Quantifying Factors Affecting Quality of Service in Mobile Ad Hoc Networks

Kiran K. Vadde
Violet R. Syrotiuk
Computer Science & Engineering
Arizona State University
P.O. Box 878809
Tempe, AZ 85287-8809
kvadde@asu.edu
syrotiuk@asu.edu

Support for *quality of service* (QoS) is increasingly important in *mobile ad hoc networks* (MANETs) with the emergence of delay-sensitive applications. This article quantifies the impact of factors and their interactions on the performance of real-time flows through statistical analysis of data gathered in simulation. The factors considered include QoS architecture, routing protocol, medium access control (MAC) protocol, mobility model, and offered load. The QoS architectures considered include stateless (Swan), stateful (Insignia), and no support for QoS. For routing, proactive (OLSR) and reactive (DSR, AODV) protocols are considered. The IEEE 802.11 distributed coordination function (DCF) and its QoS-aware extension *enhanced* DCF (EDCF) are the MAC protocols considered. The authors find that the stateless architecture of Swan better supports QoS than the stateful approach of Insignia or the classic architecture in the two mobility models considered.

Keywords: Quality of service (QoS), mobile ad hoc networks (MANETs), factor interaction, statistical analysis

1. Introduction

Research to support *quality of service* (QoS) in *mobile ad hoc networks* (MANETs) has largely been motivated by the need to support voice communication. This is the primary application in battlefield and in emergency situations, where MANETs are best deployed. What makes supporting QoS in MANETs a challenge is that the network operates without any centralized control or fixed infrastructure. Frequent changes in the network topology result from node mobility and from the time-varying characteristics of the wireless channel. Such network dynamics add to the difficulty of supporting QoS (i.e., estimating and provisioning resources to real-time flows to satisfy their rate, delay, or jitter requirements).

Similar to the differentiated and integrated service architectures for wired networks, QoS architectures have emerged for MANETs [1, 2]. These architectures make use of techniques such as admission and flow control, traffic shaping, and others to regulate best-effort traffic to satisfy the QoS needs of real-time traffic. Individual protocols are made QoS aware by differentiating real-time and best-effort packets and/or flows. For example, a QoS-aware routing protocol selects paths based on metrics such as delay, bandwidth, or load balancing rather than hop count [3, 4], and a QoS-aware *medium access control* (MAC) protocol provides packets of different traffic classes with differentiated channel access. Improving cross-layer protocol interactions has been critical for improved network performance [5, 6].

Since there are very few MANET testbeds, simulation has provided a valuable tool to model MANETs and network architectures with high fidelity and to measure their performance. Initially, simulation was used to measure the performance of various protocols run individually in different network settings. For example, Royer, Lee, and Perkins [7] compare the performance of the Wireless Routing Protocol (WRP), the Fisheye State Routing (FSR), and the Adhoc On-Demand Distance Vector (AODV) routing protocol over the Carrier Sense with Multiple Access (CSMA), Multiple Access with Collision Avoidance (MACA), Floor Acquisition Multiple Access (FAMA), and IEEE 802.11 MAC protocols, varying the pause time of the random waypoint mobility model. Their results show that performance of WRP and FSR did not change significantly with the MAC protocol, while AODV outperformed other routing protocols when run over IEEE 802.11.

Perkins et al. [8] compare the performance of the Dynamic Source Routing (DSR) and AODV routing protocols running over the IEEE 802.11 MAC protocol for different network loads, network sizes, and pause times in the

SIMULATION, Vol. 81, Issue 8, August 2005 547-560

DOI: 10.1177/0037549705060236

random waypoint mobility model. Their results show that the performance of DSR and AODV varies based on the simulation parameters. For a large number of traffic sources, the performance of AODV exceeds that of DSR.

While such studies help us understand how a protocol performs in different settings, they provide little information on how or to what extent protocols interact. Bai, Sadagopan, and Helmy [9] went a step further. They used simulation to study the impact of mobility models on the AODV, DSR, and Destination-Sequenced Distance Vector (DSDV) routing protocols. Their results show that the performance of all three protocols changes significantly with the underlying mobility model. The difference in performance is attributed to the underlying graph properties of the mobility model. Of particular interest is the decomposition of the routing protocols into "building blocks" to gain more insight into how mobility creates performance variations across the protocols.

At about the same time, Barrett et al. [10] used more rigorous techniques to characterize the interaction between the MAC and routing protocols in MANETs. They used statistical *design of experiments* (DOE) [11] to determine whether factors interact with each other in a significant way. This is a well-known methodology used for factor interaction studies in many disciplines ranging from social sciences to industrial engineering. Statistically, interaction between two factors exists when the effect of a factor on a response variable is modified by another factor in a significant way. Starting with a saturated model, they applied backward elimination. This method checks each k-way factor interaction for significance using *analysis of variance* (ANOVA) techniques and eliminates it if it is found to be insignificant. In this way, the smallest model that explains the simulation data is found. We applied DOE to quantify cross-layer protocol interactions affecting service delivery in MANETs [12].

There are two aspects to any experimental problem: the design of the experiment and the statistical analysis of the data. In this article, we select five factors of mixed levels that represent a useful subset of possible factors to consider in order to bound our study. The factors we consider are (1) QoS architecture, (2) routing protocol, (3) MAC protocol, (4) mobility model, and (5) offered load. We select average real-time packet delay, jitter, real-time throughput (throughput of real-time flows only), and total throughput (throughput of real-time and best-effort flows) as our responses. We then perform a statistical analysis of the data collected from experiments run in the `ns-2` network simulator [13] using ANOVA techniques in Design-Expert [14]. This allows us to quantify the main effects and interactions of factors that best explain the response variables in our study.

Our results show that the QoS architecture does contribute to the response variables. Swan in general performs better than Insignia and classic architectures. However, the combination of the MAC protocol with which it performs best is dependent on the routing protocol over which it operates. With DSR and Optimized Link State Routing (OLSR), Swan with the enhanced distributed coordination function (EDCF) has the best performance with respect to average delay and real-time throughput. However, with AODV, Swan over IEEE 802.11 has the best performance. This is due to the differences in interactions between the routing and MAC protocols. EDCF performs poorly in the presence of congestion, and this negatively affects AODV, causing higher overall average delays.

Of course, not only the question of which factors and factor interactions affect observed performance but also the question of *how* these factors and their interactions work to cause the observed performance require an answer. Design of experiments provides answers for the former question; addressing the latter question is equally important, as understanding how factors and their interactions work is likely to be critical for effective cross-layer protocol designs. In this article, we focus on quantifying both main effects and interactions of factors on responses.

This article is organized as follows. In section 2, we briefly explain the simulation models used. In section 3, we describe the network responses measured and present as well as interpret the simulation results. A statistical analysis of the simulation results, quantifying the factors and their interactions, is presented in section 4. The interaction of the protocols within the architecture leaves substantial research questions, which we elaborate on in section 5, after summarizing our findings.

2. Simulation Models

We use the network simulator `ns-2` version 2.26 [13] installed on a Pentium IV 2.4-GHz processor with 2 GB RAM running Linux. It is a discrete event simulator implemented in C++. The Monarch group [15] integrated extensions into the `ns-2` simulator to support wireless communications between mobile nodes. Specifically, these extensions include radio propagation models, a channel model, and node movement and location update—all essential to modeling MANETs.

To apply DOE, the first step is to identify the factors and the level of each factor for our experiments. To bound our study, we consider the following five factors:

1. QoS architecture,
2. routing protocol,
3. MAC protocol,
4. mobility model, and
5. offered load.

2.1 QoS Architecture Models

In support of QoS, a spectrum of architectures has been proposed, ranging from stateless (differentiated services) to stateful (integrated services). For MANETs, an example of a stateless approach is Swan, while Insignia is an example of a stateful approach.

In Swan [1], individual nodes along the route from a source to a destination do not maintain any state information regarding the admitted real-time flows. In Swan, admission control is performed only at the source node to decide whether to admit or reject a real-time flow based on the available bandwidth in its neighborhood. Intermediate nodes regulate their best-effort traffic to meet the QoS needs of real-time flows routed through them. The channel access delay, a local measure of congestion, is used to determine the rate at which to regulate the best-effort traffic.

Intermediate nodes, not just the source, perform admission control and maintain the QoS state on flows admitted in Insignia [2]. Insignia performs flow adaptation and restoration to meet the QoS needs of real-time flows and to match them to the available resources; this is achieved using in-band signaling. Insignia is therefore a heavy-weight QoS architecture in terms of memory, computation, and communication when compared to Swan.

For the factor of QoS architecture, we consider three levels: Swan, Insignia, and “classic” with no provisions for QoS.

2.2 Routing Protocol Models

The problem of routing is fundamental in MANETs since each node is capable of functioning as a router, forwarding packets in addition to being a source or destination of packets. We consider both proactive and reactive protocols in our study; all have advanced to the next stage of standardization by the Internet Engineering Task Force (IETF) MANET working group [16].

In DSR [17], the source is responsible for computing the route for a packet. When a node wishes to communicate with another node, it floods a route request (RREQ) through the network to discover a route to the destination. When the RREQ reaches the destination or a node that is aware of a route to the destination, forwarding stops. A route reply (RREP) packet is sent back to the source on the reverse path, with the full source route to the destination embedded. This source route is included in the header of each data packet, enabling stateless forwarding. The route maintenance mechanism monitors the status of source routes in use, detects link failures, and repairs routes with broken links. Nodes operating in promiscuous mode listen to ongoing traffic and cache overheard routes; these may help reduce the scope of the RREQ flood.

AODV [18] is similar to traditional distance vector protocols in that it maintains routing tables with one entry per destination. AODV builds routes using RREQ and RREP control packets similar to the route discovery mechanism in DSR. The main difference is that as a RREP propagates back to the source, each node sets up a forward path entry to the destination in its routing table. Once the source node receives the RREP, it may begin to forward data packets to the destination.

While DSR and AODV are reactive routing protocols, the OLSR protocol [19] is proactive; it builds/maintains routes to all nodes on a continuous basis rather than on an as-needed basis. OLSR makes use of *multipoint relays* (MPRs). An MPR is a subset of neighbors that reach the two-hop neighborhood, allowing efficient flooding of control messages. MPRs exchange link state information to form routes. Sequence numbers are used to guarantee loop-free routes, and timers are maintained to refresh route entries.

For the factor of the routing protocol, we consider three levels: AODV, DSR, and OLSR.

2.3 MAC Protocol Models

The MAC protocol is fundamental in all networks whose basis is a broadcast channel. The MAC protocol is directly responsible for controlling access to the communication resources.

The IEEE 802.11 DCF [20] protocol is the dominant MAC protocol in MANETs due to its simplicity and lack of synchronization requirements. It is a *carrier-sense multiple access* with *collision avoidance* (CSMA/CA) protocol. It is well established that IEEE 802.11 is ineffective for QoS since it does not perform packet differentiation [21].

There are several approaches to extend IEEE 802.11 to support traffic classes. In EDCF [22], traffic flows are classified based on their priority. The traffic from each class has a distinct queue and also a different backoff window. The backoff window is used to regulate nodes in accessing the channel. The backoff counter for each of the transmission queues is run separately, and the data packets of the queue whose backoff counter expires first are transmitted. If more than one backoff counter expires, data packets of the queue with the highest priority are transmitted.

We consider IEEE 802.11 DCF and its QoS-aware extension, EDCF, as the two levels of the MAC protocol. In EDCF, the backoff window size for voice and data packets, respectively, is [15, 31] and [31, 1023]. The backoff window for control packets is [7, 15]; these packets have higher priority than the voice or data packets to ensure that broken routes are repaired quickly to minimize service disruption to the established flows.

2.4 Mobility Models

A mobility model governs node movement in the simulation area. Although not considered in our study, some simulators also include terrain models (e.g., such as TIREM [23]) and the effects of buildings and foliage on propagation.

We consider two mobility models for individual nodes in a flat, unobstructed area in our study: the grid and the *random waypoint* (RWP) models. In the grid mobility model, the simulation area is divided into grid squares, and nodes

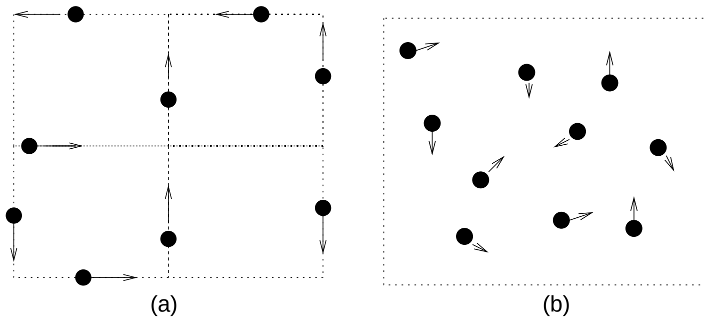


Figure 1. Mobility models: (a) grid and (b) random waypoint

are allowed to move only along the grid lines. When a node reaches an intersection, it decides to move in the same direction with a given probability; otherwise, it changes direction. This simulates movement in a city where there is an underlying grid structure formed by streets and avenues. An example of such movement is shown in Figure 1(a). In the figure, a black circle denotes a mobile node, and the arrow indicates the direction of its movement.

In the random waypoint (RWP) mobility model, a node selects a destination at random and moves toward it with a fixed speed. Once it reaches the destination, it pauses for a time determined by a simulation parameter. The algorithm then repeats. This models individuals moving from place to place performing an activity at each destination. An example of nodes moving according to the RWP mobility model is given in Figure 1(b).

2.5 Offered Load

Real-time traffic is modeled using three voice traffic flows of 64 Kbps. The network load is varied by increasing the number of best-effort flows. These best-effort flows are modeled as TCP connections between the same source and destination pairs as the real-time flows. This is done to ensure that the TCP (best-effort) flows follow the same route as the real-time flows to better observe the service differentiation.

2.6 Factor Summary

Table 1 summarizes the factors considered in our simulation. Running an experiment with every factor set to every possible level (a full factorial design) results in $3 \times 3 \times 2 \times 2 \times 4 = 144$ different experiments. We repeat each experiment with 10 different seeds and take the average of these 10 runs. The size of the confidence interval is 20% of the plotted value in the worst case 95% of the time.

2.7 Scenario Generation

Following scenario generation in earlier simulation studies [1, 2], 50 nodes are distributed over a 1000×1000-m area. Nodes are connected to their peers via a shared 11-Mbps interface. The transmission range of each node is 250 m.

All the nodes in the simulation model, including source and destination nodes, move at the speed of 2 m/sec, which corresponds to the speed of an individual walking. For experiments using the RWP mobility model, we distribute the nodes according to the stationary distribution to improve confidence of the validity of the results [24]. Nodes move continuously (i.e., they do not pause). For the grid mobility model, a 10×10 grid overlays the simulation area. Nodes are initially placed randomly on the grid. Nodes move along the grids in the x or y direction and bounce back if they approach the simulation area boundary. At a grid intersection, nodes continue to move along in the same direction with a probability of 0.5 and change direction to the left or right with a probability of 0.25 each. This ensures that nodes move along the grid in both x and y directions.

Each experiment runs for 200 seconds. The voice traffic is initiated 5 seconds into the simulation between node pairs (3, 18), (17, 20), and (0, 6), while the best-effort flows begin after 40 seconds to ensure that the source-destination routes have been established and used by each flow. The maximum number of packets generated by each flow is 2500 to ensure that voice traffic and TCP data traffic exist for the duration of the simulation. The size of real-time packets is 512 bytes, while best-effort packets are 128 bytes in size.

3. Simulation Results

In this section, we present our simulation results. We collect the following responses from our experiments.

- **(Real-time) average delay:** The average end-to-end delay experienced by a packet between its initiation at the source and its receipt at the destination. This value includes queuing delays as well as channel access delays. We report the average delay of real-time packets since only the real-time traffic is delay sensitive.
- **Jitter:** The average interarrival time between real-time packet receipts at the destination node. Jitter is a measure of transmission quality; low jitter corresponds to a better quality transmission.

Table 1. Factors and their levels

Factor	Levels of Factors
Quality-of-service architecture	Swan, Insignia, Classic
Routing protocol	Adhoc On-Demand Distance Vector (AODV), Dynamic Source Routing (DSR), Optimized Link State Routing (OLSR)
Medium access control (MAC) protocol	IEEE 802.11, enhanced distributed coordination function (EDCF)
Mobility model	Grid, random waypoint
Offered load	0, 3, 6, 9 additional best-effort flows

- **Real-time throughput:** The number of real-time packets received per unit time, expressed in bytes/sec. Voice requires an end-to-end delay of 400 msec for acceptable quality. Any real-time packet received whose delay is greater than 400 msec is not included in this real-time throughput calculation.
- **Total throughput:** The combined throughput of real-time and best-effort traffic. The real-time traffic is assumed to meet the delay requirement to be included, while every best-effort packet received at its destination is included. This metric determines the effectiveness of protocols in using the unused bandwidth by real-time traffic for delivering best-effort traffic.

We present our results within the context of a mobility model. Sections 3.1 and 3.2 present the results for the RWP and grid mobility models, respectively. To make the results less cluttered, we present the results for each routing protocol separately. To improve the readability of the graphs, when IEEE 802.11 [EDCF] is used as the MAC protocol, solid [dashed] lines are used.

3.1 Fixed Mobility Model: Random Waypoint

3.1.1 DSR in RWP

Figures 2 and 3 show the results of experiments in which DSR is fixed as the routing protocol. Figure 2(a) shows the average delay of real-time packets. The Swan QoS architecture over EDCF has the smallest delay among all network architectures. Real-time packets are differentiated from the best-effort packets both by the QoS architecture and the MAC protocol, giving the best performance for real-time packets.

Insignia over 802.11 has the worst performance because the flow adaptation and restoration performed increase the control packet overhead. This causes congestion in the network, leading to increased delay for the real-time packets. However, when Insignia is paired with EDCF as the MAC protocol, it decreases the average delay for the real-time packets since service differentiation is provided by the EDCF protocol. Insignia over EDCF performs worse than the classic architecture over EDCF because of the flow adaptation and restoration overhead.

When no QoS architecture is used, EDCF performs better than 802.11 because EDCF has a smaller backoff window size for real-time packets compared to that for best-effort data packets. In 802.11, there is a single queue and no service differentiation; hence, real-time packets suffer larger delays.

Swan over 802.11 performs better than 802.11 alone as Swan regulates the best-effort packets to reduce the delays for real-time packets. The number of route requests made by DSR is quite low due to the aggressive route caching, which also decreases the route repair time. Swan over 802.11 performs better than EDCF in the classic architecture; this suggests that admission control is more helpful than packet differentiation at the MAC level. However, having *both* admission control as part of QoS architecture and packet differentiation at the MAC level is best of all, as seen from the lowest delay for Swan over EDCF.

Figure 2(b) shows the real-time packet jitter. Swan over EDCF has the lowest jitter, and 802.11 in the classic architecture has the highest jitter. The classic architecture over EDCF has higher jitter than Swan over EDCF at low traffic loads (i.e., at 0 and 3 best-effort flows). At higher traffic loads (i.e., 6 and 9 best-effort flows), both have the same jitter. Insignia over 802.11 has higher delay (see Fig. 2(a)), but it has lower jitter than the classic architecture over 802.11 as it tries to make sure that the real-time flows have the required bandwidth along the chosen route. Insignia over EDCF has lower jitter than Insignia over 802.11 since service differentiation with flow adaptation allows real-time packets to arrive at the destination faster, thereby decreasing the jitter.

Figure 3(a) compares the throughput of the real-time flows. Swan over EDCF performs the best, and the classic architecture over 802.11 performs the worst; this follows from the results on delay discussed above. At the lowest traffic load (i.e., where there are only real-time flows and no TCP flows), all network architectures have almost the same performance. The reason for this is that when there are no best-effort flows, there is no traffic regulation in Swan, and there is also no real service differentiation at the MAC layer.

Figure 3(b) shows the total throughput. The x-axis in this figure has only three points in contrast to the previous figure with four data points. The total throughput when there are no TCP flows is the same as the real-time throughput with zero TCP flows, which is shown in Figure 3(a); hence, this point is not included. Swan over EDCF has the best total throughput, and Insignia over 802.11 and the

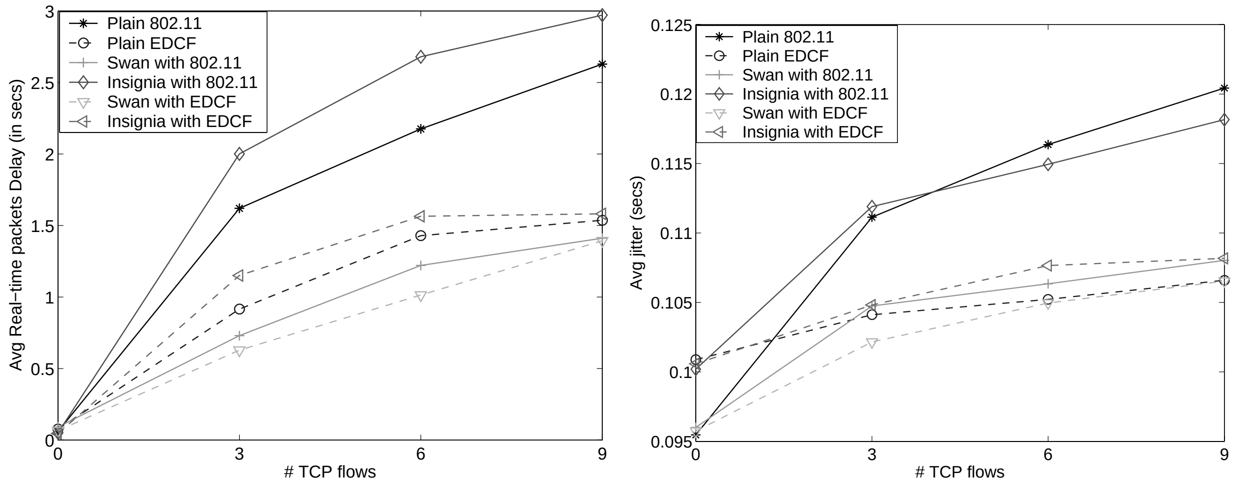


Figure 2. Dynamic Source Routing (DSR) in the random waypoint (RWP) mobility model: average real-time packet (a) delay and (b) jitter

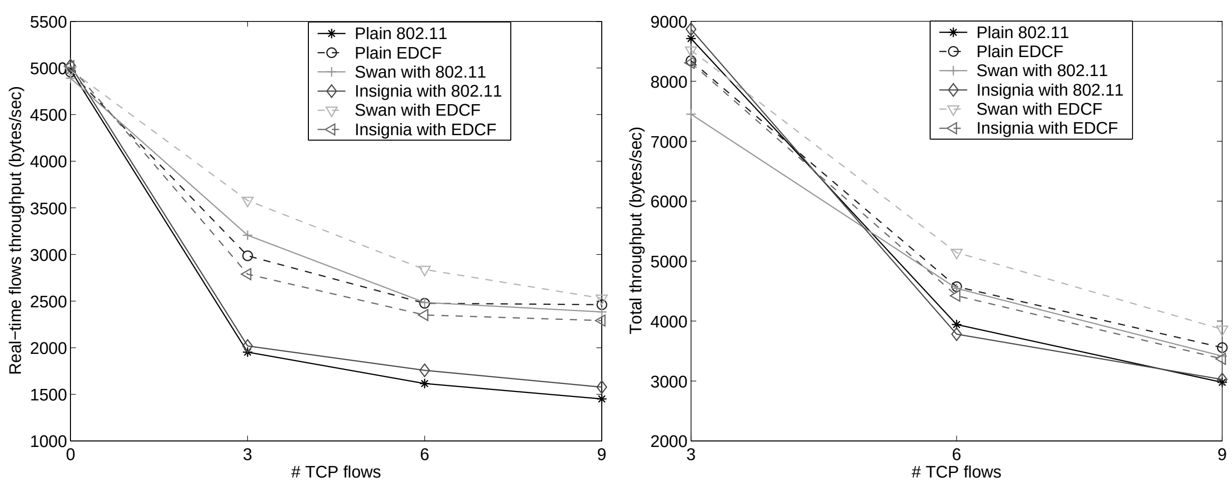


Figure 3. Dynamic Source Routing (DSR) in the random waypoint (RWP) mobility model: (a) real-time throughput and (b) total throughput

classic architecture over 802.11 have the worst performance. The reasoning given for the delay comparison applies here, too.

3.1.2 AODV in RWP

Figure 5 shows results with AODV fixed as the routing protocol. As Figure 5(a) shows, the best performance is obtained when AODV is run with Swan over 802.11; Insignia over EDCF has the worst performance. Of surprise is that network architectures using EDCF have higher delays than those using 802.11. Intuitively, EDCF with its service differentiation should perform better than 802.11 without service differentiation.

The routing protocol plays an important role in the effectiveness of service differentiation at the MAC layer. AODV generates substantially more (seven times) control packets than DSR, as Figure 4 shows. The reason for this is the way RREQs propagate in AODV and DSR, as well as the caching mechanism used in DSR. DSR uses aggressive caching to maintain route information, whereas AODV does not perform caching. When the nodes move at slower speeds (as used in our simulation), the routes cached remain valid most of the time, and DSR does not perform network-wide flooding; hence, it generates fewer control packets. In contrast, AODV performs an expanding ring search to find routes, and since it does not use caching,

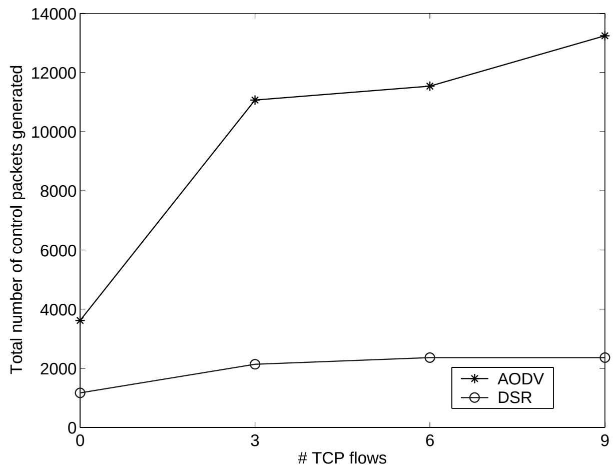
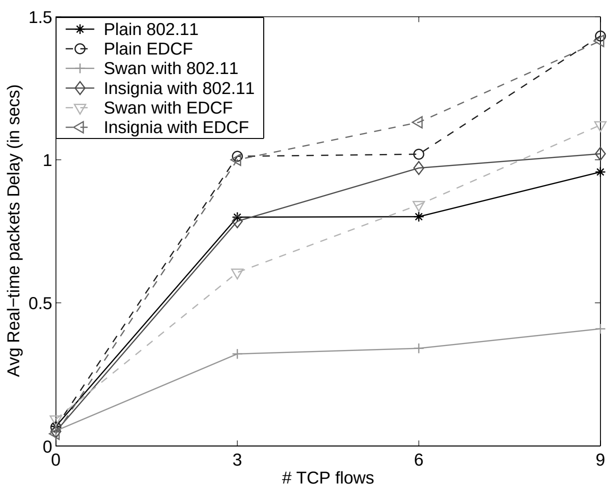


Figure 4. Number of control packets generated by the routing protocol



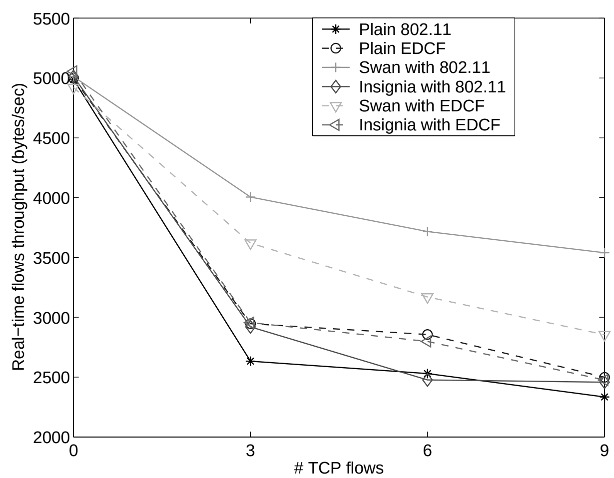


Figure 5. Adhoc On-Demand Distance Vector (AODV) in the random waypoint (RWP) mobility model: average real-time (a) delay and (b) throughput

route requests can propagate deep into the network. Bai, Sadagopan, and Helmy [9] observed the same results.

When the number of control packets generated by the routing protocol is high, congestion occurs, leading to higher contention for the channel by the MAC protocol. With EDCF, collisions of the control packets cause a ripple effect of collisions with the real-time packets. EDCF uses a fixed contention window of [15, 31] for real-time packets; with each collision, EDCF selects a backoff time from this small interval for packet retries. Since nodes choose from a small backoff interval, at high congestion, there are many retransmissions, leading to larger queuing delays and dropped packets. This is the reason for larger delays of network architectures using EDCF.

Figure 5(b) shows the real-time throughput achieved. As the figure shows, Swan over 802.11 has the best performance. Swan over EDCF performs poorly compared to Swan over 802.11, as explained earlier. Network architectures using EDCF (except for those with Swan) perform better than those using 802.11 for real-time throughput. This is due to the absence of a strong interaction between Insignia and EDCF, as well as between the classic architecture and EDCF. The reason why the classic architecture over EDCF has higher real-time throughput than when run over IEEE 802.11 (despite the fact that EDCF responds poorly to congestion) is that once congestion eases, EDCF delivers more packets than IEEE 802.11.

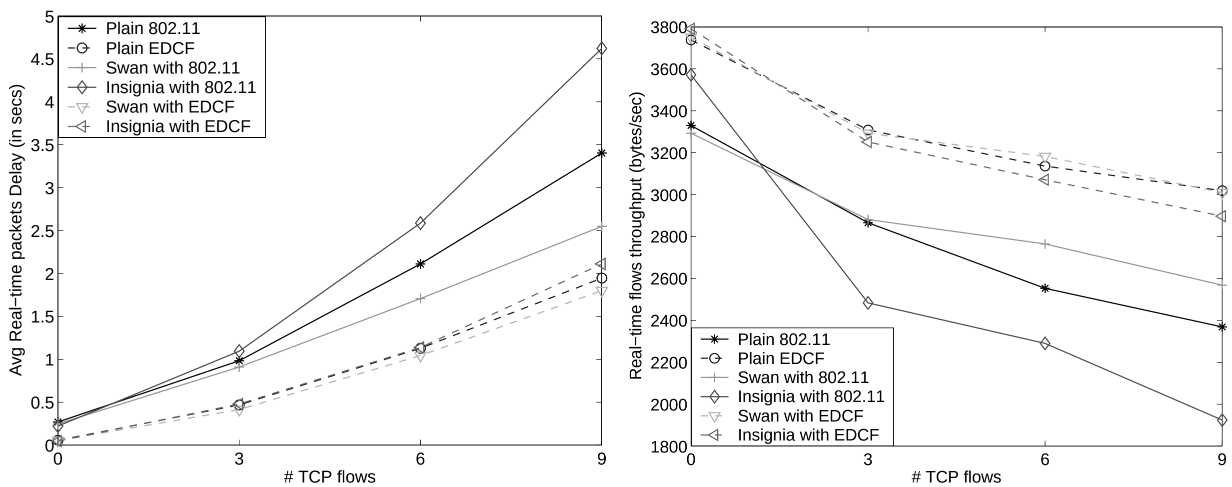


Figure 6. Optimized Link State Routing (OLSR) in the random waypoint (RWP) mobility model: average real-time (a) delay and (b) throughput

Jitter and total throughput follow a trend similar to real-time packet delay and real-time throughput, respectively; hence, they are not shown separately.

3.1.3 OLSR in RWP

Figure 6 shows results when OLSR is fixed as the routing protocol. Figure 6(a) shows the average delay of real-time packets. Swan over EDCF achieves the shortest delay among all combinations. As with DSR, in OLSR, real-time packets are differentiated from the best-effort packets both by the QoS architecture and the MAC protocol, giving the best performance for real-time packets. Insignia with IEEE 802.11 has the highest average real-time packet delay.

An interesting observation is that all combinations with EDCF perform better than those with IEEE 802.11 as the MAC protocol. This is in contrast with the average delay results of AODV and DSR protocols (see Figs. 2 and 5), where some combinations with IEEE 802.11 performed better than those with EDCF. The reason for this is that both AODV and DSR are reactive protocols forming strong interactions with the underlying MAC protocol. The efficiency of AODV and DSR depends on how the MAC protocol delivers the control packets and on how it interacts with the routing decisions. Since OLSR is proactive, the effect of the MAC protocol is limited to the data packet delays at the MAC layer and does not affect the route formation delays. EDCF, being a QoS-aware MAC protocol, contributes to lower delays compared to IEEE 802.11.

Figure 6(b) shows the real-time throughput performance of OLSR. As the figure shows, Swan over EDCF has the best performance, and it is closely followed by classic over EDCF. With interfering best-effort traffic (i.e., 3, 6, and 9 TCP flows), the performance of Insignia over IEEE 802.11 degrades quickly and has the worst performance. However, when there are no interfering TCP flows, independent of the MAC protocol, Insignia performs better than the Swan and classic architectures. This is due to Insignia having fewer packet drops at different queues in the protocol stack than the Swan and classic architectures, allowing it to deliver more packets. The combinations with EDCF outperformed those with IEEE 802.11; this is consistent with the average delay results (see Fig. 6(a)).

OLSR has higher average packet delays and lower throughput than AODV and DSR, as seen from the higher scale for delay and lower scale for throughput. This is not surprising as OLSR has higher control packet overhead from frequent HELLO message exchange and MPR selection/relay messages. These results are consistent with those reported in Choi and Ko [25].

3.2 Fixed Mobility Model: Grid

In this section, we present simulation results with the nodes moving according to the grid mobility model. As before, to improve readability, we present the results with the routing protocol fixed, and we use solid [dashed] lines when IEEE 802.11 [EDCF] is used as the MAC protocol.

3.2.1 DSR in Grid

Figure 7(a) shows the average delay of real-time packets when DSR is fixed as the routing protocol. Swan with 802.11 has the lowest delay compared with the other combinations. The classic architecture over 802.11 and Insignia over 802.11 have the worst performance. Insignia and the classic architecture over EDCF perform better than over 802.11. When there are no interfering TCP flows, Swan

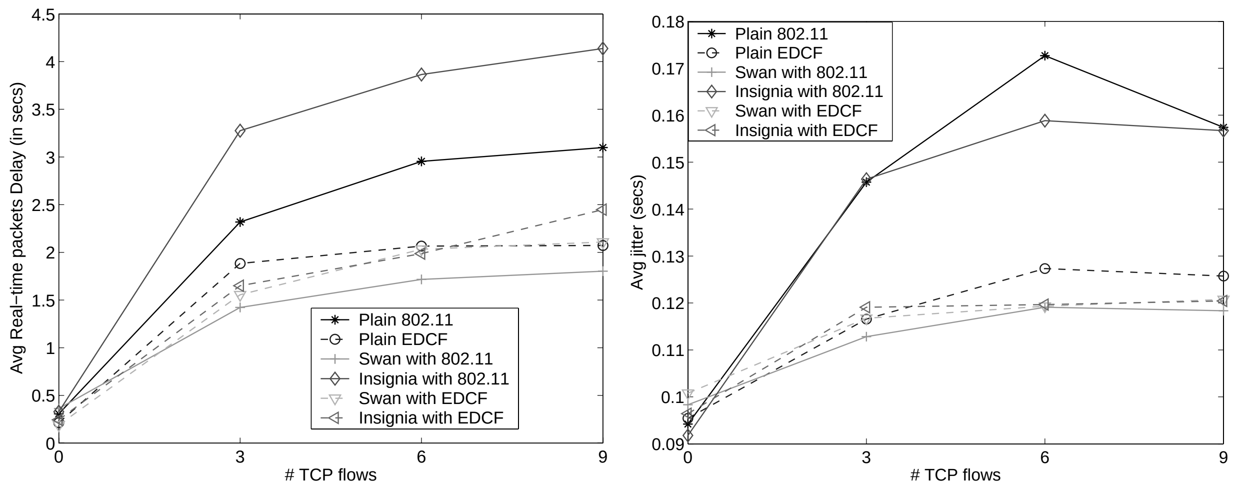


Figure 7. Dynamic Source Routing (DSR) in the grid mobility model: average real-time (a) delay and (b) jitter

over EDCF performs better than Swan over IEEE 802.11. However, as the number of TCP flows increases, the performance reverses; this is counterintuitive. Recall that Swan over EDCF performs better than Swan over 802.11 at all traffic loads for DSR in the RWP mobility model (see Fig. 2(a)). The reason for the anomaly is that the packet delays of EDCF are higher in the grid mobility model than in the RWP mobility model. Figure 8 shows the difference in average packet delays for DSR under both mobility models. Both EDCF and IEEE 802.11 have higher delays when nodes move according to the grid mobility model than the RWP mobility model. For EDCF, the rate of increase in the packet delay with the number of TCP flows is higher in the grid mobility model than in the RWP model.

Swan estimates the bandwidth available using MAC delays, which, in turn, is used to admit and regulate real-time flows. Since EDCF has high packet delays in the grid mobility model, Swan responds by regulating the real-time flows, degrading their priority to best effort. Consequently, real-time packets suffer large queuing delays, resulting in increased average delay. As already established, EDCF performs poorly with high contention. On the other hand, IEEE 802.11, with its larger backoff interval, responds to the contention by increasing the backoff interval with each failure, which can ease the contention. Although Swan running over IEEE 802.11 does observe higher delays with contention, it quickly restores the real-time flows once the contention has eased, leading to lower average delays. When the network is congested, EDCF is aggressive, sending real-time packets faster; therefore, it suffers a longer contention period than IEEE 802.11, degrading the quality of the real-time flows.

Figure 7(b) compares the average real-time packet jitter. It follows almost the same trend as the average real-time packet delays; the difference in performance of Swan over EDCF and Swan over IEEE 802.11 is minimal. Figure 9(a) shows the real-time throughput; Swan over EDCF performs the best when there is no interfering best-effort TCP traffic. However, as the number of TCP flows increases, its performance falls. On the other hand, Swan over 802.11 performs better than Swan over EDCF with an increasing number of TCP flows. Again, the reason for this is due to congestion and the relatively small backoff interval in EDCF.

In Figure 9(b), we see that the classic architecture over 802.11 has the highest total throughput followed by Insignia over 802.11. Since EDCF handles congestion poorly, packet delivery is delayed, which increases the number of queued packets. Since buffer space at the MAC layer is limited, packets are dropped. This decreases the total number of packets sent from the source to the destination. So the network architectures with EDCF have less total throughput. Swan over 802.11 has the least total throughput due to the traffic regulation performed by Swan. This limits the number of best-effort TCP packets sent from the source to the destination, resulting in lower total throughput. Insignia over 802.11 has lower total throughput than the classic architecture over 802.11 because Insignia manages only the real-time flows, leading to higher real-time throughput but suffering lower total throughput.

3.2.2 AODV in Grid

The network performance when the routing protocol is fixed as AODV is shown in Figure 10. Swan over IEEE 802.11 has the lowest average delay. The average delay with Swan over EDCF and the classic architecture over EDCF is poor when compared with Swan over 802.11. With DSR, the performance of Swan over EDCF deteriorated only at high traffic loads (i.e., 3, 6, and 9 TCP

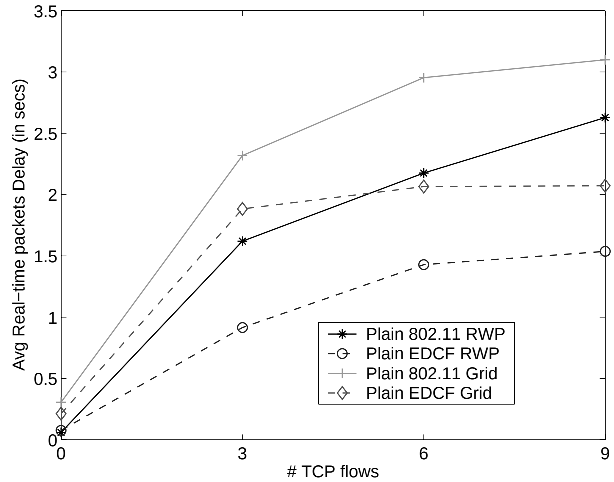


Figure 8. Comparison of Dynamic Source Routing (DSR) packet delays

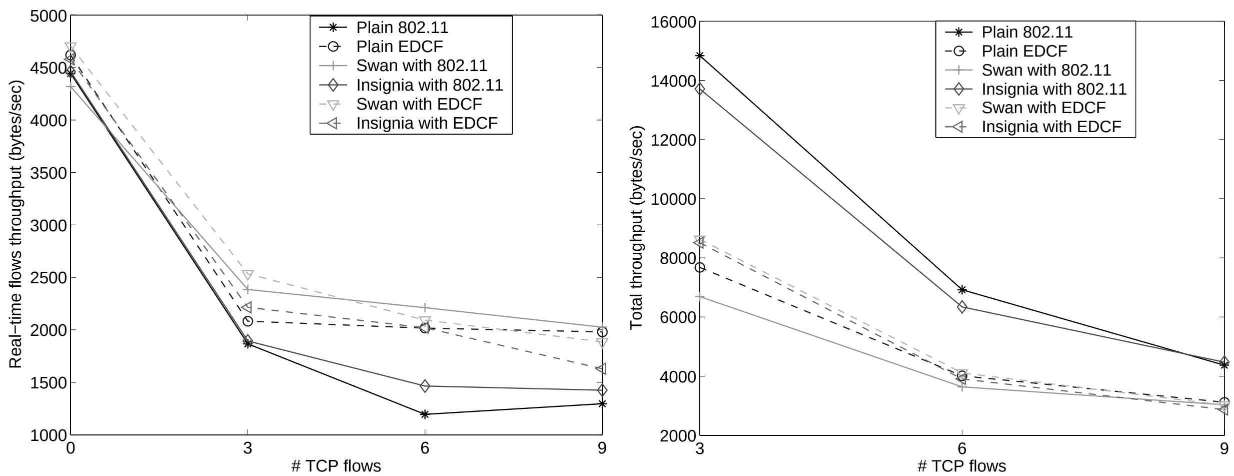


Figure 9. Dynamic Source Routing (DSR) in the grid mobility model: (a) real-time throughput and (b) total throughput

flows) (see Fig. 7(a)), but with AODV, the performance of Swan over EDCF is always worse than Swan over IEEE 802.11. The reason is that even at lower traffic loads, AODV generates more control packets than DSR, increasing the congestion in the network. As observed in section 3.2.1, EDCF performs poorly with congestion, which further affects Swan, leading to higher delay and lower throughput.

Average real-time packet jitter follows a trend similar to the average real-time packet delay, and total throughput follows a trend similar to the DSR total throughput (see Fig. 9(b)); hence, these results are not shown separately.

3.2.3 OLSR in Grid

Figure 11 shows the average delay for OLSR. As the figure shows, the delay is much higher in the grid mobility model. With increasing network load, the average delay increases rapidly and is almost double that of the random waypoint model. OLSR uses MPRs to disseminate packets, and node movements along grid positions cause OLSR to recompute more often leading to higher packet delays. The performance of real-time throughput, jitter, and total throughput have similar characteristics and are not shown separately.

3.3 Discussion

To summarize the simulation results, with AODV and DSR, the performance of Swan over EDCF depends on the performance of EDCF at the MAC layer. When EDCF experiences low MAC delays, Swan over EDCF improves the QoS provided to the real-time flows. However, if EDCF

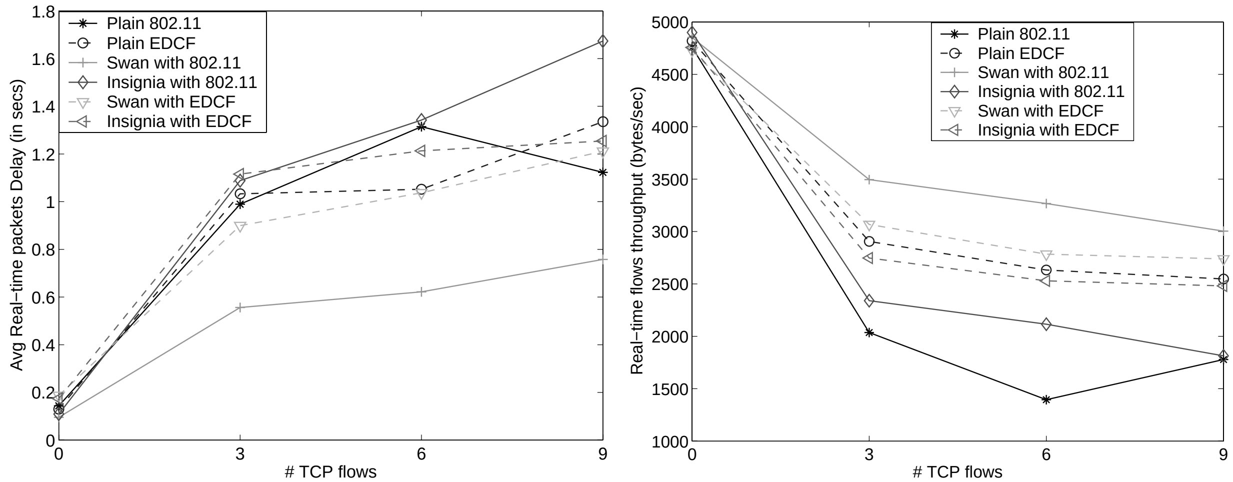


Figure 10. Adhoc On-Demand Distance Vector (AODV) in grid mobility model: average real-time (a) delay and (b) throughput

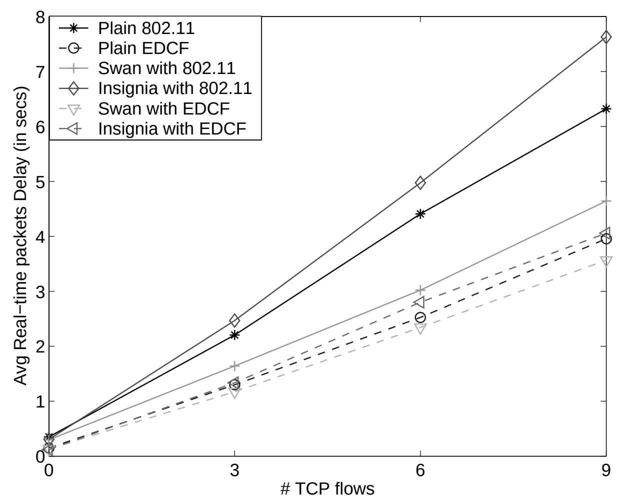


Figure 11. Optimized Link State Routing (OLSR) in the grid mobility model: average real-time delay

suffers increasing MAC delays due to congestion, Swan over EDCF degrades in performance. The performance of EDCF depends on the underlying mobility model and the number of control packets generated by the routing protocol, as these control packets contend with the real-time data packets. If the control packet overhead is high, EDCF performs poorly and vice versa. However, with OLSR, the effect of the MAC protocol is limited to the packet delays and does not affect the routing protocol in terms of route formation delays. The performance of the routing protocols depends primarily on the underlying mobility model.

Although IEEE 802.11 has higher delays than EDCF as a result of a single packet queue, an adaptive (and larger) backoff interval responds better to congestion. Hence, at high traffic loads, Swan over IEEE 802.11 performs better than the classic architecture over EDCF and Swan over EDCF in the grid mobility model. Although Swan is affected by IEEE 802.11 MAC delays at the point of congestion, it quickly restores the real-time flows to their original priority once congestion has eased.

With the RWP mobility model, DSR has low control packet overhead, leading to good performance of EDCF, which in turn helps Swan perform well. AODV has higher control packet overhead and a corresponding decrease in the performance of EDCF and Swan. With the grid mobility model, both DSR and AODV have high control packet overhead, again resulting in poor performance of EDCF and Swan. This increase in control packet overhead is attributed to the restricted movement of the mobile nodes in the simulation area.

Insignia has higher overhead than Swan as it is a stateful QoS architecture. Insignia makes sure that real-time flows have the required bandwidth along the selected route but does not regulate the best-effort traffic. As a result, with each burst in best-effort traffic, it has to find alternate paths with the required bandwidth for real-time flows, which leads to higher delays than when no QoS architecture is present. However, since Insignia adapts and restores real-time flows, it has higher real-time throughput than the classic architecture in general. Also, Insignia with DSR as the routing protocol has better jitter characteristics than the classic architecture in both mobility models.

4. Statistical Analysis

To quantify the contributions of each factor to the QoS provided, we perform a statistical analysis of the simulation results. Statistical analysis helps identify the most important factors affecting a response variable. This analysis can guide a network designer to direct efforts to the important factors and factor interactions to further improve the QoS support provided. The analysis is presented using an *effects table* and an *interaction graph*. An effects table shows the contributions of the factors to the response variable measured as a percentage. This helps quantify the importance of each factor on the response variables. The percent contribution is calculated by adding up the total sum of squares and then taking each term's sum of squares and dividing by the total. Sum of squares is the measurement of deviation from the mean. An interaction graph shows the factor interactions visually in the form of a graph.

As we did for the simulation results in section 3, we perform the statistical analysis for a fixed mobility model.

Table 2 shows the contribution of each factor to average real-time packet delay, average real-time packet jitter, real-time throughput (RT Tput), and total throughput (Total Tput). In the following tables, "Q" represents the QoS architecture, "R" represents the routing protocol, "M" represents the MAC protocol, and "L" represents the offered load in terms of the number of best-effort TCP flows. Two-way and higher factor interaction terms are also present. Terms that contribute at least 5% to the response are considered significant and are shown in bold.

As Table 2 shows, the routing protocol (R) and offered load (L) contribute the most to the average delay for the grid mobility model and for the RWP model. The two-way interaction between R and L is significant in both of the mobility models. For average real-time jitter, the routing protocol (R), QoS architecture (Q), and offered load individually contribute in the grid mobility model. The two-way interactions QR (i.e., QoS architecture and routing protocol), QM (i.e., QoS architecture and MAC protocol), and RL (i.e., routing protocol and offered load) also contribute. In the random waypoint mobility model, the same terms contribute, although with varying contributions, except for RL interaction, which is insignificant.

For real-time throughput, in both the grid and the RWP mobility models, offered load has the most significant contribution. The routing protocol also contributes in both mobility models. The two-way interactions are not very significant for the real-time throughput response for the grid mobility model, but RL makes a significant contribution in the RWP mobility model. For total throughput, for the grid mobility model, the offered load is most significant. For the RWP mobility model, offered load is the single most important factor, contributing almost 77% to the response. The routing protocol and the interaction between the routing protocol and offered load also contribute.

The effects table (Table 2) shows that the contributions of the protocols to the QoS provided changes depending on the mobility model. Across both mobility models, for all response variables, offered load plays a significant role. With an increase in offered load, protocols at all layers of the network architecture need to coordinate to meet the QoS requirements of the real-time flows (recall EDCF and Swan).

Table 2 provides high-level information about the important factors affecting network performance; we saw that the percentage contribution of offered load is very high. In general, we know that not only are individual protocols important, but so is their interaction—however, this is not too prominent in the effects table, as load takes most of the contribution. To better understand the protocol interactions, we performed a statistical analysis after fixing the offered load at the highest level (i.e., 9 flows). Table 3 shows the percentage contribution of protocols and their interaction for this case.

Now, for both mobility models and for almost all response variables, all protocols have high individual contribution. The two-way interactions of the MAC protocol with the QoS architecture and the routing protocol are very significant. This validates the conclusions we made from the simulation results. As we saw in the simulation results, EDCF is heavily affected by the routing protocol being used, which in turn affects the QoS architecture.

Figure 12 shows the interaction between the QoS architecture and the MAC protocol on real-time throughput for the DSR routing protocol, with nodes moving according to the grid mobility model. (An interaction graph is not a graph in the usual sense; see Montgomery [11].) As the figure shows, Swan over EDCF has lower real-time throughput than Swan over IEEE 802.11. Insignia and the classic QoS architecture have higher real-time throughput when run over EDCF than when run over IEEE 802.11. We do not include the other two-way interaction graphs due to the lack of space.

5. Conclusions and Future Work

Providing QoS in MANETs is challenging due to wide variations in network resources caused by node mobility and the wireless medium. In this article, we analyzed the

Table 2. Effects table for delay, jitter, real-time throughput, and total throughput for each mobility model

	Grid Mobility Model				Random Waypoint Mobility Model			
Source	Delay	Jitter	Real-Time Throughput	Total Throughput	Delay	Jitter	Real-Time Throughput	Total Throughput
Q	3.30	**6.67**	4.15	2.81	4.87	**5.58**	3.37	0.00
R	**21.16**	**11.38**	**5.31**	4.72	**10.81**	**32.79**	**8.32**	**8.87**
M	3.67	3.90	2.96	1.24	2.46	0.00	1.00	0.92
L	**44.22**	**34.42**	**74.75**	**69.55**	**51.86**	**13.24**	**64.56**	**76.90**
QR	0.45	**11.40**	0.29	0.46	0.47	**17.22**	0.91	0.32
QM	1.89	**8.03**	2.24	4.50	1.69	**5.88**	0.86	0.40
QL	1.39	2.61	1.37	3.31	2.12	0.81	1.84	1.44
RM	3.02	2.13	0.39	1.90	**8.03**	3.60	4.63	0.63
RL	**16.44**	**6.04**	0.46	2.95	**10.94**	1.88	**11.51**	**8.81**
ML	1.34	3.94	0.43	1.17	0.99	1.39	0.00	0.18

Table 3. Effects table for fixed load of nine TCP flows for each mobility model

	Grid Mobility Model				Random Waypoint Mobility Model			
Source	Delay	Jitter	Real-Time Throughput	Total Throughput	Delay	Jitter	Real-Time Throughput	Total Throughput
Q	**6.86**	**15.33**	**25.92**	**5.04**	**11.82**	4.24	**19.26**	**9.98**
R	**72.30**	**17.33**	**33.10**	**45.47**	**51.09**	**67.45**	**34.65**	**58.34**
M	**7.60**	**18.22**	**18.83**	**7.80**	**6.93**	2.20	4.79	**13.58**
QR	1.39	**12.95**	2.52	8.84	1.58	**11.78**	2.39	**6.31**
QM	3.90	**21.72**	**15.42**	**19.41**	**5.77**	3.34	**6.21**	0.12
RM	**7.31**	1.57	3.15	**10.70**	**21.21**	1.89	**29.30**	**9.95**

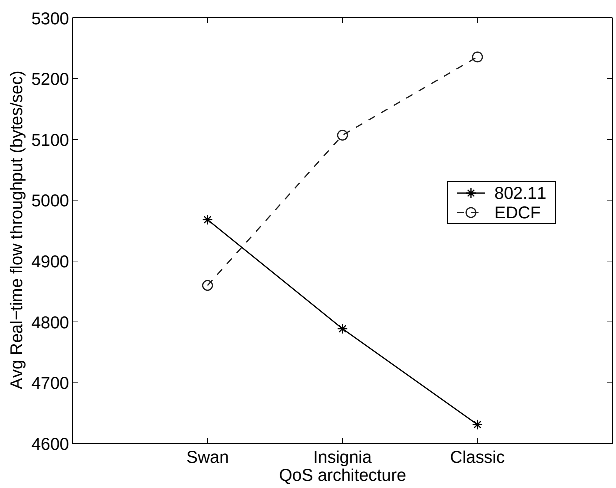


Figure 12. Interaction graph for real-time throughput for Dynamic Source Routing (DSR) in the grid mobility model

impact of five factors (QoS architecture, routing protocol, MAC protocol, offered load, and mobility model) on the QoS responses of real-time packet delay, jitter, real-time throughput, and total throughput. The performance of the MAC protocols (IEEE 802.11 and EDCF) is not the same across mobility models (grid and random waypoint) and routing protocols (AODV, DSR, and OLSR). Through statistical analysis, a strong interaction between the MAC protocol and the QoS architectures, the MAC protocol and the routing protocols, and the MAC protocol and offered load is found. These interactions were quantified using statistical analysis and validate the simulation results. Our study helps network designers choose the network architecture most likely to produce the desired performance under the anticipated conditions, ultimately leading to better performance.

In our future work, we plan to extend our study to include additional factors. In addition, we plan to apply *response surface methodology* (RSM) to optimize factors robustly.

6. Acknowledgments

We are grateful for the useful comments from the anonymous referees that have improved our article. We thank Tracy Camp at the Colorado School of Mines for `ns-2` code for steady-state initialization, as well as the COMET group at Columbia University for `ns-2` code for Swan and Insignia. This research was supported in part by NSF grant ANI-0240524.

7. References

[1] Gahng-Seop, A., A. Campbell, A. Veres, and L. Sun. 2002. SWAN: Service differentiation in stateless wireless ad hoc networks. In *Proceedings of the Twenty-First Annual Joint Conference of the IEEE Computer and Communication Societies (INFOCOM'02)*, June, pp. 457-66.

[2] Lee, S., G. Ahn, X. Zhang, and A. Campbell. 2000. INSIGNIA: An IP-based quality of service framework for mobile ad hoc networks. *Journal of Parallel and Distributed Computing* 60 (4): 374-406.

[3] Chen, S., and K. Nahrstedt. 1999. Distributed quality-of-service routing in ad-hoc networks. *IEEE Journal on Selected Areas in Communications* 17 (8): 1488-1505.

[4] Zhu, C., and M. Corson. 2002. QoS routing for mobile ad hoc networks. In *Proceedings of the Twenty-First Annual Joint Conference of the IEEE Computer and Communication Societies (INFOCOM'02)*, June, pp. 958-67.

[5] Cui, S., A. J. Goldsmith, and A. Bahai. 2004. Joint modulation and multiple access optimization under energy constraints. In *Proceedings of the IEEE Global Telecommunications Conference*, vol. 1, December, pp. 151-5.

[6] Cui, S., R. Madan, A. J. Goldsmith, and S. Lall. 2005. Joint routing, MAC, and link layer optimization in sensor networks with energy constraints. In *Proceedings of the IEEE Conference on Communications*, May, vol. 2, pp. 725-9.

[7] Royer, E., S.-J. Lee, and C. Perkins. 2000. The effects of MAC protocols on ad hoc network communications. In *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC'00)*, September, pp. 543-48.

[8] Perkins, C., E. Royer, S. Das, and M. Marina. 2001. Performance comparison of two on-demand routing protocols for ad hoc networks. *IEEE Personal Communications Magazine* 8 (1): 16-28.

[9] Bai, F., N. Sadagopan, and A. Helmy. 2003. IMPORTANT: A framework to systematically analyze the impact of mobility on performance of routing protocols for adhoc networks. In *Proceedings of the Twenty-Second Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM'03)*, vol. 2, pp. 825-35.

[10] Barrett, C., A. Marathe, M. V. Marathe, and M. Drozda. 2002. Characterizing the interaction between routing and MAC protocols in ad-hoc networks. In *Proceedings of the Third ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc'02)*, pp. 92-103.

[11] Montgomery, D. 2005. *Design and analysis of experiments*. New York: John Wiley.

[12] Vadde, K., and V. Syrotiuk. 2004. Factor interaction on service delivery in mobile ad hoc networks. *IEEE Journal on Selected Areas in Communications* 22 (7): 1335-46.

[13] The network simulator—`ns-2` (version 2.26), University of California, Berkeley. http://www.isi.edu/nsname/ns/

[14] Design Expert software, State Ease Inc. http://www.statease.com

[15] Wireless and mobility extensions to `ns-2`, Carnegie Mellon University. http://www.monarch.cs.cmu.edu/cmu-ns.html

[16] Internet Engineering Task Force (IETF) MANET Working Group. IETF draft. http://www.ietf.org/html.charters/manet-charter.html

[17] Johnson, D., and D. Maltz. 1996. *Mobile computing*. Amsterdam: Kluwer Academic.

[18] Perkins, C., and E. Royer. 1999. Ad hoc on-demand distance vector routing. In *Proceedings of the Second IEEE Workshop on Mobile Computing Systems and Applications*, February, pp. 90-100.

[19] Clausen, T., P. Jacquet, A. Laouiti, P. Muhlethaler, and Q. L. Viennot. 2001. Optimized link state routing protocol. In *Proceedings of the IEEE International Multitopic Conference (INMIC'04)*, December, pp. 62-8.

[20] IEEE. 1999. *IEEE standard 802.11: W-LAN medium access control & physical layer specifications*. IEEE.

[21] Choi, S., J. Prado, N. Shankar, and S. Mangold. 2003. IEEE 802.11e contention-based channel access (EDCF) performance evaluation. In *Proceedings of the IEEE International Conference on Communications (ICC'03)*, May, pp. 1151-6.

[22] Benveniste, M., G. Chessan, M. Hoeben, A. Singla, H. Teunissen, and M. Wentink. 2001. Enhanced distributed coordination function (EDCF). Working document 802.11-01/131r1, IEEE.

[23] NTIS. n.d. *Master propagation system (MPS11) user's manual*. Washington, DC: U.S. Department of Commerce, NTIS.

[24] Navidi, W., and T. Camp. January-March 2004. Stationary Distributions for the Random Waypoint Mobility Model, *IEEE Transactions on Mobile Computing*, 3 (1): 99-108.

[25] Choi, J.-M., and Y.-B. Ko. 2004. A performance evaluation for ad hoc routing protocols in realistic military scenarios. In *Proceedings of the Ninth International Conference on Cellular and Intelligent Communications (CIC'04)*, October.

Kiran K. Vadde *earned his Ph.D. in computer science from Arizona State University (ASU) in 2005. He obtained an M.S. in computer science from ASU in December 2002 and an M.Sc. in information systems in May 2000 from the Birla Institute of Technology and Science (BITS), Pilani, India. His research interests are in the areas of ad hoc networks, cross-layer interaction, routing and MAC protocols, quality of service, and wireless networks.*

Violet R. Syrotiuk *earned her Ph.D. in computer science from the University of Waterloo (Canada) in 1992. She joined Arizona State University in 2002 and is currently an assistant professor of computer science and engineering. Her research is currently supported by three grants from the National Science Foundation and a DARPA Connectionless Networks subcontract from General Dynamics Decision Systems. She serves on the editorial board of* Computer Networks *and on the Technical Program Committee of several major conferences, including MobiCom and Infocom. Her research interests include mobile ad hoc and sensor networks, particularly MAC protocols, with an emphasis on adaptation, topology-transparency, energy efficiency, dynamic spectrum utilization, mobile network models, and protocol interaction and cross-layer design. She is a member of the ACM and the IEEE.*