Statistical QoS Routing for IEEE 802.11 Multihop Ad Hoc Networks

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***Abstract*—In this paper, we propose a model-based quality-of-service (QoS) routing scheme for IEEE 802.11 ad hoc networks. Unlike most of QoS routing schemes in the literature, the proposed scheme provides stochastic end-to-end delay guarantees, instead of average delay guarantees, to delay-sensitive bursty traffic sources. Via a cross-layer design approach, the scheme selects the routes based on a geographical on-demand ad hoc routing protocol and checks the availability of network resources by using traffic source and link-layer channel modeling, taking into consideration the IEEE 802.11 characteristics and node interactions. Our scheme extends the well developed effective bandwidth theory and its dual effective capacity concept to multihop IEEE 802.11 ad hoc networks. Extensive computer simulations demonstrate that the proposed scheme is effective in satisfying the end-to-end delay bound to a probabilistic limit.**

***Index Terms*—Ad hoc network, call admission control, end-to-end delay, IEEE 802.11 MAC, resource allocation, routing.**

I. INTRODUCTION

THE attractive infrastructure-less nature of wireless ad hoc networks draws significant attention from researchers in both academia and industry. Recently, the increasing demand on multimedia applications in wireline networks makes QoS provisioning for wireless ad hoc networks a very desirable objective. However, some unique characteristics of wireless ad hoc networks make QoS provisioning technically challenging, such as shared wireless medium, mobility, and distributed multi-hop communications.

We consider the end-to-end delay as a QoS measure in this paper. We present a statistical (model-based) QoS routing scheme that provides stochastic delay guarantee, such as $Pr(D > D_{max}) \leq \epsilon$ (where D represents the end-to-end packet delay, D_{max} is the delay bound, and ϵ is the delay violation probability upper bound) for IEEE 802.11 DCF multihop ad hoc wireless networks. With the recent advances in localization techniques that can fit small and low power devices [3], requiring position information of ad hoc network nodes no longer represents a limitation to location-based routing. As a result, the proposed scheme uses the greedy perimeter stateless routing (GPSR) [4] as a location-based on demand ad hoc routing protocol to discover a route to the destination of a new flow. Location based routing protocols are characterized by their scalability and efficient bandwidth utilization as they do not flood the network to find the path for a destination [5]. The discovered route is tested for admission using a fully distributed and model-based resource allocation process, which checks if the discovered route can satisfy the required delay bound of the new flow probabilistically without affecting other network flows already in service.

Following novel cross-layer design, the resource allocation process takes into account the characteristics of the IEEE 802.11 DCF and the dynamics of its service process by using both traffic and link-layer channel models [6]. We extend the well developed effective bandwidth theory and effective capacity concept [7] to IEEE 802.11-based ad hoc networks in order to provide stochastic end-to-end delay guarantees to multihop connections.

The rest of the paper is organized as follows. Section II gives an overview of the most relevant research works. The system model is introduced in Section III. Section IV provides the necessary background for the effective bandwidth theory and the channel effective capacity. It also illustrates the basic equations used throughout the paper in order to calculate both the effective bandwidth and the effective capacity. Section V discusses cross-layer design aspects of QoS routing over the IEEE 802.11 DCF. Section VI presents the proposed QoS routing scheme. Section VII provides the simulation results for the QoS routing scheme validation and performance evaluation. Section VIII concludes this research.

II. RELATED WORKS

Several QoS routing protocols have been introduced in the literature. In the context of wireless ad hoc networks, the MAC layer affects the way that the QoS routing protocol selects a QoS-enabled path. Here, we adopt IEEE 802.11 DCF as it is fully distributed in terms of network control and data communication, which conforms with the nature of ad hoc networks. Some QoS routing research based on other MAC protocols such as time-division multiple access (TDMA) MAC is introduced in the literature [8]-[9]. Mobile nodes in a TDMA-based ad hoc network are difficult to synchronize in time without a centralized controller, which has to be within a range of all the nodes in the network. QoS routing protocols that are based on multi-channel MAC protocols (e.g. [10]-[14]) are not easy to implement in an ad hoc networking environment. Multi-channel MAC protocols enable nodes in the same neighborhood to communicate concurrently in different channels without interfering with one another. Communication channels may be distinguished either by different frequencies such as using multiple IEEE 802.11 [12]-[13] channels or

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using different spreading codes/carriers [10] or a combination of spreading codes/carriers and time slots [14]. However, it is difficult for a sender and a receiver to tune to the same channel in a distributed fashion. Some multichannel MAC proposals use more resources (i.e., one radio interface for control channel and another for data channel) [11] or use time synchronization [12] [13], while others require signaling exchanges in order to assign different channels to different nodes [14]. Using multiple radio interfaces is not convenient for small ad hoc nodes such as personal digital assistants (PDAs). Exchange signaling messages in the link-layer level increases the energy consumption of the ad hoc network nodes.

Recently, several IEEE 802.11-based QoS routing protocols have been proposed. They can be classified into measurement-based and model-based schemes. Measurement-based schemes such as [16]-[19] may involve channel monitoring and probing for available resources, which consumes the energy of the battery-powered devices and the scarce radio bandwidth. The QoS routing schemes proposed in [20]-[21] provide average delay guarantees without taking into account the effects of statistical traffic and the variation of the service time of IEEE 802.11 DCF under different traffic loads. In [22], a traffic-aware routing scheme for real-time traffic is introduced. The scheme provides link and path transmission time model-based prediction in order to control the average end-to-end delay without any call admission control or resource reservation techniques. Jacquet et al. [23] propose a routing scheme to provide a stochastic end-to-end delay guarantee for IEEE 802.11 ad hoc networks. The scheme is model-assisted measurement based as it measures both the collision probability and the average channel occupancy. It does not support any call admission control or resource reservation for QoS provisioning.

In comparison, the novelty of this research lies in two aspects: (i) The proposed scheme, via cross-layer design, selects the routes satisfying the end-to-end delay bound probabilistically based on a statistical resource allocation process without consuming the limited processing power of the ad hoc network nodes or the channel bandwidth in frequent measurements or traffic monitoring; (ii) The statistical multiplexing capability of the IEEE 802.11 DCF [6] is exploited by applying the effective bandwidth theory and its dual the effective capacity concept to multihop connections in order to achieve an efficient utilization of the shared radio channel while satisfying the end-to-end delay bound.

III. System Model

Consider an ad hoc network with a single and error-free physical channel. The network nodes may be active nodes (traffic sources) and/or packet forwarders (routers), or just receivers (sinks). All network nodes can move with limited mobility. The mobility process is assumed to be ergodic. We assume that the network is connected (i.e., a routing path always exists between each source node and destination node in the network). Consider the network in a non-saturated condition [24]. All the traffic sources are ergodic iid exponential on-off traffic sources (i.e., the on and off times are independent exponential random variables). It has been shown in [1] that the on-off sources can be used successfully to model different multimedia traffic types. For each node, i, that has a traffic source, the traffic parameters are the average on time $1/\alpha_i$, the average off time $1/\beta_i$, and a constant data rate R_i during an on time period. The QoS requirement is captured by $D_{i_{max}}$ and $\in$.

The MAC protocol is the IEEE 802.11 DCF. The channel access is done via a binary exponential backoff procedure. Following the carrier-sense multiple access with collision avoidance (CSMA/CA) protocol as described in [25], the contention window (CW) size initially is set to CW_{min}. After an unsuccessful transmission, the CW size is doubled up to a maximum value. In order to resolve the hidden terminal problem, the IEEE 802.11 employs the four-way handshake RTS-CTS-DATA-ACK mechanism as described in [24]-[25]. In this mechanism, a node starts its packet transmission by sending a request-to-send (RTS) frame and then waiting for a clear-to-send (CTS) frame from the intended receiver. The reception of a CTS frame reserves the channel for the RTS transmitter. We assume that the carrier sense (CS) range is adjusted properly to completely eliminate the hidden terminal problem. Adjusting the CS range to cover a relatively large area around the receiver greatly reduces packet collisions due to the hidden terminal problem, because potential hidden interferers become able to sense the sender transmission [26].

Recently, there has been a growing research focus on location based routing in order to improve network scalability and reduce the total routing overhead [27]-[28]. Location based routing for ad hoc networks becomes possible and practical with the availability of advanced localization techniques that do not depend on the global positioning system (GPS) [3] [29] and with the emerging of ultra wideband (UWB) technology that offers low power and precise location determination methods [30]. As a result, the network layer protocol used for route discovery and maintenance is greedy perimeter stateless routing (GPSR) protocol, which is an on-demand location-based ad hoc routing. The resource allocation at the network layer is coupled with the GPSR routing protocol. The GPSR uses a technique called greedy packet forwarding [4]. In this technique, the sender of a packet includes the approximate position of the recipient in the packet. When an intermediate node receives the packet, it forwards the packet to the geographically closest neighbor with respect to the packet destination. This process is repeated at each discovered hop until the destination is reached. GPSR guarantees to find a routing path between a sender and its destination (when the network is connected) by using another technique called perimeter routing when greedy forwarding fails due to the presence of a void gap between a sender and its destination [4].

IV. Preliminaries

A. The Effective Bandwidth of a Traffic Source

The effective bandwidth approach is to show that the queue length and the corresponding delay at a node can be bounded exponentially for different stochastic traffic types, if an amount of bandwidth equal to the effective bandwidth of the source is provided by the channel [1].

Consider a queue of infinite buffer size served by a channel of constant service rate c. Let D denote the total delay (queuing delay + service time) that a source packet experiences. By using the large deviation theory [31], it can be shown that the probability ϵ that D exceeds a delay bound of D_{max} is given by

$$\epsilon = \Pr\{\mathrm{D} \geq \mathrm{D}_{\max}\} \approx e^{-\theta_b D_{\max}} \quad (1)$$

where the exponent θ_b is the solution of

$$\theta_b = c\eta_b^{-1}(c). \quad (2)$$

In (2), $\eta_b^{-1}(.)$ is the inverse function of $\eta_b(.)$ which is the effective bandwidth of the traffic source, given by

$$\eta_{\mathrm{b}}(\mathrm{x}) = \lim_{\mathrm{t}\to\infty} \frac{1}{t}\frac{1}{x}\log E[e^{xA(t)}], \forall x > 0 \quad (3)$$

where $A(t)$ is the arrival process of the source, i.e. the number of packet arrivals in the interval [0, t]. Thus, the source (having a delay bound D_{max}) will experience a delay-bound violation probability of at most ϵ if the constant channel capacity c is at least equal to its effective bandwidth [31].

B. The Effective Capacity of a Channel

The effective capacity of a channel is the dual of the effective bandwidth theory when the channel capacity is time varying. Let $S(t)$ denote the service process of the channel (the amount of data that the channel can carry) in bits over the time interval [0, t]. The effective capacity function is defined for stationary and ergodic $S(t)$ as [31]

$$\eta_c(x) = -\lim_{t\to\infty} \frac{1}{t}\frac{1}{x}\log E[e^{-xS(t)}], \forall x > 0. \quad (4)$$

Similar to the effective bandwidth theory, it can be shown that the probability of the delay D exceeding a certain delay bound D_{max} satisfies [7]

$$Pr\ \{D \geq D_{\max}\} \approx e^{-\theta_c D_{\max}} \quad (5)$$

where the exponent θ_c is the solution of

$$\theta_c = u\eta_c^{-1}(u). \quad (6)$$

Therefore, a source should limit its data rate to a maximum of u in order to ensure that its delay bound (D_{max}) is violated with a probability of at most ϵ.

C. Time Variant Arrival and Service Processes

It has been shown in [7] that, if both the traffic source rate and the channel capacity are time varying, both the effective bandwidth of the source and the effective capacity of the channel should be equal in order to satisfy the stochastic delay bound. Then for a large enough D_{max}, the total delay satisfies

$$\frac{1}{D_{\max}}\log\Pr(D > D_{\max}) = -\theta \quad (7)$$

where θ is given by

$$\theta = r\eta_c(r) \quad (8)$$

and r is the unique solution of the equation

$$\eta_c(r) = \eta_b(r). \quad (9)$$

In fact, (7) also holds if there are intermediate wireless links from the traffic source to the sink, regardless if the service statistics of those wireless links are independent or not [7].

V. Cross-Layer Design for QoS Routing

In this section, we discuss three different cross-layer design aspects, which are related to the characteristics of multihop IEEE 802.11 DCF connections and strongly affect the design of our model-based QoS routing scheme. First, we address the complexity of the QoS routing problem and our heuristic approach to solve it. Second, we obtain a general formula for the capacity process of a multihop connection on a shared wireless channel, calculate the effective capacity of that connection, and estimate the capacity variation of an IEEE 802.11 DCF multihop connection. Third, we discuss how the IEEE 802.11 contention-based access affects the network resource allocation.

A. The QoS Routing Problem

We address the QoS routing problem of finding a path that satisfies a stochastic end-to-end delay guarantee, i.e.,

$$\Pr\left(\sum_{i=1}^{n} d_i > D_{\max}\right) \leq \epsilon \quad (10)$$

where d_i is the packet delay for link i, and n is the number of hops in the route.

This problem has been shown to be an NP-hard problem even if there is a network topology database available to keep state information of nodes and links in the network [32]. Hence, a heuristic approach is required in order to obtain a solution in a reasonable time and with a minimal amount of signaling, as there is no centralized entity that can hold state information in an ad hoc network.

Under the assumption of random traffic pattern (i.e., each source node initiates packets to a randomly chosen destination), it has been indicated in [33] that the geographical routing helps to find routes that are close in distance to straight line paths between traffic sources and their corresponding destinations and hence it approaches the upper bound on per node capacity for an IEEE 802.11 DCF ad hoc network. High per node capacity translates directly to less delay per hop. In fact, hop count should be taken into account in order to reduce the inefficient use of bandwidth due to shared channel interference and packet collisions. Actually, a small number of hops indicates that a small number of nodes compete for the shared channel, which in turn reduces the packet collision probability. As a result, short routes represent good candidates to be tested for network admission in order to achieve the end-to-end delay bound, as they minimize the overall network resources used for the transmission of a packet from its source to its destination. However, routes with an increasing hop count should be tested whenever short routes pass a congested area of the network.

Our heuristic approach takes into consideration the IEEE 802.11 characteristics, while taking the hop count into account by using the GPSR protocol to discover short routes in terms of distance. A resource allocation procedure is applied after the route discovery in order to check if there are sufficient network resources available for the new call request. If the admission fails, another route will be selected subsequently using the GPSR protocol after forcing it to choose a longer route and then the resource allocation procedure repeats.

B. Capacity Prediction for a Multihop Connection

One design objective of our QoS routing protocol is to guarantee that the admission of a new call will not affect the QoS guarantee of calls already in service. Due to the random nature of traffic flows, a stochastic estimation of the capacity process of the multihop connection is required, in order to guarantee sufficient network resources for the whole call duration. Actually, a stochastic model for the capacity variations of any route strongly depends on the behavior of the service process of the MAC protocol. This implies a difficulty in designing a QoS routing protocol as an independent network layer, and hence cross-layer design is mandatory.

Consider a multihop connection that consists of a source, a sink, and K intermediate links. The service provided by this multihop connection over a time interval $[0, t]$ is given by [7]

$$S(0,t) = \inf_{0=t_0 \le t_1 \le \ldots \le t_{K-1} \le t_K = t} \left\{ \sum_{k=1}^{K} S_k(t_{k-1}, t_k) \right\} \quad (11)$$

where $S_k(t_{k-1}, t_k)$, k = 1,2, ..., K, is the service process of link k over a time interval $[t_{k-1}, t_k]$. Directly from (11), we can infer that [7]

$$S(0,t) \le \min_k S_k(0,t), \quad k = 1, 2, \ldots, K. \quad (12)$$

The IEEE 802.11 DCF is used as an access mechanism for the multihop connection over a shared wireless channel, where all the K links are in the same carrier sense range and hence only one of them can transmit at a time. The IEEE 802.11 DCF has been shown to have a short and a long term fairness properties [34]. Therefore, without loss of generality, we consider every link will seize a chance to transmit only at some time interval (t_{k-1}, t_k) out of the whole interval (0, t), where $0 \le t_1 \le \ldots \le t_{K-1} \le t_K = t$. The service process of the end-to-end connection $S(0,t)$ in an IEEE 802.11 DCF channel can be obtained from (12) as

$$S^{DCF}(0,t) = \min_k S_k(t_{k-1}, t_k), \quad k = 1, 2, \ldots, K \quad (13)$$

since any link k has the chance to transmit only during the time interval (t_{k-1}, t_k). It is worth noting that, although all the K links can hear each other, each link k has a unique service process since it contends for the channel with a unique set of neighbors.

According to [7], the effective capacity for a multihop connection $\eta_{mc}(x)$ is given by

$$\eta_{cm}(x) = \min_k \eta_{ck}(x) \quad (14)$$

where $\eta_{ck}(x)$ is the effective capacity of link k.

As an example, consider the K links in a multihop connection that use the same IEEE 802.11 DCF channel with rate c. If we assume a deterministic service process ct for each hop, which is the case of a low traffic load [6], then by using (13), taking the MAC fairness into consideration, we can approximate the service of the IEEE 802.11 DCF end-to-end connection by

$$S^{DCF}(0,t) = c(t_k - t_{k-1}) = \frac{ct}{K}. \quad (15)$$

By using (14) and (4), we can obtain the effective capacity of the multihop connection for the DCF as c/K, while it is equal to c for the single hop case. This is consistent with what is illustrated in [33]. In [6], we have shown that the service process of the IEEE 802.11 DCF channel has a different behavior dependent on the traffic load in the network, and defined different regions of operation based on the traffic load. In the first region with a low traffic load (up to 50% of the saturation traffic load), the collision probability is low (less than or equal to 0.1), and the service process can be approximated by a deterministic process. In the second region where the traffic load is higher (up to 80% of the saturation load), the service process of the IEEE 802.11 DCF channel fed by on-off traffic sources can be approximated by a Markov modulated Poisson process (MMPP). Note that the utlization factor (the ratio of the packet arrival rate to the service rate) in an IEEE 802.11 DCF network increases nonlinearly when the traffic load increases [6]. Both the first and second regions of operation are characterized by a low utlization factor (around 0.2), as when the traffic load approaches saturation, the increase of the utlization factor with traffic load becomes very steep (as the service rate decreases rapidly) and hence it is difficult to guarantee a bounded queuing delay [6]. By increasing the utilization factor up to one, a less than 10% increase of network throughput can be achieved [6].

The effective capacity of an IEEE 802.11 DCF multihop connection can be obtained based on (14). The effective capacity for an IEEE 802.11 DCF link (single-hop connection) is given by the average service rate in the first operation region and by the following expression in the second operation region [6]

$$\eta_c(x) = \frac{sp\left(Q + (e^{-x} - 1)\,\Phi\right)}{x} \quad (16)$$

where Q is the transition rate matrix for the link, Φ is a diagonal matrix with Poisson rates for the link, and sp(A) is the spectral radius of matrix A.

The resource allocation procedure embedded in our QoS routing protocol ensures that when the effective bandwidth of an on-off traffic source feeding a multihop wireless connection is equal to the effective capacity of this connection, the end-to-end packet delay exceeds the required delay bound with a violation probability of at most ϵ. The effective bandwidth for an on-off source is given by [1]

$$\eta_b(x) = \left(\frac{R}{2} - \frac{\beta+\alpha}{2x}\right) + \sqrt{\left[\frac{R}{2} - \frac{\beta+\alpha}{2x}\right]^2 + \frac{\beta R}{x}}. \quad (17)$$

The proposed resource allocation procedure solves (9) (using (17) and the operation region-dependent effective capacity) at every hop, calculates the actual delay bound, and finally compares it with the required delay bound. If the hop with minimum effective capacity does not achieve the delay bound, the multihop connection will not achieve it according to (14).

C. Awareness of Available Network Resources

The spatial frequency reuse in an IEEE 802.11 DCF-based network allows multiple simultaneous transmissions over the single radio channel in the network since, for any node,

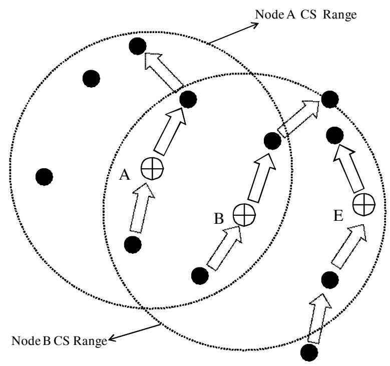

Fig. 1. Network topology for illustrating spatial reuse and interference awareness.

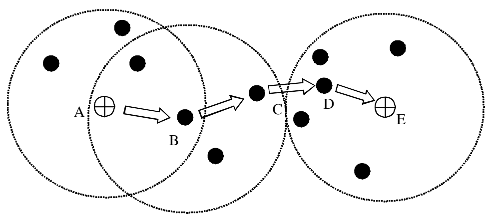

Fig. 2. Network topology for illustrating the route discovery procedure.

the physical channel covers only the area of the node's CS range. Nevertheless, the spatial reuse complicates the resource allocation process for IEEE 802.11 DCF ad hoc networks. Every node may contend for the physical channel on a different coverage area associated with a different set of neighbors. The transmission is completely prohibited when the channel is sensed busy even if it does not cause any intolerable interference. Therefore, a cross-layer design for any network-layer resource allocation process that works over the IEEE 802.11 MAC protocol is mandatory, in order to take into consideration its special characteristics.

According to (14), the available effective capacity of a multihop connection is determined by the minimum effective capacity among its hops. Due to the spatial reuse and the shared nature of the IEEE 802.11 DCF channel, the effective capacity of any hop in a multihop connection is the minimum effective capacity among the CS neighbors of that hop. For example, in Figure 1 where nodes A and E are not in the CS range of each other, node A cannot join the network if it requires an effective capacity of $3c/4$ given that B and E have already running flows with an effective capacity of $c/4$ each. If node A relies only on its own effective capacity calculation, it would admit itself into the network, depleting the network resources from node B.

VI. Statistical QoS Routing Scheme

The proposed statistical QoS routing scheme contains a route discovery and maintenance procedure and a resource allocation procedure (for admission control and resource reservation). The two procedures are described in the following subsections.

A. Route Discovery and Maintenance

The procedure consists of two phases. The first phase is the discovery part, which is responsible for discovering possible routes to be tested for admission by the resource allocation process. The second phase is the route maintenance, which is invoked either during the resource allocation process or when the route is broken. Consider the route as shown in Figure 2, where the nodes are labeled by $A,\ B,\ldots,E$ from the source to the destination. The procedure works as follows.

Step 1: The GPSR protocol provides every node with a neighbor list, including the neighbor position and ID, via a simple beaconing procedure [4]. The source node A starts to discover a route by sending a "Route Request" (RR) message to the geographically closest neighbor with respect to the packet destination [4] as shown in Figure 2. The message includes the approximate position (the xy-coordinates) of the destination and the following traffic flow information: the total delay bound, the flow ID, the node ID, and the traffic tuple (α, β, R). Node A also stores the ID of the discovered node to be used later in forwarding the data packets. After that, node A starts a call setup timer.

Step 2: The node records necessary information of the traffic flow in a table, referred to as Flow Table, and appends its ID to the RR packet. The node then starts discovering another intermediate node as node A does in Step 1 and forwards the RR message to it, and so on, till the destination is reached.

Step 3: Every node that receives the RR message records the ID of the node that it forwards the packets to (referred to as "next hop") and the ID of the node that it receives the packets from (referred to as "previous hop"). In fact, the GPSR protocol discovers the route on a packet-by-packet basis, which is not suitable for QoS provisioning. As a result, the proposed scheme discovers the route only once by the GPSR protocol, and then uses the "next hop" and the "previous hop" information in forwarding data and signaling packets. This implies that a kind of virtual circuit is established between the source and the destination, which facilitates resource allocation.

The route is considered broken at some point, if it cannot admit the traffic flow or is no longer able to forward the packets of an admitted flow (i.e., the maximum retransmission limit of the MAC protocol is reached) at that point. The route repair part acts differently based on the status of the traffic flow as follows.

- If there is no sufficient resources at any intermediate hop (e.g., node B or node C in Figure 2) during the resource allocation procedure, node C for instance initiates the discovery of a new route by excluding the current "next hop" node from its neighbor list and applying again the three steps mentioned precedingly. When the destination receives an RR packet again for a flow, it implies that the route is broken and so the destination initiates a new resource allocation procedure for that flow.
- If the flow is already admitted and the route breaks at any intermediate hop other than the first hop, the node at the route breakage point starts to repair the route following the three steps mentioned precedingly, but by sending a "Route Repair" (RP) message instead of an RR message. When the destination receives the RP message, it starts the resource allocation procedure only for the repaired section of the route in order to reduce the amount of signaling used and to shorten the route breakage time.

The destination also starts a route repair timer.

If the route breaks at the first hop (at node A) for any reason, the source node initiates a new route discovery process.

B. Resource Allocation

The procedure consists of a fully distributed statistical CAC procedure and a resource reservation procedure. The resource reservation proceeds side by side with the CAC procedure in order to resolve the competition among flows that want to join the network simultaneously. Note that the resource reservation for any node is temporary, it lasts until the node cancels it.

We assume that every node acting as a packet forwarder (whether or not it has a local traffic source) is able to measure the statistics of the packet arrival process such as average number of packet arrivals per unit time, the variance, and the autocovariance (the covariance between the arrival process and a unit time-shifted version of it). As these measurements do not require any channel monitoring, the receiver is not kept on all the time, saving the energy for the battery-powered devices. The packet arrivals at a packet forwarder are characterized by an exponential on-off traffic model. The validity of this approximation is discussed in Appendix. Using these measurements and the approximation, node i is able to obtain the traffic tuple (α_i, β_i, R_i) based on the following set of equations

$$u_i = \frac{\beta_i}{\beta_i + \alpha_i} \tag{18}$$

$$R_{avg} = R_i u_i \tag{19}$$

$$R_{\sigma} = R_i^2 u_i (1 - u_i) \tag{20}$$

$$R_{cov} = R_i^2 u_i (1 - u_i) e^{-\left(\frac{\beta_i}{u_i}\right)} \tag{21}$$

where R_{avg}, R_{σ} and R_{cov} are the measured time average, variance and autocovariance of the packet arrival process for node i. It is worth noting that the node stores traffic tuples (its tuple and the tuples of its CS neighbors) in a table (referred to as "CS Information Table") only for a certain amount of time (based on how fast the network topology changes) and available to be used for other admission inquiries, hence keeping a minimal amount of signaling exchanges.

The call admission control and the resource reservation procedure is presented in the following:

Step 1: After the destination (node E in Figure 2) receives the RR message, it records the source route and sends an "Admission Request" message to its neighbor in the route (node D in Figure 2).

Step 2: Node D broadcasts a "Reservation Request" message to its CS neighbors using one of the methods indicated in [18] or by using a lower data rate so that its transmission can reach a longer distance than the original transmission range. The message contains the flow ID and source node traffic tuple. The nodes in the CS range of node D that do not have a valid "CS Information Table" obtain the traffic tuples of the nodes in their CS ranges by sending "Information Request" messages and receiving "Information Response" messages from those nodes.

Step 3: By using the "CS Information Table", the traffic tuples for the reserved flows, and the traffic tuple of the new flow, each CS neighbor of node D runs the CAC algorithm developed in [6], which can be briefly summarized in the following.

- *Check operation region*: Each neighbor determines whether the service process in its CS range can be approximated by a deterministic process (the first region) or by an MMPP (the second region) by calculating the average traffic rate (λ) using
$$\lambda = \frac{R\beta}{\alpha + \beta} \tag{22}$$
and then checking the operating region of its channel [6]. If the average rate is close to the saturation (around 80% or higher of the saturation traffic load), the node declines the reservation request [6].
- *Check admission*: Each neighbor checks the admission by solving (9), to get the unique solution r and then applies r in (8) to get θ. By replacing D_{max} with D_{act} in (7) and using the value of θ, the delay bound D_{act} that can achieve a violation probability of at most ϵ can be calculated. If the local or relayed traffic flows of the neighbor have more than one service class, D_{max} represents the strictest delay bound among the different service classes. As the channel of the neighbor is equally shared among N other active nodes, if $D_{max} \geq N D_{act}$, then the flow can be admitted into the network, otherwise it cannot.

Note that in the first operation region, if the average service rate is higher than the constant rate of the traffic flow (at the on time), the flow can be admitted to the network.

Step 4: Each CS neighbor of node D replies to the "Reservation Request" message based on the outcome of the CAC algorithm either by a "Reservation Accept" or an "Admission Decline" message. If the reservation is accepted, the neighbor stores the traffic tuple of the new flow in another table called "Flow Reservation Table" with the flow ID, the hop index and the ID of node that reserved the resources of the flow. The information in the "Flow Reservation Table" is stored temporarily for some time to prevent reserving the same network resources for more than one flow. The reservation information also allows the resource allocation procedure to take the self interference from the hops of the same traffic flow into consideration. The neighbor also includes its own traffic tuple in the "Reservation Accept" message. If the reservation is rejected, the neighbor sends an "Admission Decline" message to node D.

Step 5: Node D proceeds according to the outcome of Step 4. If node D receives any "Admission Decline" message, it will go directly to Step 6. If node D receives only "Reservation Accept" messages, it will use the traffic tuples of its CS neighbors included in the received messages and the traffic tuples of the previously reserved flows in order to apply the CAC developed in [6]. This lets node D check if the the admission of the new flow will affect the flows originated or forwarded by it. Based on the CAC result, node D accepts or rejects the flow admission.

Step 6: In the case that D rejects the flow or receives an "Admission Decline" message from any of its CS neighbors, it notifies node C by sending an "Admission Decline" message,

TABLE I
IEEE 802.11 SYSTEM PARAMETERS [25]

System Parameter	Value
Packet payload	256 Bytes
PHY header	128 bits
ACK	112 + PHY header
RTS	160 + PHY header
CTS	112 + PHY header
Slot Time	50 μs
SIFS	28 μs
DIFS	128 μs
Basic Rate	1 Mbps
Data Rate	2 Mbps
CW_{min}	16
Backoff Stages (m_b)	5
Transmission Range	$250m$
Carrier Sense Range	$550m$

then node C invokes the route discovery and maintenance procedure. On the other hand, if node D accepts the flow, it stores the flow information in its own "Flow Reservation Table". After that, it forwards the "Admission Request" message to node C (Figure 2), and node C in turn starts the same procedure from Step 2.

Step 7: The procedure is repeated until the source node is reached and the flow is admitted. If any of the setup timer or repair timer expires, the source node or the destination node, respectively, sends an "Admission Stop" message to all the nodes in the route in order to remove all the flow-related information from the "Flow Table" and the "Flow Reservation Table" and to stop any running activity associated with it.

Note that we assume that the topology does not change dramatically during the resource allocation procedure. Indeed, high user mobility represents a limitation to our scheme as it is difficult to estimate the available resources in an infrastructureless network where the topology changes fast and there is no centralized entity to keep track of the locations of available resources.

VII. Simulation Results

The performance of the proposed statistical QoS routing protocol is evaluated using the ns-2 simulator. Mobile nodes move in an unobstructed plane [4] following the *random waypoint* model [35]. In the model, a node chooses its speed and destination randomly, moves to the destination, then pauses for a certain pause time, and so on. A longer pause time means a lower mobility profile. The simulation is done for a network having 50 mobile nodes, which move over an area of $670 \times 670m^2$ with a certain speed. Table I gives the system parameter values used in the analysis and simulations (where the same abbreviations as in [25] are used). We run the simulation for 15 minutes of system time. Traffic flows start at random times and continue for a session time uniformly distributed from 5 minutes to 15 minutes. The traffic are iid on-off exponential flows generated at source nodes with average on time of 0.4 seconds and average off time of 5 seconds. A packet size of 1024 bytes is used.

We conduct two different sets of computer simulations. The first set aims at validating the resource allocation performance obtained by using the proposed QoS routing scheme. As the proposed scheme uses statistical estimation to allocate resources for new flows, the second set of simulation results study the effect of mobility on the performance of the proposed QoS routing scheme.

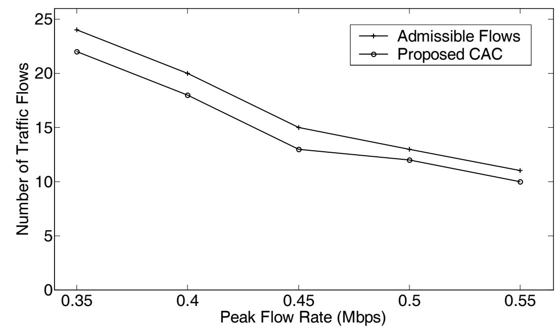

Fig. 3. Admitted flows from the proposed scheme and admissible flows with different flow rates.

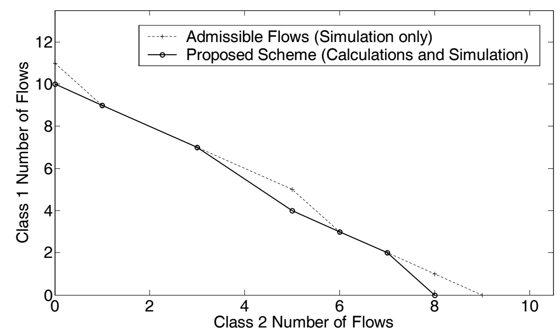

Fig. 4. The admission region with two classes of traffic

A. QoS Routing Scheme Validation

In this set of computer simulations, we use a low mobility speed of 1 meter per second and pause time of 30 seconds. All the traffic flows have the same delay bound requirement of $150ms$. Figure 3 shows the number of admitted traffic flows using our proposed CAC scheme and the admissible number of flows for different data peak rates during an on time. We obtain the admissible number of flows using computer simulations by trying many different route sets. A route set means the route members and the neighbors of those members. The routes that have the same set of neighbors and route members will have the same available resources. We force the GPSR protocol to select routes of different lengths by changing its route selection criteria and we gradually increase the network traffic load by increasing the number of traffic flows in order to find the maximum admissible number of flows having the satisfactory end-to-end delay bound with a violation probability of 0.05. As shown in Figure 3, the number of admitted flows using our proposed scheme is very close to the admissible number.

In order to study the admission performance of our QoS routing protocol with different service classes, we conduct another experiment using two service classes with two corresponding peak flow rates. The first service class has a data rate of $550Kbps$ at the on time and requires a delay bound of $150ms$, while the second service class has an on time data

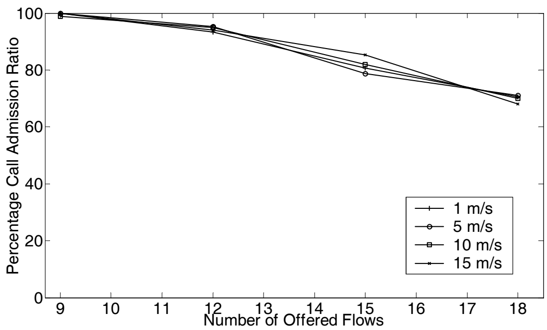

Fig. 5. Call admission ratio in percentage.

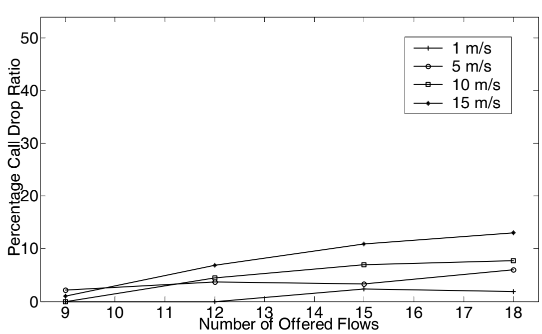

Fig. 6. Call drop ratio in percentage.

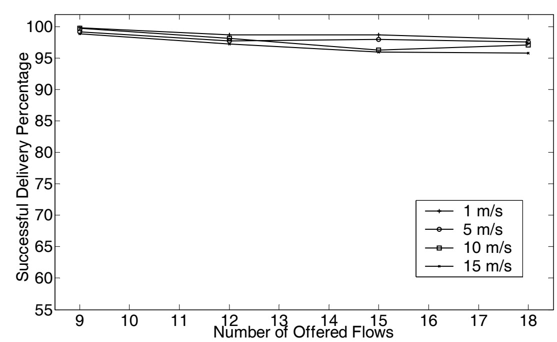

Fig. 7. Successful packet delivery percentage.

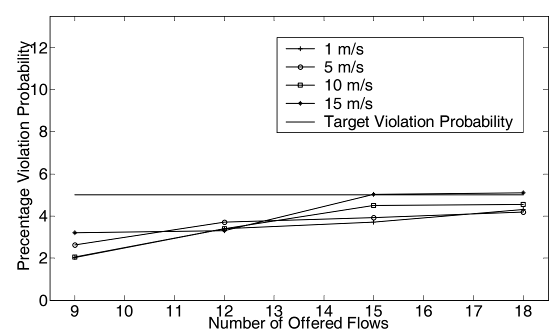

Fig. 8. Delay bound violation probability in percentage.

rate of $650Kbps$ and requires a $200ms$ delay bound. We load the network with a different number of flows in each class and obtained the admissible number of flows by following the same way as in the preceding experiment. Figure 4 shows the admission region of the two service classes. It is observed that the flow number pairs from our QoS routing scheme closely match those of admissible flows.

B. Effect of Mobility on Performance Metrics

To the best of our knowledge, there are no unified performance metrics to evaluate QoS routing protocols for ad hoc networks. Here, we study the performance of our QoS routing scheme under different user speeds of $1m/s$, $5m/s$, $10m/s$, and $15m/s$ with zero pause time. The offered traffic load is increased from 9 to 18 flows (by 3 in each step). All the traffic flows have a peak rate of $500Kbps$ and require a delay bound of $150ms$. We evaluate the performance of the proposed QoS routing scheme using the following six metrics.

• Call admission ratio, defined as the ratio of the number of admitted flows to the number of offered flows. Figure 5 shows that the call admission ratio decreases with the number of offered traffic flows, leading to an almost constant amount of traffic flows admitted simultaneously in the network. Figure 5 also shows that the call admission ratio is slightly affected by the speed of mobile nodes.

• Call drop ratio, defined as the ratio of the the number of dropped flows to the number of the admitted flows. Figure 6 shows that the call drop ratio is less than 5% for low node speeds (i.e., $1m/s$ and $5m/s$); however, the ratio increases when node speed increases since high mobility causes frequent route breakages.

• Successful delivery percentage, defined as the ratio of the number of packets delivered successfully to the total number of packets transmitted for the completed flows. This metric measures the quality of packet delivery of admitted flows. Figure 7 shows that the successful delivery percentage is higher than 95% for all the node speeds, which indicates the effectiveness of the proposed route discovery and maintenance procedure.

• Packet delay violation probability, defined as the ratio of the number of packets arrived after the delay bound to the total number of packets successfully received. Figure 8 shows the achieved percentage delay violation probability with respect to the 5% target probability. It indicates that our proposed resource allocation procedure is effective in satsifying the required delay bound probabilistically. From Figure 8, we notice that there is an increasing trend of the violation proability with an increasing number of offered traffic flows for high mobility (for 9 flows, the network is under utilized as shown in Figure 3 for the same peak rate). The reason for the trend is the inaccuracy of the temporary reservation process when a large number of flows tries to join the network at the same time while some of the nodes that temporarily reserved resources for those flows may move to far locations during the call admission process.

• Overhead percentage, defined as the percentage of the number of overhead bytes in both data packets and routing (signaling) packets to the number of bytes in data packets. Although this metric is not a QoS-related metric, it evaluates the efficiency of the QoS routing scheme in terms of wireless bandwidth usage. Figure 9 shows that the overhead percentage

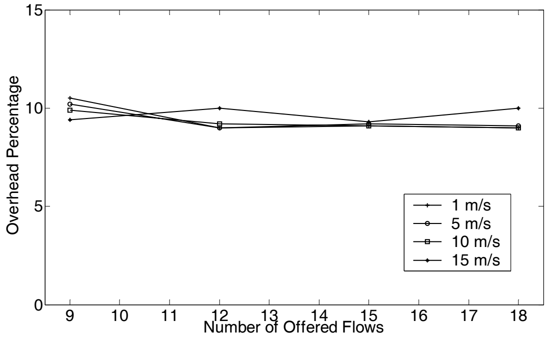

Fig. 9. Overhead percentage.

TABLE II
THE NUMBER OF ROUTING PACKETS OF THE PROPOSED ROUTING SCHEME.

Node Speed	$1m/s$	$5m/s$	$10m/s$	$15m/s$
Routing Packets	48880	49648	49486	50455

is affected slightly by mobility, where it is generally less than 10% for all the node speeds except for $15m/s$, where it is slightly higher than 10%.

- Number of routing (signaling) packets. This metric is also a non-QoS metric. It is introduced here for the sake of comparison with other non-QoS routing protocols such as destination sequential distance vector (DSDV), ad hoc on demand distance vector (AODV), and temporally ordered routing algorithm (TORA) [35]. The number of flows that have been used in [35] is high (20 flows) but with very low data rates in the order of $2Kbps$. We simulate a network with the same coverage area, node density, and equivalent traffic load as in [35]. We use 9 traffic flows and $500Kbps$ peak rate for each flow since it has been indicated that varying the number of traffic sources is equivalent to varying the sending rate [35]. Table II indicates that the number of routing packets slightly increases with the node speed due to the signaling overhead in the maintenance procedure to repair broken routes. From Table II, we observe that the order of the routing packet number compares well with non-QoS routing protocols such as DSDV which has approximately 41000 routing packets, AODV which has around 40000 with a node speed of $20m/s$ but with a long pause time (200–300 seconds), and TORA which has more than 50000 routing packets at a node speed of $1m/s$.

We compare our proposed QoS routing protocol with ad hoc QoS on demand routing protocol (AQOR) [20], which has been evaluated with similar performance metrics such as call admission ratio, percentage of late packets (same definition of the packet violation probability), and percentage of packets successfully received [20]. We conduct a computer simulation using the same area and the same average traffic load of $40Kb/s$ as in [20]. At mobility speed of $1m/s$ and zero pause time, our proposed routing scheme is able to admit 17 traffic flows, while AQOR is just capable of admitting almost 10 traffic flows. At higher average traffic load and node mobility speed, our proposed scheme also outperforms AQOR as shown in Figures 5-8 compared to the results in [20]. For the percentage of late packets, the AQOR can achieve 0.8% with 10 flows and almost 1.7% at 15 flows. Our QoS routing protocol can achieve almost 4% at 17 traffic flows. The reason for that is the low admission ratio that AQOR has, which results in the network under utilized. As we point out in Section II, AQOR does not take into account the statistical characteristics of the service time of the IEEE 802.11 DCF under different traffic loads. This makes the CAC decisions taken by AQOR more conservative than our proposed scheme and leads eventually to less efficient resource utilization.

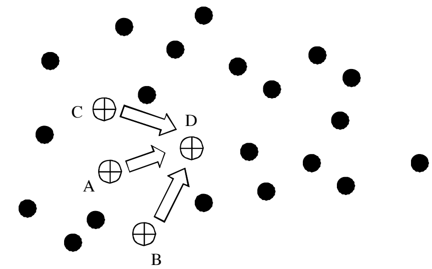

Fig. 10. Packet forwarding by node D.

VIII. CONCLUSION

In this paper, we propose a model-based QoS routing scheme for IEEE 802.11-based ad hoc networks loaded with bursty and delay-sensitive traffic. Following a cross-layer design approach, the proposed scheme offers a stochastic end-to-end delay guarantees. The scheme relies on a location-based ad hoc on-demand routing protocol (GPSR) to discover routes to the destination of a new traffic flow. A fully distributed and model-based resource allocation process (for admission control and resource reservation) checks if the selected route can admit the traffic flow without affecting other flows already in service. The resource allocation process extends the well developed effective bandwidth theory and effective capacity concept to IEEE 802.11 DCF mulithop connections in order to estimate the available network resources for a new traffic flow. Extensive computer simulations validate the proposed QoS routing scheme and show that it is efficient in resource utilization while satisfying the delay bound probabilistically with a low overhead.

ACKNOWLEDGEMENTS

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Appendix

In this appendix, we justify our assumption that the packet arrivals from other nodes to a packet forwarder (that has or does not have a traffic source) can be modeled as a virtual on-off source. First we consider the case of a packet forwarding node which does not have any locally generated traffic. Let this node be node D in Figure 10. Let M denotes the total number of active nodes in the carrier sense range of D, including node D. We define two group of nodes. The first group contains all the nodes which forward their packets to node D, such as nodes A, B and C in Figure 10. Let G

denote the number of nodes in the group. The other group contains all other active nodes that are in the carrier sense range of node D and including node D itself, which has $M-G$ nodes. We investigate the approximate distribution of the on time T_{on} (i.e., a duration over which node D receives packets with relatively short inter-arrival time, less than the average packet service time). We define R_j as the residual backoff time of node j in the first group. Similarly, R_i is the residual backoff time of node i in the second group. We can show the approximate memoryless behavior of T_{on} by the aid of the following two equations

$$\Pr(T_{on} > s) = \Pr(\min_j R_j > s) \Pr(\min_j R_j < \min_i R_i) \quad (23)$$

$$\Pr(T_{on} > s + t | T_{on} > t) \approx Pr(\min_j R_j > s) \Pr(\min_j R_j < \min_i R_i) \quad (24)$$

where s and t are two different arbitrary time intervals. In right hand side of (23), the first term is the probability that the minimum residual backoff time among the nodes in the forwarding group is longer than s, which implies that those nodes have packets waiting to be transmitted. The second term is the probability that the minimum residual backoff time of the forwarding group is less than the minimum residual backoff time of the other active nodes in the carrier sense range. Actually, if the nodes that are not in the forwarding group seize the channel, node D will start its off time. We can explain (24) by considering the following three cases: (i) A successful transmission (by one of the nodes in the forwarding group) happened over the interval $[t, s+t]$. In this case, the backoff counter of the node which successfully sent a packet will be reset to a new value, giving the chance to the residual time of any of the nodes in the forwarding group to be longer than s with the same probability as in (23) regardless the time t; (ii) A collision happened to the packet sent by one of the forwarding nodes. The backoff counter value for the node that sent the packet will be reset and selected uniformly from the doubled contention window size. Again the time t will not affect the probability of the minimum residual time to be longer than s, since that minimum may be selected from a different node; (iii) No transmission happened in between t and $s+t$. In this case, $Pr(T_{on} > s+t)|T_{on} > t)$ is different from $Pr(T_{on} > s)$. However, this case may happen only for short values of s, and so the T_{on} distribution is not exactly exponential.

The near memoryless behavior of the off time can be explained by the following equation

$$\Pr(T_{off} > s) = e^{-s \sum_{j=1}^{G} \beta_j} \prod_{j=1}^{G} (1-\rho_j) + \left[\left(1 - \prod_{j=1}^{G} (1-\rho_j) \right) \Pr(\min_j R_j > \min_i R_i) \Pr(\min_i R_i > s) \right] \quad (25)$$

where ρ_j is the utilization factor at node j of the packet forwarder group. Since the utilization factor is kept low by the CAC in the first and second operation regions [6], (25) can be approximated to

$$\Pr(T_{off} > s) \approx e^{-s \sum_{j=1}^{G} \beta_j}. \quad (26)$$

This concludes the justification of the exponential on-off traffic model approximation at packet forwarders (routers).

The second case is when the packet forwarder has already a local exponential on-off traffic source. It has been shown in [36] that the superposition of the two on-off sources (one for packet forwarding and the other for local traffic) has the same characteristics and effect on the node queue in terms of packet delay as an exponential on-off source on the long term and relatively short term as well. The results in [36] support our approximation of modeling the packet arrival in source/router nodes as exponential on-off sources.

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