A Hierarchical Model for Bandwidth Management and Admission Control in Integrated IEEE 802.16/802.11 Wireless Networks

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Abstract—
In this paper, we present a hierarchical bandwidth management and admission control framework for integrated IEEE 802.16/802.11 wireless networks. Developed based on a game-theoretic model, the framework aims to satisfy the quality of service (QoS) requirements of all the users in this integrated network. In particular, at the first level of this hierarchical model, the bandwidth allocation problem among the standalone subscriber stations (SSs) and the WLAN access points (APs)/routers is formulated as a bargaining game. Based on the allocated bandwidth to the SSs, groups of connections in different service types in the standalone SSs cooperate among each other at the second level of the game to share the bandwidth in a fair manner. The admission control for connections from the standalone SSs is devised based on the improvement in total utility of the corresponding service types. For the WLAN connections, estimated traffic load is used by an admission control game to decide whether a new connection from a WLAN node can be admitted or not.

Keywords—Bandwidth management, admission control, IEEE 802.16-based broadband wireless access, IEEE 802.11, game theory.

I. INTRODUCTION

While IEEE 802.11-based wireless local area networks (WLANs) were designed to provide high speed connection for local/indoor users, IEEE 802.16-based wireless metropolitan area networks (WMAN) have been developed for outdoor applications requiring larger service area. IEEE 802.16 [1] is a viable technology to provide wireless connectivity among the WLANs (e.g., wireless hotspots). Integration of these technologies introduces a new flexible wireless network environment to support broadband wireless Internet connectivity, especially in areas where wired Internet infrastructure is unavailable.

Issues related to integration of cellular networks, WLAN, and mobile ad hoc networks (MANET) were identified in [2]. In [3], a resource management and admission control algorithm to support QoS in cellular/WLAN environment was proposed and a system architecture based on DiffServ internetworking was presented. Performance study of IEEE 802.16 broadband wireless access was presented in [4] and the relationship among application throughput, channel utilization, and adaptive modulation and coding scheme was analyzed. In [5], a fair service flow management scheme for IEEE 802.16 broadband wireless access was proposed where the uplink and the downlink bandwidth are dynamically adjusted to satisfy the QoS requirements based on deficit fair priority queue scheduling algorithm. However, these works considered connections only from standalone subscriber stations (SSs).

In this paper, we present a hierarchical bandwidth management and admission control framework for integrated IEEE 802.16/IEEE 802.11 wireless networks. We consider a system model in which IEEE 802.11 WLAN access points (APs) are connected to the Internet via IEEE 802.16 WMAN links. We present a two-level hierarchical model for radio resource allocation in this integrated network. In particular, at the first level a bargaining game between the set of standalone SSs and the WLAN APs is formulated. Based on the results of the bargaining game, at the second level, connections corresponding to the different service types in the standalone SSs establish a coalition to share the allocated bandwidth. The admission control policy is devised based on the result of bandwidth allocation. Specifically, the admission control method for connections from standalone SSs is based on the total utility of the services. For admission control of a new connection in a WLAN, a non-cooperative game between the corresponding WLAN AP and the WMAN BS is formulated. The admission control problem can be formulated as a general sum game between these two networks. The advantage of this hierarchical model lies in its computational simplicity which is due to the fact that the game-theoretic algorithms can be performed in each level independently.

II. SYSTEM MODEL AND ASSUMPTIONS

A. Network Model

We consider a single IEEE 802.16 base station (BS) serving two types of connections: standalone SS and WLAN (Fig. 1). For standalone SS, the connection is dedicated to a single user (which is presumably shared among sessions of different types) while the WLAN connection is shared among the WLAN nodes. To provide differentiated services, the sessions from a standalone SS can use any one of the following service types: UGS (unsolicited granted service), PS (polling service) or BE (best-effort), in which different types of services have different bandwidth requirements.

The 802.16 BS allocates bandwidth to SSs and WLAN APs. The total amount of allocated bandwidth to the SSs is shared among the different connections in the SSs. Each WLAN AP is
We consider uplink transmissions from standalone SSs and the WLAN nodes. Data traffic from the standalone SSs is transmitted directly to the 802.16 BS. For WLANs, each AP/wireless router has a dual radio transceiver which can work using both 802.11 and 802.16 interfaces. While the AP relays the local traffic in a WLAN using 802.11 interface, it transmits the Internet traffic to the BS using 802.16 radio interface (Fig. 1).

### B. IEEE 802.11/802.16 AP/Wireless Router
To avoid interference, we assume that the dual radio interface at a 802.11/802.16 AP/wireless router uses different frequency bands. Data packets corresponding to local and Internet traffic (which can be distinguished based on the IP packet header) are stored in separate queues. Packets from the Internet traffic queue will need to be fragmented and reformatted into 802.16 frames before transmission to the BS using the 802.16 radio interface. This protocol adaptation is performed at the MAC layer for 802.11 and 802.16 traffic.

### C. Uplink Transmission in the IEEE 802.16 Air Interface
We consider a single BS with multiple connections from SSs using the TDMA/TDD access mode based on single carrier modulation (e.g., as in WirelessMAN-SC). Adaptive modulation and coding is used to adjust the transmission rate in each frame according to the channel quality. The modulation and coding schemes for the 802.16 air-interface are specified in [1].

The relationship between burst size $B_i$ and transmission rate $R_i$ for any connection $i$ in a frame can be expressed as follows:

$$B_i = R_i \left( C \sum_{n=1}^{7} I_n \Pr_n(\gamma) \right)^{-1} F$$

where $C$ is the channel bandwidth, $I_n$ is the number of transmitted bits per symbol for AMC state $n$, $F$ is the frame size, and $Pr_n(\gamma)$ is the probability of using AMC state $n$ [6].

### III. BANDWIDTH ALLOCATION

#### A. Hierarchical Model for Bandwidth Management
The game theory-based hierarchical bandwidth management model is shown in Fig. 2. The players in this game are the standalone SSs, the WLAN APs/routers and the different types of connections (i.e., UGS, PS, and BE) in standalone SSs. In the first level, a bargaining game is used to allocate resources (i.e., transmission bandwidth) to the SSs and the WLAN APs so that both of these groups of players are satisfied. Then in the second level, based on the allocated bandwidth to the SSs, a cooperative game model is used to achieve fair resource sharing among different types of connections in the SSs.

The bandwidth allocated to the WLAN APs/routers at the first level of the game is shared among the WLAN connections for Internet traffic. Also, for Internet connections initiated by the WLAN nodes, an admission control game is formulated to decide whether a new connection can be admitted or not. The decision of this game is determined based on Nash equilibrium.

In order to define the payoff received by the players in the game, we use sigmoid utility function which represents quantitatively the satisfaction on received transmission rate $R$. This function is defined as follows:

$$U(R) = \frac{1}{1+\exp(-g(R-h))},$$

where $g$ and $h$ are the parameters of the sigmoid function.

#### B. Bargaining Game
To determine the burst size (i.e., bandwidth) for standalone SSs and WLAN APs/routers, we formulate a bargaining game [7]. In general, for a two-person bargaining game, the players try to make an agreement on trading a limited amount of resource. These two individuals have a choice to bargain with each other so that both of them can gain benefit higher than that they could have obtained by playing the game without bargaining. Let $\Sigma B_{SS}$ and $\Sigma B_{WL}$ denote the burst size for standalone SSs and WLAN APs (used for serving Internet connections from WLAN nodes), respectively. The average transmission rate for the groups of standalone SS and WLAN connections can be obtained from

$$R_{SS}(\Sigma B_{SS}) = N_{SS} \Sigma B_{SS} \left( C \sum_{n=1}^{7} I_n \Pr_n(\gamma_{SS}) \right) F^{-1}$$

$$R_{WL}(\Sigma B_{WL}) = N_{WL} \Sigma B_{WL} \left( C \sum_{n=1}^{7} I_n \Pr_n(\gamma_{WL}) \right) F^{-1}$$

where $\Sigma B_{SS} + \Sigma B_{WL} = F$, and $\gamma_{SS}$, $\gamma_{WL}$, $N_{SS}$, $N_{WL}$ denote the average SNR and the total number of standalone SSs and WLAN APs/routers, respectively. The utilities for these groups of connections are $\phi_{SS}(\Sigma B_{SS}) = U(R_{SS}(\Sigma B_{SS}))$ and $\phi_{WL}(\Sigma B_{WL}) = U(R_{WL}(\Sigma B_{WL}))$. 

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1 We use the term “node” to refer to a node in the IEEE 802.11 WLAN and the term “station” to refer to an SS connected to the IEEE 802.16 BS directly.
The payoff pair for the two players is given by
\( \{(\phi_{SS}(\Sigma_{SS}), \phi_{WL}(\Sigma_{WL})) : 0 \leq \phi_{SS}(\Sigma_{SS}) \leq 1, 0 \leq \phi_{WL}(\Sigma_{WL}) \leq 1\} \) (i.e., feasible set). If an agreement between both the players in the game cannot be reached, the utility that the players will receive is given by the threat point \( (\phi_{SS}'(\cdot), \phi_{WL}'(\cdot)) \). In particular, \( (\phi_{SS}'(\cdot), \phi_{WL}'(\cdot)) = (0, 0) \) is the threat point for this bargaining game. The Pareto optimality of the game defines an agreement such that one player cannot increase his utility without decreasing the utility of the other player.

The equilibrium strategy of this game refers to the set of strategies for which all the players are satisfied with their received payoff. We define the equilibrium as in (2) [8] where \( F \) is the feasible set.

C. Cooperative Game through Coalition

After the solution of the bargaining game is determined, the connections (of different service types) from the standalone SSs will share the corresponding amount of bandwidth resource (i.e., burst size). Each type of connection in a standalone SS has different bandwidth requirements. To utilize the allocated bandwidth effectively, a cooperative game (through coalition) among different types of connections in the standalone SSs can be formulated. We consider each type of connection (i.e., UGS, PS, and BE) as a player of this cooperative game, and the objective of this game is to divide the bandwidth among the players and the solution must be stable from the cooperation point of view.

1) N-Person Game in Coalition Form: Let us define a finite set \( \mathcal{A} \) of players (i.e., \( \mathcal{A} = \{\text{UGS}, \text{PS}, \text{BE}\} \)). A real positive number \( \Sigma_{SS} \) denotes the burst size allocated to all connections from standalone SSs, and \( D_{SS}^{(j)} \) represents the required burst size for player \( j \) (i.e., \( j \in \{\text{UGS}, \text{PS}, \text{BE}\} \)). We consider the case where \( \sum_{j \in \mathcal{A}} D_{SS}^{(j)} \geq \Sigma_{SS} \). If \( B_{SS} \) denotes the solution, the rule of this game can be expressed as follows:

\[
0 \leq B_{SS}^{(j)} \leq D_{SS}^{(j)}, \quad \forall j \in \mathcal{A}, \quad \sum_{j \in \mathcal{A}} B_{SS}^{(j)} = \Sigma_{SS}.
\]  

Note that, the required burst size for service type (i.e., player) \( j \) can be obtained from

\[
D_{SS}^{(j)} = N_{SS}^{(j)} \lambda_{SS}^{(j)} \left( C \sum_{n=1}^{7} I_{n} \Pr(n) \right)^{-1} F
\]

where \( \lambda_{SS}^{(j)} \) is the bandwidth requirement and \( N_{SS}^{(j)} \) is the number of connections in service type \( j \) from standalone SSs.

A coalition \( \mathcal{S} \) is defined as a subset of \( \mathcal{A} \), \( \mathcal{S} \subset \mathcal{A} \). In this case, \( \emptyset \) and \( \mathcal{A} \) denote an empty coalition and a grand coalition, respectively. The coalition form of an N-person game is defined by the pair \( (\mathcal{A}, \nu) \) where \( \nu \) is a characteristic function of the game.

In particular, for this game, the characteristic function can be defined as follows:

\[
\nu(\mathcal{S}) = \max \left( 0, \Sigma_{SS} - \sum_{j \notin \mathcal{S}} D_{SS}^{(j)} \right)
\]

for all possible coalition \( \mathcal{S} \).

2) Shapley Value: We consider Shapley value [9] as the solution of the bandwidth allocation game. To compute Shapley value, let us define the value function \( \phi(v) \) as the worth or value of player \( j \) in the game with characteristic function \( \nu \). The Shapley value can be obtained by considering the utility that an individual receives depending on the order that player joins the coalition. The Shapley value \( \phi(\nu) \) can be computed as follows:

\[
\phi_i(\nu) = \sum_{S \subseteq \mathcal{A}, i \in \mathcal{A}} \frac{(|S|! \cdot (n - |S|)!)}{n!} (\nu(S) - \nu(S - \{i\}))
\]

where \( |S| \) indicates the number of elements in the set \( S \). The assigned burst size for the SS connection \( i \) is \( \phi_i \).

IV. ADMISSION CONTROL

A. Admission Control of Connections in Standalone SSs

For connections in service type \( j \) (i.e., \( j \in \{\text{UGS}, \text{PS}, \text{BE}\} \)), the burst size allocated to connection \( k \) depends on the channel quality \( \gamma_{SS}^{(k)} \) as follows:

\[
B_{SS}^{(j)}(k) = \frac{\sum_{n=1}^{7} I_{n} \Pr(n) \gamma_{SS}^{(k)}}{\sum_{k=1}^{7} \sum_{n=1}^{7} I_{n} \Pr(n) \gamma_{SS}^{(k)}}.
\]

Then, the admission control mechanism can be established based on the utility and the allocated burst size. In particular, when a new connection in service type \( j \) arrives (from a standalone SS), the 802.16 BS decides whether this connection can be accepted or not by considering the change in total utility. The total utility for service type \( j \) can be computed from

\[
W_{SS}^{(j)} = \sum_{k} U \left( B_{SS}^{(j)}(k) \sum_{n=1}^{7} I_{n} \Pr(n) \gamma_{SS}^{(k)} \right).
\]

Note that, a new connection is accepted only when the total utility increases, and rejected otherwise.

B. Admission Control of WLAN Nodes

When a WLAN node intends to initiate an Internet connection, a connection request message is sent to the corresponding AP/wireless router. This message contains the bandwidth requirement of the new connection. Upon receiving the request message, the AP estimates the amount of available bandwidth in the WLAN, and then an admission control game (i.e., general sum game) is invoked to check whether the bandwidth requirement for the new connection can be satisfied or not. If so, the new connection is accepted. If the link between the AP and the 802.16 BS lacks sufficient bandwidth to admit the new connection, the AP requests the BS to allocate more bandwidth. Upon receiving request from a particular AP, the BS performs bandwidth reallocation among standalone SSs and WLAN APs.

After the reallocation process is finished at the BS, the AP updates the amount of available bandwidth assigned by the BS. Then, the admission control game is performed again. If the bandwidth requirement of the new connection still cannot be satisfied that connection is rejected.
\( \phi_{SS}(\Sigma B_{SS}), \phi_{WL}(\Sigma B_{WL}) = \arg \max_{(\phi_{SS}(\Sigma B_{SS}), \phi_{WL}(\Sigma B_{WL})) \in \mathcal{F}} (\phi_{SS}(\Sigma B_{SS}) - \phi_{SS}(\cdot)) (\phi_{WL}(\Sigma B_{WL}) - \phi_{WL}(\cdot)). \) (2)

1) Transmission Rate in WLAN: The estimated received bandwidth \( \hat{E}^{(j)}_{WL}(k) \) of node \( k \) in network \( j \) is assumed to be equal to the bandwidth requirement. However, in the saturated case, it is obtained as follows:

\[
\hat{E}^{(j)}_{WL}(k) = \frac{\hat{P}_r \times C_{WL} \times \lambda^{(j)}_{WL}(k)}{\sum_j \lambda^{(j)}_{WL}(k)}
\]

(9)

where \( \lambda^{(j)}_{WL}(k) \) is the bandwidth requirement of connection \( k \) in WLAN \( j \), \( C_{WL} \) is the channel rate in the WLAN, and \( \hat{P}_r \) is the measured probability of successful transmission.

2) Formulation of the Admission Control Game for WLAN: The burst size allocated to WLAN connection \( j \) depends on the channel quality \( \tau^{(j)}_{WL} \) as follows:

\[
B^{(j)}_{WL} = B_{WL} \sum_{n=1}^{7} I_n \Pr_n(\tau^{(j)}_{WL}) \]

(10)

We formulate a two-person general sum game between WMAN and WLAN. We consider a non-cooperative game since bandwidth allocation by WMAN and WLAN is performed independently and both the networks must ensure that the bandwidth requirement of the new connection (if accepted) can be satisfied. In this case, the pure strategy for both players is to either accept or reject the new connection in the WLAN. The payoff for the case when a new connection is accepted can be obtained as follows:

\[
P_M(A, .) = U \left( \frac{\lambda^{(j)}_{WL}(k)}{\sum_j \lambda^{(j)}_{WL}(k)} B^{(j)}_{WL} \sum_{n=1}^{7} I_n \Pr_n(\tau^{(j)}_{WL}) \right)
\]

\[P_L(., A) = U(\hat{E}^{(j)}_{WL}(k))\]

where \( \lambda^{(j)}_{WL}(k) \) is the bandwidth requirement, \( \hat{E}^{(j)}_{WL}(k) \) is the estimated throughput for node \( k \) in WLAN \( j \), and \( P_M(R, .) = P_L(., R) = 0 \) in the case that the new connection is rejected. A new connection from node \( k \) in WLAN \( j \) is accepted if for WMAN and WLAN the pure strategy (accept, accept) is a Nash equilibrium.

The pure strategy pair \( (M^*, L^*) \) \( (M^*, L^* \in \{\text{Accept, Reject}\}) \) is a Nash equilibrium if

\[
P_M(M^*, L^*) \geq P_M(M, L^* \forall M \quad (11)
\]

\[
P_L(M^*, L^*) \geq P_L(M^*, L \forall L. \quad (12)
\]

To determine the Nash equilibrium, we use the best response function [7].

V. PERFORMANCE EVALUATION

A. Parameter Setting

We consider a TDMA/TDD-based uplink transmission scenario from a particular SS to the BS. The SSs are stationary. The transmission bandwidth is 25 MHz. Multiple SSs access the uplink channel in TDMA mode and the downlink transmissions share the same frequency channel (i.e., use TDD mode).

The transmission frame size is 1 ms. AMC is used in which the modulation level and the coding rate are increased if the channel quality permits. We assume a cell size of 5 km, and the average received SNR is in the range of 7-26 dB. Bandwidth requirements for UGS, PS, and BE services are 400, 500, and 300 Kbps, respectively. For WLAN, we assume that the channel rate is 10 Mbps and the cell radius is 50 meters. The wireless router/WLAN AP operates in DCF mode. The bandwidth requirement for a node in WLAN is 400 Kbps.

B. Simulation Results

1) Variation of Allocated Bandwidth Under Different Channel Qualities: We vary the channel quality (i.e., average SNR) for connections between WLAN AP/router and the 802.16 BS and observe the variation in bandwidth allocation (i.e., burst size) for standalone SS connections (Fig. 3). When the channel quality becomes better, the 802.16 air interface at the WLAN router can use AMC with higher number of transmitted bits per symbol. Therefore, at the equilibrium point the burst size allocated for WLAN routers decreases to achieve the same transmission rate.

Fig. 3. Bandwidth allocation between standalone SSs and WLAN APs/routers under different channel quality.

2) Performance of Cooperative Game - Variation of Allocated Bandwidth among Different Connection Types: We evaluate the variation of bandwidth allocation based on cooperative game for different connection types in standalone SSs. The transmission rates for UGS, PS, and BE connections are shown in Fig. 4(a). In this case, we fix the number of PS and BE connections at 15 and 20, respectively, while that of UGS connections is varied. The transmission rate for the UGS connections increases as the number of UGS connections increases. Since the objective of the cooperative game is to allocate the resource to all players in the coalition in a fair manner, the transmission rate of UGS connections increases while that of PS and BE connections decreases at the same rate.
Variation of Total Utility of Standalone SSs: Next, we show the total utility at standalone SSs from UGS, PS, and BE connections (in Fig. 4(b)). In this case, the number of PS and BE connections is 15 and 20, respectively. As expected, when the number of connections increases, the total utility increases linearly. However, at a certain point, since the bandwidth requirement of ongoing connections cannot be satisfied (due to too many connections), the total utility decreases. This is evident from the different maximum points in Fig. 4(b). Therefore, an admission control rule for standalone SSs can be established by considering the change in total utility.

Performance of Admission Control Method for WLANs: The variation in throughput per connection under different number of WLAN nodes is shown in Fig. 5(a). We use 90 percent of the bandwidth requirement as a threshold to determine bottleneck. First, we consider nodes with bandwidth requirement of 800 Kbps, and the total number of WLAN routers is assumed to be 2. This results in a light load scenario in the WMAN while a heavy load scenario in the WLAN. Therefore, the bottleneck is at the WLAN since the channel becomes saturated and the collision probability increases due to a large number of nodes. Second, we consider nodes with transmission rate requirement of 400 Kbps and the number of WLAN routers is assumed to be 5. In this case, WLANS have light traffic load while WMANS have heavy traffic load. Therefore, the bottleneck occurs at the link between the WLAN AP and the WMAN BS.

VI. CONCLUSION

In this paper, a hierarchical bandwidth management for IEEE 802.16/802.11 integrated wireless networks has been proposed. A game-theoretic model has been applied to achieve fair and efficient radio resource allocation for the WMAN and the WLAN users. Specifically, a bargaining game has been used to determine the optimal burst size for WMAN and WLAN connections. A cooperative game has been formulated, and the Shapley value has been used to obtain the solution of the bandwidth allocation problem for different types of WMAN connections. Also, an admission control scheme based on variation in total utility has been presented. For WLAN connections, an admission control based on non-cooperative game has been used to determine whether a new WLAN connection can be accepted or not. An extensive performance evaluation has been performed and the numerical results have shown that the proposed framework can provide fair bandwidth allocation among the connections in an integrated WMAN/WLAN network.

REFERENCES