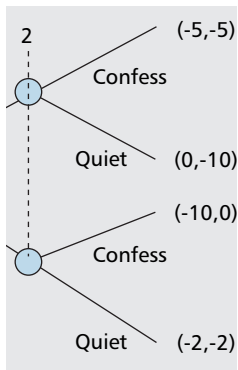


# RADIO RESOURCE MANAGEMENT GAMES IN WIRELESS NETWORKS: AN APPROACH TO BANDWIDTH ALLOCATION AND ADMISSION CONTROL FOR POLLING SERVICE IN IEEE 802.16

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The authors propose an adaptive bandwidth allocation and admission control scheme for polling service in IEEE 802.16-based wireless metropolitan area network.

## ABSTRACT

Game theory is a mathematical tool developed to understand competitive situations in which rational decision makers interact to achieve their objectives. Game theory techniques have recently been applied to various engineering design problems in which the action of one component impacts (and perhaps conflicts with) that of any other component. In particular, game theory techniques have been successfully used for protocol design and optimization (e.g., radio resource management, power control) in wireless networks. In this article we present an overview of different game theory formulations. Then a survey on the game-theory-based resource management and admission control schemes in different wireless networks is presented, and several open research issues are outlined. To this end, we propose an adaptive bandwidth allocation and admission control scheme for polling service in an IEEE 802.16-based wireless metropolitan area network. A noncooperative game is formulated, and the solution of this game is determined by the Nash equilibrium for the amount of bandwidth offered to a new connection. The admission control policy ensures QoS for all connections in the system.

## INTRODUCTION

Wireless metropolitan area network (WMAN) technology based on the IEEE 802.16 standard [1] and its evolutions (i.e., 802.16-2004, 802.16e, 802.16g) have been developed to provide high-speed broadband wireless connectivity for multimedia traffic. Also known as Worldwide Interoperability for Microwave Access (WiMAX), IEEE 802.16-based technology is a promising alternative for last mile broadband

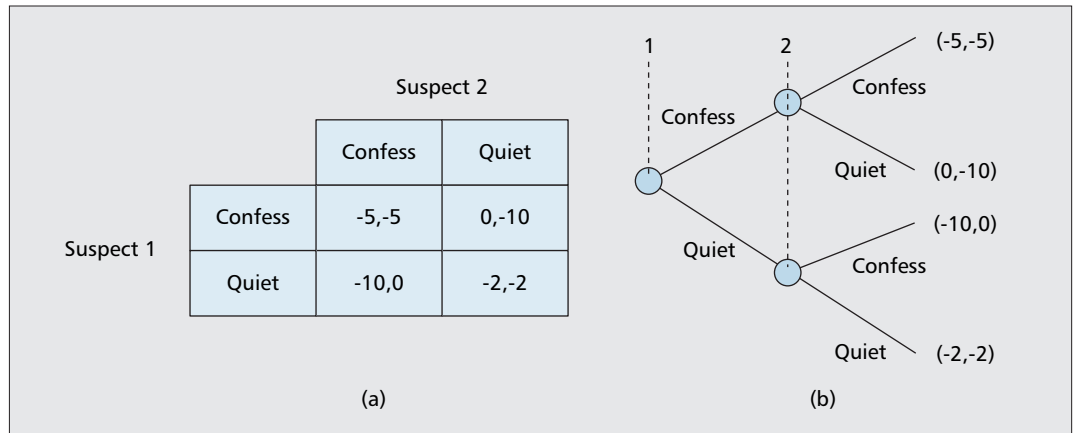
wireless access. Even though the physical layer specifications and MAC protocol signaling are well defined in the standard, the resource allocation and admission control policies for the IEEE 802.16 air interface remain open issues. However, bandwidth allocation and connection admission control are necessary for IEEE 802.16 networks to support the quality of service (QoS) requirements for the different types of connections. In particular, in the IEEE 802.16 standard two service classes (i.e., real-time and non-real-time polling services) require strict delay and throughput guarantee.

In this article we investigate the application of game theory to the resource management problem in wireless networks. Game theory techniques were adopted to solve many protocol design issues (e.g., resource allocation, power control, cooperation enforcement) in wireless networks. In a multiuser network, wireless services are provided to multiple users in which each is assumed to be rational enough to achieve the highest performance. Therefore, game formulations can be used, and a stable solution for the players can be obtained through the concept of equilibrium.

We first present the basic concepts of game theory. Then related work in the area of resource management and admission control in different types of wireless networks, including wireless local area networks (WLANs), code-division multiple access (CDMA) cellular networks, orthogonal frequency-division multiplexing (OFDM) wireless networks, and multihop wireless networks, are reviewed. To this end, we propose a game-theoretic model for bandwidth allocation and admission control for polling service in IEEE 802.16 networks.

The objective of the proposed game-theoretic model is to find the equilibrium point between

Two important characteristics of a game are individualism and mutual independence. While individualism influences the rationality and the cooperation among the players, mutual independence determines the actions of the players in response to those of other players.



■ **Figure 1.** a) Strategic form and b) extensive form for the Prisoners' Dilemma.

real-time and non-real-time polling service connections to offer bandwidth to a new connection while the QoS requirements of both the ongoing connections and the new connection can be met. We represent the payoff in this game by user utility calculated as a function of the perceived delay and throughput performances for the connections. Among the available strategies of both types of connections, the *Nash equilibrium* is determined, and the decision on admission control is made based on the perceived QoS performance at the Nash equilibrium. The connection- and packet-level performance of the proposed bandwidth allocation and admission control scheme are investigated.

## GAME THEORY AND RESOURCE MANAGEMENT IN WIRELESS NETWORKS

### GAME THEORY BASICS

A game is described by a set of rational players, the strategies associated with the players, and the payoffs for the players. A rational player has his/her own interest, and therefore will act by choosing an available strategy to achieve that interest. In this case a player is assumed to be able to evaluate exactly or probabilistically the outcome or payoff of the game, which depends not only on his/her action but also on other players' actions. There are two types of strategies: pure and mixed. While in a pure strategy a player chooses a specific strategy deterministically, in a mixed strategy at least one player in the game randomly chooses a strategy using a probability distribution. Two important characteristics of a game are individualism and mutual independence. While individualism influences the rationality (i.e., self-interest) and cooperation among players, mutual independence determines the actions of the players in response to those of other players.

### POPULAR GAME THEORY MODELS

**Noncooperative Game** — In a noncooperative game, a player is unable to bind and enforce agreements with other players. A noncooperative game can be represented in either strategic or extensive form. In the extensive form the timing

of the decision of each player is captured in a tree diagram; therefore, it is suitable for playing the game in sequence. In the strategic form (or matrix form), the information on timing in decision making is ignored; this form is mostly used for a game in which the players act simultaneously.

To illustrate, let us consider the well-known *Prisoners' Dilemma* in which two suspects of a crime are arrested. However, the police lack enough evidence to convict them unless at least one suspect confesses. The police place the suspects in separate rooms and give them the choices/strategies (to either *confess* or remain *quiet*) and the corresponding consequences (Fig. 1). If neither of them confesses, both will be convicted for a minor offence and jailed only for two months. However, if either of them confesses, the confessed suspect will be released immediately while the other suspect will be convicted for a serious offence and jailed for 10 months. If both confess, they will be jailed for five months. Since both the suspects are rational, they want to minimize the amount of time in prison. This situation can be modeled as a game, and the strategic and extensive forms of this game are presented in Fig. 1a and 1b, respectively.

In the strategic form, the first and second suspects choose the strategies in the row and in the column, respectively. The payoffs for a strategy pair are shown in a matrix form (e.g., the payoff pair (-5, -5) denotes that both suspects will be jailed for five months). In the extensive form, the decision tree of the game shows all possible strategies for both suspects. The strategic and extensive forms are closely related. Given an extensive form of the game, there is only one associated strategic form. However, given a strategic form, there is one or more associated extensive form depending on the given additional information (e.g., sequence of actions).

In a noncooperative game the solution (or the equilibrium of the game) is the set of strategies adopted by the players such that none of the players wants to deviate from the solution. In this equilibrium, which is referred to as a *Nash equilibrium*, each player's chosen strategy is optimal given that every other player chooses the equilibrium strategy as well. If this property

does not hold, there will be at least one player who wants to adopt a different strategy. When the players adopt a pure strategy, the game may have zero, one, or many Nash equilibria, while there is at least one Nash equilibrium for a mixed strategy.

One efficient method to obtain a Nash equilibrium is to use the best responses of the players. The best response of a player is defined as the best strategy of that player given other players' strategies. First we identify the best response (i.e., optimal strategy) of each player given other players' strategies. After all possible combinations of players' strategies have been considered, the Nash equilibrium is identified as the set of best responses of all the players. For the Prisoners' Dilemma, the best response of the first suspect, given that the second suspect chooses to confess, is to confess. Similarly, if the second suspect chooses to be quiet, the best response for the first suspect is to confess. Repeating this process to obtain the optimal strategies for the second suspect given the first suspect's action, we will reach the Nash equilibrium at which both the suspects choose to confess.

However, note that in cases where the objective is to maximize the total system performance or minimize the total cost, the equilibrium of the game might not guarantee the optimal solution. Also, the concept of the equilibrium may not be useful when any one of the players in the game does not prefer to choose the equilibrium solution.

In general, a game can be played only once or be repeated. The former is referred to as a single-stage game, while the latter is referred to as a multistage game. In a multistage game, the players are aware of the previous actions by other players and adapt their strategies (i.e., nonstationary strategies) accordingly. Also, the payoff of playing the current game may depend not only on the current stage but also on the behavior of other players in the future.

In many applications (e.g., those related to wireless protocol design and optimization) the issues related to existence and uniqueness of a Nash equilibrium become crucial. In such a case it has to be ensured that the system will not reach a point at which the players cannot make a decision since a stable and optimal strategy does not exist. Also, if the solution of the game exists, the system must eliminate ambiguity by ensuring that the stable and optimal strategy set for all the players is unique. Otherwise, if the system has multiple Nash equilibria, a method to obtain the best strategy among these Nash equilibria must be provided. A similar procedure can be used to obtain the Nash equilibrium for a mixed strategy.

Another important issue is the convergence of the solution. Since in many cases a closed-form solution is not available and/or the solution must be obtained in a decentralized way, a numerical method and/or distributed algorithm is required. The system must ensure that the distributed algorithm and/or numerical method converges to the stable solution of the game. Also, the rate of convergence is important for online execution of the algorithm.

**Bargaining Game** — In a bargaining game, the players cooperatively try to come to an agreement, and the players have a choice to *bargain* with each other so that they can gain maximum benefit, which is higher than what they could have obtained by playing the game without cooperation. A bargaining game can be used for resource allocation between two players. The amount of resource allocated to each player affects the payoff of the other player (e.g., if one player receives a larger amount of resource, the other player will receive a smaller amount). Therefore, all players seek the optimal and fair portion of resource through negotiation.

A two-player bargaining game is described by the pair of payoffs for the two players and the threat point that denotes the payoff each player will receive if bargaining fails. One of the axioms for Nash solution of the bargaining game is that the Pareto optimality for the feasible set is compact and convex. The Pareto optimality defines an agreement such that one player cannot increase his/her utility without decreasing the utility of the other player(s). This Pareto optimality will ensure the efficiency of the solution.

**Other Game Theory Models** — Noncooperative games such as the *Cournot* game and cooperative games such as the *bankruptcy* game are two other game theory models that can be used for radio resource management in wireless networks.

## APPLICATION OF GAME THEORY FOR RADIO RESOURCE MANAGEMENT IN WIRELESS NETWORKS

Game theory techniques can be used to design and analyze radio resource allocation protocols and corresponding network dynamics. Radio resources generally refer to radio channel (i.e., frequency band, time slot, channel access code) and transmission power. In a resource management game, multiple players (e.g., users and network service providers) act rationally to achieve their objectives.

**Radio Resource Management Games for IEEE 802.11 WLANs** — In [2] a noncooperative game theory approach was proposed for optimal random channel access in IEEE 802.11 networks. The players of this game formulation are the nodes in the network, and the strategy of each player is the probability of a transmission attempt if there is a packet in the queue. The payoff is defined as the utility due to successful packet transmission. A distributed algorithm to achieve the Nash equilibrium of channel access was proposed considering the constraint on battery power at the mobile node as well.

In [3] a radio resource sharing game among multiple wireless networks sharing the unlicensed frequency spectrum was proposed to support the QoS requirements in an IEEE 802.11 WLAN. Two different approaches, single- and multistage games, were used to analyze the QoS of multiple networks in utilizing the available frequency spectrum. The players of the game are the different wireless networks, the strategy of each player corresponds to demand for resource allocation, and the payoff is the utility function

An important issue is the convergence of the solution. Since in many cases a closed-form solution is not available and/or the solution is required to be obtained in a decentralized way, a numerical method and/or a distributed algorithm is required.

In particular, the Nash equilibrium of this repeated game cannot achieve the highest system throughput. However, by guaranteeing a fair long-term channel access for each player, the total throughput achieved by all the nodes (and hence the network utilization) can be maximized.

obtained based on throughput, channel access period length, and transmission delay. Nash equilibrium was considered as the solution of the game in a bargaining domain. This single-stage game was extended to a multistage game by considering cooperation and defection behaviors of the players in playing the game.

For the carrier sense multiple access with collision avoidance (CSMA/CA)-based medium access control (MAC) protocol for channel access in IEEE 802.11, a noncooperative game was formulated in [4]. The players of this noncooperative game are the mobile nodes, and the strategy of each player is the data rate and average payload size. The payoff of each player is the achievable throughput. It was observed that the distributed coordination function (DCF) results in an undesirable Nash equilibrium in which the wireless channel is not efficiently utilized. In particular, the Nash equilibrium of this repeated game cannot achieve the highest system throughput. However, by guaranteeing fair long-term channel access for each player, the total throughput achieved by all the nodes (and hence the network utilization) can be maximized.

**Radio Resource Management Game for CDMA Mobile Wireless Networks** — In CDMA wireless networks allocation of transmission power is crucial to achieve the desired transmission rate and error performance for ongoing connections. In [5] a distributed power control algorithm was proposed in which the transmission power of each mobile was obtained from the Nash equilibrium of a noncooperative game formulation. The players of this game are the mobiles in a cell, and the strategy of each mobile is the transmission power. The payoff is determined based on signal-to-interference ratio, which determines the transmission quality. An iterative algorithm was proposed to obtain the Nash equilibrium. For a similar system model, the game formulation in [6] considered different types of detectors (i.e., matched filter, decorrelator, and minimum mean square error) in the receivers. Also, multiple receiver antennas were considered.

In [7] an integrated admission control and rate control method using game theory was proposed for CDMA wireless networks in which user *churning* among the different service providers was taken into account. The admission control problem was formulated as a noncooperative nonzero sum game between two players. The first player is a service provider whose strategy is to either accept or reject an incoming connection. The second player of this game is an incoming connection whose strategy is to either accept the offered service or *churn* to another service provider. The payoff of a service provider is obtained from the net revenue gained from the ongoing connections and the incoming connection. The payoff of an incoming connection is obtained from the utility due to assigned transmission rate and the penalty incurred if the connection chooses to churn. Nash solution of a pure strategy was considered to determine whether an incoming connection can be accepted or not.

In a voice-oriented wireless network, users are generally more sensitive to dropping handoff

calls than blocking a new call. In [8], the problem of optimizing the call admission control thresholds in a multiservice CDMA networks to prioritize handoff calls over new calls was formulated as a game. The players of this game are the service classes whose strategies are the corresponding thresholds for handoff calls (which are to be chosen such that the handoff call dropping probability is maintained at the target level), and the payoff for a player is the bandwidth utilization.

**Radio Resource Management Games for OFDM Wireless Networks** — OFDM can enhance the performance of wireless transmission by transmitting data bits over multiple subcarriers. OFDM-based radio transmission has been adopted in the IEEE 802.16 and 802.11 standards. In [9] a noncooperative game was formulated for OFDM-based wireless networks to minimize transmission power while achieving the target rate requirement. The players of this game are different users transmitting data over multiple subchannels in a multicell OFDM network. The strategy is the transmission rate and power allocated to each subchannel, and the payoff is calculated as the utility function based on transmission rate and power. This distributed rate allocation game was used to analyze a two-user two-subchannel system.

**Radio Resource Management Games for Multihop Wireless Ad Hoc/Sensor Networks** — In multihop networks, especially in sensor networks, energy is the most scarce resource. To conserve energy, a node needs to consider whether a received packet should be forwarded or dropped. In [10] the packet forwarding policy in a sensor node was formulated as a game and the Nash equilibria were studied. The players in this game are the wireless nodes, and the strategy for each player is the level of cooperation to forward a received packet. The payoff for each node is computed from normalized throughput and the cost of forwarding packets (i.e., energy consumption). Different strategies (e.g., always defect, always cooperate, tit-for-tat) in a multistage game were studied analytically for different spatial distributions of the nodes and the topology of the network. An extensive survey on the applications of game theory in a wireless ad hoc network with an emphasis on packet forwarding was presented in [11]. Game-theoretic models for the different wireless systems used in the literature are summarized in Table 1.

**Application of Game Theory Techniques for Radio Resource Management in 4G and Cognitive Wireless Networks** — Emerging wireless technologies such as IEEE 802.16-based WMAN technologies and cognitive radio networks will be important segments in the evolving fourth-generation (4G) wireless systems. IEEE 802.16/WiMAX technology intends to provide broadband connectivity to both fixed and mobile users in a WMAN environment. To provide flexibility for different applications, the standard supports two major deployment scenarios: last mile broadband wireless access (i.e., point-to-multipoint) and backhaul network (i.e., mesh mode).

Issues	Game type	Players	Strategy	Payoff
QoS support in WLAN [3]	Single- and multistage bargaining game	Wireless networks	Demand for resource allocation	Throughput, length of access period, and transmission delay
Inefficiency of Nash equilibrium in IEEE 802.11 [4]	Multistage noncooperative game	Mobile nodes	Data rate and payload size	Achievable rate
Optimal channel access in IEEE 802.11 [2]	Noncooperative game	Mobile nodes	Channel access probability	Probabilities of successful packet transmission and receive
Power control in CDMA [5, 6]	Noncooperative game	Users' mobiles	Transmission rate and power	Signal interference ratio and transmission rate
Admission control in CDMA [7]	Noncooperative game	Base station and new connection	Accepting or rejecting a new connection and transmission rate	Revenue and transmission rate
Capacity reservation in CDMA [8]	Bargaining game	Service classes	Trunk reservation	Bandwidth utilization
Resource allocation in OFDM networks [9]	Noncooperative game	Users	Transmission rate and power	Received transmission rate and power
Packet forwarding in multihop network [10]	Single- and multistage noncooperative game	Wireless nodes	Level of cooperation to forward a packet	Throughput and energy

■ **Table 1.** *Game theory and applications in wireless networks.*

Although the physical and MAC layer signaling are well defined in the standard, radio resource management (e.g., bandwidth allocation, admission control) remains as an open issue. Game theory techniques can be applied for resource allocation among the SSs and/or among the connections in an SS so that the network utility is maximized while satisfying the QoS requirements for the different connections.

One of the main features of 4G networks will be heterogeneity in the wireless access environment in which a mobile can connect to multiple radio interfaces (e.g., WMAN, WLAN, cellular radio) simultaneously. Network selection and efficient load balancing among different types of networks would be required to achieve high-speed connectivity with seamless mobility. Game theory techniques can be used for radio resource management in a heterogeneous environment. For example, each network service provider can be modeled as a player of the game, and the strategy is the amount of offered bandwidth to a connection. The solution of the game can be obtained to maximize the network service providers' profit while satisfying the mobile users.

Cognitive radio is being considered as a useful technique to improve radio spectrum utilization and communication reliability. Game theory can be applied to design intelligent software radio with a capability to decide on the optimal and stable strategy for the mobiles in accessing the radio spectrum [12]. In cognitive radio networks a mobile learns and adapts to the environment (e.g., interference and congestion) to enhance network performance. The game-theoretic decision making process in such a network can be made dynamic, in which the strategy of one player can be altered depending on other players' actions.

## GAME-THEORETIC FRAMEWORK FOR BANDWIDTH ALLOCATION AND ADMISSION CONTROL IN IEEE 802.16 BROADBAND WIRELESS NETWORKS

### OVERVIEW OF THE IEEE 802.16/WiMAX STANDARD

**Physical Layer** — The physical layer of the IEEE 802.16 air interface operates either at 10–66 GHz (i.e., IEEE 802.16) or 2–11 GHz band (i.e., IEEE 802.16a), and it supports data rates in the range of 32–130 Mb/s depending on the bandwidth (e.g., 20, 25, or 28 MHz) as well as the modulation and coding schemes used. IEEE 802.16 specifies different air interfaces for different frequency bands. In the 10–66 GHz band, the air interface is Wireless-SC (single carrier). In the 2-11 GHz band, three different air interfaces supporting non-line-of-sight (NLOS) communication can be used: WirelessMAN-SCa for single-carrier modulation, WirelessMAN-OFDM for OFDM-based transmission with time-division multiple access (TDMA), and WirelessMAN-OFDMA for orthogonal frequency-division multiple access (OFDMA). To enhance the data transmission rate, adaptive modulation and coding (AMC) is supported in IEEE 802.16.

**Medium Access Control Layer** — IEEE 802.16/WiMAX uses a connection-oriented MAC protocol that provides a mechanism for the SSs to request bandwidth from the BS. IEEE 802.16/WiMAX standard supports both frequency-division duplex (FDD) and time-division duplex (TDD) transmission modes. For TDD, a MAC frame is divided into uplink and downlink

For each connection, a separate queue (with size of  $X$  PDUs) is maintained for buffering the PDUs from the corresponding application. Adaptive modulation and coding is used to adjust the transmission rate dynamically in each transmission frame according to the channel quality.

subframes. The lengths of these subframes are determined dynamically by the BS and broadcast to the SSs through downlink and uplink MAP messages (UL-MAP and DL-MAP) at the beginning of each frame. The MAC protocol in the standard supports dynamic bandwidth allocation. In this case each SS can request bandwidth from the BS by using BW-request protocol data units (PDUs).

**Service Types in IEEE 802.16** — IEEE 802.16 standard defines the following four types of services, each of which has different QoS requirements:

- Unsolicited grant service (UGS) supports constant-bit-rate (CBR) traffic.
- Real-time polling service (rtPS) supports real-time traffic in which delay is an important QoS requirement.
- Non-real-time polling service (nrtPS) requires a QoS guarantee not as tight as that for rtPS. This is suitable for applications such as file transfer with guaranteed throughput.
- Best effort service (BE) is for traffic with no QoS guarantee requirement.

### SYSTEM MODEL

We consider a single BS serving multiple connections from different SSs through the TDMA/TDD access mode using single carrier modulation (e.g., as in WirelessMAN-SC). For each connection, a separate queue (with size of  $X$  PDUs) is maintained for buffering the PDUs from the corresponding application. AMC is used to adjust the transmission rate dynamically in each transmission frame according to the channel quality [1].

Bandwidth  $b$  is defined as the number of PDUs that can be transmitted in one frame using basic rate  $ID = 0$ . Using a queuing analytical model [13], various QoS performance measures such as *PDU dropping probability*, *queue throughput*, and *average delay for a PDU* can be obtained. We denote the average PDU transmission delay and throughput, when bandwidth  $b(i)$  is allocated to connection  $i$ , by  $\bar{d}(b(i))$  and  $\tau(b(i))$ , respectively.

### BANDWIDTH ALLOCATION AND CONNECTION ADMISSION CONTROL GAME

**Bandwidth Allocation and Connection Admission Control Procedure** — The proposed bandwidth allocation and admission control procedure works as follows. When a new connection is initiated, the new connection informs the BS of the type of the connection (i.e., rtPS or nrtPS), traffic parameters (i.e., arrival rate) and the QoS requirements (i.e., delay or throughput requirement). Then the BS invokes the bandwidth allocation and admission control algorithm.

In particular, the BS seeks the amount of bandwidth, to be taken from ongoing rtPS and nrtPS connections, to provide to the new connection. A conflicting situation arises since the ongoing rtPS and nrtPS connections want to maximize their QoS performance, while the BS wants to maximize its total utility. The Nash equilibrium gives the amount of bandwidth to be contributed by the ongoing rtPS and nrtPS connections to a new connection.

**Utility Function** — The utilities are used to determine the payoff for the game. In the system model under consideration, the utility for connection  $i$  depends on average delay  $\bar{d}(b(i))$  and throughput  $\tau(b(i))$  for rtPS and nrtPS, respectively, where  $b(i)$  denotes the amount of bandwidth allocated to connection  $i$ . We use the modified sigmoid function to obtain utility as a function of these performance measures. If  $d_{req}$  and  $\tau_{req}$  denote the delay and throughput requirements, the utility for rtPS and nrtPS connections can be expressed as a function of allocated bandwidth as follows:

$$U_i(b(i)) = \begin{cases} 1 - \frac{1}{1 + \exp(-g_{rt} \times (\bar{d}(b(i)) - d_{req} - h_{rt}))}, & \text{for rtPS} \\ \frac{1}{1 + \exp(-g_{nrt} \times (\tau(b(i)) - \tau_{req} - h_{nrt}))}, & \text{for nrtPS.} \end{cases} \quad (1)$$

**Game Formulation** — The noncooperative game for bandwidth allocation can be described as follows:

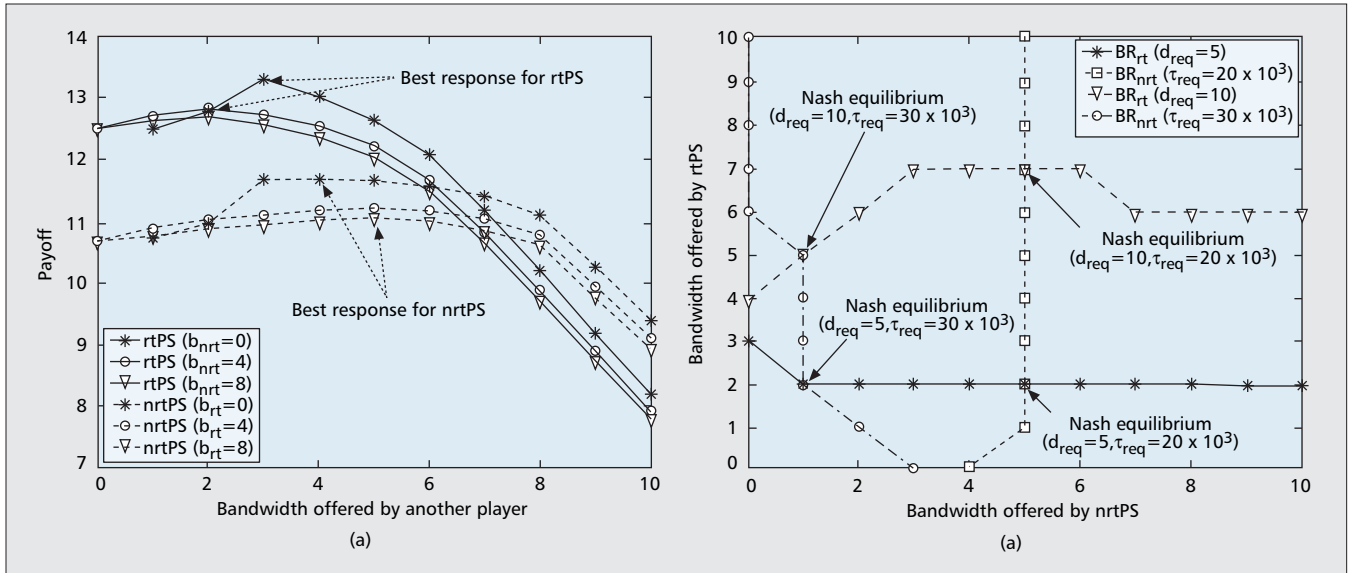
- **Players:** The two players of this game are the rtPS and nrtPS connections.
- **Strategies:** The strategy of each of the players is the amount of bandwidth offered to a new connection and is denoted by  $b_{rt}$  and  $b_{nrt}$ , respectively.
- **Payoffs:** The payoff for rtPS/nrtPS connections is the total utility of the ongoing rtPS/nrtPS connections (after bandwidth adaptation) plus the utility gained from the new connection, which is proportional to the amount of offered bandwidth by rtPS/nrtPS connections. Note that the sum of these payoffs gives the payoff for the BS. In particular, the payoff functions for rtPS and nrtPS connections, when the amounts of offered bandwidth are  $b_{rt}$  and  $b_{nrt}$  (i.e.,  $b_{rt}, b_{nrt} \in \{0, 1, \dots, b_{max}\}$ , where  $b_{max}$  is the highest amount of bandwidth that can be offered to a new connection), are defined as follows:

$$\phi_{rt}(b_{rt}, b_{nrt}) = \sum_{i \in S_{rt}} U_i(b(i)) + U_{new}(b_{rt}, b_{nrt}) \frac{b_{rt}}{b_{rt} + b_{nrt}} \quad (2)$$

$$\phi_{nrt}(b_{rt}, b_{nrt}) = \sum_{i \in S_{nrt}} U_i(b(i)) + U_{new}(b_{rt}, b_{nrt}) \frac{b_{nrt}}{b_{rt} + b_{nrt}} \quad (3)$$

where  $S_{rt}$  and  $S_{nrt}$  denote the sets of ongoing rtPS and nrtPS connections, respectively, and  $U_{new}(b_{rt} + b_{nrt})$  denotes the utility of a new connection with offered bandwidth of  $b_{rt} + b_{nrt}$ .

**Solution of the Game** — We consider Nash equilibrium as the solution of this game. The Nash equilibrium of a game is a strategy profile (list of strategies, one for each player) with the property that no player can increase his/her payoff by choosing a different action, given the other players' actions [14]. To determine the Nash equilibrium, we use the *best response function*. The best response function of the rtPS connections  $BR_{rt}(b'_{nrt})$ , given that the ongoing nrtPS connec-



■ **Figure 2.** a) Payoff functions under different offered bandwidth; b) best responses for rtPS and nrtPS connections.

tions choose strategy  $b'_{nrt}$ , is defined as  $BR_{rt}(b'_{nrt}) = \max_{b_{rt}} (\phi_{rt}(b_{rt}, b'_{nrt}))$ . Similarly, the best response function of nrtPS connections  $BR_{nrt}(b'_{rt})$ , given that ongoing rtPS connections choose strategy  $b'_{rt}$ , is expressed as  $BR_{nrt}(b'_{rt}) = \max_{b_{nrt}} (\phi_{nrt}(b'_{rt}, b_{nrt}))$ . The strategy pair  $(b^*_{rt}, b^*_{nrt})$  is a Nash equilibrium if and only if  $b^*_{rt} = BR_{rt}(b^*_{nrt})$  and  $b^*_{nrt} = BR_{nrt}(b^*_{rt})$ .

**Admission Control** — In order to guarantee delay and throughput requirements for rtPS and nrtPS connections, admission control is used. In this case the admission controller checks whether the solution of the game satisfies the QoS requirement of a new connection or not. If so, the admission controller checks whether the delay or throughput performance of the ongoing connections degrades below the target level. If not, a new connection is admitted, and rejected otherwise. Note that the amount of bandwidth allocated to a new connection is  $b^*_{rt} + b^*_{nrt}$ .

## PERFORMANCE EVALUATION

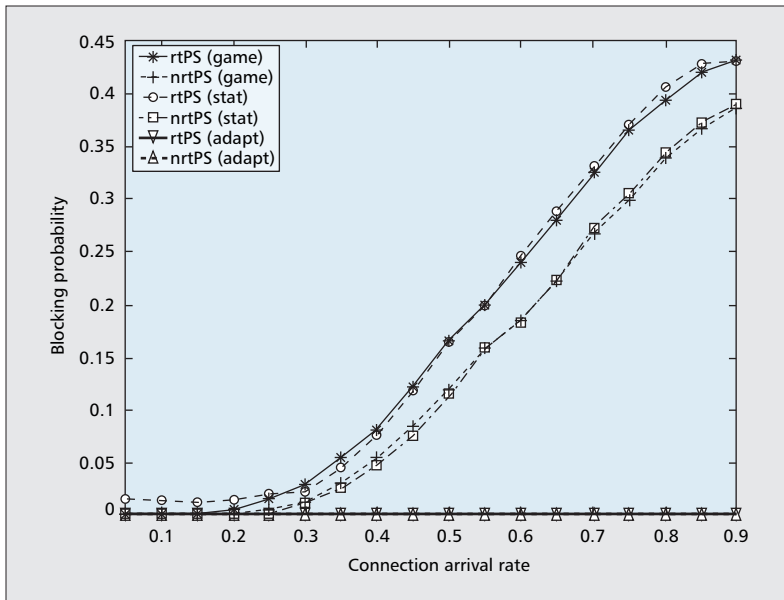
**Parameter Setting** — We consider a TDMA/TDD-based uplink transmission scenario from the SSS to a BS. The PDUs from a connection are buffered into a single queue, and the queue size for each of the connections is assumed to be 200 PDUs (i.e.,  $X = 200$ ). The transmission bandwidth is 25 MHz. The transmission frame size is 1 ms. AMC is used in which the modulation level and coding rate are adjusted based on the channel quality. When *rate ID 0* is used (i.e., binary phase shift keying [BPSK] and coding rate 1/2), the maximum bandwidth for data transfer is 10 Mb/s. We reserve 100 units of bandwidth for both rtPS and nrtPS traffic. For evaluating queuing performance for a particular connection, we assume that the average SNR is 15 dB.

The QoS constraints for the rtPS and nrtPS connections are assumed as  $\bar{d}_{req}(i) = 5$  frames and  $\tau_{req}(i) = 20$  PDUs/frame, respectively. The parameters of the utility function in Eq. 1 are set as follows:  $g_{rt} = 2$ ,  $g_{nrt} = 5$ ,  $h_{rt} = h_{nrt} = 0$ . We

compare the performance of the proposed scheme with that of admission control with static and adaptive bandwidth allocation schemes. For the adaptive scheme, the amount of allocated bandwidth is dynamically adjusted according to the number of ongoing connections. For the static scheme, an incoming connection is statically allocated with the minimum amount of bandwidth so that it is able to achieve the minimum required delay and throughput performances (for the rtPS and nrtPS connections, respectively). For this, the QoS performance measures from the queuing model presented in [13] are used.

**Payoff Function and Best Response** — Figure 2a shows the payoffs for ongoing rtPS and nrtPS connections in offering bandwidth to a new connection. As expected, the payoff first increases since the amount of bandwidth offered to a new connection can increase the utility by an amount which is higher than the amount of decrease in utility of the ongoing connections. However, when the offered bandwidth becomes large, the utility gained from the new connection cannot compensate the loss of total utility. Therefore, the payoff decreases. We observe that given another player's strategy (i.e., offered bandwidth), one player will have a particular best response. For instance, if nrtPS offers zero bandwidth to a new connection, the best response of rtPS would be to offer three units of bandwidth to a new connection. Similarly, if rtPS offers four units of bandwidth, the best response of nrtPS would be to offer five units of bandwidth to a new connection.

Figure 2b shows the best responses of rtPS and nrtPS connections under different requirements. The Nash equilibrium is the location at which the best responses of rtPS and nrtPS connections intersect. With different delay and throughput requirements for rtPS and nrtPS connections, different Nash equilibria are observed. As expected, when the delay or



■ **Figure 3.** Connection blocking probability for different admission control schemes.

throughput requirement becomes tighter, rtPS and nrtPS connections can offer only a small amount of bandwidth to a new connection.

**Performance of the Admission Control and Bandwidth Allocation Scheme** — We assume that the connection arrival process in the cell follows Poisson distribution, and the mean arrival rate varies from 0.05 to 0.9 connections/min. Connection holding time is exponentially distributed with an average of 20 min. The normal rate and peak rate of an incoming connection are assumed to be uniformly distributed in the range of 1–20 and 21–40 PDUs/frame, respectively. The probability of peak rate is also uniformly distributed between 0.1 and 0.5.

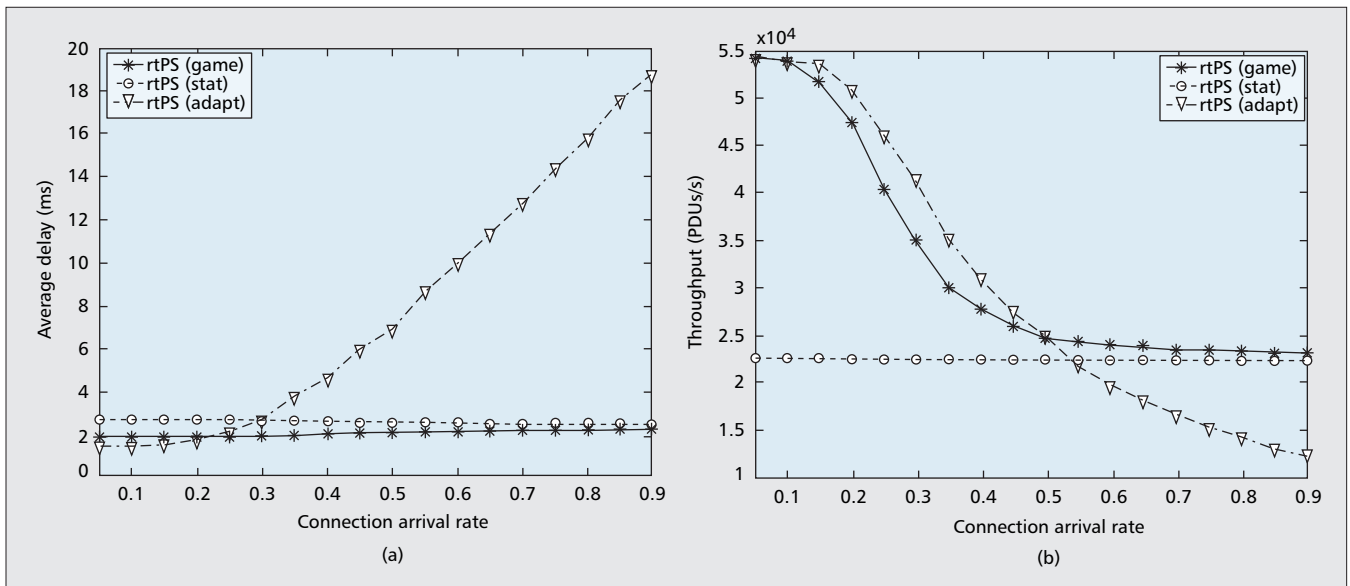
Figure 3 shows typical variations in connection blocking probability with traffic arrival rate.

Figures 4a and 4b show average delay and throughput for rtPS and nrtPS connections, respectively. With the adaptive scheme, even though the blocking probability is minimized (Fig. 3), the delay and throughput requirements cannot be met (Figs. 4a and 4b) when the traffic load in the cell becomes higher.

On the other hand, the static bandwidth allocation can satisfy the delay and throughput requirements (Figs. 4a and 4b). As expected, when the traffic load in a cell increases, the connection blocking probability increases for both the static and proposed schemes. To provide QoS guarantee to ongoing connections, some incoming connections must be blocked. Moreover, the game-theoretic solution to bandwidth allocation can provide smaller delay and larger throughput for rtPS and nrtPS connections, while the blocking probability performance is similar to that of the static scheme.

## CONCLUSIONS

We have first reviewed the popular game theory techniques and their applications in radio resource management for different types of wireless networks. Then we have presented an adaptive bandwidth allocation scheme for real-time and non-real-time polling services in IEEE 802.16/WiMAX networks. A noncooperative game has been formulated in which the amount of bandwidth to be offered to a new connection is determined from the Nash equilibrium. The solution of the game maximizes the total payoff for the connections (i.e., the payoff of the BS), which is a function of the QoS requirements (e.g., delay, throughput) of the connections. Based on the solution of the game, an admission control scheme has been proposed that ensures QoS guarantee for all the polling service connections in the network. The performance of the proposed bandwidth allocation and admission control framework has been evaluated by simulations and compared to that of traditional schemes.



■ **Figure 4.** a) Average delay; b) throughput for different admission control schemes.



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## REFERENCES

- [1] IEEE 802.16, Local and Metropolitan Area Networks — Part 16," 2003.
- [14] M. J. Osborne, *An Introduction to Game Theory*, Oxford Univ. Press, 2003.
- [2] E. Altman, V. S. Borkar, and A. A. Kherani, "Optimal Random Access in Networks with Two-Way Traffic," *Proc. IEEE PIMRC '04*, vol. 1, Sept. 2004, pp. 609–13.
- [3] L. Berlemann et al., "Radio Resource Sharing Games: Enabling QoS Support in Unlicensed Bands," *IEEE Network*, vol. 19, no. 4, July–Aug. 2005, pp. 59–65.
- [4] G. Tan and J. Guttag, "The 802.11 MAC Protocol Leads to Inefficient Equilibria," *Proc. IEEE INFOCOM '05*, vol. 1, Mar. 2005, pp. 1–11.
- [5] S. Koskie and Z. Gajic, "A Nash Game Algorithm for SIR-based Power Control in 3G Wireless CDMA Networks," *IEEE/ACM Trans. Net.*, vol. 13, no. 5, Oct. 2005, pp. 1017–26.
- [6] F. Meshkati et al., "An Energy-Efficient Approach to Power Control and Receiver Design in Wireless Data Networks," *IEEE Trans. Commun.*, vol. 53, no. 11, Nov. 2005, pp. 1885–94.
- [7] H. Lin et al., "ARC: An Integrated Admission and Rate Control Framework for Competitive Wireless CDMA Data Networks Using Noncooperative Games," *IEEE Trans. Mobile Comp.*, vol. 4, no. 3, May–June 2005, pp. 243–58.
- [8] J. Virapanicharoen and W. Benjapolakul, "Fair-Efficient Guard Bandwidth Coefficients Selection in Call Admission Control for Mobile Multimedia Communications using Game Theoretic Framework," *Proc. IEEE ICC '04*, vol. 1, June 2004, pp. 80–84.
- [9] Z. Han, Z. Ji, and K. J. R. Liu, "Power Minimization for Multi-Cell OFDM Networks using Distributed Non-Cooperative Game Approach," *Proc. IEEE GLOBECOM '04*, vol. 6, Nov.–Dec. 2004, pp. 3742–47.
- [10] M. Felegyhazi, J. Hubaux, and L. Buttyan, "Nash Equilibria of Packet Forwarding Strategies in Wireless Ad Hoc Networks," *IEEE Trans. Mobile Comp.*, vol. 5, no. 5, Sept.–Oct. 2006, pp. 463–76.

- [11] V. Srivastava et al., "Using Game Theory to Analyze Wireless Ad Hoc Networks," *IEEE Commun. Surveys & Tutorials*, vol. 7, no. 4, 4th qtr. 2005, pp. 46–56.
- [12] J. O. Neel, J. H. Reed, and R. P. Gilles, "Convergence of Cognitive Radio Networks," *Proc. IEEE WCNC '04*, vol. 4, Mar. 2004, pp. 2250–55.
- [13] D. Niyato and E. Hossain, "A Game-Theoretic Approach to Bandwidth Allocation and Admission Control for Polling Services in IEEE 802.16 Broadband Wireless Networks," *Proc. 3rd Int'l. Conf. QoS in Heterogeneous Wired/Wireless Networks (QShine'06)*, Canada, Aug. 7–9, 2006.

## ADDITIONAL READING

- [1] C. T. Chou and K. G. Shin, "Analysis of Adaptive Bandwidth Allocation in Wireless Networks with Multilevel Degradable Quality of Service," *IEEE Trans. Mobile Comp.*, vol. 3, no. 1, Jan.–Mar. 2004, pp. 5–17.

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