Joint Connection Admission Control and Routing in IEEE 802.16-Based Mesh Networks

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Abstract—Connection admission control and routing are two important mechanisms in the provision of quality of service (QoS) in IEEE 802.16-based wireless mesh networks. In this paper, we intend to develop an optimal model which aims to maximize the total revenue from all carried connections in the mesh network while provide QoS support for each service class. We formulate the problem as a decision process and apply optimization techniques to obtain the optimal policies. Simulation results show that the proposed joint admission control and routing scheme can significantly improve the achieved system revenue, successfully prioritize different service classes, and effectively guarantee the QoS constraints such as new or handoff connection blocking probability.

I. INTRODUCTION

Recently, WiMax systems [1], based on the IEEE 802.16 family of standards, are emerging as a promising alternative for delivering last mile broadband wireless access. Wireless mesh networks are basically multihop wireless networks that consist of mesh routers and mesh clients. The mesh routers form the backhaul of the wireless mesh networks. Some mesh routers that connect to the Internet backbone via high-bandwidth wired connections [2] are called gateway nodes. WiMax, which provides greater bandwidth and transmission range, is an ideal candidate to provide fast backhaul for large wireless mesh network.

Admission control and routing are two important mechanisms in the provision of guaranteed QoS in wireless networks. Admission control and routing have been intensively studied in multihop mobile ad hoc networks [3] and [4]. However, WiMax based backhaul mesh networks have different characteristics compared with mobile ad hoc network [2]. The QoS provisioning algorithms developed in mobile ad hoc networks might not be applied directly in wireless mesh networks.

There is some work in the literature studying admission control and routing in mesh networks. Authors of [5] propose a radio resource management framework, which combines subchannel allocation, admission control and routing, for IEEE 802.16-based wireless mesh networks. A tandem queueing model is developed to obtain the end-to-end delay, throughput, and packet dropping probabilities. A route will be selected based on the estimated end-to-end transmission delay. In [6], an admission control scheme is proposed for multihop wireless backhaul networks with QoS support. It assumes a tree topology rooted at the gateway in the backhaul and admits a subset of connections based on their rate and delay requirements. However, these schemes only consider a single class of service, and the extension of these schemes to the case of multiple classes may not be an easy task. Moreover, in wireless mesh networks, handoff of ongoing connections between base stations is necessary in order to provide seamless mobility support to mobile clients. Since forced termination of an ongoing connection is more annoying than blocking a new connection attempt from user’s point of view, handoff connections should be given a higher priority.

To the best of our knowledge, the design of optimal joint admission control and routing that can maximize the overall revenue while guaranteeing the QoS for multiple classes in 802.16-based mesh networks has not been addressed in previous work. In this paper, we first formulate the admission control and routing problem in mesh networks as a semi-Markov decision process (SMDP) [7], then present a linear programming (LP) based algorithm to compute the optimal admission control and routing policy. The objective is to maximize the overall revenue from all carried connections while guarantee the QoS for each class of service. The novel features of the proposed scheme are as follows: (1) It can optimally control whether or not to admit as well as to which route to admit a new or handoff connection. (2) It considers different reward rates for different service classes, and the overall revenue can be maximized. (3) The network layer QoS constraint, such as blocking probabilities for new or handoff connections, can be guaranteed. (4) Handoff connections are given higher priority over new connection requests in the same class. Therefore, handoff dropping QoS can be guaranteed.

The rest of the paper is organized as follows. Section II describes the 802.16-based mesh networks and the QoS provision problem. Section III presents our proposed joint admission control and routing scheme. Section IV presents the numerical and simulation results. We conclude this study in section V.

II. SYSTEM MODEL

A. IEEE 802.16-Based Mesh Networks

We consider a wireless metropolitan area mesh network in which the infrastructure/backbone is built using IEEE 802.16 technology. The mesh network consists of fixed wireless mesh routers and end mobile clients. The wireless mesh routers...
form a multihop wireless backbone to relay traffic to and from mobile clients. An IEEE 802.16 cell consists of a base station and one or more mobile stations based on point-to-multipoint (PMP) network topology. Wireless mesh routers also serve as base stations to mobile stations within their coverage area. Mobile clients roam among base stations and access the wired network via the gateways.

IEEE 802.16 supports both time division duplex (TDD) and frequency division duplex (FDD) operations. We assume the backhaul transmission in the mesh networks uses TDD scheme based on orthogonal frequency-division multiplexing (OFDM) technology with time division multiple access (TDMA). Assume adaptive modulation and coding is used and frequency division duplex (FDD) operations. We assume network via the gateways.

III. FORMULATION OF JOINT ADMISSION CONTROL AND ROUTING

In this section, the optimal admission control and routing problem in wireless mesh networks is formulated as a SMDP [7]. When a new or handoff connection arrives at a base station/mesh router, a decision must be made as to whether or not to admit and to which route to admit the arrival based on the available resource in the mesh network. These time instances are called decision epochs and decisions are called actions in the SMDP framework. The action chosen is based on the current state of the network. The state information includes the number of sessions of each class of traffic on each route in the mesh network. The optimality criterion for the SMDP is the long-run average reward per unit time. An LP algorithm is used to provide the optimal admission control policy.

We describe an IEEE 802.16-based wireless mesh network as a set of nodes \( N = \{1, \ldots, N\} \) that includes all the mobile clients and mesh routers/gateways and a set of wireless links \( L = \{1, \ldots, L\} \) that includes all the backhaul links as well as the links between mobile stations and base stations. Each link \( l \) has a total capacity of \( B(l) \) units of bandwidth. The mesh network offers \( J \) different classes of services and the connections arrive according to independent Poisson process. The intensity of arrival and the average holding time for each class of service is \( \lambda_j \) and \( 1/\mu_j \), respectively. When a new or handoff connection of class \( j \), with original node \( O \) and destination node \( D \) arrives, it can be either rejected (with zero reward) or accepted (with reward \( r(j) \), which can be interpreted as the average reward for carrying the \( j \)th class connection). In order to accept the connection, we need to choose a route \( k \) from the set of all feasible routes from \( O \) to \( D, K = \{1, \ldots, K\} \). Assume the bandwidth requirement for the new arrival is \( b(j) \). Each node and each link along the chosen route must have at least \( b(j) \) units of bandwidth available for the new connection. In order to obtain the optimal solution, it is necessary to identify the state space, decision epochs, actions, state dynamics, rewards and constraints in the mesh networks.

A. State Space, Decision Epochs and Actions

The state of the considered system can be described by a matrix

\[
x(t) = \begin{bmatrix} z_1^1(t) & z_2^1(t) & \cdots & z^K_1(t) \\
z_1^2(t) & z_2^2(t) & \cdots & z^K_2(t) \\
\vdots & \vdots & \ddots & \vdots \\
z_1^J(t) & z_2^J(t) & \cdots & z^K_J(t) \end{bmatrix} \in \mathbb{Z}_+^{J \times K},
\]

(2)

where \( z^j_k(t) \) denotes the number of class \( j \) connections that are currently active and carried on route \( k \).
In mesh networks, given a link \( l \in L \), a path may or may not pass link \( l \). All the traffic passing link \( l \) should not exceed its capacity. We define \( f^l(k) \) as

\[
f^l(k) = \begin{cases} 
0, & \text{if path } k \text{ does not pass link } l; \\
1, & \text{if path } k \text{ passes link } l.
\end{cases}
\]

The state space \( X \) of the system comprises of any state matrix that satisfies

\[
\sum_{k=1}^{K} \sum_{j=1}^{J} f^l(k)z^k_a(b(j) \leq B(l), \forall l \in L,
\]

where \( B(l) \) denotes the link capacity and \( b(j) \) is the effective bandwidth required by the \( j \)th class traffic. In 802.16-based wireless mesh networks, the bandwidth corresponds to a set of time slots and frequencies. In this paper, we assume the traffic characteristics, the desired packet-level QoS guarantees, and the scheduling can together be represented by this effective bandwidth. Techniques for computing the effective bandwidth for different traffic characteristics and QoS requirements can be found in [10].

Therefore, the state space of the SMDP can be defined as

\[
X = \left\{ x \in \mathbb{Z}^{J \times K}_+ : \sum_{k=1}^{K} \sum_{j=1}^{J} f^l(k)z^k_a(b(j) \leq B(l), \forall l \in L) \right\}.
\]

The state of the mesh network changes whenever certain events take place. We choose the decision epochs to be the set of all connection arrival and departure instances. At each decision epoch \( t_n \), \( n = 0, 1, 2, \ldots \), the network makes a decision for each possible connection arrival and departure that may occur during the time interval \( [t_n, t_{n+1}] \). These decisions are collectively referred to as an action. Action \( a(t_n) \) at decision epoch \( t_n \) can be defined as

\[
a(t_n) = \begin{bmatrix} a^1_1(t_n) & a^2_1(t_n) & \cdots & a^K_1(t_n) \\
\vdots & \ddots & \cdots & \vdots \\
a^1_J(t_n) & a^2_J(t_n) & \cdots & a^K_J(t_n) \end{bmatrix},
\]

where \( a^j_k(t) \) denotes the action for class \( j \) connections carried on route \( k \). If \( a^j_k(t) = 1 \), admit a class \( j \) connection on route \( k \). If \( a^j_k(t) = 0 \), reject it. We assume a connection can only be admitted to one route.

The action space can be defined as

\[
A = \{ a : a \in \{0, 1\}^{J \times K}, j = 1, 2, \ldots, J, k = 1, 2, \ldots, K, \}
\]

\[
a^j_k \neq 1, i f a^j_k = 1 \text{ and } k_1 \neq k_2, k_1, k_2 = 1, 2, \ldots, K \}.
\]

For a given state \( x \in X \), a selected action should not result in a transition to a state that is not in \( X \). In addition, action \( \{0\}^{J \times K} \) should not be the only possible action in state \( \{0\}^{J \times K} \). Otherwise, new connections are never admitted into the network and the system cannot evolve. Therefore, the action space of a given state \( x \in X \) is defined as:

\[
A_x = \{ a \in A : a^j_k = 0 \text{ if } (x + e^u_{jk}) \notin X, j = 1, \ldots, J, \\
k = 1, \ldots, K, a \neq \{0\}^{J \times K}, i f x = \{0\}^{J \times K} \}.
\]

where \( e^u_{jk} \in \{0, 1\}^{J \times K} \) denotes a matrix containing only zeros except for the \( j \)th row and \( k \)th column component, which is 1. \( (x + e^u_{jk}) \) corresponds to an increase of number of class \( j \) connections carried on route \( k \) by 1.

### B. State Dynamics and Reward Function

The state dynamics of the mesh network can be characterized by the state transition probabilities of the embedded chain \( P_{xy}(a) \) and the expected sojourn time \( \tau_x(a) \) for each state-action pair.

\[
\tau_x(a) = \left( \sum_{k=1}^{K} \sum_{j=1}^{J} \lambda^k_j a^k_j + \sum_{k=1}^{K} \sum_{j=1}^{J} \mu^k_j z^k_j \right)^{-1}.
\]

The state transition probabilities are

\[
P_{xy}(a) = \begin{cases} 
\lambda^k_j a^k_j \tau_x(a), & \text{if } y = x + e^u_{jk}, j = 1, \ldots, J, k = 1, \ldots, K; \\
\mu^k_j z^k_j \tau_x(a), & \text{if } y = x - e^u_{jk}, j = 1, \ldots, J, k = 1, \ldots, K; \\
0, & \text{otherwise.}
\end{cases}
\]

The average reward criterion is considered as the performance criterion. For any policy \( u \in U \) and an initial state \( x_0 \), the average reward is defined as

\[
J_u(x_0) = \lim_{T \to \infty} \frac{1}{T} E \left[ \int_0^T r(x(t), a(t)) dt \right],
\]

where \( r(x(t), a(t)) \) is the expected reward until the next decision epoch when \( a(t) \) is selected in state \( x(t) \). The aim is to find an optimal policy \( u^* \) that maximize \( J_u(x_0) \) for any initial state \( x_0 \). Based on the action \( a \) taken in a state \( x \), a reward \( r(x, a) \) occurs to the network. The reward can be expressed as \( r(x, a) = \sum_{k=1}^{K} \sum_{j=1}^{J} w^k_j a^k_j \), where \( w^k_j \) is the weight associated with class \( j \) connection on route \( k \).

### C. Constraints

In the current problem formulation, SNR constraints of all connections in the system can be guaranteed by restricting the state space in (3). It is also necessary to put constraints on blocking probabilities of certain classes of traffic or handoff traffic arrivals. Therefore, we need to formulate connection blocking probability constraints in our model. Since we have derived the expected sojourn time \( \tau_x(a) \) for a given state-action pair, the blocking probability for class \( j \) can be defined as the fraction of time the system is in a set of states \( X^b_j \subset X \) and the chosen action is in a set of actions \( A^b_{x_j} \subset A \), where \( x^b_j \in X^b_j \) and \( A^b_{x_j} = \{ a \in A : a^k_j = 0, k = 1, \ldots, K \} \).

\[
P^b_j = \lim_{T \to \infty} \frac{1}{T} E \left[ \int_0^T \sum_{k=1}^{K} (1 - a^k_j(t)) \tau_x(t)(a(t)) dt \right] = \frac{\sum_{x \in X^b_j} \sum_{a \in A^b_{x_j}} \tau_x(a)}{\sum_{x \in X} \sum_{a \in A} \tau_x(a)}.
\]

The constraints related to the blocking probability can be expressed as \( P^b_j \leq \gamma_j, j = 1, 2, \ldots, J \). The blocking probability
constraints in the system can be addressed in the linear programming formulation in (12) by defining a cost function related to these constraints, $C_j^C(x, a) = \prod_{k=1}^{K} (1 - a_j^k)$.

D. Linear Programming Solution to the SMDP

The optimal policy $u^*$ of the SMDP is obtained by solving the following LP

$$\max_{z_{xa} \geq 0, x \in X, a \in A_x} \sum_{x \in X} \sum_{a \in A_x} r(x, a) \tau_x(a) z_{xa}$$

Subject to

$$\sum_{a \in A_y} \sum_{x \in X} P_{xy}(a) z_{xa} = 0, \ y \in X$$

$$\sum_{x \in X} \sum_{a \in A_x} z_{xa} \tau_x(a) = 1$$

$$\sum_{x \in X} \sum_{a \in A_x} \prod_{k=1}^{K} (1 - a_j^k) \tau_x(a) \leq \gamma_j, \ j = 1, 2, ..., J \ (12)$$

The decision variables are $z_{xa}, x \in X, a \in A_x$. The term $z_{xa} \tau_x(a)$ can be interpreted as the steady-state probability of the system being in state $x$ and $a$ is chosen. The first constraint is a balance equation and the second constraint can guarantee that the sum of the steady-state probabilities to be one. The network layer new and handoff connection blocking probabilities constraints are expressed in the third one. Since sample path constraints are included in (12), the optimal policy obtained will be a randomized policy: the optimal action $a^* \in A_x$ for state $x$ is chosen probabilistically according to the probabilities $z_{xa}/\sum_{a \in A_x} z_{xa}$.

E. Computational Complexity and Implementation Issues

To obtain the optimal admission control and routing policy, we need to 1) construct the state space $X$ in (4) and 2) solve the LP in (12). Both procedures are done offline. Once we have the optimal policy, the network just checks the current system state (the number of connections of each class on each route) and executes the policy (to which route to admit, reject, or admit with a probability). For some networks, the state space and computational complexity will be very large. In this case, recent advances in reinforcement learning [11] can be used to break the curse of dimensionality. The formulations in this paper are still applicable in the reinforcement learning method.

Our proposed scheme maintains multiple routes and activates one route at a given time. Potential bottleneck links/nodes might exist within the mesh network. We need to avoid bottlenecks when selecting a route to admit a new or handoff connection. This can be achieved by modifying the reward function and set it as a function of its current amount of available capacity and utilization level.

IV. SIMULATION RESULTS

In this section, we describe the performance of the proposed optimal admission control and routing scheme by simulations. We compare the performance of the proposed scheme with the existing scheme, in which the route that satisfies the link capacity constraint and has the least end-to-end delay will be selected when a new connection arrives. We show that the proposed scheme can achieve significant performance improvement over the existing scheme.

A. Parameter Settings

We consider a wireless mesh network in which the wireless communications between mobile stations and base stations/mesh routers and the backhaul transmissions among mesh routers are all based on 802.16 TDMA/TDD techniques [1]. Assume the air interface is 256-carrier OFDM with TDMA scheme, of which 192 are modulated with data and 8 are used as pilot signals. The simulation parameters and values are illustrated in table I. In our simulations, we consider the following scenario. The wireless backhaul mesh network consists of 3 nodes and 3 pairs of unidirectional wireless backhaul transmission links. The bandwidth for each pair of backhaul links are 4MHz, 5MHz, and 7MHz and average SNR at the receivers is 15dB. The average channel capacity is 7.28Mbps, 9.09Mbps, and 12.58Mbps, which can be obtained from (1).

B. Performance Improvement

Two classes of video traffic are considered in the system with arrival rate $\lambda_1$, $\lambda_2$, respectively. The service rates are $\mu_1$ and $\mu_2$. The connection arrival rate in the system is $\lambda = \lambda_1 + \lambda_2$. Assume the connection arrival process follows Poisson process. The admission control and routing scheme is invoked whenever a connection arrives or departs. We evaluate the performance of our proposed scheme under various traffic load scenarios.

Fig. 1 shows the average reward in different traffic load scenarios. In this example, 40% of the total new connection arrivals in the systems are the first class traffic and 60% are the second class traffic. The service rate $\mu_1 = \mu_2 = 0.03$. The bandwidth requirements for the two classes of traffic are 1Mbps and 2Mbps. The reward weight are $w_1 = 1$ and $w_2 = 2$. From fig. 1, we can see that the reward gained in the proposed scheme is always better than the existing scheme. The reward ratio between different classes may vary with different network operators. Fig. 2 shows average reward increases when the fraction of traffic with larger reward weight increases. The traffic arrival rate $\lambda_1 = 0.016$ and $\lambda_2 = 0.024$. The service rate $\mu_1 = \mu_2 = 0.03$. We can see from fig. 2, the proposed scheme has bigger reward gains than the existing scheme.
The proposed scheme supports multiple classes of service, which is more flexible for bandwidth allocation. Fig. 3 shows the blocking probabilities for two different classes of services in the condition of various traffic load and service rates. Assume 60% percent of the traffic is the first class traffic and 40% percent is the second class traffic. We can see from fig. 3, the blocking probability for the first class of service with low priority is higher than the second class of service. The proposed scheme also guarantees the network level QoS such as connection blocking probabilities for new or handoff connections. Fig. 4 shows the blocking probability of handoff connections in mesh networks. In this example, we set up a target blocking probability, 1%, for handoff connections. There is a single class of traffic with different arrival rates and the service rate $\mu = 0.08$. We can see from fig. 4, the proposed optimal admission control scheme can guarantee the handoff blocking probability under various network load.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we have presented an optimal admission control and routing scheme to provide QoS guarantee in IEEE 802.16-based wireless mesh networks. We formulated the problem as a SMDP process, and then gave an LP solution to it. The proposed scheme considers multiple classes of services. The revenue can be maximized and the connection blocking probabilities of higher priority service or handoff connections can be guaranteed. Simulation results have been presented to illustrate the performance of the proposed approach.

Future work is in progress to consider packet-level QoS, such as packet delay, in the admission control and routing problem in wireless mesh networks.

REFERENCES