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Cross-Layer Design for QoS in Wireless Mesh Networks

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Abstract Cross-layer design for quality of service (QoS) in wireless mesh networks (WMNs) has attracted much research interest recently. Such networks are expected to support various types of applications with different and multiple QoS and grade-of-service (GoS) requirements. In order to achieve this, several key technologies spanning all layers, from physical up to network layer, have to be exploited and novel algorithms for harmonic and efficient layer interaction must be designed. Unfortunately most of the existing works on cross-layer design focus on the interaction of up to two layers while the GoS concept in WMNs has been overlooked. In this paper we propose a unified framework that exploits the physical channel properties and multi-user diversity gain of WMNs and by performing intelligent route selection and connection admission control provides both QoS and GoS to a variety of underlying applications. Extensive simulation results show that our proposed framework can successfully satisfy multiple QoS requirements while it achieves higher network throughput and lower outage as compared to other scheduling, routing and admission control schemes.

Keywords Cross-layer design · Wireless mesh networks · QoS · GoS

1 Introduction

Wireless mesh networks (WMNs) is a relatively new and promising key technology for next generation wireless networking that have recently attracted both the academic and industrial interest [1]. Mesh networks are expected gradually to partially substitute the wired network infrastructure functionality by being able to provide a cheap, quick and efficient solution for wireless data networking in urban, suburban and even rural

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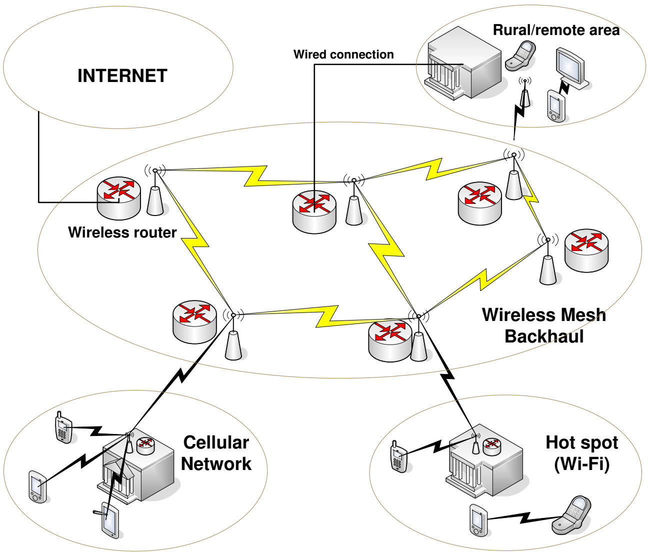

Fig. 1 Typical wireless mesh network scenario.

environments. Their popularity comes from the fact that they are self-organized, self-configurable and easily adaptable to different traffic requirements and network changes. Mesh networks are composed of static wireless nodes/mesh routers (WMR) that have ample energy supply. Each node operates not only as an conventional access point (AP)/Intenet gateway (IGW) to the internet but also as a wireless router able to relay packets from other nodes without direct access to their destinations [2]. The destination can be an internet gateway or a mobile user served by another AP in the same mesh network. Moreover, some nodes may only have the backhauling functionality, meaning that they do not serve any mobile user directly but their purpose is to forward other APs' packets.

Mesh networks must meet a number of technical requirements. First of all, they must meet the high capacity needs of the access nodes that have to forward the accumulated traffic of their underling users. Furthermore, they have to cope with multiple strict quality-of-service (QoS) requirements of the end user applications, including end-to-end (ETE) packet delay, throughput, and packet-error-rate (PER). Finally they must provide a large enough effective communication range to ensure that no APs (or groups of APs) are isolated from the Internet gateways. In order to satisfy the above requirements, a range of novel techniques has to be exploited. Such technology enablers include but not limited to multi-hopping, various multiple antennas techniques, novel medium access control (MAC), routing and connection admission control algorithms.

In traditional cellular network settings, the grade-of-service (GoS) has been a fundamental parameter to define the quality of voice services [3,4], as a benchmark to define the desired performance of a particular trunked system by specifying a desired likelihood of a user obtaining channel access. However, in WMNs with different QoS requirements, 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.

Unfortunately, most of the current work on WMNs protocol analysis and design is mainly based on a layered approach. This layered architecture by providing modularity and transparency between the layers, led to the robust scalable protocols in the Internet and it has become the de facto architecture for wireless systems. However, the spatial reuse of the spectral frequency, the broadcast, unstable and error prone nature of the channel and different operational time scales for protocol layers, make the layered approach suboptimum for the overall system performance of WMNs. For instance, bad resource scheduling in MAC layer can lead to interference that affects the performance of the PHY layer due to reduced signal-to-interference-plus-noise-ratio (SINR) and ultimately deteriorates the overall network performance. Local capacity optimization with opportunistic scheduling techniques that exploit the multi-user diversity may increase the overall outgoing throughput of the transceivers but they can also generate new bottlenecks in several routes in the network. Moreover, imprecise estimation of the impact of newly admitted sessions on existing ones running in the network may jeopardize all sessions' QoS.

These are primarily why cross-layer design for improving the network performance has been a focus of much recent work. In a cross-layer paradigm, the joint optimization of control over two or more layers can yield significantly improved performance. Caution needs to be exercised though, since cross-layer design has the potential to destroy the modularity and make the overall system fragile. Other importance challenges that have to be taken into account during the design of cross-layered solution for WMNs is the different operation time-scales between coding, scheduling and routing algorithms; especially in the case that system performance estimations in different layers have to be performed. Moreover, since WMNs have to support a wide variety of applications and services, there are multi-constrained QoS requirements that have to be jointly satisfied by the cross-layer approach. For instance, additive (cost, delay, jitter, etc.), multiplicative (PER and path break probability), and concave (throughput, etc.) metrics have to be jointly taken into account which has been proven NP-complete [5].

In this paper we present a heuristic low-complexity cross-layer framework that includes a connection admission control scheme, a multi-constrained QoS routing algorithm and a distributed proportional-fair scheduling algorithm that attempts to tackle the aforementioned challenges and provide QoS support to any WMNs. Directional antenna transmission with adaptive modulation schemes have been considered in the PHY layer while channel prediction in different time-scales is included to assist and guide the optimum operation of the overlying layers and algorithms. Extensive simulation results show that our algorithms can successfully guarantee multi-constrained QoS while at the same time achieving better network performance compared to other standard techniques.

2 Related Work

Cross-layer design has been widely used to improve the network performance in a wireless network [6–10] that generally includes two aspects of design methods: theoretical mathematical modeling and practical protocol design.

Layered protocol architecture is one of the most important factors that has made networking so successful. However, there has been a lack of a systematic approach to analyze whether layering of protocols is optimal or not. The layering as optimization decomposition [11] fills a gap between theoretical methods and practical aspects of protocol design. In this method, various protocol layers are integrated into one single coherent optimization function, in which asynchronous distributed computation over the network is applied to solve a global optimization problem in the form of generalized network utility maximization (NUM). The key idea of layering as optimization decomposition is to decompose the optimization problem into sub-problems, each corresponding to a protocol layer and functions of primal or Lagrange dual variables, coordinating these sub-problems correspond to the interfaces between layers. However, the above formulation is based on a deterministic fluid model that cannot capture the packet-level details and microscopic queuing dynamics.

On the other hand, cross-layer design through individual/some protocol layer design can significantly improve the network performance in two ways: loosely coupled and tightly coupled. In the loosely coupled cross-layer design, optimization is carried out without crossing layers but focusing on one protocol layer. Parameters in other protocol layers are taken into account by information exchange and deliveries from multiple layers to perform cross-layer design. With such information, the performance is improved because a better (more accurate or reliable) parameter is used, but the algorithm itself does not need a modification. On the other hand, in the tightly coupled cross-layer design, merely information sharing between layers is not enough, but algorithms in different layers are optimized altogether as one optimization problem. Our proposed cross-layer design architecture takes the advantage of loosely coupled design paradigm where MAC and routing protocols exchanges information in packet level like delay, SINR, PER etc. and connection level QoS requirements, but at the same time, routing and connection admission control algorithms are determined by one single design criterion “QoS performance index” (tightly coupled). Due to optimization execution across layers, we can expect that better performance improvement can be achieved by both the loosely and the tightly coupled cross-layer design than only one of them is used. Furthermore, the advantage of adopting both schemes for cross-layer design is that it does not totally abandon the transparency between protocol layers.

Researchers, meanwhile, have been focusing on individual protocol layer design for QoS in wired/wireless networks. [12, 13] have addressed extensively on multi-constrained QoS routing algorithms in wired network based on network state [14, 15] to overcome the NP-complete difficulties of providing optimum routes that guarantee multiple QoS constraints [5]. Meanwhile, QoS routing algorithms for wireless ad-hoc networks have been previously explored in [16–20]. However, they either overlook the multi-hop queueing delays since only the packet processing time was considered or simply calculate the available bandwidth in terms of slot and reserved for QoS flows that fails to exploit the opportunistic scheduling gain in fast-fading channels.

Scheduling for WMNs has drawn a lot of research attention recently that generally includes centralized [21–23] and distributed solutions. Centralized scheduling algorithms are based on graph theory assuming that a central controller has full knowledge on network. The method finds the optimal set of non-overlapping links with the highest total throughput of the graph, however proven NP-complete [24, 25]. Distributed solutions like [26] is commonly used as the MAC protocol in wireless adhoc networks. Moreover, the election-based scheduling algorithm specified in the IEEE 802.16 standard [27] or [28] for multi-hop mesh networks are some other scheduling schemes.

However, due to the completely random link selection, neither of the algorithms takes advantage of multi-user diversity in the wireless environments, nor providing QoS with routing algorithms.

As for connection admission control, not much work [29,30] has been done to provide both QoS and GoS provisions for heterogenous traffics in WMNs. In [31], a joint centralized scheduling and time slot allocation based admission control algorithm is proposed for WiMAX networks, which allows admitting a flow if extra unused slots are sufficient to satisfy bandwidth requirement. The integrated framework of routing and admission control for IEEE 802.16 distributed mesh networks was studied in [32]. Similarly, in ad-hoc network settings, [33] proposed a AODV routing protocol based admission control, whereas it blocks the over-loaded flow requests on the routing discovery procedure.

In this paper, we propose a cross-layer design paradigm for QoS in wireless mesh networks that includes a connection admission control scheme together with a multi-constrained QoS routing algorithm in the network layer and a distributed opportunistic proportional fair (OPF) scheduler in MAC layer. Our contribution are summarized in the following:

(1) We propose a multi-constrained QoS routing algorithm to overcome the NP completeness of integrating more than one QoS metrics (i.e., delay, throughput and PER) in a unified utility function.

(2) We manage to successfully couple the proposed routing algorithm with a novel opportunistic scheduling scheme that maximizes the network throughput. The main difficulty is that such a scheme, while it exploits the wireless channel fluctuations and multiuser diversity gain, it can not guarantee hard resource reservation required by the network layer to provide QoS. Moreover, routing and scheduling decisions have inherently different operation time scales and this makes difficult the cross layer interaction if QoS needs to be guaranteed.

(3) A tightly coupled design framework, combining routing and admission control, is proposed where a unified optimization criterion “QoS performance index” that combines multiple QoS constraints to indicate the QoS experience of each route is used. The proposed connection admission control scheme is fully distributed and capable of estimating the impact of new flows on existing flows’ QoS to strictly prevent the new session consuming much network resources. Meanwhile, multi-level QoS allows network resources to be organized and used in an optimal way to maximize the network resources utilization.

The remainder of the paper is organized as follows. In Section 3, the cross-layer system model is introduced. The proposed QoS routing algorithm is discussed in Section 4. Section 5 describes the distributed opportunistic scheduler and its interaction with the routing algorithm. The connection admission control scheme with both QoS and GoS provisions is demonstrated in Section 6. Extensive simulation results follow on Section 7 while Section 8 concludes the paper.

3 System Model

Consider a wireless mesh network comprises a set of n_r number of wireless mesh routers, denoted as $V_R = \{v_r | r = 1, 2, \ldots, n_r\}$ and a set of n_g number of Internet Gateways denoted as $V_G = \{v_g | g = 1, 2, \ldots, n_g\}$. If further consider an arbitrary node i, it has K_i number of one-hop neighbors within fixed transmission range, where these neighbors are $k = 1, 2, ..., K_i$. Each node maintains separate queues for each link/direction of transmission and newly arrived packets will be placed into their corresponding queue according to the pre-determined route that they belong.

The network runs under a time-division multiple access (TDMA) slotted framework while we assume that all nodes are synchronized to the slot boundaries. Each time frame consists of the control phase, comprises f_c fixed-size time slots for control messages, and the data transmission phase that consists of f_d fixed-size time slots for data. During the period of one time frame, we assume block fading channel that remains relatively constant. Scheduling decisions are taken by all nodes in the network simultaneously at the beginning of each time frame at the control phase, and stay unchanged until the next frame. The PHY layer employs adaptive modulation and coding techniques (AMC), where there are a finite number V of transmission modes, each of which corresponds to a unique modulation and coding scheme and one particular interval of the received SINR. The transmission rate at each mode is proportional to its spectral efficiency, i.e., transmission mode v can transmit maximum c_v packets in one time slot, where $v = 1, 2, ..., V$, or $H = f_d c_v$ packets in a time frame. Furthermore, in order to reduce the interference to adjacent concurrent transmissions and increase the frequency reuse and channel capacity, the WMRs are equipped with directional antennas. Power control is not considered in this phase, i.e., all the nodes have the same fixed transmission power.

Each WMR independently generates data sessions/flows according to the Poisson distribution. Each QoS flow with index q has to fulfill a set of QoS constraints that include ETE packet delay D_q^r, throughput T_q^r and PER E_q^r. We denote this set as (D_q^r, T_q^r, E_q^r). Let π_{sg} further denote the route set from source mesh router s to a particular gateway node g. A route π_{st}^k from a source WMR with index s to a destination IGW indexed g within the route set π_{sg} is concatenated by a set of links $\{(v_i, v_j)\}$, for all $v_i, v_j \in V_R \bigcup V_G$. Therefore, we could formally express the route from s to g as (1), where total m candidate routes exist. For the k^{th} route,

$$\pi_{sg}^k = \left\{ \biguplus (v_i, v_j) | \forall v_i, v_j \in V_R \cup V_G \right\} \tag{1}$$

where $k = 1, 2, \ldots, m$. In the following discussions, we use term session and flow for the traffic input, (v_i, v_j) and (i, j) for the link between v_i and v_j interchangeably.

4 QoS Routing Algorithm

As it has been mentioned above the problem of providing optimum routes that guarantee multiple QoS constraints has been proven to be NP-complete [5]. Therefore, in order to facilitate the information delivery and exchange (loosely-coupled) among PHY, MAC and network layers, we define a generalized QoS utility that gives the unified framework to design a cross-layer approach achieving best overall performance. Given a session q with three QoS requirements (D_q^r, T_q^r, E_q^r), ETE delay, throughput, and PER, we introduce a "**QoS outage ratio**", $\mathbf{R}$, that experienced by each QoS metric, which is the measurements over requirement. More specifically, we define the ratio $\mathbf{R}$ for each of the QoS requirement as follows:

4.1 $\mathbf{R}_k^D$

ETE packet delay outage for route π_{sg}^k is defined as the actual delay measurement, $\sum_{(i,j)\in\pi_{sg}^k} D_{ij}^a$, over the QoS delay requirement D_q^r, i.e.,

$$\mathbf{R}_k^D(q) = \frac{\sum_{(i,j)\in\pi_{sg}^k} D_{ij}^a}{(1-\beta_D)D_q^r}. \tag{2}$$

4.2 $\mathbf{R}_k^T$

Throughput outage is formulated as the ratio between the throughput requirement T_q^r and actual *bottleneck* link throughput, $\min_{(i,j)\in\pi_{sg}^k} T_{ij}^a$, the minimum of all one-hop throughputs along route π_{sg}^k, i.e.,

$$\mathbf{R}_k^T(q) = \frac{(1+\beta_T)T_q^r}{\min_{(i,j)\in\pi_{sg}^k} T_{ij}^a} \tag{3}$$

4.3 $\mathbf{R}_k^E$

PER outage is defined as the multiplication of all one-hop error rate, $1-\prod_{(i,j)\in\pi_{sg}^k}(1-E_{ij}^a)$, over PER requirement E_q^r since this is a multiplicative constrain, i.e.,

$$\mathbf{R}_k^E(q) = \frac{1-\prod_{(i,j)\in\pi_{sg}^k}(1-E_{ij}^a)}{(1-\beta_E)E_q^r} \tag{4}$$

A resource reservation margin factor has been introduced as β_D, β_T and β_E for delay, throughput and PER respectively. In other words β_i represent the additional resources that we reserve beyond the QoS requirements in order to provide a safe guard for imperfect resource estimations, system and channel fluctuations. This is a free parameter that can be defined and modified by the network operator/administrator based on the network requirements. Some results and discussions on the impact of the parameter β_i on the QoS outage probability, channel resources and session blocking probability is given in [34].

Since a session has to fulfil the set of QoS requirements, a source-to-gateway route will be feasible if and only if all defined outage ratios are less than one,

$$\left(\mathbf{R}_k^D(q), \mathbf{R}_k^T(q), \mathbf{R}_k^E(q)\right) \leq 1 \tag{5}$$

However, some constraints may not be critical in some applications (for instance, many broadband data services may not be delay sensitive). In order to efficiently cope with this issue we introduce the indication function $\mathbf{I}_p$, where $p = D, T, E$, expressed as

$$\mathbf{I}_p = \begin{cases} 1 \text{ if parameter } p \text{ is critical in QoS flow } q \\ 0 \text{ otherwise} \end{cases} \tag{6}$$

An example of the resource reservation margin factors and indication functions chosen for three types of QoS flows in the network, namely, voice-over-IP, interactive-video and broadband data services respectively, is demonstrated in Table 1.

Table 1 Traffic Types with Relevant Resource Reservation Factors

	voice-over-IP	Interactive-video	Broadband Data
$\mathbf{I}_D, \beta_D$	1, variable	1, variable	0, —
$\mathbf{I}_T, \beta_T$	1, variable	1, variable	1, variable
$\mathbf{I}_E, \beta_E$	0, —	1, variable	1, variable

4.4 QoS Route Selection

Our multi-constrained "QoS performance index" in route π_{sg}^k can be formulated as

$$\mathbf{U}_{sg}^k = \max\left[\mathbf{I}_D \mathbf{R}_k^D(q), \mathbf{I}_T \mathbf{R}_k^T(q), \mathbf{I}_E \mathbf{R}_k^E(q)\right] \tag{7}$$

and the proposed multi-objective routing decision function in order to take an optimum heuristic decision is given by,

$$\mathbf{S}(k^*) = \min_{\forall \pi_{sg}^k \in \pi_{sg}} \mathbf{U}_{sg}^k \tag{8}$$

where route $\pi_{sg}^{k^*}$ is chosen. In other words, we are choosing the route with the minimum overall QoS outage probability.

5 Distributed Opportunistic Proportional Fair Scheduling Algorithm

We assume that each node schedules one of the links associated with it in the control frame. Then the objective of our scheduling algorithm is to identify not only the duplexing mode (transmitting or receiving) but also the specific direction (to which neighbor) of the next communication in an opportunistic manner. For example, if a node is receiving a great deal of interference, it may be more appropriate for the node to choose to transmit, provided that the intended receiver is expected to receive properly. On the contrary, if a node finds that one of its incoming links of the highest profit among all of its associated links, then the node may prefer to receive from that link. In our scheduling algorithm, every directional link is assigned with a utility representing the benefit of transmitting on this link in the next time frame, and hence the opportunistic approach is to choose a combination of concurrent links with the highest aggregated instantaneous utility.

On the other hand, uncertainty in link capacity of WMNs due to randomness of lower-layer protocols and wireless channel may degrade the performance of routing protocols. Furthermore, it is difficult to guarantee system performance if an opportunistic MAC layer is deployed, because opportunistic approaches usually introduce more fluctuating instantaneous performance at individual nodes. Therefore, it is important to propose a utility function, or scheduling metric, which not only achieves opportunistic gain but also supports quality of service as committed by the routing algorithm in use. Otherwise, the QoS promised by the routing protocol to its applications cannot be guaranteed.

5.1 Utility Definition

The proposed co-operation between the scheduling and routing algorithms is in a "request-enforce" manner. Multi-constrained QoS routing algorithm introduced in Section 4 needs to estimate the future long term link capacity as it is crucial in order to maintain an effective statistics table for various source and destination node pairs. As a result, it is desirable for the routing layer to specify a target throughput allocation among links on each node along a route and then request the scheduling algorithm to enforce such throughput allocation. Please note that rather than achieving the precise target throughput for each link, or, "hard" QoS, the objective of our algorithm is to achieve the relative target throughput for each link scaled by a per-node (not per-link) proportionality constant, or, "soft" QoS. Thus achieving the relative target by the proposed scheduler effectively yields the actual throughput target.

Since the scheduling framework is fully distributed, we focus on one individual node in the following derivation of a new utility definition. Here we treat the incoming and outgoing links equally as competitors. For an arbitrary node i with K_i neighboring nodes, it has maximum $2K_i$ candidate links to schedule for transmission in every time slot. The routing algorithm periodically estimates the throughput demand on each link associated with each node in the next time frame, and provides the scheduler with a target throughput allocation $\mathbf{a}_i = (a_i(1), a_i(2), \ldots, a_i(2K_i))$ to achieve the desired QoS. In our proposed routing algorithms, routing demand $a_i(k)$ associated with with link (i,k) is computed as,

$$a_i(k) = \sum_{\forall q, \text{if}(i,k) \in \pi_{sg}^{k}(q)} (1+\beta_T) T_q^r \tag{9}$$

i.e., the accumulated throughput demands of all sessions running through link (i,k).

Then our goal here is to define an appropriate utility with which the scheduler's allocation of the long-run throughput $\phi_i = (\phi_i(1), \phi_i(2), \ldots, \phi_i(2K_i))$ for all links is proportional to the target allocation $\mathbf{a}_i$, i.e., $\phi_i^* = c_i \mathbf{a}_i$, where c_i is a positive proportionality constant for node i and ϕ_i^* is the optimal solution for node i. [35] proved that if the optimization problem for each node i is to maximize the objective function $f(\phi_i)$ as,

$$\max_{\phi_i} f(\phi_i) = \max_{\phi_i} \sum_{k=1}^{2K_i} a_i(k) \log \phi_i(k) \tag{10}$$

such that,

$$\sum_{k=1}^{2K_i} \phi_i(k) \le C, \tag{11}$$

Then the optimal solution $\phi_i^* = (\phi_i^*(1), \phi_i^*(2), \cdots, \phi_i^*(2K_i))$ is directly proportional to $\mathbf{a}_i = (a_i(1), a_i(2), \ldots, a_i(2K_i))$ element by element. Correspondingly, the optimal solution ϕ_i^* for the optimization problem is proportional to the target throughput allocation $\mathbf{a}_i$. In other words, the scheduling utility (or metric) for all link (i,k) from 1 to $2K_i$ of node i is,

$$M_i(k) = a_i(k) \frac{\rho_i(k)}{\phi_i(k)} \tag{12}$$

where $\rho_i(k)$ is the instantaneous supportable data rate for link (i,k) and $\phi_i(k)$ is the long-time average of $\rho_i(k)$. $\rho_i(k)$ is calculated from Shannon's capacity formula,

$$\rho_i(k) = W \log(1 + \beta_{ik}^t \gamma_{ik}^t) \tag{13}$$

where W is the system bandwidth, γ_{ik}^{t} is the receiving SINR and β_{ik}^{t} captures the unpredicted interference effects.

5.2 Distributed Framework

Since it has been shown that a collision free method for utility exchange is feasible, we assume here that utility values of both incoming and outgoing links is available to the node, and the two ends of each link keep the same latest utility value to make scheduling decisions.

The first stage of the framework is for each node to choose the link with the highest utility among all the incoming and outing links to activate for the next time frame. Then in the ideal case, $\frac{N}{2}$ links with the highest utilities will be chosen to activate in an N-node mesh network.

However, the main difficulty in implementing this idea in a distributed way is the possibility that a node makes a decision conflicting with neighbors in terms of duplexing mode. It is difficult to improve the scheduling on all the nodes in the network in order to find a conflict-free solution that yields the best performance because fundamentally with a distributed algorithm, nodes have no prior knowledge about its neighbors' duplexing status at this decision making stage. Therefore, we retain the conflict-free decisions, and add one round of control exchange to solve the conflicts locally. Simply, our solution is to exchange the initial decision made among neighboring nodes and let nodes with a collided destination give up the intended transmission

A formal description of our distributed scheduling framework is as follows. It is composed of two control phases:

5.2.1 Utility exchange and initial decision making

Each node exchanges the utility function of each of its incoming and outgoing links with its neighbors. After that, each node chooses the link with the best utility to be the initial decision of the next transmission

5.2.2 Initial decision exchange and final decision making

Each node exchanges the initial decision to all its neighbors, including the IDs of the associated transmitting (origin) and receiving (destination) nodes. Based on the initial decision exchanges, each node with an initial decision of "transmit" checks if the desired receiving node is having the same "transmit" initial decision. If so, the node gives up the intended transmission. Otherwise, the node starts transmission in that direction in the next slot. Each node with an initial decision of "receive" also find outs the best transmitter based on the initial decision exchanges, and configures its physical layer to receive data from that direction in the next time slot.

To sum up, the proposed framework has demonstrated following merits:

(1) It is fully distributed without deadlock. Nodes make scheduling decisions simultaneously, and do not need to wait for other nodes' decisions to make its own decision.

(2) It exploits multi-user diversity. Although in mesh networks, it is very likely that the fluctuation of wireless links is weak, the multi-user diversity can be realized

with other aspects such as differences in propagation loss (with random node layout), independent incoming and outgoing channel qualities and dynamic interference.

(3) It tends to generate smooth interference, compared to random schedulers. Since the scheduling decisions are related to the instant utility, as long as the utility function is with strong time coherence, the link schedule shall generate interference with reasonably strong temporal correlation.

6 Connection Admission Control Algorithm

Researchers have so far developed various connection admission control 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, the distributed, proportional-fair scheduler proposed in Section 5 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. However, it 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.

6.1 Connection Admission Control Estimation

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 started with source s has already traversed through different routes within route set π_{sg}. We keep the updated information (QoS performance index values) for each route $\pi_{sg}^k \in \pi_{sg}, k = 1, 2, ..., m$, which are the maximum of three QoS utilities defined in (7). It is worth noting that this information represents the route quality for some specific QoS requirements from time to time. We use an aggregated, time-varying "resource utilization index", $\mathbf{Q}_{sg}^k(t)$, between s and gateway g as in (14) to denote these QoS constraints,

$$\mathbf{Q}_{sg}^k(t) = \sum_{\forall q \in k^{\text{th}} \text{ route}} Q(q) \tag{14}$$

where $Q(q) = T_q^r(1 - E_q^r)$.

Connection admission control scheme is initialized when new session indexed q arrives in the mesh network with multiple QoS constraints at time t. 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 π_{sg}^k.

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

$$\mathbf{Q}_{sg}^{k}(t^{*}) = \mathbf{Q}_{sg}^{k}(t) + Q(q) \tag{15}$$

We can now estimated the route quality (QoS performance index) $\mathbf{U}_{sg}^{k}(t^{*})$, derived from:

$$\mathbf{U}_{sg}^{k}(t^{*}) = f\Big\{\mathbf{Q}_{sg}^{k}(t^{*})\Big\} \tag{16}$$

if assuming new flow is admitted. This flow could be accepted by route π_{sg}^{k}, and goes past the IQoSR procedure and start transmission, if and only if it satisfies the condition (17),

$$\mathbf{U}_{sg}^{k}(t^{*}) \leq 1 \tag{17}$$

otherwise the k^{th} route is partially rejected for the reason that multi-level QoS and GoS resource management introduced later may release some resources due to GoS supports and thus possibly the k^{th} route is feasible.

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

Before introducing the multi-level QoS and GoS resource management scheme, we are interested to show the time-varying achievable "route capacity" associate π_{sg}^{k} with respect to different flows' QoS requirements running concurrently on the route. Recall that from the $\mathbf{Q}_{sg}^{k}(t) \sim \mathbf{U}_{sg}^{k}(t)$ curve we can show the impact of new sessions on the exiting flows, we can also show the maximum flow bound $\mathbf{Q}_{sg}^{k,\max}(t)$ on the route corresponding to the maximum QoS performance index equivalent to 1, i.e.,

$$\mathbf{U}_{sg}^{k}(t^{*}) = f\Big\{\mathbf{Q}_{sg}^{k,\max}(t)\Big\} = 1 \tag{18}$$

Because of the known curve f, "route capacity" $\mathbf{Q}_{sg}^{k,\max}(t)$ is also known by interpolation and estimation.

6.2 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 multi-level 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. Under the multi-level QoS context, we define GoS 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 μ.

$$\mathrm{GoS} = \frac{\mathrm{N_{HQoS}}}{\mathrm{N_{HQoS}} + \mathrm{N_{LQoS}}} \geq \mu \tag{19}$$

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 GoS $\geq \mu$) 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 6 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 GoS $\geq \mu$ must be satisfied and repeats the prediction scheme until one of the route k^* can accommodate the route, or admission, otherwise performance rejection to the new flow.

7 Simulation Results

We develop a slotted, event-driven OPNET [36] simulator which comprises PHY, MAC and network layers, where channel model/adaptive modulation and coding schemes, different MAC scheduling and routing algorithms are implemented respectively. WMRs and IGWs are randomly deployed in 2D-square in a way that no disconnected clusters of nodes exist in the network as in Fig. 2. A number of client/servers are attached to the backhaul network to emulate the access points where traffics are generated according to Poisson process to be routed to certain IGWs. Different traffic patterns are considered, i.e., VoIP, video and data services, attached with three QoS constraints, throughput, ETE packet delay and PER. ETE packet delay consists of queuing and transmission delays. In PHY layer, the Rayleigh fading channel model [37] is used to generate the link characteristics among WMRs and IGWs. PER is simulated based on the SINR curve for the used adaptive modulation and coding scheme (AMC). Infinite-persistent automatic retransmission request scheme in MAC layer is assumed in case of packet failure. The simulation parameters are summarized in Table 2.

The performance of the proposed cross-layer architecture highly depends on the accurate estimation of multiple parameters in different protocol layers required for

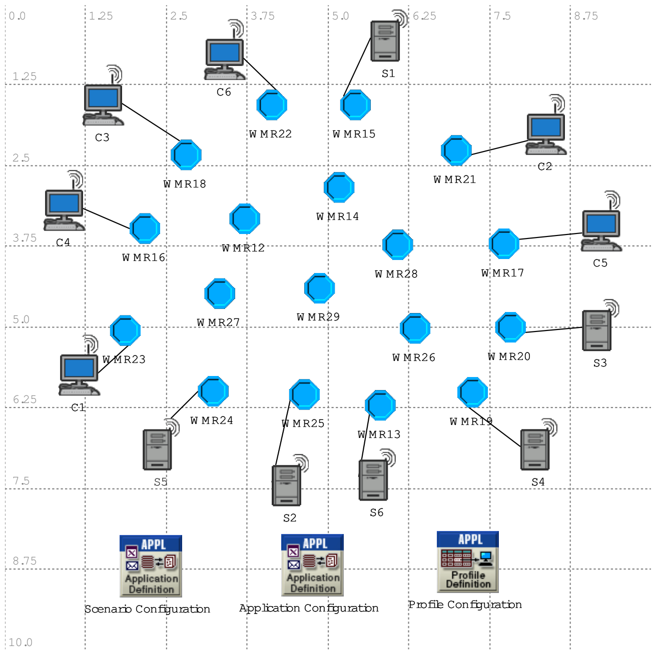

Fig. 2 Example of the standard scenario used in our simulation campaign. The WMN consists of eighteen wireless mesh routers with six client/server pairs.

Table 2 Network configuration parameters

Parameter	**Value**
Channel Model	Rayleigh fading model
Path Loss Coefficient	3.5
Directional Antenna Pattern	Side lobe: -25dB, Main lobe: 30°
Adaptive Modulation and Coding	BPSK-1/2, QPSK, 16QAM, 64QAM, 128QAM
Doppler Frequency	25Hz
System Bandwidth	50MHz
Slot Duration	80μs
Slots per Frame	100
Frame Duration	8ms
MAC Packet Length	1024 bytes
Number of WMR	5-35, Typical number 18
Number of Client/Server pair	6
Network Area	10 km $\times$ 10 km square
Transmission Range	2 km
Traffic Patterns	FTP, VoIP and Video
Queue Length	Infinite

the QoS routing, scheduling and admission control decisions, that includes real-time monitored/measured per-link statistics like T_{ij}^a, D_{ij}^a, and E_{ij}^a for throughput, delay and PER on (i, j). These statistics are updated periodically according to the scheduling and routing operational time-scales to represent the most recent channel qualities and queue status.

7.1 Overall Network Performances

In this section, we assess our proposed cross-layer design paradigm for QoS in wireless mesh networks that comprises a distributed opportunistic proportional fair scheduling algorithm (Dist) in MAC layer, a multi-constrained QoS routing (IQoSR) and route capacity estimation based admission control algorithm used in network layer (IQoSR+RC-CAC), to compared with the exiting benchmark protocol Round robin scheduler [38] (RR) and AODV routing scheme, as shown in Table 3. It is investigated in terms of gateway goodput in Fig. 3a, and average QoS outage probability among all sessions in Fig. 3b, with different network sizes and traffic loads.

Fig. 3a depicts the behaviors of overall gateway goodput w.r.t. different network sizes (i.e., placing different number of nodes in a fixed network area) and traffic inter-arrival times. It is interesting to observe that there is an optimal network size in terms of node density for a given traffic inter-arrival time for both schemes 'Dist+IQoSR+RC-CAC" and "RR+AODV". On the one hand, distributed opportunistic scheduling algorithm in this case could take advantage the multi-user diversity gain by always selecting the best wireless channel among all neighbors, and QoS routing and admission control algorithms can not only successfully select the best candidate route in the larger range of route pool but also accurately predict the impact of new session admissions on the existing ones, and thus grantee QoS. However, since network resources (time-slot, codes, power etc.) are limited and shared, those gains decrease when the network size is larger; meanwhile this may potentially create more co-channel interferences due to concurrent transmissions, and thus deteriorate the per-node/gateway goodput as known by Gupta et. al's work in [39]. Furthermore, if wireless mesh routers are sparsely distributed, i.e., small number of nodes exist, the opportunistic gain could not fully exploited by distributed scheduler, and route selected may not be good enough to provide QoS. These are primarily why there is an optimal operation point for the number of nodes in a given network to maximize the gateway goodput. Finally, as we increase the traffic input rate, higher goodput is expected, but always twice higher than what "RR+AODV" scheme achieves.

Fig. 3b demonstrates the average QoS outage probability of all completed sessions as a function of both traffic load and network size. This is defined as the probability of any of the QoS requirements of a session to fail during the lifetime of the given session, or $\mathbf{U}_{sg}^{k} > 1$. The proposed cross-layer scheme "Dist+IQoSR+RC-CAC" achieves always 15% lower outage probabilities than "RR+AODV" due to the accurate resource estimation of network layer routing and admission control schemes to prevent new sessions consuming too much resources of existing sessions in the network. Meanwhile, distributed scheduler interacts with the routing algorithm to provide long-term throughput as well as multi-user diversity gain. However, as we increase the number of mesh routers in a given network area, potentially we may generate more co-channel interferences due to more concurrent transmissions thus may deteriorate the session quality (higher QoS outage), however, for a fixed traffic load, the multi-user diversity gain of wireless channel boosts the gateway throughput although for any single session the potential QoS failure may increase.

Table 3 Cross-layer performance comparisons

MAC	Routing	Admission Control	Cross-Layer Term
Round Robin	AODV	-	RR+AODV
Distributed OPF	IQoSR	RC-CAC	Dist+IQoSR+RC-CAC

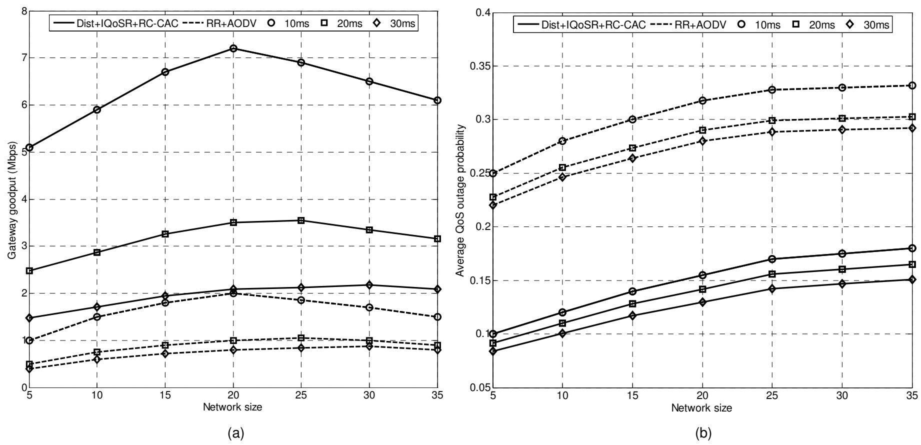

Fig. 3 Simulation results on (a) Average network goodput (b) QoS outage probability per session value, both figures are plotted with respect to (w.r.t.) different network sizes and different new session inter-arrival time.

7.2 Performance Evaluations on Scheduling and Routing Algorithms

The loosely-coupled cross-layer design for distributed opportunistic scheduling (Dist) and integrated multi-constrained QoS routing (IQoSR) algorithms is assessed as compared to conventional Round robin scheduler [38] (RR) and AODV routing protocol. Table 4 summarizes these four comparisons while Fig. 4a and Fig. 4b demonstrate the gateway goodput and average QoS outage probability among all sessions with different traffic loads.

Fig. 4a shows that the opportunistic scheduler considered in our framework can guarantee high gateway goodput even for small inter-arrival rates when the offered network traffic is getting high. On the other hand, the "RR+AODV" scheme provides a much lower goodput compared with all other three schemes since the scheduler fails to exploit the multi-user diversity gain of wireless channel (or, channel resources are reserved) and routing protocol creates bottleneck links in the network by transporting traffics through the shortest paths. "Dist+AODV" and "RR+IQoSR" run between the lower-bound performance of "RR+AODV" and upper-bound performance of "Dist+IQoSR" since they take advantage of wireless channel to provide either high throughput or end-to-end QoS, but not both.

The above judgement for four schemes become clearer in Fig. 4b that demonstrates the average QoS outage probability for all sessions. It could be seen that all four schemes successfully guarantee better QoS if we increase traffic inter-arrival time, or less traffic load in the network. However, as more traffic is injected into the network without an

Table 4 Scheduling and routing performance comparisons

MAC	Routing	Cross-Layer Scheduling and Routing Term
Distributed OPF	IQoSR	Dist+IQoSR
Distributed OPF	AODV	Dist+AODV
Round Robin	IQoSR	RR+IQoSR
Round Robin	AODV	RR+AODV

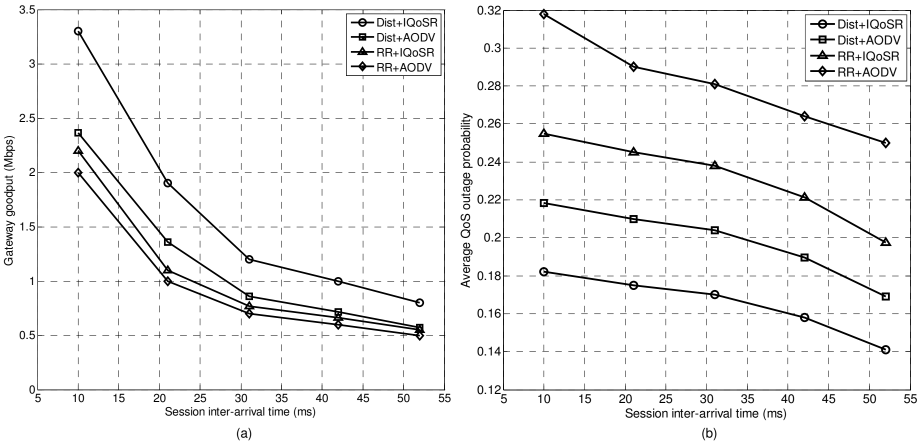

Fig. 4 Simulation results on (a) Average network goodput (b) QoS outage probability per session value, both figures are plotted w.r.t. different new session inter-arrival time.

efficient connection admission control scheme, the outage probability rises due to the severe impacts of new traffic on the QoS of the existing flows already running in the network.

7.3 Performance Evaluations Connection Admission Control Algorithm

Now, we turn our attention to connection admission control algorithm performance as a result of tightly-couple cross-layer design approach. The proposed algorithm ("Dist+ IQoSR+RC-CAC") is compared with the "Dist+IQoSR" that does not include an efficient prediction scheme for connection admission control. We also compare our scheme with conventional layer 2 and 3 techniques "RR+AODV", and with the recently proposed statistical admission control "SCAC" [40] algorithm as benchmarks. The performances are investigated in terms of gateway goodput in Fig. 5a, and average QoS outage probability of existing sessions in Fig. 5b.

Fig. 5a shows that "Dist+IQoSR+RC-CAC" outperforms all other schemes in terms of overall gateway goodput. An important observation is that the proposed framework can successfully achieve high goodput even for small traffic inter-arrival rate (heavy load conditions), i.e., 1.4 times more than "Dist+IQoSR+SCAC", 2.2 times more than "Dist+IQoSR", and 3.2 times more than "RR+AODV". This is primarily because that the connection admission control scheme can admit or reject new sessions

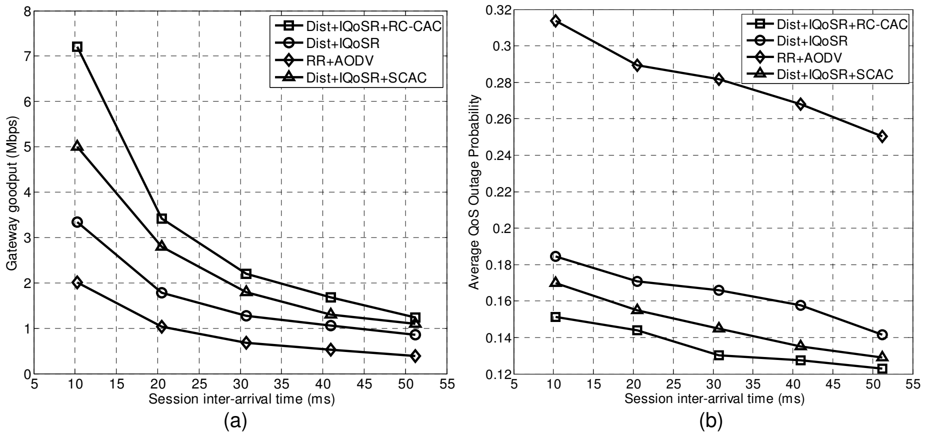

Fig. 5 Simulation results on (a) Gateway goodput (b) QoS outage probability per session value, for premium, regular and all completed sessions, both figures are plotted w.r.t. the new session inter-arrival time.

to maximize the end-to-end resource utilization in the network range by predicting the route capacity. By monitoring the resource occupancies along each route, it accurately identifies links and routes with potentially limiting resources and captures the impact of new arrival flows on the existing ongoing sessions. This will result in lower QoS outage probability as shown in Fig. 5b, especially when the network operates at heavy traffic conditions. Meanwhile, the GoS management allows certain bandwidth resources preserved for higher-level users. On the other hand, "SCAC" achieves high goodput when the traffic load is high due to its Gaussian traffic arrival assumption, but when the traffic load is relatively low, it fails to accurately estimate the achievable capacity region, thus make wrong decisions on flow admission which turns into lower goodput and higher QoS outage probability.

Fig. 5b illustrates the probability of QoS outage of all completed 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, or $\mathbf{U}_{sg}^{k} > 1$. It is interesting to observe that even for high network loading conditions, our proposed algorithm can guarantee 85% of all sessions satisfying their all QoS requirements of the underlying application, as compared to 81% if no admission control is used, 82% if "SCAC" is used, and 68% for "RR+AODV". This is because the impact of new admitted session on existing flows has been estimated and accurately reflected during the route capacity estimation phase.

8 Conclusions

Cross-layer design for QoS in wireless mesh networks has attracted much interest from both academic and industrial communities. Unlike existing works that focus either on global optimization decomposition or barely information delivery among layers, we propose a novel cross-layer framework that includes connection admission control together with QoS routing in the network layer and distributed opportunistic proportional fair scheduling in MAC layer. We defined a novel utility function that is exchanged between an efficient distributed opportunistic proportional fair scheduler and a multi-constrained QoS routing algorithm. Furthermore, a novel tightly-coupled design method for joint routing and admission control has been demonstrated, where a unified optimization criterion "QoS performance index" that combines multiple QoS constraints to indicate the QoS experience of each route has been proposed. Extensive simulation results and analysis shows the success of our framework to combine algorithms and techniques from three different layers and achieve the best overall performances as compared to other schemes.

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