and degree of freedom. Then, *MSE* and *RMSE* are as follows:
$$MSE = \frac{SSE}{f} \quad \text{and} \quad RMSE = \sqrt{MSE}. \tag{4}$$

B. Analysis of End-To-End Delay

In this subsection, we discuss the performance impact of the routing protocols on end-to-end delay under various loads and network topologies. Then we perform the statistical analysis on the experimental results to obtain the polynomial regressions for OLSR and AODV.

1) **Analysis of End-To-End Delay for OLSR:** As a proactive protocol, OLSR generates routing overhead periodically and continuously to react faster to the network variations in MANETs. The performance impact of OLSR on end-to-end delay is shown in Fig. 2. We observe that, in all topologies, initially end-to-end delay increases rapidly with respect to packet size. However, as the packet size is increased further, the delay does not rise sharply, and the difference between end-to-end values for data streams with higher packet sizes is comparatively less. Note that the transition point, where the difference in the delay values starts reducing, has almost a similar value under different network topologies. For example, we observe in the figure that the transition point is somewhere around 256 bytes. This phenomenon helps us to reach a conclusion that when data streams consist of packet size less than 256 bytes, the percentage network bandwidth consumed by OLSR in transmitting the overhead than in transmitting the data packets is comparatively higher leading to higher impact on the delay. However in case of data streams with packet size bigger than 256 bytes, OLSR consumes smaller percentage of the network bandwidth in transmitting the routing overhead.

In addition, we see that the difference between end-to-end delay for smaller packet sizes is larger than that of bigger packet sizes under various topologies. We observe that as the network size expands, end-to-end delay values for various packet sizes are not affected in the same proportion as the increase in the network size. Therefore, the previous observations suggest that OLSR causes higher performance impact in terms of the percentage network bandwidth consumed on end-to-end delay in the small networks with low activities (data streams with lower packet sizes) than in the large networks with higher activities.

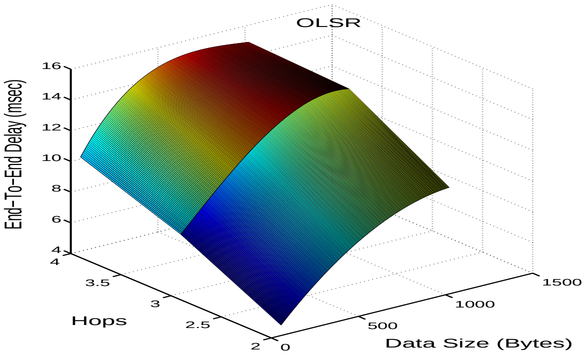

Fig. 2. OLSR: End-to-End Delay Comparison.

Let $\sigma_{\rm o}(x,h)$ represent end-to-end delay for OLSR, which is a function of data size x and number of hops (or path length) h. Using the different statistics discussed previously, we find that the most suitable polynomial regression for $\sigma_{\rm o}(x,h)$ can be modeled by

$$\sigma_{\rm o}(x,h) = a_2(h)x^2 + a_1(h)x + a_0(h). \tag{5}$$

The coefficients of this polynomial, $a_i(h)$ ($i = 0,1,2$ and $h = 2,3,4$), are

$$\overrightarrow{a}(\mathbf{h}) = \begin{pmatrix} -0.005127 & 12.38 & 4005 \\ -0.001064 & 11.45 & 7204 \\ -0.02191 & 20.49 & 9047 \end{pmatrix} \tag{6}$$

$$SSE = \begin{cases} 9.466E-30 & h=2 \\ 1.026E-29 & h=3 \\ 8.52E-29 & h=4 \end{cases} \tag{7}$$

Since obtained values of SSE and R-square are small enough for an appropriate statistical model, no further approximation is necessary in Adjusted R-square and RMSE. As a result, the values of all the statistics emphasize a good match of the polynomial expression with the experimental data. We also studied higher degree polynomials in finding more accurate model; however, we find that the coefficients of higher order terms in the higher degree polynomials are extremely small. We conclude that the polynomial of order-two is the closest approximation for the experimental data of end-to-end delay for OLSR routing protocol.

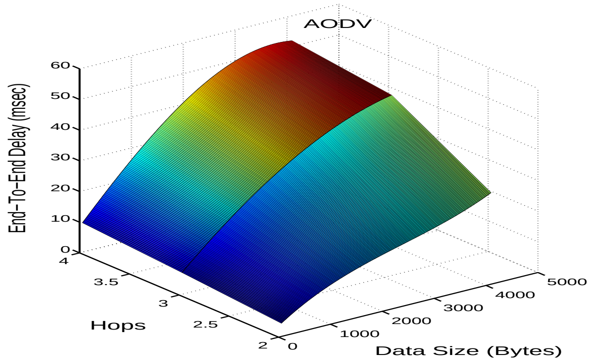

Fig. 3. AODV: End-to-End Delay Comparison.

2) **Analysis of End-To-End Delay for AODV:** As a reactive protocol, AODV starts route establishment phase only when a path failure is detected, or a source node demands for the route establishment. However, AODV transmits route maintenance packets periodically. The performance impact on end-to-end delay due to the routing overhead generated by AODV is shown in Fig. 3. We see that end-to-end delay in all the network topologies increases almost linearly with respect to packet size. In addition, difference in end-to-end delay for various topologies for the same packet size is large. Therefore, it implies that control packets generated by AODV increase in the same proportion as the increase in the network size and the network activities. This phenomenon suggests that AODV may impose more scalability problems in large MANETs.

To derive a polynomial model using statistic analysis, let $\sigma_{\rm a}(x,h)$ represent end-to-end delay for AODV which is a function of data size x and number of hops (or path length) h. Then, polynomial regression $\sigma_{\rm a}(x,h)$ can be modeled by

$$\sigma_{\rm a}(x,h) = c_1(h)e^{c_2(h)x} + c_3(h)e^{c_4(h)x}. \tag{8}$$

with coefficients of $c_i(h)$ $(i = 1, 2, 3, 4$ and $h = 2, 3, 4)$ as

$$\overrightarrow{c}(\mathbf{h}) = \begin{pmatrix} 11.98 & 0.0002229 & -8.548 & -0.001357 \\ 20.78 & 0.0002047 & -15.17 & -0.001179 \\ 27.96 & 0.0001522 & -20.22 & -0.001116 \end{pmatrix} \quad (9)$$

$$SSE = \begin{cases} 0.03915 & h = 2 \\ 0.3166 & h = 3 \\ 0.5984 & h = 4 \end{cases} \quad (10)$$

$$\mathrm{R} - square = \begin{cases} 0.9999 & h = 2 \\ 0.9997 & h = 3 \\ 0.9997 & h = 4 \end{cases} \quad (11)$$

We find that the values of SSE are not close to zero. It suggests that further approximation to find a better statistical model is necessary. However, the values of R-square are close to unity, therefore, further adjustment to Adjusted R-square and RMSE to obtain a more suitable statistical model is not required. Although, we are able to find some other statistical models with lower values of SSE, those models diverge with respect to large packet sizes. As in case of AODV, we observe experimentally that end-to-end delay keeps increasing with packet size and number of hops, the statistical model given by (8) is the most appropriate to describe the behavior of the routing protocol accurately. Moreover, we find that the obtained statistical model and the experimental results suggest that the end-to-end delay for AODV increases rapidly with respect to packet size and network size. However in realistic scenarios, end-to-end delay can not increase to an infinite value, therefore it means that after a certain network size, all packets will be dropped by the network running AODV. Therefore, as we concluded previously, scalability in MANETs running AODV is a cause of concern.

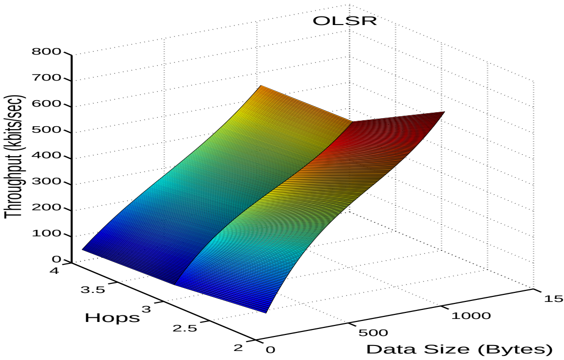

Fig. 4. OLSR: Throughput Comparison.

C. Analysis of Throughput

Throughput is an important metric to understand the performance impact caused by the routing protocols. In this subsection, we present the experimental values of throughput along with the statistical models for OLSR and AODV to gain deeper insights about the performance impact.

1) **Analysis of Throughput for OLSR:** Experimental results on throughput for OLSR are shown in Fig. 4. We observe that throughput is increasing as the size of packet increases. This similar phenomenon is observed for all various topologies in the network. In addition, we see that the difference in the values of throughput for equal packet sizes between 2-hop and 3-hop topologies is more than that of between 3-hop and 4-hop topologies. It means that as the network expands from 2-hop to 3-hop or 4-hop, throughput achieved during the transmission of data streams with equal packet sizes does not vary considerably. This observation suggests that as the network expands, throughput decreases slowly. As a result, we can conclude that OLSR performance degrades slowly as the network expands. Also, it suggests that OLSR can provide better network scalability than AODV. Now, we find the statistical model to establish relation among packet size, number of hops and throughput. Let $\eta_o(x, h)$ represent the throughput of the network running OLSR, which is function of data size x and number of hops (or path length) h. We find that the most suitable polynomial regression for $\eta_o(x, h)$ can be modeled by

$$\eta_o(x, h) = b_2(h)x^2 + b_1(h)x + b_0(h). \quad (12)$$

The coefficients of this polynomial, $b_i(h)$ $(i = 0, 1, 2$ and $h = 2, 3, 4)$, are

$$\overrightarrow{b}(\mathbf{h}) = \begin{pmatrix} -0.000507 & 0.7013 & 6.027 \\ -0.001028 & 1.001 & 4.019 \\ -0.001605 & 1.451 & 19.28 \end{pmatrix} \quad (13)$$

$$SSE = \begin{cases} 4.564E - 25 & h = 2 \\ 3.201E - 25 & h = 3 \\ 7.694E - 25 & h = 4 \end{cases} \quad (14)$$

SSE values for different topologies are presented in (14). Values of R-square for various values of h are equal to 1. Values of SSE close to zero and values of R-square equal to 1 show the accordance of the model with respect to the experimental measurements. We observe that coefficients for second order term are very small which suggests that initially throughput increases almost linearly with smaller packet sizes. However, as the packet size is increased further, throughput increases slowly. Moreover, as the number of hops between two communicating nodes is increased in the network, throughput decreases slowly.

2) **Analysis of Throughput for AODV:** Throughput analysis helps us gain insights about the performance impact caused by the route discovery and the route maintenance phases of AODV protocol. Fig. 5 shows the experimental values of throughput for AODV in different scenarios. We see that throughput increases as the packet size of data stream is increased. However, increase in throughput for bigger packet sizes is not in the same proportion as the increase in the packet size. Also, we observe that if we transmit data streams of equal packet sizes in the networks with different number of hops, throughput decreases faster as the number of hops are increased from 2 to 3 or 4 between two communicating nodes. These observations suggest that as the network expands and packet size increases, performance of the network running AODV degrades at a faster rate. Therefore, like the observations discussed for end-to-end delay for AODV, observations for throughput values also suggest that scalability is an issue in the networks running AODV routing protocol. To find the analytical expression, first we define few symbols. Let $\eta_{\mathrm{a}}(x,h)$ be throughput achieved in an AODV network, which is function of data size x and number of hops (or path length) h. We find that the most suitable regression for $\eta_{\mathrm{a}}(x,h)$ can be modeled by

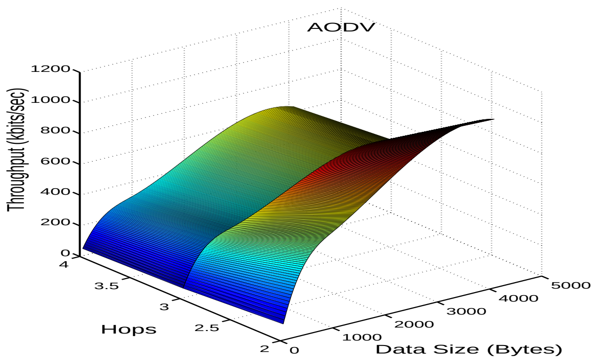

Fig. 5. AODV: Throughput Comparison.

$$\eta_{\mathrm{a}}(x,h) = d_1(h)e^{d_2(h)x} + d_3(h)e^{d_4(h)x}. \quad (15)$$

with coefficients of $d_i(h)$ ($i = 1,2,3,4$ and $h = 2,3,4$) as

$$\vec{d}\,(\mathbf{h}) = \begin{pmatrix} 558.8 & 0.0001653 & -536.5 & -0.002743 \\ 332.1 & 0.0001764 & -324 & -0.003096 \\ 255 & 0.0002214 & -251 & -0.003054 \end{pmatrix} \quad (16)$$

$$SSE = \begin{cases} 0.6897 & h = 2 \\ 0.1494 & h = 3 \\ 0.144 & h = 4 \end{cases} \quad (17)$$

Values of SSE for different topologies are presented in (10). Values of R-square for various values of h are equal to 1. We observe that the values of SSE are not close to zero, however, we observe that the values of R-square are equal to unity, therefore, further adjustments to adjusted R-square and RMSE to obtain a closer model are not necessary. According to the model obtained, we observe that throughput keeps increasing with the increase in packet size. But in practical situations, it is not true due to fragmentation of bigger size packets into smaller packet to comply with the network's MTU.

IV. Empirical Analysis Of Routing Overhead

Routing protocols generate control messages in response to changes in the network. As control messages consume part of the network bandwidth, they degrade network performance and are termed as the routing overhead. To quantify the percentage network bandwidth consumed by the routing overhead, we develop a simple analysis to establish a relationship between *effective transmission time* and *overhead transmission time*. *Effective transmission time* is defined as the percentage network bandwidth used in transmitting the entire data stream, whereas *overhead transmission time* is defined as the percentage network bandwidth used in transmitting the routing overhead. Our aim is to determine the real-time values of the ratio of effective transmission time and overhead transmission time based on experimental results in various scenarios. While computing the ratio, we exclude the overhead generated by the MAC layer by computing the effective data transmission rate.

Let h denote the number of hops between two communicating nodes i and j, N denote the number of packets of size d transmitted between the two nodes, and T_e be the effective data transmission rate experienced at the network layer. Let T denote the actual data rate which is set to 11Mbps in the testbed. T_e captures overhead generated due to MAC layer which we determine using the results presented in [6]. Based on the analysis provided in [6], we observe that effective data transmission rate varies with the size of data packet. Therefore, we determine per packet overhead due to MAC layer in terms of data bytes. Let per packet overhead for a data stream with packet size d be β_d. Then, T_e and T can be related as follows:

$$T_e = \frac{d \cdot T}{d + \beta_d}, \quad \text{or} \quad \beta_d = d(\frac{T}{T_e} - 1). \quad (18)$$

Assume that transmission of an entire data stream consists of k time sequences where each time sequence is composed of average effective transmission time and average overhead transmission time as shown in Fig. 6. Let average effective transmission time and average overhead transmission time be denoted as $\overline{T_\gamma}$ and $\overline{T_\zeta}$, respectively. Then we have

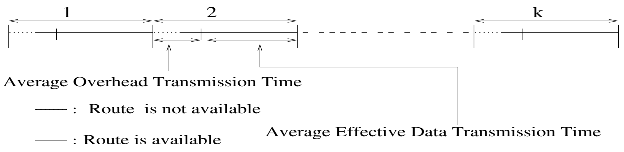

Fig. 6. Time Sequences.

$$T_\gamma = k\overline{T_\gamma} \quad , \quad T_\zeta = k\overline{T_\zeta} \quad \text{and} \quad \frac{T_\zeta}{T_\gamma} = \frac{\overline{T_\zeta}}{\overline{T_\gamma}}. \quad (19)$$

Since all mobile nodes in the indoor testbed are close to each other physically, only one mobile node can transfer the data at a time. Since every data packet has to travel $2h$ number of hops in the network, each hop will have $\frac{\overline{T_\gamma}}{2h}$ time duration to transmit the data packet. Therefore, number of packets transmitted during the time $\frac{\overline{T_\gamma}}{2h}$ by the source node i, denoted as $\overline{N}$, is

$$\overline{N} = \frac{\overline{T_\gamma}T}{2h(d + \beta_d)}. \quad (20)$$

Therefore, achieved throughput in transmitting data stream of size Nd is provided as follows,

$$\eta_{ij}(h,d) = \frac{Nd}{k(\overline{T_\gamma} + \overline{T_\zeta})}. \quad (21)$$

By simple manipulations and using $k = \frac{N}{\overline{N}}$ and $\overline{N}$ in (21), the relation between $\overline{T_\zeta}$ and $\overline{T_\gamma}$ can be shown as,

$$\frac{\overline{T_\zeta}}{\overline{T_\gamma}} = \frac{d \cdot T}{2h(d+\beta_d)\eta_{ij}(h,d)} - 1. \qquad (22)$$

The value of $\eta_{ij}(h,d)$ used in the above equation is obtained through real-time experiments as explained in Section II.

A. Observations

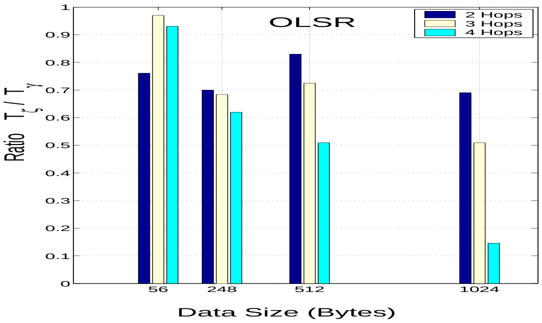

Fig. 7. Ratio of T_ζ to T_γ in OLSR Network.

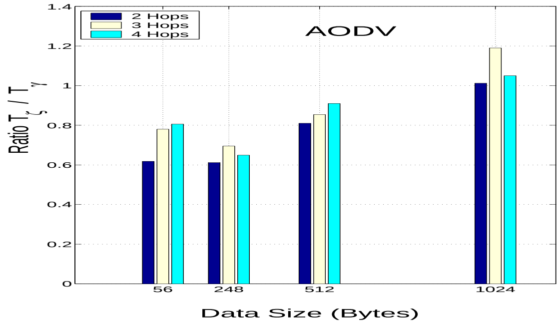

Fig. 8. Ratio of T_ζ to T_γ in AODV Network.

By substituting the experimental values for throughput in (22), the ratio of T_ζ and T_γ has been calculated for AODV and OLSR. From Figs. 7 it is observed that as network size expands, the percentage routing overhead generated by OLSR reduces, which is in accordance with the fact that OLSR is more suitable for the large networks. In contrast, from Fig. 8, we observe that the percentage overhead generated by AODV increases as the size of the network increases which is also in agreement with the fact that AODV performance degrades rapidly as the network size expands. Based on these observations, we can conclude that as the network size increases, networks running AODV suffer higher performance degradation than the networks running OLSR.

In addition, we observe from Fig. 7 that, in the two hop topology, the routing overhead generated by OLSR is almost similar for various packet sizes. Whereas, for other topologies, the percentage overhead generated by OLSR decreases. In case of AODV, we observe that percentage overhead increases as packet size increases in all topologies. It is due the fact that AODV generates higher amount of the routing overhead as the traffic load starts increasing in the network.

V. Conclusion

In this paper, we address the issue of performance degradation due to the routing overhead in MANETs. We performed a real-time experimental study to analyze the performance impact of routing protocols in terms of delay and throughput. Using statistical-analytic approach, we derived the statistical models with non-linear regressions for OLSR and AODV to obtain an in-depth understanding of the routing behavior beyond the scenarios configured in the testbed. In addition, we provided a simple analysis to compute the network bandwidth consumed by the routing overhead in various scenarios. As we used various mobile devices consisting different hardware platform, our results are applicable for heterogeneous ad-hoc networks as well. We believe that, this work not only provides fundamental knowledge and observation of the performance impact by the routing protocols, and it also has significant contributions to the modeling, analysis, and design of efficient routing protocols for MANETs.

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