Real-Time Traffic Support in Heterogeneous Mobile Networks

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Abstract

Multi-hop mobile wireless networks have been proposed for a variety of applications where support for real-time multimedia services will be necessary. Support for these applications requires that the network is able to offer quality of service (QoS) appropriate for the latency and jitter bounds of the real-time application constraints. In this paper, we analyze the primary challenges of realizing QoS in mobile wireless networks with heterogeneous devices and propose a QoS framework for real-time traffic support. We address the problem in three ways: estimate the path quality for real-time flows, mitigate the impact of node heterogeneity on service performance, and reduce the impact of interfering non-real-time traffic. Specifically, our proposed QoS framework first utilizes a call setup protocol at the IP layer to discover paths for real-time flows, as well as to perform admission control by accurate service quality prediction. The underlying routing protocol also enables transparent path selection among heterogeneous nodes to provide stable paths for real-time traffic delivery. We then use a prioritized MAC protocol to provide priority access for flows with real-time constraints to reduce interference from unregulated non-real-time traffic. We foresee the utility of our proposed solution in heterogeneous mobile networks, such as campus or community-wide wireless networks. In these environments, resource-rich or fixed wireless routers may be leveraged to achieve better service quality when heterogeneity of node capability and movement is significant. Through experimental results, we demonstrate the utility and efficiency of our approach.

1 Introduction

Wireless networking and multimedia content are two rapidly emerging technological trends. Among types of wireless networks, multi-hop networks provide a flexible means of communication when there is little or no infrastructure, or the existing infrastructure is inconvenient or expensive to use. With the development of mobile wireless networks, we can anticipate that multimedia applications will become popular in personal networks or other collaborative scenarios. For instance, large-scale wireless networks with thousands of mobile users have increased in deployment, where popular applications include VoIP, streaming multimedia, and peer-to-peer file sharing [11]. Hence, the support of multimedia services over wireless networks becomes increasingly critical for the development and support of applications over the future wireless Internet.

We target the support of real-time traffic with latency and jitter constraints in mobile networks, such as campus or community-wide networks. In these environments, networks are likely to consist of many heterogeneous nodes. A recent study on the changing usage of a campus-wide wireless network [12] indicates an increase in the heterogeneity of the types of clients used, with more embedded wireless devices such as PDAs and mobile VoIP clients. Within these networks, fixed wireless routers may be placed in classrooms or kiosks in a multi-hop mesh to serve as a network backbone. Students or residents can move freely within the network and perform peer communications through PDAs and laptops. Such multi-hop mesh networks have witnessed a recent increase in deployment [3, 15, 17, 20, 23] and are poised to become even more prevalent. Devices within these networks are likely to have heterogeneous capabilities, such as battery, processing power and network load. Because heterogeneous networks are rapidly becoming a major component of the wireless Internet, they can be leveraged to provide efficient and robust QoS support to real-time flows.

One major challenge of supporting multimedia services is that certain quality of service (QoS) metrics must be satisfied. There has been significant research on providing QoS in wired networks. For instance, Intserv [27] and Diffserv [9, 21] are two well-known approaches. In wireless networks, however, several unique characteristics make QoS provisioning more challenging. These characteristics include the shared wireless medium, mobility, and the distributed multi-hop communication. Many of the QoS solutions for wired networks rely on the availability of precise link utilization information. In mobile networks, however, all traffic within a wireless node's transmission range contends for medium access. The shared nature of the communication channel makes resource estimation more difficult. Multi-hop interference introduces further challenges to the problem, making it complex to accurately determine the available resources. However, without sufficiently accurate resource prediction, it is difficult to provide multimedia services with satisfactory quality.

Heterogeneous node characteristics and resources also brings new obstacles to QoS ensurance in mobile wireless networks. For instance, a resource-constrained device, such as a battery-powered PDA, is unlikely to sustain a long multimedia session, while a bandwidth-constrained device (e.g., an overloaded node) will have difficulty supporting a high bandwidth multimedia stream. In addition to these inherent features, node mobility also has two important impacts on network performance. First, the movement of a node on an active path often leads to a link break and subsequent loss of packets. This effect is even more severe in large-scale networks with long communication paths. The packet loss after the link break, accompanied by increased packet transmission delay during a route repair, significantly degrades the QoS of the stream. The second effect is the load increase due to node movement. Movement brings new traffic into a communication area, due to both the moving node's ongoing traffic and the flood of control packets in the network during the route repair. Hence, it is important to mitigate the negative impact of heterogeneous node resources and node mobility to maintain the service quality and to leverage these differences whenever possible.

Finally, communication within a multi-hop wireless network is primarily distributed. There is no centralized node that can provide resource coordination for the network; every node is responsible for its own traffic and is unaware of other traffic flows in the network. Best-effort traffic, i.e., flows without stringent service requirements, may be injected into the network and then interfere with ongoing real-time traffic. Minimization of the interference from non-real-time traffic is needed to ensure high quality to real-time flows.

Bearing in mind these objectives, we propose a cross-layer QoS framework between the MAC and IP layers. In particular, the framework consists of three important components: a routing protocol that transparently makes routing decisions to adapt to and leverage the heterogeneity of nodes; an efficient MAC protocol that provides prioritized access for flows with real-time constraints to reduce interference from unregulated non-real-time traffic; and a call setup protocol that combines IP and MAC layer information to perform admission control through accurate service quality prediction. We foresee the utility of our proposed solution in heterogeneous multi-hop mesh networks, such as campus or community-wide wireless networks. In these environments, applications such as Instant Messaging, IP telephony, and interactive distance learning lectures all require quality of service provisioning. If the wireless network includes Internet access points, real-time services from or to the Internet can also be provided with the needed quality.

The remainder of this paper is organized as follows. Section 2 describes related work. Section 3 presents our proposed framework. Specifically, Section 3.1 explains the prioritized access protocol used to reduce interference and alleviate the impact of node mobility. Section 3.2 describes a modification to a routing protocol such that heterogeneous node capabilities and mobility can be incorporated. Section 3.3 presents an integrated call setup process that combines the IP and MAC layer solutions and supports real-time flows through accurate service quality prediction. The performance of our proposed approach is evaluated in Section 4, and finally Section 5 concludes the paper.

2 Related Work

Many routing schemes and frameworks have been proposed to provide QoS support for ad hoc networks [2, 7, 8, 19, 29]. Among them, INSIGNIA [19] uses an in-band signaling protocol for distribution of QoS information. The information is included in the IP headers of the data packets, and the available resources are calculated at each station the packet traverses based on "soft-state" traffic reservation information. SWAN [2] improves INSIGNIA by introducing an Additive Increase Multiplicative Decrease (AIMD)-based rate control algorithm. Both [7] and [8] utilize a distance-vector protocol to collect end-to-end QoS information via either flooding or hop-by-hop propagation. CEDAR [29] proposes a core-extraction distributed routing algorithm that maintains a self-organizing routing infrastructure, called the "core". The core nodes establish a route that satisfies the QoS constraints on behalf of other nodes.

None of these approaches significantly diverge from QoS approaches for wired networks, and they do not completely address the differences between wired and wireless networks. Specifically, they often do not consider the contentious nature of the MAC layer, nor the neighbor interference on multi-hop paths. This leads to inaccurate path quality prediction for real-time flows. Additionally, most of the solutions do not consider the fact that a newly admitted flow may disrupt the quality of service received by ongoing real-time traffic flows. Furthermore, service differentiation is often desired in wireless networks. Most of the solutions do not provide accurate quality estimation when flows of multiple priorities exist.

Recently, other work has proposed to improve the performance of MAC protocols through support of service differentiation. Many of these approaches specifically target IEEE 802.11 [30]. For example, studies in [1, 5, 13, 18] propose to tune the contention windows sizes or the inter-frame spacing values to improve network throughput, while studies in [1, 4, 16, 24, 34] propose priority-based scheduling to provide service differentiation. Most of these solutions utilize different backoff mechanisms, different DIFS lengths, or different maximum frame lengths, based on the priority of the traffic. Based on this previous work, we propose a priority access mechanism in our framework that considers the current channel collision probability in determining the backoff behavior of different priority traffic. This enables us to achieve adaptive service differentiation.

Our model of utilizing resource-rich and fixed wireless backbone is similar to recent commercial deployments of multi-hop wireless networks, such as "rooftop" and "community wireless networks" [3, 17, 23]. Other companies are field-testing multi-hop wireless networks that use stationary or minimally mobile nodes to provide broadband Internet access [15, 20]. In these solutions, all traffic flows only through these designated wireless routers. In our work, however, traffic may flow through the fixed wireless routers, or direct connections between the mobile users can be leveraged. The decision of which path is selected is application-dependent. Furthermore, our work focuses on the QoS aspect of providing real-time services in multi-hop wireless networks, which is not specifically addressed in these previous solutions.

3 QoS Framework

Our proposed cross-layer QoS framework consists of three important components at both the MAC and IP layers to enable real-time traffic delivery over heterogeneous mobile wireless networks. In this section, we first present the design of an efficient MAC protocol that provides prioritized medium access for real-time traffic. We next describe our routing modification to incorporate the heterogeneous aspects of the target network environment to better support real-time traffic. Based on the these two components, we then propose a call setup process that performs admission control through accurate service quality prediction. Finally, we summarize our proposed framework.

3.1 Prioritized medium access

Communication in multi-hop wireless networks often occurs in a distributed fashion. There is no centralized point that can provide resource coordination for the network; every node is responsible for its own traffic and is unaware of other traffic. Consequently, best-effort traffic, which traverses both mobile nodes and fixed routers, interferes with real-time traffic.

The impact of interference becomes more severe as mobility increases. As described in Section 1, node movement brings new traffic to the communication area and results in a load increase at a node, due to both the moving node's ongoing traffic and the increase in control packets during a route repair. In particular, if a node with ongoing best-effort traffic moves to the communication area of a node supporting real-time traffic, the increased contention is likely to result in degraded quality for real-time traffic, particularly if congestion occurs.

3.1.1 Heterogeneous traffic interference

There are two general scenarios where best-effort traffic significantly interferes with real-time traffic, resulting in reduced quality for real-time flows. The first scenario occurs when best-effort and real-time traffic share the same fixed wireless routers, thereby causing *intra-node contention*. Best-effort flows may select routes via the fixed wireless routers if there is available capacity. However, this can result in a new real-time flow being denied admission because there is not enough remaining capacity in the paths through the routers. Figure 1 illustrates an example where a best-effort flow (indicated by the dotted line) traverses the fixed wireless router R. Later, a real-time flow (indicated by the solid line) is unable to be admitted because the router R does not have enough remaining capacity.

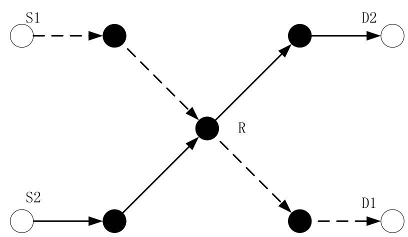


Figure 1: Intra-node interference at fixed wireless router R.

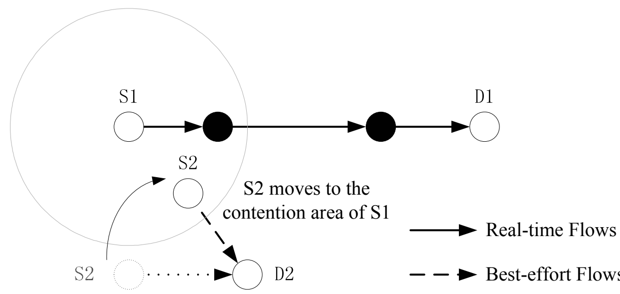


Figure 2: Mobility caused inter-node interference.

The second scenario occurs due to node mobility. Mobile users with ongoing sessions may move around freely. A pre-established high-quality flow will experience degraded performance when nodes with ongoing flows move into the contention range. We call this *mobility-induced inter-node contention*. An example is shown in Figure 2. Since preventing users from moving is not a desirable or realistic solution, a more flexible medium access mechanism is needed.

To reduce the contention caused by mobile users with ongoing traffic and to alleviate its impact on the real-time traffic, we propose an adaptive service differentiation mechanism at the MAC layer to achieve prioritized medium access.

3.1.2 Priority scheduling

The IEEE 802.11 Distributed Coordination Function (DCF) [30] is widely used in ad hoc networks as the medium access mechanism. The operation of DCF is based on CSMA/CA. A node with a packet ready for transmission waits until the channel is sensed idle for a specified time duration, called the Distributed Inter Frame Spacing

(DIFS) period. If the channel is sensed busy, the node defers the transmission until it senses the channel to be idle for a period of DIFS. The random backoff timer is uniformly chosen in a range of [0, $CW-1$] slots, where CW is the contention window size. Essentially, DCF is a contention based scheme where the backoff time of a node after a collision can be written in the following way:

$$f_{pri} = Rand[0, 2^r CW_{min}] \times T_{slot} \quad 0 \leq r \leq m \tag{1}$$

where r and m denote the number of attempted retransmissions and the maximum allowed number of retransmissions, respectively.

To support differentiated service, the IEEE 802.11 Working Group is integrating QoS support into the 802.11 MAC protocol as an enhancement to the basic operation of DCF. In this 802.11e standard, Enhanced DCF (EDCF) [14] is introduced to provide service differentiation for channel access. The basic approach of EDCF includes two distinctions from DCF: (1) assignment of different CW_{min} values to different priority classes; (2) assignment of an Arbitration IFS (AIFS), instead of DIFS, to different traffic classes, resulting in smaller AIFS values for high priority classes.

In the following sections, we describe these different approaches of 802.11e EDCF and propose our adaptive differentiation mechanism.

Priority-based AIFS

In the DCF protocol, a node waits to transmit a packet until the channel is sensed idle for a DIFS duration, and an ACK packet is sent after a SIFS (shorter than DIFS) period so that ACK packets have a greater probability of obtaining channel access than RTS/Data packets. In EDCF, by assigning different Arbitrary IFS (AIFS) values to different traffic classes, differentiation is achieved; high priority classes with smaller AIFS values have a higher channel access probability. Hence, the waiting time before a node transmits a packet can be represented by the following:

$$T_{wait} = AIFS_{pri} + f_{pri} = AIFS_{pri} + Rand[0, 2^r CW_{min}] \times T_{slot} \quad 0 \leq r \leq m \tag{2}$$

Priority-based CW_{min}

Instead of varying the AIFS duration for priority flows, differentiation can also be achieved by changing the backoff behavior of different traffic classes. For instance, a different set of CW$_{min}$ and CW$_{max}$ values can be assigned to different traffic classes. The backoff function f of a flow with priority pri is then decided by:

$$f_{pri} = Rand[0, 2^r CW[pri]_{min}] \times T_{slot} \quad 0 \leq r \leq m \tag{3}$$

This results in high priority traffic with smaller CW$_{min}$ values. Consequently, high priority traffic waits for a shorter period before the next transmission attempt after a collision and thus has a greater likelihood of acquiring the channel.

Adaptive priority scheduling

Each of the above techniques aids in service differentiation; however, the parameters are typically statically assigned and cannot adapt to the dynamic traffic load. This reduces the usage efficiency of the network. For instance, if low priority traffic is configured to use a pre-defined large backoff window, it will experience longer service latency regardless of whether there is competing high priority traffic present in the network. On the other hand, a small static value for high priority traffic will result in inefficient collisions and backoffs when multiple high priority flows compete for channel access. This will reduce the channel efficiency. Hence, it is difficult to find suitable static values to achieve a good trade-off between the service differentiation and network efficiency, given an unknown and dynamically changing traffic composition in the network.

To this end, we propose an adaptive scheme to address this trade-off. The basic idea is that, because the state of wireless networks can vary greatly due to mobility and channel interference, it is advantageous to adjust the backoff behavior according to the amount of traffic in the channel. Specifically, collisions should be avoided. Given a high traffic load in the network, the number of collisions and subsequent packet retransmissions significantly affects the throughput and packet delivery latency [18]. Hence, it is beneficial to take the collision rate into consideration in the backoff scheme.

To achieve service differentiation and to adapt to the current traffic load, we combine the collision rate with the exponential backoff mechanism in IEEE 802.11. We have:

$$f_{pri} = Rand[0, (2^r + R_{col} \times pri) \times CW_{min}] \times T_{slot} \quad 0 \leq r \leq m \tag{4}$$

where pri is a variable associated with the priority level of the traffic and R_{col} denotes the collision rate between a station's two successful frame transmissions. The collision rate can be measured passively using the mechanism described in [32]. By applying Eq. (4), traffic with different priority levels will have different backoff behaviors when collisions occur. Specifically, after a collision occurs, low priority traffic will back off for longer, and subsequently high priority traffic will have a better chance of accessing the channel.

Summary for adaptive priority scheduling

Utilization of our proposed adaptive priority scheduling will result in the successful delivery of real-time sessions when different types of traffic simultaneously exist in the network. To address intra-node interference, the prioritized access mechanism allows a new real-time flow to be serviced, even when there are best-effort flows sharing the same path. By applying the prioritized mechanism, when inter-node interference caused by mobility occurs and subsequently the channel collision rate increases, the best-effort traffic will experience a longer backoff time than the real-time traffic and will become less likely to access the channel. Therefore, the impact of best-effort traffic on real-time flows is mitigated. We will demonstrate the advantage of our mechanism in both service differentiation and channel efficiency in dynamic network conditions through simulations in Section 4.

3.2 Routing in heterogeneous networks

Our targeted multi-hop networks consist of mobile users such as students and residents carrying PDAs and laptops. Fixed or minimally mobile nodes such as wireless routers may be placed at strategic locations to provide network backbone access. These devices are likely to have heterogeneous resources, such as power, load and mobility rates.

The majority of proposed multi-hop routing protocols do not consider the resources or capabilities of nodes during path selection; the likelihood of a resource-constrained or a highly mobile node being included on a communication path is the same as a resource-rich or a stationary node. Routes consisting of highly mobile nodes, for instance, students bicycling on campus, will change frequently. Similarly, the inclusion of battery-powered nodes may result in broken paths due to battery depletion. Consequently, a path that satisfies a flow's QoS requirements may not last the entire data session. When links break, on-demand routing protocols typically initiate a new route discovery process to acquire a new routing path. It is also possible to implement optimizations such as local repair or maintenance of multiple concurrent routes. Such optimizations have the potential of reducing the delay in repairing a broken path. However, performance degradation during route discovery or routing path changes is inevitable, i.e., packet loss occurs and packet delivery latency increases. This results in significant packet jitter due to both delay during the route discovery and delay disparities between the new and old routes. This effect is more severe in large networks where longer communication paths are more prone to break, particularly when heterogeneous node capability and mobility rates exist. While best-effort traffic may be somewhat tolerant to these events, the quality of real-time traffic can be significantly degraded to the point that it is unacceptable. Hence mitigating the impact of heterogeneous node capabilities, as well as node mobility, is important to maintain the established service quality.

We propose to leverage specific node capabilities and mobility for different types of traffic. Specifically, for real-time traffic, such as multimedia streaming, resource-powerful devices are preferred along the routing path. This is because these applications often demand intensive computations and high data rates which increase the power consumption. Fixed or less mobile nodes are also preferred along paths for real-time traffic to avoid the performance degradation experienced when paths break due to node mobility. In our targeted environment, resource-rich and/or stationary devices, e.g., powered wireless routers, can be placed on building rooftops, on light poles and at kiosks to provide a stable backbone for QoS support.

To leverage resource-rich and fixed wireless devices, a multi-hop routing protocol must be modified to prefer routes that include these nodes. Otherwise, it will be difficult to select stable communication paths.

3.2.1 Routing modifications

Using the AODV routing protocol [22] as an example, we propose modifications to the routing protocol to reflect the selection of resource-rich and stationary routes for real-time traffic. Several recent routing protocols [6, 28] have suggested a node should add extra delay relative to its available resources (e.g., power) so that the selection of resource-poor devices can be avoided. However, the extra delay introduced by a node is dependent on the hop count of alternative paths. This information is usually unknown to each intermediate node. For simplicity, the routing solution can avoid nodes whose remaining power is below a certain threshold. More complicated schemes can be utilized, if, for instance, the profile of traffic flows (e.g., a VoIP call with median duration of 63 seconds [12]) and energy consumption is known a priori. In this case the selection threshold can be adjusted dynamically. The intermediate node, upon reception of a route request, checks its current power against the estimated needed power by the control packet. The node does not forward the route request message if its available power is less than what is needed, thereby preventing its inclusion on the selected path. In consideration of mobility, only the fixed nodes respond to the control packets by either forwarding the Route Request (RREQ) or unicasting a Route Reply (RREP) when a source node initiates route discovery for real-time traffic with strict quality requirements. A mobile node does not respond to a route request unless it is the destination. In this case it replies with a RREP. This change in operation can be achieved by marking the data packet with a real-time traffic label. For instance, the ToS field in the IP header can be set. Routing control packets, such as RREQs and RREPs, can then include this information accordingly.

The inclusion of more powerful and less mobile nodes along transmission paths, combined with the prioritized MAC scheduling mechanism in Section 3.1 and path quality prediction method in Section 3.3.1, ensures real-time traffic flows through routes with higher stability, thereby reducing the probability of path breaks. This increases the likelihood that the QoS requirements can be satisfied. If a route through preferred nodes is not discovered on the first discovery attempt, the second route discovery can alleviate this requirement and allow all nodes to participate. Figure 3 illustrates an example network where real-time and best-effort traffic utilize different routes.

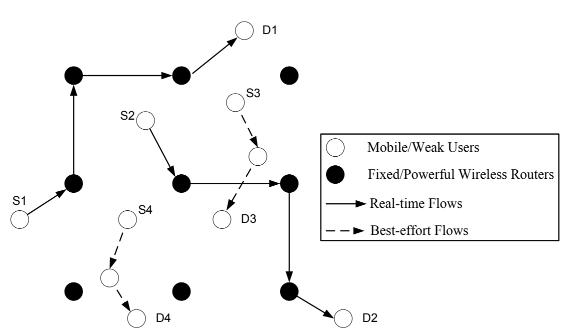


Figure 3: An example of the routes for different traffic classes.

It can be argued that only the fixed wireless routers should be used for all traffic within the ad hoc network, since they provide the most stable paths. This, however, will not result in high spatial reuse throughout the network and will consequently result in low utilization of the network capacity. Note that the addition of fixed relay nodes may not be necessary for small ad hoc networks. Applications without real-time constraints also may not need the benefits of the stable routes provided by fixed wireless routers. However, in large ad hoc networks, the introduction of fixed relay points will greatly improve the quality of service through the minimization of path breaks and the subsequent reduction of packet loss. This will result in low packet jitter, which is essential for real-time traffic.

Given the described routing modification, we next explain how real-time traffic can be supported using the proposed QoS Framework. Specifically, we discuss how the MAC layer model and prediction algorithm can be combined with the modified routing protocol so that accurate multi-hop service quality prediction can be provided.

3.3 Integrated support of real-time traffi c delivery

3.3.1 MAC layer modeling

When a real-time flow needs admission, it is important to estimate whether the transmission path satisfies the flow's QoS requirement. This requires accurate estimation of channel utilization and prediction of flow quality, i.e., throughput and/or transmission delay. Service quality prediction thus enables effective admission control when the network is saturated.

The proposed QoS approach is based on our previous work of a model-based service quality prediction mechanism [32]. Given the MAC layer scheduling mechanism, such as our proposed adaptive priority scheduling algorithm in Section 3.1, the model analyzes the channel utilization and calculates throughput and delay both per-flow and aggregated system-wide. We can thus apply the model to provide quality prediction for both ongoing traffic and new flows. In this way, a correct flow admission decision can be made according to the quality of service policy of the network.

The input of the analytical model is a set of flows $A = \{a_1, a_2, ..., a_s\}$ in the network, where s denotes the total number of priority classes supported by the system, and $\forall a_i \in A$, where a_i is the number of flows of priority class i. The output of the model is the average throughput or delay for each flow. This model assumes assumes nodes operate in a saturated condition and the impact of hidden terminal is minimal. It also does not consider unexpected

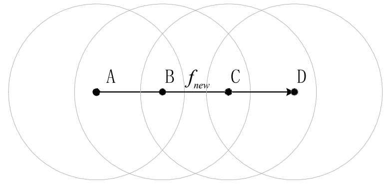


Figure 4: An example topology.

wireless interferences. To mitigate these effects, the model can be combined with measurement results as run-time feedback to improve estimation accuracy. Specifically, we maintain an moving average value of the actual channle collision rate measured at the MAC layer. Based on this value, we make adjustment to model prediction of channel access rate and collision ratio. A detailed description of service quality prediction using an analytical model can be found in [32]. We also discuss the impact of the measurement intervals on the accuracy of model prediction in [32].

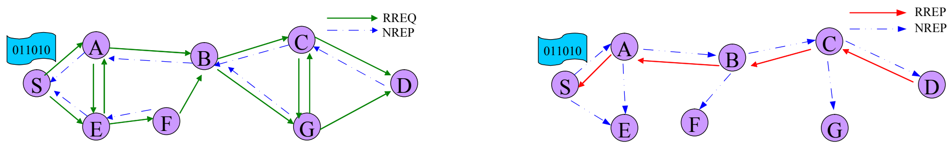
The MAC layer model provides channel statistics for a node's local contention area. However, because paths typically consist of multiple hops, a local decision is not sufficient for the selection of an entire transmission path. Furthermore, due to interference from neighboring nodes, the resources available to a new flow consist of the minimum of the available resources in the neighborhood of nodes on the path.

For example, in Figure 4, the circles indicate the transmission range, and hence neighborhood, of each node. Suppose node A requests a new flow using the path $A \rightarrow B \rightarrow C \rightarrow D$, and the resource consumption of the flow is x. In this case, the resource consumption is actually $2 \times x$ at nodes A and C, and $3 \times x$ at node B. This is because all nodes within transmission range of each other contend for medium access. Therefore, the actual resource consumption is not just the requirement of the flow, but the total of the resources consumed in the neighborhood of all the nodes along the transmission path.

We have briefly described our analytical model that provides throughput and delay analysis for MAC scheduling algorithms. We next illustrate how this model can be integrated with the routing protocol to provide a high quality path for real-time traffic.

3.3.2 Call setup process

Service quality prediction in a multi-hop network is accomplished by the utilization of a call setup protocol. The call setup process must first analyze the interference relationship among the nodes along the potential transmission path, as well as disseminate the requirements of the flow along the path. Then the estimated throughput or delay can be calculated using the analytical model described in Section 3.3.1. Finally, once the information is propagated to the source, the source can choose the path that best meets the flow's QoS requirement.



(a) Request phase.

(b) Reply phase.

Figure 5: Call setup process.

In our solution, we base the call setup process on the modified AODV routing protocol described in Section 3.2. The protocol can be divided into a Request and a Reply phase, as shown in Figures 5 (a) and 5 (b). In the request phase, the source node sends RREQ messages for the new flow. RREQ messages, indicated by solid arrows, include QoS information such as the traffic class of the flow, the required quality, and the minimum throughput or the accumulated delay through previous hops. Upon reception of the RREQ packet, each intermediate node adds a pending record for the flow in its routing table and rebroadcasts the RREQ if the flow is locally admissible. This indicates that the predicted quality of the new flow meets the needed service requirement, i.e., the minimum available bandwidth through the previous hops is larger than the flow's throughput requirement, or the accumulated delay over previous hops is smaller than the latency requirement. If the requirement cannot be satisfied, the RREQ packet is dropped. Intermediate nodes notify neighbors about the potential load through the broadcast of Neighbor Reply messages (NREP), indicated by the dotted lines in Figure 5 (a). The local flow set information of each node, disseminated by NREP packets, is needed to determine the input to the model. The RREQ packet reaches the destination if a path with the needed quality exists.

During the reply phase, the destination node sends a RREP message along the reverse path to the source node, as shown in Figure 5 (b). In this phase, intermediate nodes have updated neighbor load information through the NREP packets transmitted in the request phase. They can now more accurately compute the predicted quality of the flows and forward the RREP if the new flow is locally admissible. The source node then selects an optimal path based on the path quality. The nodes along the selected path send NREP packets to confirm the admitted flow status with their neighbors. In this way, all nodes that are affected by the new flow receive updated channel utilization information.

3.3.3 Handling call setup failures

A source node may not be able to find a valid path using the fixed routers if the ongoing traffic over those routers results in a congested wireless medium. In this case, there are several possibilities to accommodate a new QoS session:

1. The new flow backs off for a given interval and tries to set up the call after the backoff period. This is a simple solution whereby nodes passively wait for an ongoing session to end so that network resources can be obtained.

2. The requested flow lowers its service requirement level. For instance, it can request a lower bit rate. In some cases, this will allow the needed quality of the flow to be met by the network.

3. If more intelligence is provided by the network, the mobile user with the new flow can leverage its mobility capability to improve its quality of the service by moving to a less congested area [25, 26]. Since the wireless routers are placed in fixed locations, the network can indicate the location of another less congested wireless router if the resource utilization information about other peers is known. The mobile user can then choose to move toward that router to obtain service via the new route.

In our simulations, we explore the performance of our proposed approach using the first solution. We plan to investigate the other two solutions in future work.

3.4 Summary of the framework

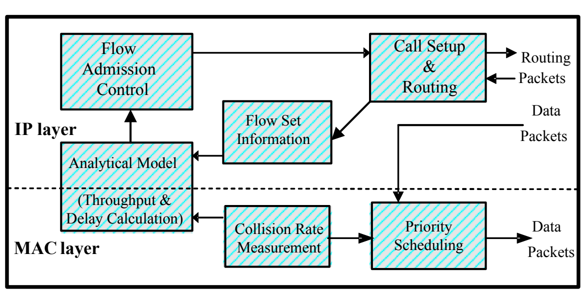


Figure 6: Functionalities of the framework at IP and MAC layers.

We now briefly summarize the functionality of our proposed framework, as well as our implementation architecture. Figure 6 depicts the corresponding modifications at the IP and MAC layers of a node, as well as the high-level interaction between them. Upon reception of a flow request, the call setup process builds an end-to-end path as well as performs admission control using the routing process described in Section 3.2. Note that our QoS framework enables flexible admission control with a wide range of quality policies. The network quality policy can be, for instance, to maximize the network-wide throughput, or to admit the maximum number of high quality flows that can be supported. For each new flow request, a flow admission control component checks whether the quality requirement of the new flow can be met without bringing quality degradation to ongoing traffic through the fixed wireless routers in the network. Specifically, this is achieved based on the resource estimation information of the path, which is the output of our analytical model, as described in Section 3.3. The input of the model is the flow information disseminated along the route setup, as well as the run-time collision rate measurement results. Note that the admission control calculation occurs only at resource-rich and fixed wireless routers. After a route with the needed quality for a new flow is set up, the MAC layer priority scheduling component described in Section 3.1 schedules data packet transmissions according to the packet's priority level.

Typically, wireless users with real-time applications running on their mobile devices will begin to connect to their nearby access point and try to set up a multimedia session. Utilizing this framework, the call setup will succeed and an end-to-end path will be obtained if the flow is admissable. Otherwise, the flow will not be admitted when the network is already congested. Similar to cellular network users wandering around observing signal strength bars on their display, wireless network users may also proactively change their location and connect to another access point for better quality of service. In addition, if the wireless network has built-in intelligence about spatial distribution and access medium congestion, it can further guides users to new access points for better network services.

4 Experimental Study

We have implemented the proposed approach in the NS-2 [10] simulator and conducted experiments to verify our resource estimation model and evaluate the effectiveness of our QoS solution. The experimental studies focus on examination of the efficiency of our framework in real-time traffic support in heterogeneous multi-hop wireless networks.

4.1 Experiment setup

We use networks with 50 nodes in a $1000m \times 1000m$ simulated area with average path length of 3.3 hops. Communication node pairs are randomly chosen among all the nodes. Data flows include both real-time and best-effort traffic, with characteristics as shown in Table 1. For real-time traffic, we model voice over IP data encoded with G.711. Each data point represents the average result of ten runs with different seeds and each run is executed for 300 seconds.

Table 1: Traffic parameters

Traffic Type	Priority	Packet Size (bytes)	Data Rate (Kbps)
Real-Time (G.711 VoIP)	High	160	64
Best-Effort (CBR)	Low	500	80

We demonstrate the effectiveness of our integrated QoS framework in supporting real-time traffic over multi-hop wireless networks in the following experiments.

The first set of simulations demonstrates the efficiency of our proposed MAC layer adaptive priority scheduling mechanism in a dynamic environment, i.e., with different compositions of real-time and best-effort traffic. Static networks are utilized in this set of experiments and all nodes are equally resource-rich, i.e., we do not consider the impact of heterogeneous nodes.

The second set of simulations investigates the effectiveness of our heterogeneous routing solution in supporting real-time traffic. Three sets of experiments are performed and we compare our solution with the unmodified AODV routing protocol. We first examine our adaptive routing solution in a 50 node static heterogeneous network. Devices are assigned a range of resource capabilities, e.g., nodes have varying power levels. Specifically, the threshold of the remaining power to support real-time traffic as described in Section 3.2.1 is based on typical wireless VoIP traffic with a G.711 codec. Therefore, the data rate is 64 kbps with an average packet size of 160 Bytes. According to the study in [31], energy costs are $1.6W$ for packet transmissions and $1.2W$ for packet receptions. $1.0W$ is consumed while idle by typical wireless devices. Hence, for a VoIP session with median duration of 63 seconds [12], the energy consumption is simply calculated as 5103 Joules at the sending node, 8883 Joules at the forwarding node and 3843 Joules at the receiving nodes. We use these values to examine whether a resource-constrained device can support a real-time flow request. The second set of experiments examines the effectiveness of our adaptive routing solution in a mobile network with heterogeneous node mobility. The third set of experiments investigates the performance of our adaptive routing solution in supporting real-time traffic in a network with mixed traffic compositions.

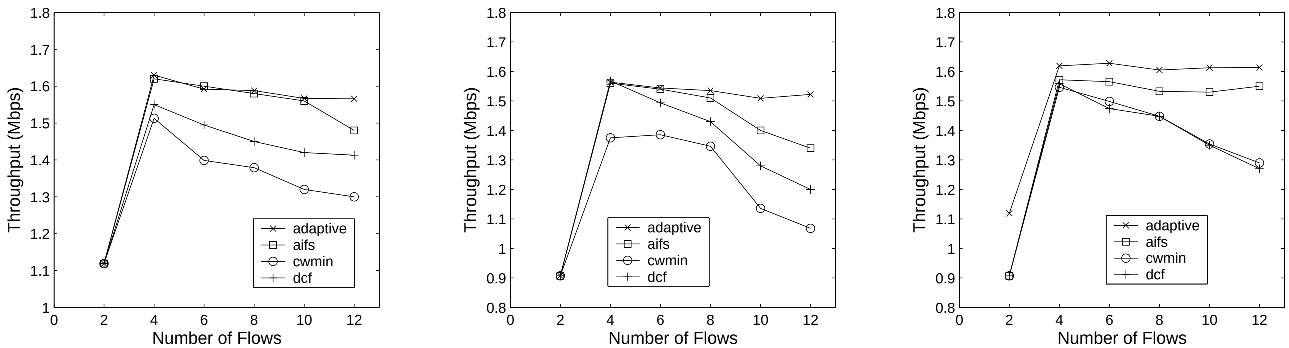
The third set of simulations evaluates our integrated QoS solution by examining the received quality of real-time flows in a heterogeneous network. In this set of experiments, we utilize our adaptive MAC mechanism. We first examine the efficiency of admission control using service quality prediction with unmodified AODV routing, i.e., heterogeneous capabilities and mobility are not considered. We call the case without QoS provisioning *AODV* and the scenario with QoS provisioning *AODV-QoS*. We then examine the effectiveness of the QoS solutions with our heterogeneity-adaptive routing solution. We call the scenario *heterogeneous* when QoS is not used, and *heterogeneous-QoS* when QoS is incorporated. For simplicity, resource-rich and fixed wireless routers are placed in a grid 200m apart, where transmission range for each node is set to 250m. More advanced placement techniques [33] could also be used. In these two experiments, real-time traffic sessions are generated at intervals of 5 seconds. Each session lasts for 100 seconds.

In all experiments with mobility, nodes move according to random waypoint mobility model. An exception occurs during a real-time session between a randomly chosen source and destination pair. During the session, both the end nodes are static. Studies have shown users typically do not move, or move minimally, when they are engaged in a multimedia session, such as typing an Instant Message, viewing a lecture, or watching a multimedia stream [11]. Once the session ends, the users resume movement. On the other hand, users engaged in voice applications tend to have increased mobility. In this case, our assumption does not hold. In this case, our framework may not perform well because we primarily address the problem at routing and wireless medium access layers. Advanced buffering techniques at the application layer and TCP connection migration mechanisms will be needed to support seamless wireless services. We currently do not address this issue in this paper.

4.2 Performance metrics

The efficiency of our proposed framework is evaluated through the following performance metrics:

- **Packet Delivery Ratio (PDR)**: the average fraction of transmitted data packets that are successfully delivered at the destination.



(a) Equal number of high priority and low priority flows.

(b) High priority flows only.

(c) Low priority flows only.

Figure 7: Aggregated network throughput.

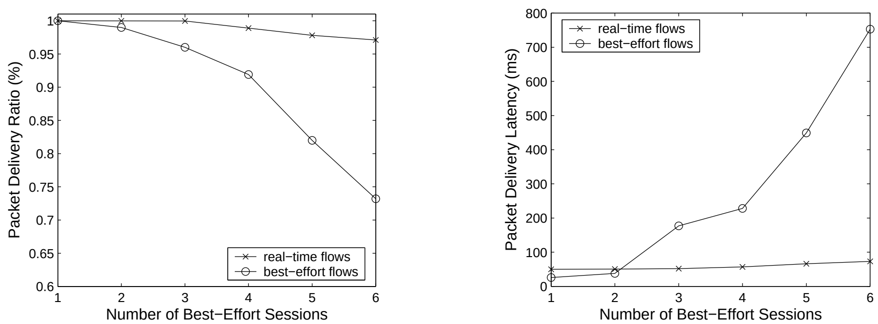
- **Average Transmission Delay**: the average end-to-end delivery latency from the source to the destination.
- **Jitter**: the delay variation between consecutive packets. This is an important metric for real-time traffic. A smaller jitter indicates a higher quality flow.
- **Protocol Overhead**: the number of routing control packet transmissions per data packet delivered in the network. Each hop-wise transmission of a routing packet is counted as one transmission.

4.3 Results

Efficiency of the adaptive MAC protocol

In this set of experiments, we first compare our proposed adaptive priority scheduling mechanism (denoted as *adaptive*) with other alternatives, i.e., varying the AIFS (denoted as *aifs*), and varying the CW_{min} (denoted as *cwmin*). For comparison, we also include the results of the standard DCF protocol (denoted as *dcf*).

Figure 7 shows the results for a 50 node static network with different traffic compositions. Specifically, we examine the scenarios where the number of real-time and best-effort flows are equal, as well as scenarios where only one type of traffic is presented. In all cases, our proposed adaptive MAC protocol outperforms the other solutions, resulting in more efficient use of the channel. Our solution can dynamically adapt to the traffic load by adjusting the node backoff behavior according to the channel collision probability while the other approaches utilize a static configuration and hence are unable to adapt to changes in the traffic load. For instance, when the traffic solely consists of real-time traffic flows (i.e., high priority traffic), the differentiation mechanisms that utilize a static small CW_{min} value (as indicated by the circle marks in Figure 7) suffer significantly from the increased contention. On the other hand, when traffic is only best-effort (i.e., low priority), schemes that utilize a static large backoff window size result in low channel efficiency. We also examine flow fairness among different priorities in this set of experiments and observe that flows with the same priority received roughly fair quality of service and no flows suffer from starvation by competing with peer flows .



(a) PDR with increasing number of best-effort sessions.

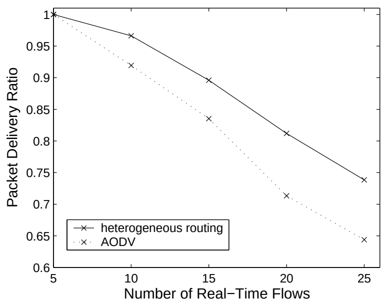
(b) Delay with increasing number of best-effort sessions.

Figure 8: Results for mixed traffic in a 50 node static network.

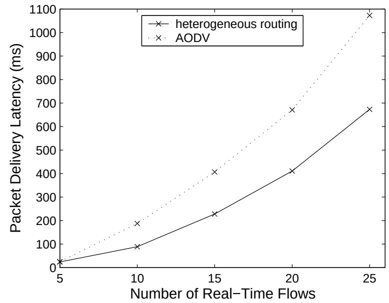
We next evaluate the performance of our solution when adaptive scheduling is utilized in a 50 node network with a mixed set of flows. The traffic set includes both high priority real-time traffic and low priority best-effort traffic. The number of real-time traffic sessions is held constant at five.

Figures 8(a) and (b) show the quality of both flow types in the network as the number of best-effort sessions increases. The packet delivery ratio of the real-time traffic does not drop significantly when the number of best-effort flows increases and the network becomes more congested. We also noticed that the aggregated bandwith consumption in this case is about $0.7MB$, roughly the maximum achievable bandwidth of a $1MB$ wireless channel. Accordingly, the average delay of the real-time traffic remains roughly constant, as shown in Figure 8(b). On the other hand, the quality of the best-effort traffic degrades when the traffic load is high. There is a significant drop in PDR and a surge in the delay. The results indicate the effectiveness of the prioritized medium access mechanism in providing higher priority to real-time traffic. This helps to meet the quality requirements of the real-time flows.

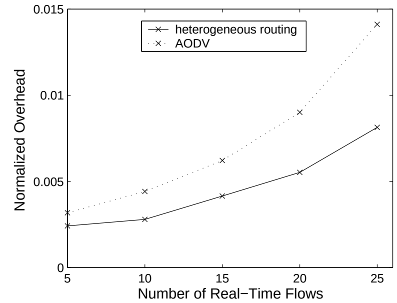
In these simulations, we again observe fair flow quality among the same traffic type, i.e., all real-time flows receive roughly equal service quality. We also notice that as the number of best-effort flow increases, best-effort



(a) Packet delivery ratio.



(b) Average delivery latency.



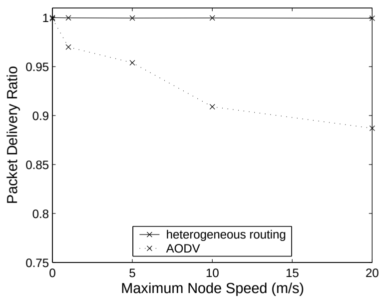
(c) Protocol overhead.

Figure 9: Performance of power adaptive routing in heterogeneous networks.

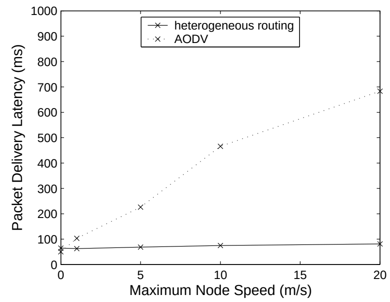
traffic receives high percentage of performance degradation (e.g., 30% in PDR) and this degradation increases non-linearly, indicating the additional penalty to best-effort traffic when competing with real-time traffic. On the other hand, we also notice slight performance degradation for real-time traffic. This is especially true when the network is approaching saturation. In this case, knowledge about the maximum achievable network bandwidth and the proportion of different traffic class will help both our MAC protocol and service quality analysis for better performance. For instance, an appropriate pri can be determined in Eq. (4) so that real-time traffic can gain higher chance of channel access when competing with real-time traffic.

Routing in heterogeneous networks

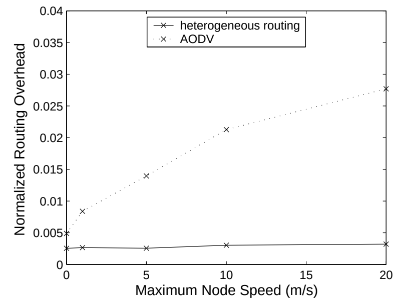
This set of experiments evaluates the benefits of incorporating heterogeneous node capabilities and mobility in the routing decision. We first examine the service quality of real-time traffic with two different types of nodes, i.e., nodes with unlimited power and nodes with low power levels. We use VoIP traffic sessions with a median duration of 63 seconds. There are 50 randomly placed static nodes in this simulation set. We compare the results of our solution with the unmodified AODV routing protocol. Figure 9 shows the performance received by the real-time flows. Because our solution prefers resource-rich nodes in the selection of routing paths, real-time traffic flows through the powerful nodes, thereby avoiding the weak nodes whose remaining power is not sufficient to support the incoming flow. Hence, as shown in Figure 9 (a) and (b), our solution (denoted as *heterogeneous routing*) achieves a higher packet delivery ratio and lower packet delivery latency than the unmodified routing protocol (denoted as *AODV*). The use of unmodified AODV routing results in path breaks due to power depleted



(a) Packet delivery ratio.



(b) Average delivery latency.

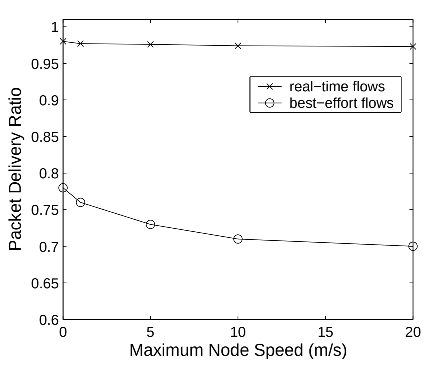


(c) Protocol overhead.

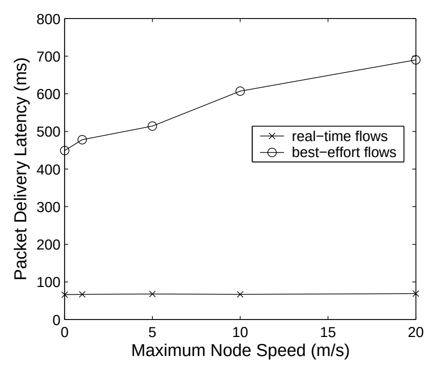
Figure 10: Performance of mobility adaptive routing in heterogeneous networks.

nodes. Subsequently, new routes must be discovered so that the data session can continue. As a result, the control overhead increases, as shown in Figure 9 (c).

We next examine the impact of node mobility on the quality of real-time traffic and evaluate the benefits of our adaptive routing solution. As mobility increases, the frequency of link changes also increases. Figure 10 shows the performance of real-time traffic in a heterogeneous network when half the nodes are static and the other half move at a pre-assigned speed. We set the number of real-time flows to five and study the performance as node mobility increases. As Figure 10 shows, our solution achieves better service quality for real-time traffic because it prefers stationary nodes in the selected routing paths. As mobility increases, the unmodified AODV routing protocol experiences a significant drop in the packet delivery ratio, as well as an increase in latency, due to the intermediate link breaks. Hence, leveraging the fixed wireless routers mitigates the impact of mobility by avoiding link breaks in the intermediate nodes. Similarly, our solution results in less control overhead due to a reduced need for route repairs.

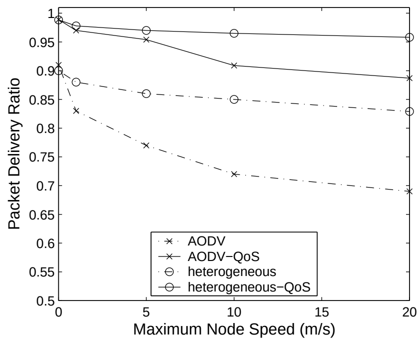


(a) PDR with varying node speed.

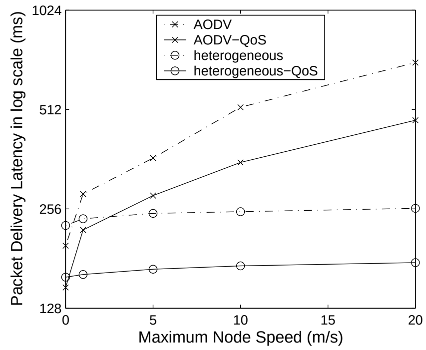


(b) Delay with varying node speed.

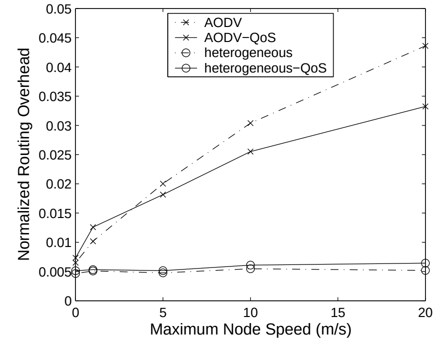
Figure 11: Results for mixed traffic in a 50 node mobile network.



(a) Packet delivery ratio.



(b) Delay.



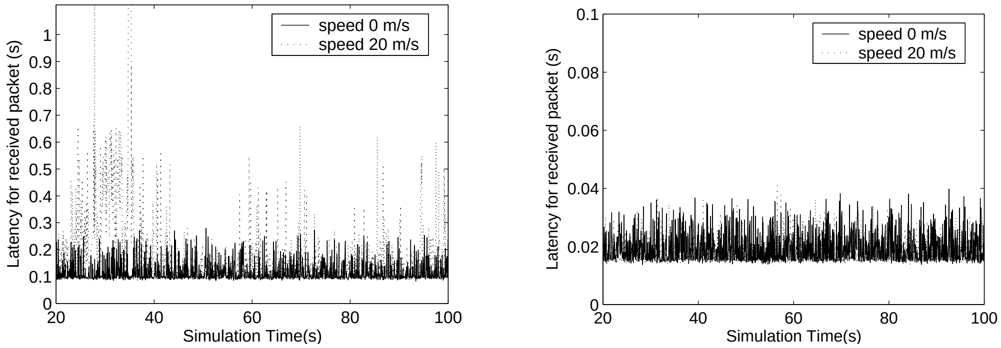
(c) Protocol overhead.

Figure 12: Average quality of flows with 10 sessions in a 50 node network.

We next examine the scenario where mixed traffic classes exist in a 50 node network with heterogeneous node mobility. As we explained in Section 3.1, node movement can bring unregulated best-effort traffic into contention with the real-time traffic. Figures 11(a) and (b) show the quality of both types of flows as node movement increases. There are five real-time and five best-effort sessions in this experiment. The results show that the packet delivery ratio of the real-time traffic remains constant as nodes move, as does the average packet latency. This indicates the effectiveness of our routing solution of utilizing stationary routes for real-time traffic delivery. The results also illustrate the effectiveness of our prioritized scheduling mechanism in reducing the interference from best-effort traffic, thereby providing satisfactory quality to real-time flows, i.e., packet delivery latency is constantly below 100 ms.

Integrated QoS solution

In this set of simulations, we evaluate the received quality of real-time flows both with and without QoS provisioning. Figure 12 presents the performance results of a 50 node network with 10 real-time sessions. As the figures demonstrate, our QoS approach achieves better performance than the non-QoS routing protocol due to the flow quality prediction. As mobility increases, the solutions using the unmodified AODV routing protocol experience a significant drop in packet delivery, as well as an increase in latency, due to the intermediate link breaks. In addition, leveraging the resource-rich and fixed wireless routers mitigates the impact of mobility by avoiding link breaks in the intermediate nodes. The control overhead of our QoS solution is roughly equivalent to the non-QoS solution,



(a) AODV-QoS. (b) Heterogeneous-QoS.

Figure 13: Sample latency traces for 50 node networks.

as shown in Figure 12(c). Our call setup process incurs extra control overhead due to neighbor exchanges (NREP packets). However, this extra overhead is countered by the capability of our protocol to avoid network congestion. When fixed and resource-rich wireless routers are utilized, the overhead is further reduced because network-wide control packet flooding is avoided.

Figure 13 illustrates a sample latency trace of an admitted real-time flow of the QoS provisioning scheme both with and without the use of fixed wireless routers. In a static network, the QoS protocol is effective in achieving a small delay variance, i.e., small jitter. However, in a mobile environment, the frequent broken paths and subsequent route discoveries result in a large delay variation, thereby causing high jitter. With the assistance of fixed wireless routers, the delay variance is much lower than that of the unmodified AODV routing scenario. When the nodes are not moving, the AODV-QoS approach provides slightly lower packet delivery latency than our heterogeneous-QoS approach. This can be explained because the hop-count diameter of $O(\sqrt{n})$ in grid-like structures is larger than the $O(\ln(n))$ diameter for randomly connected structures.

4.4 Summary

In this section, we performed three sets of experiments to demonstrate the effectiveness of our integrated QoS framework. We first examined the efficiency of our adaptive MAC protocol in a dynamic environment with different traffic compositions. We next investigated the benefits of incorporating heterogeneous node capabilities and mobility in making routing decisions to support real-time traffic. We then demonstrated that QoS provisioning improves the delivery ratio and decreases the packet latency by rejecting the admission of a new flow when the network is at full capacity. Combining these techniques, i.e., enabling admission control along the paths of resource-rich and fixed wireless routers, as well as providing adaptive MAC layer scheduling, results in a high packet delivery ratio with low delivery latency, thereby satisfying the QoS requirements of real-time traffic.

5 Conclusion

This paper proposes a QoS framework to provide real-time traffic support in heterogeneous mobile networks. Specifically, the framework consists of three important components: a routing protocol that adapts to the heterogeneity of nodes; an efficient MAC protocol that provides prioritized access for flows with real-time constraints to reduce interference from unregulated non-real-time traffic; and a call setup protocol that combines IP and MAC layer information to perform admission control by accurate service quality prediction. We foresee the utility of our proposed solution in heterogeneous mobile wireless networks, such as campus or community-wide wireless networks. In these environments, devices with heterogeneous capabilities and mobility are likely to be prevalent and can therefore be leveraged to achieve better service quality.

References

[1] Imad Ada and Claude Castelluccia. Differentiation Mechanisms for IEEE 802.11. In *Proceedings of the IEEE Conference on Computer Communications (INFOCOM)*, Anchorage, AK, April 2001.

[2] Gahang-Seop Ahn, Andrew Campbell, Andras Veres, and Li-Hsiang Sun. Supporting Service Differentiation for Real-Time and Best-Effort Traffic in Stateless Wireless Ad Hoc Networks (SWAN). *IEEE Transactions on Mobile Computing*, 1(3):192–207, July-September 2002.

[3] Bay area wireless users group. http://www.bawug.org.

[4] Albert Banchs, Xavier Perez-Costa, and Daji Qiao. Providing Throughput Guarantees in IEEE 802.11e Wireless LANs. In *Proceedings of the 18th International Teletraffic Congress (ITC-18)*, Berlin, Germany, September 2003.

[5] F. Calí, M. Conti, and E. Gregori. Tuning of the IEEE 802.11 Protocol to Achieve a Theoretical Throughput Limit. *IEEE/ACM Transactions on Networking*, 8(6), December 2000.

[6] Ian D. Chakeres and Elizabeth M. Belding-Royer. Transparent Influence of Path Selection in Heterogeneous Ad hoc Networks. In *Proceedings of the 15^{th} IEEE International Symposium on Personal, Indoor and Mobile radio Communications (PIMRC)*, Barcelona, Spain, September 2004.

[7] Shigang Chen and Klara Nahrstedt. Distributed Quality-of-Service Routing in Ad-Hoc Networks. *IEEE Journal of Selected Areas in Communications*, 17(8):1–18, August 1999.

[8] T. Chen, M. Gerla, and J.T. Tsai. QoS Routing Performance in a Multi-hop, Wireless Network. In *Proceedings of the IEEE ICUPC'97*, San Diego, CA, October 1997.

[9] D.Grossman. New Terminology and Clarifications for Diffserv. Request For Comments (Draft Stardard) 3260, Internet Engineering Task Force, April 2002.

[10] Kevin Fall and Kannan Varadhan. ns Manual. *http://www.isi.edu/nsnam/ns/doc/*. The VINT Project.

[11] Tristan Henderson, David Kotz, and Ilya Abyzov. The Changing Usage of a Mature Campus-wide Wireless Network. Technical Report TR2004-496, Dartmouth College, Computer Science, Hanover, NH, March 2004.

[12] Tristan Henderson, David Kotz, and Ilya Abyzov. The Changing Usage of a Mature Campus-wide Wireless Network. In *Proceedings of the* 10^{th} *ACM/IEEE International Conference on Mobile Computing and Networking (MobiCOM'04)*, pages 187–201, Philadelphia, PA, September 2004.

[13] T. S. Ho and K. C. Chen. Performance Evaluation and Enhancement of CSMA/CA MAC Protocol for 802.11 Wireless LANs. In *Proceedings of the IEEE PIMRC*, Taipei, Taiwan, October 1996.

[14] IEEE. 802.11e Draft 3.1, May 2002.

[15] Mesh Networks Inc. Mesh Networks Technology Overview. http://www.meshnetworks.com.

[16] V. Kanodia, C. Li, A. Sabharwal, B. Sadeghi, and E. Knightly. Distributed Multi-Hop Scheduling and Medium Access with Delay and Throughput Constraints. In *Proceedings of the Seventh Annual International Conference on Mobile Computing and Networking (MobiCOM'01)*, Rome, Italy, July 2001.

[17] R. Karrer, A. Sabharwal, and E. Knightly. Enabling Large-scale Wireless Broadband: The Case for TAPs. In *Proceedings of HotNets*, Cambridge, MA, November 2003.

[18] Hwangnam Kim and Jennifer C. Hou. Improving Protocol Capacity with Model-based Frame Scheduling in IEEE 802.11-operated WLANs. In *Proceedings of the* 9^{th} *Annual International Conference on Mobile Computing and Networking (MobiCOM'03)*, pages 190–204, San Diego, CA, September 2003.

[19] S.B. Lee, Gahang-Seop Ahn, Xiaowen Zhang, and A. T. Campbell. INSIGNIA: An IP-Based Quality of Service Framework for Mobile Ad Hoc Networks. *Journal of Parallel and Distributed Computing, Special issue on Wireless and Mobile Computing and Communications*, 60:374–406, 2000.

[20] Nokia Networks. Nokia rooftop wireless routing - white paper. http://www.americasnetwork.com/americasnetwork/data/articlebrief/an 2001.

[21] K. Nichols and B. Carpenter. Definition of Differentiated Services Per Domain Behaviors and Rules for Their Specification. Request For Comments (Draft Stardard) 3086, Internet Engineering Task Force, April 2001.

[22] Charles E. Perkins and Elizabeth M. Royer. Ad-hoc On-Demand Distance Vector Routing. In *Proceedings of the* 2^{nd} *IEEE Workshop on Mobile Computing Systems and Applications*, pages 90–100, New Orleans, LA, February 1999.

[23] MIT Roofnet. http://www.pdos.lcs.mit.edu/roofnet.

[24] Robert Rozovsky and P.R. Kumar. "SEEDEX: A MAC Protocol for Ad Hoc Networks. In *Proceedings of the* 2^{nd} *ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc'01)*, Long Beach, CA, October 2001.

[25] Kimaya Sanzgiri and Elizabeth M. Belding-Royer. Leveraging Mobility to Improve Quality of Service in Mobile Networks. In *Proceedings of The First Annual International Conference on Mobile and Ubiquitous Systems: Networking and Services*, Boston, MA, August 2004.

[26] M. Satyanarayanan. Pervasive computing: Vision and Challenges. *IEEE Personal Communications*, 8:10–17, August 2001.

[27] S. Shenker, C. Partridge, and R. Guerin. Specification of Guaranteed Quality of Service. Request For Comments (Draft Stardard) 2212, Internet Engineering Task Force, September 1997.

[28] Suresh Singh, Mike Woo, and C. S. Raghavendra. Power-Aware Routing in Mobile Ad Hoc Networks. In *Proceedings of the* 4^{th} *Annual International Conference on Mobile Computing and Networking (ACM Mobicom)*, Dallas, TX, October 1998.

[29] P. Sinha, R. Sivakumar, and V. Bharghavan. CEDAR: A Core-Extraction Distributed Ad Hoc Routing Algorithm. In *Proceedings of the IEEE Conference on Computer Communications (INFOCOM)*, pages 202–209, New York, NY, 1999.

[30] IEEE Computer Society. IEEE Standard for Wireless LAN-Medium Access Control and Physical Layer Specification, November 1999.

[31] M. Stemm and R. H. Katz. Measuring and Reducing Energy Consumption of Network Interfaces in Hand-held Devices. *IEEE IEICE Transactions on Communications*, E80-B(8):1125–1131, August 1997.

[32] Yuan Sun, Xia Gao, Elizabeth M. Belding-Royer, and James Kempf. Model-based Resource Prediction for Multi-hop Wireless Networks. In *Proceedings of the* 1^{st} *IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS'04)*, pages 114–123, Ft. Lauderdale, FL, October 2004.

[33] Wireless Valley. . http://www.wirelessvalley.com.

[34] A. Veres, A. T. Campbell, Michael Barry, and Li-Hsiang Sun. Supporting Service Differentiation in Wireless Packet Networks Using Distributed Control. *IEEE Journal of Selected Areas in Communications*, 19(10):2094–2104, October 2001.