Connection Admission Control and Grade of Service for QoS Routing in Mesh Networks

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***Abstract*—Wireless mesh networks (WMNs) is a promising key technology for next generation wireless backhauling that have recently attracted both the academic and industrial interest. Such networks are expected to have high throughput demands and support various types of applications with different quality-of-service (QoS) constraints. Opportunistic scheduling has been proven highly beneficial in such networks since it takes advantage of the dynamic nature of the channel between different wireless mesh routers. Recently a promising cross-layered framework has been proposed (IQoSR, [1], [2]) that combines a distributed opportunistic scheduler with a multi-constrained QoS routing scheme and has been proven to outperform conventional layer 2 and 3 approaches. However, opportunistic scheduling cannot provide hard resource reservation; therefore, the admission of new flows in a route may jeopardize the QoS of the ongoing flows.**

In order to overcome this problem, in this work we introduce a connection admission control (CAC) scheme for different levels of QoS to efficiently manage the resources among existing and new flows. In this way, we improve the overall network performance and minimize the outage probability of the ongoing flows while we guarantee the required grade-of-service (GoS) to the underlying applications. Simulation analysis shows that the proposed scheme achieves lower blocking probability while it reduces the outage probability of the existing flows.

I. Introduction

Ubiquitous data access has long been the holy grail for service providers. Recent advantages in wireless technologies such as 802.11x and WiMAX have enabled fast and convenient data access to users. Nevertheless, backhaul architectures, that connect the access points to the core network, continue to be a bottleneck. Wireless mesh networks (WMNs) [3], an ad hoc, high-speed wireless architecture, is expected to gradually substitute the wired network infrastructure functionality by being able to provide a quick and efficient solution for wireless data networking in urban, suburban and even rural environments. It comprises static wireless mesh nodes/routers (WMR) that can operate as conventional access points/gateways either to the Internet or as relay nodes that forward data in a multi-hop way from nodes without direct access to gateways. Their popularity comes from the fact that they are easy to deploy and have a much lower cost as compared to cellular architectures. However, their main challenge is that they have to be scalable and adaptable to various dynamic data traffic requirements (such as VoIP, interactive video, remote access and gaming) that usually result to great-accumulated throughput demands. This is translated into multiple and strict QoS requirements in packet level, that include end-to-end (ETE) packet delay, throughput, and ETE packet-error-rate (PER).

Researchers have so far developed various connection admission control (CAC) schemes to provide decisions on flow admission before routing discovery is performed. This is of critical importance because newly admitted flows will change the traffic conditions across the network that will affect the cross-link interference and therefore the quality of the existing links. Therefore, the resource allocation decisions among all sessions have to be altered accordingly. The impact of such changes on existing traffics and overall network performance has not yet been well studied in the literature, considering time-varying physical channel conditions, multiple QoS requirements among different connections, etc. Moreover, if opportunistic scheduling is used in layer 2, the impact of new flows on the existing ones will be more severe since such a scheduler performs soft, rather than hard, reservation of the wireless resources required for QoS. This is why an accurate and efficient CAC scheme is of paramount importance if we want to guarantee QoS in WMNs. Generally, a source router may accept or deny incoming data flows based on predefined criteria, such as, signal quality, link throughput, packet-level parameters (e.g. PER, ETE delay etc.) and network loading conditions. Although recent works have been focused on ad-hoc wireless networks [4], they do not efficiently integrate routing and admission control in a unified approach.

In traditional cellular network settings, the grade-of-service (GoS) has been a fundamental parameter to define the quality of voice services. GoS has been well studied ([5], [6]), as a benchmark to define the desired performance of a particular trunked system by specifying a desired likelihood of a user obtaining channel access. More specifically, GoS is typically given as the likelihood that a call is blocked or a call experiencing a delay greater than a certain queuing time. However, in wireless mesh packet networks with different QoS requirements the concept of GoS needs to be altered since different parameters will affect the service experience of the end user. Especially in multi-level QoS systems, the GoS can be defined as the probability that a specific QoS level will be guaranteed throughout the whole duration of the QoS session. Therefore, the GoS threshold can highly affect the connection admission control scheme by controlling the number of sessions that can be allowed at each level. The GoS is usually closely related to the billing system of the telecommunication service provider since higher GoS can be obtained for premium users at a higher cost.

II. Related Work

Recently, not much work has been done to provide both QoS and GoS provisions in packet and connection levels for heterogeneous traffics in wireless mesh networks. [7] proposed an admission control algorithm for connections with rate and delay requirements in wireless backhaul networks. However, it assumes no channel fading and cross-interferences among links exist, and uses a tree-structure [8] MAC scheduling. In [9], a joint centralized scheduling and time slot allocation based admission control algorithm is proposed for WiMAX networks, which allows to admit a flow if extra unused slots are sufficient to satisfy bandwidth requirement. [10] proposed a locking-based approach for connection admission control in WMNs to ensure precise bandwidth reservation among neighboring nodes, however no multi-constrained QoS were studied. The integrated framework of routing and admission control for IEEE 802.16 distributed mesh networks was studied in [11]. It estimates available bandwidth in a token bucket to perform admission control with minimum time slot requirement for each connection, and it uses shortest-widest efficient bandwidth metric for route discovery. This work cannot provide real-time QoS provisions and no actual interface between routing and admission control. Similarly, in ad-hoc network settings, [12] proposed an AODV routing protocol based admission control, whereas it blocks the over-loaded flow requests during the routing discovery procedure. Works in [1], [2] studies extensively on the integrated QoS routing protocol and the actual interface between the scheduling [13] and routing schemes, to provide optimum routes that guarantee multiple QoS constraints.

In this paper, we propose a cross-layer framework that successfully integrates opportunistic scheduling, multi-constrain QoS routing, connection admission control and multi-level QoS with GoS guarantees. Our contribution is twofold:

(1) The connection admission control scheme is fully distributed and minimizes the negative effects of new flows on the existing ones (thus, minimizes the outage probability).

(2) The multi-level QoS resource management algorithm not only controls the QoS levels of the new flows but can also degrade the level of existing flows to release resources for new flows (thus, minimizes the blocking probability) while it guarantees the required GoS to the underlying applications.

The rest of the paper is organized as follows. In Section III, the system model and IQoSR protocol are briefly introduced. Section IV provides a thorough description of the proposed connection admission control scheme. In Section V, the multi-level QoS and GoS resource management algorithm is demonstrated. Performance evaluation and detailed analysis are given in Section VI and finally conclusions drawn in Section VII.

III. IQoSR Algorithm

Consider a wireless mesh network comprises a set of n_r number of WMRs, denoted as $V_R = \{v_r | r = 1, 2, \ldots, n_r\}$ and a set of n_g number of gateways denoted as $V_G = \{v_g | g = 1, 2, \ldots, n_g\}$. QoS flow q is generated with a set of constraints, ETE packet delay D_q^r, throughput T_q^r and PER E_q^r. A route Ω_{sg}^k from a source s to a gateway g within the route set Ω_{sg} is concatenated by a set of links $\{(v_i, v_j)\}$, for all $v_i, v_j \in V_R \bigcup V_G$.

Our previous results defined a new utility function based on the "dissatisfaction ratio" $\mathcal{R}$ that experienced by each QoS metric, $\mathcal{R}_k^D$ for ETE packet delay within route Ω_{sg}^k, $\mathcal{R}_k^T$ for throughput, and $\mathcal{R}_k^E$ for PER. Hence, a source-to-gateway route will be feasible if and only if all defined ratios are less than 1, $\big(\mathcal{R}_k^D(q), \mathcal{R}_k^T(q), \mathcal{R}_k^E(q)\big) \leq 1$.

Our multi-constrain QoS performance index $\mathcal{U}_{sg}^k$ in route Ω_{sg}^k can be formulated as,

$$\mathcal{U}_{sg}^k = \max[\mathcal{R}_k^D(q), \mathcal{R}_k^T(q), \mathcal{R}_k^E(q)] \tag{1}$$

and the optimum route selection decision is given by,

$$\mathcal{S} = \min_{\forall \Omega_{sg}^k \in \Omega_{sg}} [\mathcal{U}_k] \tag{2}$$

IV. Connection Admission Control Algorithm

Opportunistic scheduling has been proven a promising technology enabler for WMNs since it can take advantage of the multi-user diversity and the dynamic nature of the wireless channel. Moreover, the distributed, proportional-fair scheduler proposed in [14], [13] (and has been integrated in our framework) not only achieves network throughput improvement, but at the same time allows for more accurate channel prediction by providing high level of temporal correlation of interference. However, opportunistic scheduling comes with a certain drawback, i.e., while it maximizes the overall network throughput it cannot perform hard resource reservation that is required to provide strict QoS. This has as a result an increased outage probability of the ongoing QoS sessions. Therefore, a scheme is required to provide connection admission control to new flows by predicting their impact on the quality of service of the flows already running in the network. Our proposed scheme is described in the following.

Every mesh router in the network keeps tracks the statistics of each packet going through each particular route. For instance, consider a node s, serves as the source expected to route data to gateway node g, where m number of candidate routes exist between $s - g$ pair. Meanwhile, some flows/sessions started with source s has already traversed through different routes within route set Ω_{sg}. We keep the updated information (QoS performance index values) for each route $\Omega_{sg}^k \in \Omega_{sg}, k = 1, 2, ..., m$, which are the maximum of three QoS utilities defined in (1). It is worth noting that this information represents the route quality for some specific QoS requirements from time to time. We use a so-called "resource utilization index", $\mathcal{Q}_{sg}^k$, between s and gateway g as in (3) to denote these QoS constraints,

$$\mathcal{Q}_{sg}^{k}(q) = T_q^r(1 - E_q^r) \tag{3}$$

Connection admission control scheme is initialized when new session indexed q arrives in the mesh network with multiple QoS constraints. Next, we propose a per-route based QoS performance index estimation scheme to try to accommodate this flow without violating on-going flows on that route Ω_{sg}^{k}.

Because node s has already some information about the route Ω_{sg}^{k} quality based on "resource utilization index" levels $\mathcal{Q}_{sg}^{k}$ and corresponding QoS performance indexes $\mathcal{U}_{sg}^{k}$ entry records. Based on this $\mathcal{Q}_{sg}^{k} \sim \mathcal{U}_{sg}^{k}$ curve, the resource estimation is performed for the new connection q with new "resource utilization index" $\mathcal{Q}_{sg}^{k}(q)$. The easiest way to do this is to use polynomial curve fitting method taking $\mathcal{Q}_{sg}^{k}$ as input and $\mathcal{U}_{sg}^{k}$ as the output. For instance, the transition function obtained is denoted as $f(\cdot)$, or $\mathcal{U}_{sg}^{k} = f(\mathcal{Q}_{sg}^{k})$. As the new input, the accumulated resource utilization index $\left[\mathcal{Q}_{sg}^{k,t}\right]^*$ at present time t is defined as,

$$\left[\mathcal{Q}_{sg}^{k,t}\right]^* \quad = \quad \mathcal{Q}_{sg}^{k,t-1} + \mathcal{Q}_{sg}^{k}(q) \tag{4}$$

We can now estimated the route quality (QoS performance index) $\left[\mathcal{U}_{sg}^{k,t}\right]^*$, derived from $\left[\mathcal{U}_{sg}^{k,t}\right]^* = f\left\{\left[\mathcal{Q}_{sg}^{k,t}\right]^*\right\}$, if assuming new flow is admitted. This flow could be accepted by route Ω_{sg}^{k}, and goes past the IQoSR procedure and start transmission, if and only if it satisfies the condition (5),

$$\left[\mathcal{U}_{sg}^{k,t}\right]^* \leq 1 \tag{5}$$

otherwise route Ω_{sg}^{k} is partially rejected for flow q. Similar steps should be performed for all routes with existing "resource utilization index" $\mathcal{Q}_{sg}^{k}$ and corresponding QoS performance index $\mathcal{U}_{sg}^{k}$ record entries, until one of them is found feasible for the new flow. Therefore, our scheme by interpolation and prediction on the $\mathcal{Q}_{sg}^{k} \sim \mathcal{U}_{sg}^{k}$ curve is able to obtain a fair estimate of the QoS performance index with higher than 95% confidence bound.

V. Multi-level QoS and GoS Resource Management

In order to increase the networks resource management flexibility to handle existing and new flows we introduce a novel multi-level QoS scheme. The aim of this scheme is to reduce the blocking probability of new flows (i.e., maximize the number of simultaneous flows served by the network) while at the same time maintain a low outage for the existing flows. A typical example of multilevel QoS is the transmission of hierarchically encoded video where the video bit stream is composed of a set of hierarchical sub streams, each one enhancing the quality if the lower layer (e.g., in MPEG video).

However, in order to guarantee a satisfactory user QoS experience the algorithm has to provide a certain level of grade-of-service (GoS). Under the multi-level QoS context, we define GoS (G) as the ratio of the number of high-QoS (HQoS) flows over the overall number of served flows in the network (this can be translated as the probability a session to be served in HQoS). This has to be higher than the GoS threshold G_0.

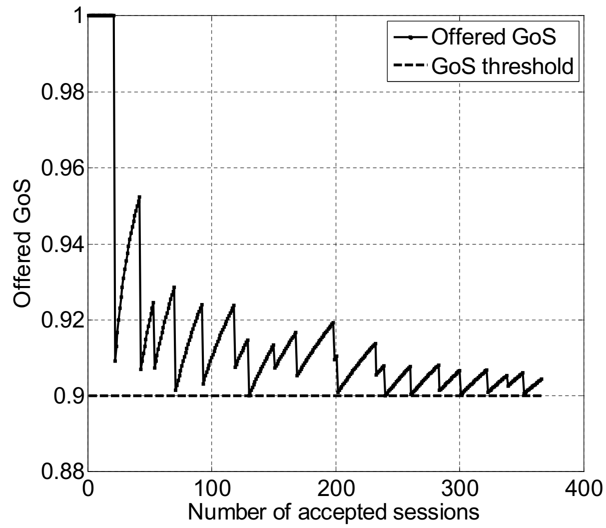

Fig. 1. Real-time demonstration of the offered GoS as a function of the number of accepted sessions.

$$G = \frac{N_{HQoS}}{N_{HQoS} + N_{LQoS}} \geq G_0 \tag{6}$$

The novelty of the proposed algorithm is that not only it successfully manages the incoming flows but also can degrade ongoing HQoS flows to LQoS (given that $G \geq G_0$) so that network resources will become available for new flows. In this way, it maximizes the number of simultaneous sessions in the network while it optimizes the provided end user QoS experience. The functionality of the proposed multi-level QoS algorithm (for simplicity, only two-levels of throughput have been considered) is described in the following steps:

Step-1: The source node uses the prediction scheme described in Section IV to check if any of the existing routes can provide high-throughput. If not, it initiates route discovery to search for new possible routes that can provide high-throughput to the session.

Step-2: If it fails to find any route that provides high-throughput, it firstly repeats the prediction scheme trying to accommodate the flow with low-throughput; and if fails again the IQoSR procedure is called with low-level throughput requirement.

Step-3: If it fails again to guarantee low-level throughput, before performing rejection, it tries to degrade the level of ongoing HQoS sessions to LQoS, given that $G \geq G_0$ must be satisfied and repeats the prediction scheme.

The pseudocode of the proposed algorithm is given by Algorithm 1. Moreover, Fig. 1 depicts the real time performance of the proposed algorithm. The GoS threshold has been set to $G_0 = 0.9$ while the low-throughput values are three times less than the high-throughput ones. It can be observed that the offered grade of service converges towards the GoS threshold as more flows (which mean more samples for the algorithm) served by the network.

Algorithm 1 : GoS Algorithm

if New session arrives **then**
Call CAC $\forall k \in \Omega_{sg}^{on}$
where Ω_{sg}^{on}, all ongoing routes from s to g
if $\exists k \in \Omega_{sg}^{on} : T_{avail}^{k} > T_{HQoS}$ **then**
Accept the session in route k with T_{HQoS} (FINISH)
else
Call IQoSR
if $\exists k^* \notin \Omega_{sg}^{on} : T_{avail}^{k^*} > T_{HQoS}$ **then**
Accept the session in route k^* with T_{HQoS} (FINISH)
else
Estimate G
if $G \geq G_0$ **then**
if $\exists k \in \Omega_{sg}^{on} : T_{avail}^{k} > T_{LQoS}$ **then**
Accept the session in route k with T_{LQoS} (FINISH)
else
Call IQoSR
if $\exists k^* \notin \Omega_{sg}^{on} : T_{avail}^{k} > T_{LQoS}$ **then**
Accept the session in route k^* with T_{LQoS} (FINISH)
else
$i = 1$
while $\frac{N_{HQoS}-i}{N_{HQoS}+N_{LQoS}} \geq G_0$ **do**
Degrade one HQoS session (HQoS $\rightarrow$ LQoS)
Call CAC $\forall k \in \Omega_{sg}^{on}$
if $\exists k \in \Omega_{sg}^{on} : T_{avail}^{k} > T_{LQoS}$ **then**
Accept the session in route k with T_{LQoS} (FINISH)
end if
$i = i + 1$
end while
Reject the session (FINISH)
end if
end if
else
Reject the session (FINISH)
end if
end if
end if
end if

VI. Performance Evaluation

We developed a slotted, time-driven cross-layer simulation platform to assess the proposed unified framework of multi-constrained multi-level QoS routing, connection admission control scheme with GoS guarantees. Fifteen wireless mesh routers are randomly and independently deployed, some of which have gateway functionality. Sessions are generated with three QoS constraints, ETE packet delay, throughput, and ETE PER. Two different throughput levels are allocated to each session and one constant GoS threshold is assumed.

In PHY Layer, the Jake's Model [15] is used for the wireless channel representation while the required PER is derived based on SINR curves for the used adaptive modulation and coding scheme. In order to reduce the interference to adjacent concurrent transmissions, increase the frequency reuse, and channel capacity, the WMRs are equipped with directional antennas. In order to exploit the multi-user diversity gain, the distributed opportunistic proportional fair scheduler ([14], [13]) is used not only to achieve a network throughput improvement, but at the same time to allow for more accurate channel predictions by providing high level of temporal correlation of interference.

The proposed cross-layer framework, referred to the graphs as "Dist+IQoSR+CAC", is compared with our previous work presented in [2], [1] which does not include multiple levels of QoS and the prediction scheme for connection admission control (referred here as "Dist+IQoSR"). We also compare our scheme with some conventional layer 2 and 3 techniques. More specifically, the round robin scheduler (RR) [16] and AODV routing protocol in [17] are used as benchmarks. The performance is investigated in terms of gateway throughput (Fig. 2a), QoS outage probability of existing sessions (Fig. 2b), and blocking probability of new sessions (Fig. 2c).

Fig. 2a shows that "Dist+IQoSR+CAC" outperforms "Dist+IQoSR" in terms of overall gateway throughput. An important observation is that the proposed framework can successfully achieve high throughput even for small traffic inter-arrival rate, i.e., heavy load conditions. This is primarily because the connection admission control scheme can admit or reject new sessions to maximize the ETE resource utilization in the network range. By monitoring the resource occupancies along each route, it accurately identifies the potentially limiting resources and the "system capacity" in terms of QoS performance index to accommodate the new flow. Meanwhile, the multi-level QoS helps in a way that even small amount of remaining resources can be successfully occupied by low-level QoS flows. It is also interesting to observe that "Dist+IQoSR+CAC" provides up to 3.5 times higher throughput for heavy load as compared to the "RR+AODV" benchmark scheme.

Fig. 2b depicts the probability of QoS outage (of the ongoing sessions) as a function of the traffic load. This is defined as the probability of any of the QoS requirements of a session to fail during the lifetime of the given session. In other words, it gives the probability of $\mathcal{U}_{sg}^{k}(q) > 1$. It is interesting to observe that the proposed algorithm can even guarantee all QoS requirements of the underlying application for 85% of the time as compared to 82% if no CAC is used and 68% for conventional schemes (i.e., for 10ms session inter-arrival time). This is because the impact of new admitted session on existing flows has been estimated and accurately considered during the QoS performance index estimation phase.

The impact of multi-level QoS and GoS in the proposed framework becomes clearer in Fig. 2c where the blocking probability of new incoming sessions is demonstrated. By allowing multiple levels of QoS (in this case he have considered 2 levels of throughput) the blocking probability can be reduced by 6-11% compare to the case with a single level of QoS.

Fig. 3 demonstrates the effect of the proposed scheme on the average number of admitted and successful sessions in the network as a function of the GoS threshold. As expected, when GoS threshold increases the total number of admitted low-level throughput sessions decreases to allow more resources for high-level throughput sessions. However, the total number of sessions admitted is going down because more stringent end-user quality is expected. Overall, it can be seen that the end user QoS experience can be significantly improved by reducing the blocking probability while maintaining a reasonable outage probability and a high GoS of the admitted sessions.

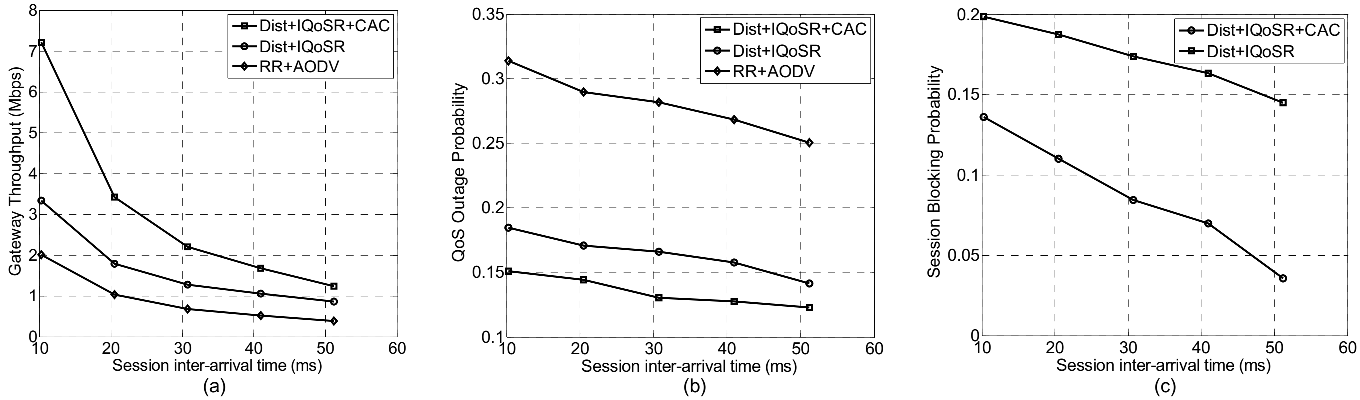

Fig. 2. Simulation results on (a) Network throughput (b) QoS outage potability per session value, and (c) New session blocking probability, all with respect to the new session inter-arrival time.

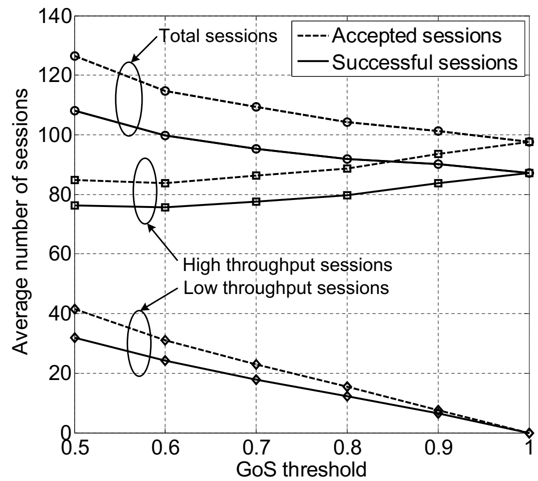

Fig. 3. Average number of admitted and successful sessions in the network as a function of the GoS threshold.

VII. Conclusions

In this paper, a novel connection admission control scheme for multi-constrained, multi-level QoS routing in wireless mesh networks has been proposed. This framework consists of two phases, i.e, the QoS performance index estimation phase, and multi-level QoS and GoS resource management phase. Extensive simulations show that the proposed cross-layer framework can successfully coordinate PHY, MAC and network layers to efficiently accommodate higher number of sessions in the network, it maintains reasonable low outage for the existing flows, and can guarantee the required GoS.

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